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TWO-PHASE FLOW AND HEAT TRANSFER IN MICROCHANNELS

TECHNICAL REPORT

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## ABSTRACT

The purpose of this study was to investigate fluid mechanic and heat transfer characteristics of two-phase two-component flow in rectangular microchannels. Experiments were conducted using rectangular aluminum channels with hydraulic diameters ranging between 56  $\mu\text{m}$  and 256  $\mu\text{m}$  and aspect ratios which varied from 0.5 to 1.5. Both single- and two-phase tests were conducted using water and gaseous argon, helium, and nitrogen as the working fluids. The Reynolds number for both types of experiments ranged from approximately 50 to nearly 10,000. The Nusselt number ranged between 0.0002 and 70. The single- and two-phase experimental data were empirically correlated, using parameters derived from a dimensional analysis. Experimental data was also used to correlate the unknown variables in derived analytical expressions.

Both single- and two-phase tests yielded excellent correlations of the friction factor. For Nusselt number, the correlations were fair to poor. Reynolds number and the combination of Reynolds number and Prandtl number were the dominant parameters in the prediction of pressure drop and heat transfer rate, respectively, in both single- and two-phase flows. The pressure drop predictions based on the semi-empirical relations by Martinelli for two-phase flows were shown to substantially over predict the pressure drop measured in these experiments.

Other findings showed that for single-phase flow, the transition from laminar to turbulent regimes of the friction factor was suppressed as the channel hydraulic diameter decreased. For gases, the suppression occurred in varying degrees between hydraulic diameters of 80  $\mu\text{m}$  and 150  $\mu\text{m}$ , with no transition seen below 80  $\mu\text{m}$ . For water, no transition was seen for any of the channel configurations tested. Two-phase friction factor data showed a definite transition from laminar to turbulent regimes at a Reynolds number of 3,000 for all channel configurations tested. It is believed that the transition was due to the intense pressure fluctuations associated with two-phase flows. For the Nusselt number, both single- and two-phase data was seen to parallel, though lower, the macroscale turbulent regime predictions. Also, no transition from laminar to turbulent regimes was seen in the Nusselt number data over the range of Reynolds numbers tested.



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## CHAPTER 1

### INTRODUCTION

The area of two-phase forced convection heat transfer in microtubes and microchannels is a burgeoning field. Though extensive work has been done in the area of single-phase liquid and gas flow through microgeometries [Choi (1991), Yu (1995), Harley et al. (1989a and 1989b), Pfahler et al. (1991, 1990a, and 1990b)], the only area where detailed analysis of two-phase heat transfer in microgeometries has taken place is in the specialized area of micro heat pipes. As the field of microfluidics continues to grow, it is becoming increasingly important to understand the mechanisms involved with heat transfer in two-phase flow through microgeometries. This importance is reiterated by the increasing number of applications which use phase change as the principal mechanism to conduct or remove heat. These fields include bioengineering and biotechnology, aerospace, mini heaters, and mini heat exchangers, electronics and microelectronics, material processing and thin film deposition technology, etc.[Peng and Wang (1993)]. Other areas of research include cooling of laser diode arrays, micro Joule-Thompson cooling devices, and the evaporator and condenser sections of micro vapor compression cycles [Drost et al. (1994)]. Much work has been done by Little (1990a, 1990b, and 1984) in developing a commercially available mini Joule-Thompson cooling device capable

of dissipating 0.25W over a few square centimeters at cryogenic temperatures. In addition, the development of a microscale Joule-Thompson cooling device is currently underway at the Institute for Micromanufacturing. This program seeks to design, fabricate using LIGA technology, package, and test a complete microscale device which may have applicability toward electronic chip cooling. A micro heat pump concept has been proposed by researchers from Battelle (Pacific Northwest National Laboratories) [Drost et al. (1994)]. The PNNL concept incorporates a sheet architecture in which the various processes of a vapor compression refrigeration system are divided into individual unit operations and sheets of material with embedded micro mechanical systems are developed that can perform each unit operation. The sheet unit operations could then be combined together to form more complex systems. The major advantage of two-phase flow is that the temperature gradient along the length of the channel is much smaller than in single-phase flow, due to the phase change phenomena. This results in larger values of the heat transfer coefficient and reduces the requirement of large liquid flow rates.

This research is intended to help bridge the gap between the existing, mainly empirical, research on single-phase flow and two-phase flow boiling of fluids in microchannels. Two component flow was used in this research instead of boiling flow. This allowed the controlling hydrodynamic and heat transfer mechanisms to be more easily identified. Governing equations for two-phase flow, both homogeneous and separated, were developed. The different flow regimes (plug, slug, etc.) were defined and discussed. The resulting equations were compared with existing experimental data and empirical

formulas. Also, new empirical formulas were derived from data that were taken as part of this research. These results were compared to the widely accepted macro scale two-phase pressure drop equations by Lockhart and Martinelli (1949), Martinelli et al. (1944), and Martinelli and Nelson (1948) and a flow regime map developed by Baker (1954).

Because this research was mainly empirical, testing of several fluids flowing through various channel configurations was carried out. To help answer some conflicting results reported previously, single-phase tests were conducted. The single-phase tests were conducted because the two-phase predictions of Martinelli rely entirely on single-phase coefficients and equations. The data that were taken were used, along with a dimensional analysis, to derive empirical formulas for pressure drop and rate of heat transfer rate in microchannels. It was intended that these experiments would shed light on the dominant mechanisms present in single and two-phase flow. Also, it was intended that a quantitative expression could be developed that would help distinguish macro- and microscale flow regimes in two-phase flow.

## CHAPTER 2

### LITERATURE SURVEY

Because the main area of focus of this research was two phase flows, a comprehensive review of single phase flow will not be given. Only a few of the papers used for comparisons will be discussed. However, excellent reviews of this area can be found in Bailey (1996), Choi (1991), and Yu (1995). To date, only one paper considering two-phase two-component flow (with no phase change) in capillary tubes was found, Suo and Griffith (1964). However, there exist several empirical studies of flow boiling in microchannels. For completeness, a review of these articles is given below. Though not usually considered with flow boiling, a large volume of empirical and analytical studies have been conducted on micro heat pipes. The research on micro heat pipes has produced many insights into the mechanics of phase change and will be very useful in future research of flow boiling in microchannels. For more information on micro heat pipes, please see Babin et al. (1990), Badran et al. (1993), Cao et al. (1993), Cotter (1984), Duncan and Peterson (1994), Gerner et al. (1992), Khrustalev and Faghri (1994), Longtin et al. (1992), Mallik et al. (1992), Peterson (1992), Peterson et al. (1993), Peterson et al. (1991), Swanson and Peterson (1995), Swanson and Peterson (1993), and Wu and Peterson (1991a and 1991b). For comparisons made later in this section, some definitions are

necessary: 1) Open-channel flow boiling is forced convection boiling over external microstructure enhanced surfaces. 2) Closed-channel flow boiling is forced convection through enclosed tubes or channels. And, 3) Pool boiling is boiling on external microstructure enhanced surfaces with no forced movement of the fluid.

### Single Phase Flow in Microchannels

Because of the reviews mentioned above, only the pertinent information on friction factors and Nusselt numbers will be presented.

#### Friction Factor

For fluid flow in macroscale rectangular channels, Hartnett and Kostic (1989) gave a relation for the Manning friction factor as

$$f \cdot Re = 94(1 - 1.3553AR + 1.9467AR^2 - 1.7012AR^3 + 0.9564AR^4 - 0.2537AR^5) \quad (2.1)$$

where AR is the aspect ratio of the rectangular channel (height /width). Though this is a macroscale equation, it provides a useful comparison.

Wu and Little (1993) have done extensive investigations of small to medium aspect ratio glass channels. Correlations for laminar, transition, and turbulent flow regimes were

given as

$$f = \frac{(110 \pm 8)}{Re} \quad Re \leq 900 \quad (2.2a)$$

$$f = 0.165(3.48 - \log(Re))^{2.4} + (0.081 \pm 0.007) \quad 900 \leq Re \leq 3,000 \quad (2.2b)$$

$$f = \frac{(0.195 \pm 0.017)}{Re^{0.11}} \quad 3,000 \leq Re \leq 15,000 \quad (2.2c)$$

Pfahler et al. (1991, 1990a, and 1990b) and Harley et al. (1989a and b) tested very low aspect ratio channels and compared their experimental findings with the Navier-Stokes predictions. For hydraulic diameters of nearly 40 microns or below, the measured pressure drop showed larger deviation from the Navier-Stokes predictions than did the channels with hydraulic diameters larger than 40 microns. This work seems to have indicated that there may exist a lower limit to macroscale theory and that below this theory, microscopic effects must be considered for accurate predictions of a pressure drop.

Choi (1991) was one of the first investigators to test gas flow in microtubes instead of microchannels. The results show that not only is the friction factor lower than predicted, but it is Reynolds number dependent in both laminar and turbulent regimes. The expressions for friction factor developed by Choi (1991) were given as

$$f = \frac{64}{Re} \left[ 1 + (30 \pm 7) \frac{u}{DC_a} \right] \quad Re \leq 2,300 \quad (2.3a)$$

$$f = 0.140 Re^{-0.182} \quad 4,000 \leq Re \leq 18,000 \quad (2.3b)$$

where  $\nu$  is the kinematic viscosity,  $D$  is the inside diameter of the microtubes, and  $C_a$  is the acoustic velocity.

Yu (1995) continued the work of Choi (1991) by considering flow of water and nitrogen gas through microtubes. The expressions developed for friction factor were

$$f = \frac{50.13}{Re} \quad Re \leq 2,000 \quad (2.4a)$$

$$f = 0.302 Re^{-0.25} \quad 6,000 \leq Re \leq 20,000 \quad (2.4b)$$

#### Nusselt Number

Choi (1991) also conducted heat transfer experiments in micro tubes. Choi (1991) concluded that Reynolds analogy does not hold for microchannel flow and that this may be due to suppression of the turbulent eddies in the small channels [Bailey (1996)]. Correlations given for the Nusselt number were

$$Nu = 0.000972 Re^{1.17} Pr^{1/3} \quad Re < 2,000 \quad (2.5a)$$

$$Nu = (3.82 \times 10^{-6}) Re^{1.96} Pr^{1/3} \quad 2,500 \leq Re \leq 20,000 \quad (2.5b)$$

For Nusselt number predictions in turbulent regimes, Wu and Little (1983) and Yu (1995) developed these expressions, respectively,

$$Nu = 0.00222 Re^{1.09} Pr^{0.4} \quad Re \leq 3,000 \quad (2.6a)$$

$$Nu = 0.0007 Re^{1.2} Pr^{0.2} \quad 6,000 \leq Re \leq 20,000 \quad (2.6b)$$



### Two-Phase Flow Boiling in Microchannels

The amount of theoretical development in closed-channel flow boiling is very limited. In fact the only general analytical developments found in this area were equations for the pressure drop in flow boiling given by Bowers and Mudawar (1994). However, these equations were based on macroscale theory. These pressure drop equations included the contributions of single-phase flow, boiling flow, and outlet conditions of the channel, where the boiling pressure drop consisted of acceleration and friction effects. Other than these equations, only heat flux correlations and experimental data were given.

### Experimentation and Findings

Zhukov and Yarmak (1990) presented a strictly empirical look at the boiling behavior of superconducting magnet windings. The experimental apparatus consisted of a 0.8 mm diameter tube 1 m long with the first 150 mm heated. For nitrogen and helium respectively, "The heat generation was up to 35 W or 20 W," the mass flow rates varied from 35 - 520 kg/m<sup>2</sup>s or 40 - 237 kg/m<sup>2</sup>s, and the inlet qualities varied from 0.0 - 0.58 or 0.0 - 0.22. The experiment considered the onset of boiling crisis from a timed heat pulse of known power. The duration of the rectangular heating pulse varied from 1 ms to 12.5 s. The change in wall temperature resulting from the heat pulse duration was measured and shown in graphical form. Though the data given were not conducive to the critical heat flux (CHF) comparisons made later, several important observations were made. First, "the onset of boiling under heat pulse should bring about an abrupt pressure rise in the heated section. The pressure rise can cause the flow to stop quickly and may even result in

reverse flow." Second, "the vapor phase growth rate in channels with pulse heat should be much lower than that corresponding to the steady state boiling regime." And third, "helium heat transfer crisis appears to be due to the pressure jump over the critical point at the onset of boiling."

Peng and Wang (1993) experimentally investigated the transition between the regions of forced convection and nucleate boiling. The experimental apparatus utilized a split flow system to control the flow rate accurately through the test section. The fluid used for testing was deionized water with an inlet temperature varied from 30°C - 60°C. For water at ambient pressure, boiling ensued "at a little over 100°C." Three channels were machined into a stainless steel plate with a width of 15 mm, a length of 60 mm, and a thickness of 2 mm. The flow channels were 0.6 mm wide and 0.7 mm high. The channels were heated by electrically heating the stainless steel. Because of this heating configuration, nonuniform spacing of the channels was chosen to provide uniform heat flux to all three sides of the channels. The top surface of the test section was Pyrex glass so that the flow could be viewed. Thermocouples were located at each end of each channel and their average value taken as the wall temperature in the data presented.

Experimental observation yielded two important events; 1) the boiling regime was fully developed nucleate boiling, and 2) bubbles did not grow in microchannel boiling. Peng and Wang (1993) mention "that the bubble growth in liquid might be concerned with the scale of the liquid bulk. If the scale of liquid bulk is large enough, bubbles grow, otherwise, no bubbles grow and exist in liquid" flowing in microchannels. What this is

saying is that in microchannel flow, the fluid properties vary enough from the bulk properties to provide a noticeable change in flow behavior. The experimental results show a dramatic increase in the slope of the heat flux when the transition to boiling is reached. Before the transition, the data was spread as would be expected. However, after the transition, the values of the heat flux for all tests were very close. Peng and Wang (1993) conclude that in this region, "heat flux may be affected by other factors besides flow velocity and liquid subcooling" and that further study is warranted to determine the mechanisms involved. Peng and Wang (1993) also compare existing macro scale Nusselt number correlations to their experimental data. For a given Reynolds number, the forced convection data was much higher than that predicted analytically. The nucleate boiling data, on the other hand was slightly lower than that predicted analytically but does show a similar trend near the region where the equations intersect. Peng and Wang (1993) do not try to explain this behavior and simply state that, "The reasons promoting the transitions and the behaviors are not recognized or understood." Peng and Wang (1993) then compared their data to experimental data of flow boiling in a 9 mm tube. There were two items of importance drawn from these comparisons; 1) before transition, the heat flux was about the same or lower for the microchannel than for the 9 mm tube; and, 2) after transition, the heat flux was markedly higher for the flow in microchannels. Other conclusions Peng and Wang (1993) reached were; 1) flow "velocity and liquid subcooling appears to have no obvious effect on the flow nucleate boiling" and, 2) "No partial (nucleate) boiling ... (is) observed or inspected for the transition from single-phase liquid

convection to nucleate boiling." Peng and Wang (1993) mention that number two above was "very strange," but no explanation was given. However, this either was an optical effect, or the experimental configuration was such that the flow transitioned past the regime of partial nucleate boiling. Finally, an observation made by Peng and Wang (1993) was "that no bubble(s) grow for flow boiling of liquid flowing through microchannels." This, also, was probably an optical effect caused by the combination of the tendency of the bubble size to decrease as it condensed back to a liquid and the tendency of the bubble size to increase with the decreasing pressure in the channel.

Bowers and Mudawar (1994) presented an experimental comparison of mini- (2.54 mm) and microchannel (510  $\mu\text{m}$ ) heat sinks with a 1 cm heated length. The 1 cm square test sections were able to accommodate three minichannels and 17 microchannels across their width. The working fluid used was R-113 with a flow rate of 19 - 95 ml/min, an inlet subcooling of 10 - 32°C, and a constant inlet pressure of 1.38 bar. Assuming a homogeneous two-phase flow model, Bowers and Mudawar (1994) used a macroscale pressure drop equation accounting for frictional and acceleration losses. The expression, considering acceleration losses, was not applicable to this research. However, the expression, considering frictional losses, was applicable. From Collier (1981),

$$-\left(\frac{dP}{dz}\right)_F = \left(\frac{2f_{TP}G^2}{\rho_f D}\right) \left[1.0 + x \left(\frac{v_{fg}}{v_f}\right)\right] \quad (2.7)$$

Integrating over the exit length (unheated) of the channel, Bowers and Mudawar (1994) obtained

$$\Delta P_o = \left( \frac{2 f_{TP} G^2 L_o}{\rho_f D} \right) \left[ 1.0 + x_L \left( \frac{v_{fg}}{v_f} \right) \right] \quad (2.8)$$

where  $\Delta P_o$  is the pressure drop through the unheated section,  $f_{TP}$  is the two-phase friction factor,  $G$  is the total mass velocity,  $L_o$  is the length of the unheated section,  $\rho_f$  is the density of the liquid,  $x_L$  is the quality at the entrance to the unheated section,  $v_{fg}$  is the difference in specific volume of the liquid and gas, and  $v_f$  is the specific volume of the liquid. Collier (1981) gave a range of  $f_{TP}$  as 0.0029 to 0.005. Bowers and Mudwar (1994) used the conservative estimate of 0.005. Equation (2.8) is directly applicable to this study. It can be used to both predict a pressure drop, given a correlation for the two-phase friction factor, or to help correlate the two-phase friction factor, given a measured pressure drop. It is shown, in Chapter 3, that equation (2.8) is virtually identical to the macroscale expression for the pressure drop derived for this study.

Besides the pressure model, a CHF correlation was given and both were shown to be in good agreement with the experimental data. The effect on heat transfer on several variables was discussed, including pressure drop (extensive), inlet subcooling, superheated exit conditions, and size. One problem associated with boiling heat transfer is "the production of vapor bubbles that lead not only to increased heat transfer but also to increased pressure drop." This problem is magnified, as would be expected, as the size of

the channel decreases. The inlet subcooling is shown to have little or no effect on the CHF. This agrees with the findings of Peng and Wang (1993). Some other features highlighted by the experimental results were; 1) "The two heat sinks demanded minimal flow rates..." (to allow complete evaporation); 2) "The small diameters of mini- and microchannels suggest an increased frequency and effectiveness of droplet impact with the channel wall in regions of high  $x_L$  (quality) values"; and, 3) "The small overall size of the heat sink seems to greatly contribute to delaying CHF by conducting heat away from the downstream region undergoing either partial or total dryout to the boiling region of the channel."

#### Experimental Data Comparison

Figures 2.1 and 2.2 are graphs of the CHF and resulting heat transfer coefficient ( $h$ ) versus the temperature difference ( $T_{\text{wall}} - T_{\text{inlet}}$ ) as compiled from Peng and Wang (1993) and Bowers and Mudawar (1994). The data points of He (1988) were referenced by Peng and Wang (1993). One important point shown in Figure 2.1 is the lack of dependency of the CHF on the liquid velocity. For the data given by Peng and Wang (1993), the CHF value of  $1.3 \text{ MW/m}^2$  corresponds to a liquid velocity of  $2.32 \text{ m/s}$  whereas the CHF value of  $0.9 \text{ MW/m}^2$  has the highest velocity of  $3.6 \text{ m/s}$ . Comparing the rectangular channel to the 9 mm tube shows the inefficiency of the 9 mm tube. A much larger temperature difference was required to achieve the same heat flux. It should be pointed out that the liquid velocity in the 9 mm tube was much lower than in the rectangular channels. Looking at the data for the micro- and minichannels, one can see

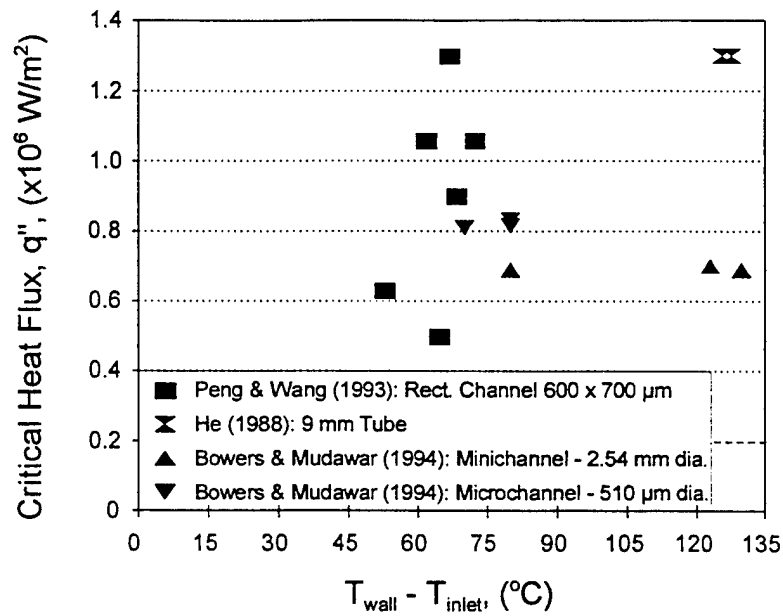


Figure 2.1: Critical heat flux comparison for mini- and microgeometries.

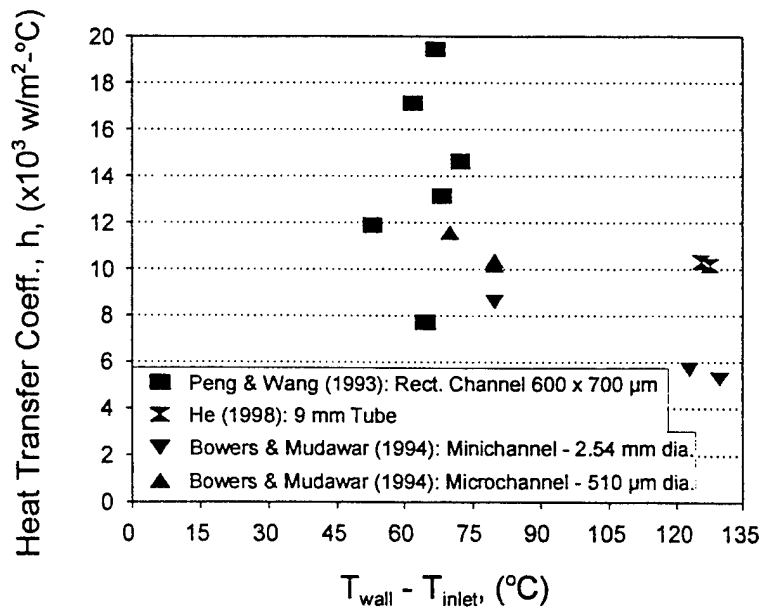


Figure 2.2: Heat transfer coefficient comparison for mini- and microgeometries.

that though there is more heat transfer per channel for the mini channels, the increased density of the microchannels make them a more effective system. Again, the one drawback to microchannels is the high pressure drop. In Figure 2.2, the same trends are seen and the effectiveness of the different configurations is more pronounced.

As a final comparison, Figure 2.3 presents the range of critical heat flux achieved for various flow configurations. The pool boiling range was developed from Anderson and Mudawar (1989), Marto and Lepere (1982), Mudawar and Anderson (1993 and 1990), and Wright and Gebhart (1982). For more information on the open-channel flow boiling, micro heat pipes, and pool boiling included in this figure, see Stanley et al.(1996). Also shown in Figure 2.3 is the ultra-high CHF achieved by Mudawar and Bowers (1995) using very high flow rates and pressures in microtubes. Figure 2.3 raises some interesting points. First, open-channel micro flow boiling achieves the highest practical CHF. However, it is the least researched of these areas and one of the most practical. Second, micro heat pipes which are the most practical and most researched, do not achieve the level of CHF possible with the other flow configurations. Third, pool boiling can achieve reasonably high values of CHF over a wide range of temperatures. And Fourth, the data from Mudawar and Bowers (1995) is offered to show what values of CHF can be achieved in closed-channel micro flow boiling. Unfortunately, this value is not currently practical in microsystems due to the high pressure and high flow rate required. However, as new and more powerful micropumps are developed, this limit will be met and even raised.



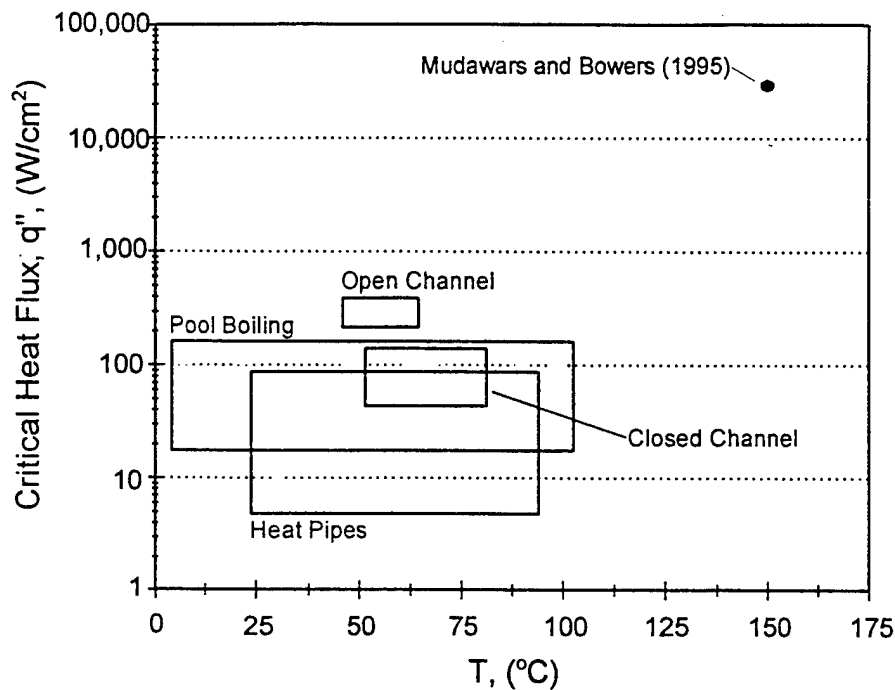


Figure 2.3: Critical heat flux ranges.

Though heat pipes will not be discussed in detail, as mentioned, one particular finding is worth noting. Swanson and Peterson (1993) found that when the operating radius of the micro heat pipes reached nearly 20 microns or below, molecular effects such as the Margoni effect must be considered to accurately model the heat pipes. That is, they found a quantifiable limit to the macroscale theory of heat pipes. This seems to indicate, along with some of the work done on single-phase gas flow in microchannels, that there is a definite lower limit to the usual macroscale theory of fluid flow. However, what this definite limit is and how to predict it for various types of fluid flow is still under debate and will require much more research in this area.

## Two-Phase Two-Component Flow in Channels

### Macroscale

By far, the most widely used and accepted correlation for the prediction of pressure drop in two-phase, two-component, flow without heat transfer are the semi-empirical correlations of Lockhart and Martinelli (1949), Martinelli et al. (1944), and Martinelli and Nelson (1948). The correlations are based on the pressure drop that occurs when only liquid flowing through the channel is multiplied by a factor which accounts for two-phase effects. Or,

$$\left( \frac{\Delta p}{\Delta L} \right)_{TP} = \phi_f^2 \left( \frac{\Delta p}{\Delta L} \right)_f \quad (2.9)$$

where  $(\Delta p/\Delta L)_{TP}$  is the pressure drop for the two-phase flow, and  $(\Delta p/\Delta L)_f$  is the pressure drop if only the liquid was flowing through the channel. The friction-pressure-drop parameter  $\phi_f$  is based on  $X$ , termed the Martinelli parameter. This parameter is

$$X^2 = \frac{(\Delta p/\Delta L)_f}{(\Delta p/\Delta L)_g} = \frac{C_f (Re_g)^m \rho_g}{C_g (Re_f)^n \rho_f} \left( \frac{1-x}{x} \right)^2 \quad (2.10)$$

where  $x$  is the fluid quality,  $\rho$  is the density of the liquid (f) and gas (g) phases respectively, and  $Re_f$  and  $Re_g$  are the liquid and gas Reynolds numbers. The Reynolds numbers are calculated from

$$Re = \frac{\dot{m}D}{A\mu} \quad (2.11)$$

where the mass flow rate is of each fluid separately and viscosity is determined for each fluid at the measured temperature and pressure of the two-phase flow. The other coefficients  $C_l$ ,  $C_g$ ,  $m$ , and  $n$  in the Martinelli parameter are based on macroscale single phase correlations. The values of these coefficients are given in Table 1. From Barron (1985), the Martinelli parameter is related to the frictional pressure drop parameter by

$$\phi_f = \frac{(X^2 + CX + 1)^{1/2}}{X} \quad (2.12)$$

where the values of  $C$  are given in Table 2. The pressure drop of only the liquid flowing through the channel is found, from macroscale theory, as

$$\left( \frac{\Delta p}{\Delta L} \right)_f = \frac{f (\dot{m}_f/A)^2}{2 g_c \rho_f D} \quad (2.13)$$

where  $f$ , the friction factor, is also determined using macroscale theory.

Table 1: Martinelli Constants

| Constant | Laminar Regime<br>Re < 2,500 | Turbulent Regime<br>2,500 < Re < 50,000 |
|----------|------------------------------|-----------------------------------------|
| $C_f$    | 64                           | 0.316                                   |
| $C_g$    | 64                           | 0.316                                   |
| m        | 1                            | 0.25                                    |
| c        | 1                            | 0.25                                    |

Table 2: Values of Constant C

| Liquid Flow Regime | Gas Flow Regime | C  |
|--------------------|-----------------|----|
| Laminar            | Laminar         | 5  |
| Turbulent          | Laminar         | 10 |
| Laminar            | Turbulent       | 12 |
| Turbulent          | Turbulent       | 20 |

Martinelli and Nelson (1948) also developed expressions for boiling two-phase flow. Because of the phase change involved, both friction and momentum pressure drops must be considered. Though the frictional pressure drop is not applicable to the proposed research, the momentum pressure drop is applicable. From Barron (1985),

$$\Delta p_m = \frac{\phi_m (\dot{m}_f + \dot{m}_g)^2}{g_c \rho_f A^2} \quad (2.14)$$

with the momentum-pressure-drop parameter given by

$$\phi_m = \frac{(1-x_{out})^2}{\alpha_{f,out}} - \frac{(1-x_{in})^2}{\alpha_{f,in}} + \left( \frac{x_{out}^2}{1-\alpha_{f,out}} - \frac{x_{in}^2}{1-\alpha_{f,in}} \right) \left( \frac{\rho_f}{\rho_g} \right) \quad (2.15)$$

where  $\alpha$  is the volume fraction of liquid at the entrance and exit of the channel. Similar to before, the Martinelli parameter,  $X$ , and the momentum-pressure-drop parameter are related by

$$\phi_m = \frac{X}{(X^2 + CX + 1)^{1/2}} \quad (2.16)$$

where the coefficient  $C$  is given in Table 2. This equation is applicable even though the quality does not change between the inlet and outlet. This is because the volume fraction of liquid does change. The reason is that the volume of the gas increases as it flows through the channel due to the local pressure decreasing. Therefore, these relations can be compared directly to the data taken in this research by combining the frictional and momentum pressure drop equation. Or,

$$\Delta p = \Delta p_f + \Delta p_m \quad (2.17)$$

Also of interest in this area is the flow regime map developed by Baker (1954). Using two parameters,  $G/\lambda$  and  $\lambda L\psi/G$ , Baker (1954) was able to plot seven different flow regimes on one graph, as seen in Figure 2.4. For the two parameters,  $G$  and  $L$  are the gas

and liquid mass flow rates per unit area, respectively. The units for  $G$  and  $L$  in Figure 2.4 are  $\text{lbm/hr-ft}^2$ .  $\psi$  and  $\lambda$  are defined by

$$\lambda = [(\rho_g/\rho_a)(\rho_f/\rho_w)]^{1/2} \quad (2.18)$$

$$\psi = (\sigma_w/\sigma_f)[(\mu_f/\mu_w)(\rho_w/\rho_f)^2]^{1/3} \quad (2.19)$$

where the subscripts refer to air (a), water (w), the particular liquid (f), and the particular gas (g). The values of the properties of the air and water are taken at standard atmospheric conditions.

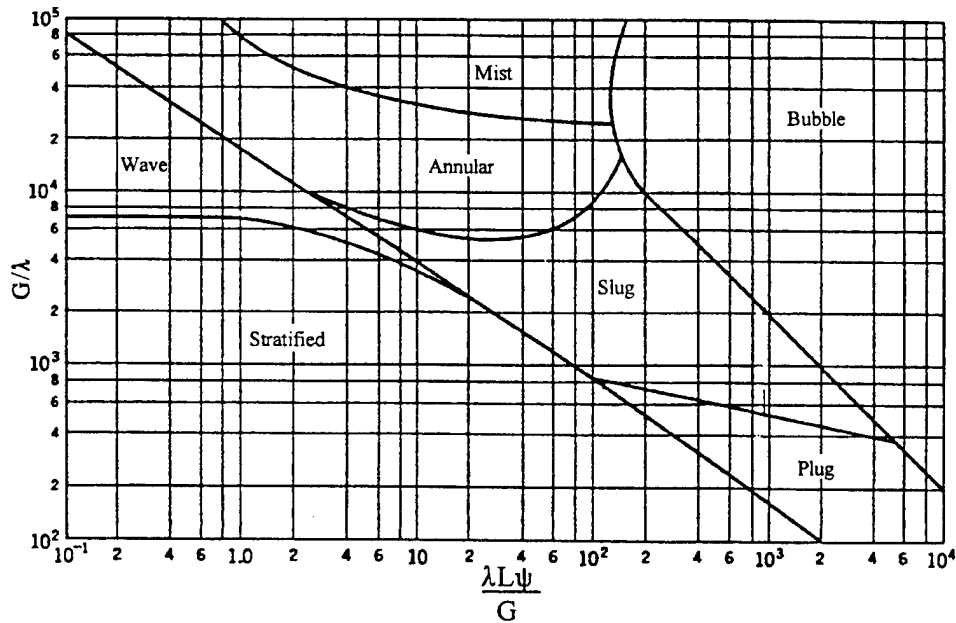


Figure 2.4: Flow Regime Map by Baker (1954).

### Microscale

The only work found concerning two-phase two-component flow was that conducted by Suo and Griffith (1964), mainly an analytical study of two-phase gas-liquid flows in capillary tubes. Though a flow regime map for annular, slug, and bubbly-slug flow was developed, the work centered on analyzing the velocities associated with long bubble motion. A dimensional analysis was conducted along with a small amount of experimentation. Some of the more important findings of the research were: 1) Surface tension and viscosity dominate over gravity. 2) For large liquid to gas viscosity ratios, the liquid film around the bubble did not move. 3) For small liquid to gas viscosity ratios, the liquid film around the bubble did move. 4) The original seven dimensionless parameters were reduced to three,  $\lambda$ ,  $\psi$ , and  $L_s/r_o$  (slug length/ radius of tube). The parameters  $\lambda$  and  $\psi$  were defined as

$$\lambda \equiv \frac{\mu_f^2}{\rho_f^2 \sigma r_o} \quad ; \quad \psi \equiv \frac{\mu_f U_B}{\sigma} \quad (2.20)$$

where  $\mu_f$  and  $\rho_f$  are the liquid viscosity and density, respectively,  $\sigma$  is the surface tension,  $U_B$  is the bubble velocity, and  $r_o$  is the tube inside diameter. For the flow regime map, the transition from slug flow was not characterized by an explicit mathematical expression. However, it was plotted on a graph of  $\psi$  versus the volume rate fraction of liquid

$(Q_f / Q_g + Q_f)$ . The transition between slug flow and bubbly-slug flow was more rigorously defined by

$$\frac{\psi^2}{\lambda^2} = Re \cdot We = 2.8 \times 10^5 \quad (2.21)$$

where  $Re$  and  $We$  are the Reynolds number and Weber number, respectively.



## CHAPTER 3

### GOVERNING EQUATIONS AND FLOW REGIMES

One of the main purposes of this research is to compare existing two-phase macroscale equations to experimental data on two-phase flow in microchannels. In this chapter, the governing equations for macroscale two-phase flow will be developed. These governing equations consist of the Conservation of Mass, Momentum, and Energy. Governing equations will be presented for both the homogeneous flow model and the separated flow model. The homogeneous flow model assumes average fluid properties based on the ratio of the liquid and gas components. The separated flow model, on the other hand, develops governing equations based on the individual behavior of each component. The one assumption that will be utilized in both models is one-dimensional flow. That is, any changes in properties across the height or width of the channel are very small compared to any changes along the length of the channel. Additionally, in this chapter, the various possible two-phase two-component flow regimes (slug flow, bubble flow, etc.) for macroscale and microscale will be defined and described.

### Homogeneous Flow

In homogeneous flow, the average properties of the combined components are based on either the volume fraction or the mass fraction of the fluid. The volume fraction, or void fraction, is defined by

$$\alpha = \frac{Q_g}{Q_g + Q_f} \quad (3.1)$$

where  $Q$  is the volumetric flow rate of the gas (g) and liquid (f). Similarly, the mass fraction, or quality, is defined as

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_f} \quad (3.2)$$

where  $\dot{m}$  is the mass flow rate of the gas (g) and liquid (f). Quality is the more commonly used variable and will be used throughout this derivation. Typical average values of a property, specific volume ( $1/\rho$ ) for example, can be calculated using the quality by

$$v_m = v_g x + (1 - x) v_f \quad (3.3)$$

where  $v_m$  is the mean value of the specific volume, and  $v_g$  and  $v_f$  are the gas and liquid specific volumes, respectively. When calculating other properties, the equation will have the same form as equation (3.3).

In addition to the one-dimensional assumption mentioned previously, the following assumptions will be used with the homogeneous flow model:

- 1) Steady flow.
- 2) Constant properties.
- 3) Both components are flowing at the same average velocity ( $\bar{u}$ ).
- 4) Thermodynamic equilibrium exists between phases.
- 5) The use of a suitably defined single-phase friction factor for two-phase flow.

The last three assumptions, as outlined by Collier (1981), are used in the more general derivation of the two-phase flow equations and apply for this investigation. The first two assumptions are specific to this derivation.

#### Conservation of Mass

From Figure 3.1, summing the mass flow rate in the x-direction yields

$$\rho \bar{u} dy dz = \left[ \rho \bar{u} + \frac{\delta}{\delta x} (\rho \bar{u}) dx \right] dy dz \quad (3.4)$$

Integrating over the cross-sectional area  $dy dz$  and noting that the partial derivative term is zero because of the steady flow assumption, we obtain

$$\rho \bar{u} A)_{in} = \rho \bar{u} A)_{out} \quad (3.5)$$

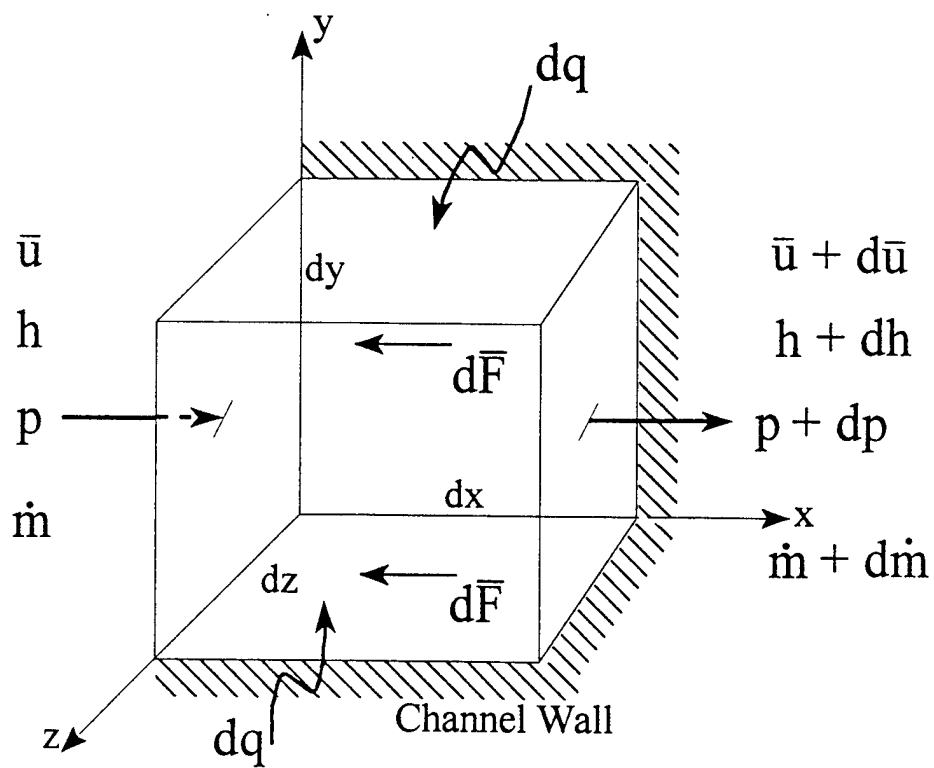


Figure 3.1: Homogeneous flow model control volume.

or, simply stated,

$$\dot{m} = \rho \bar{u} A = \text{constant} \quad (3.6)$$

Putting this equation in terms of mean properties, yields the final form of the conservation of mass equation.

$$\dot{m} = \rho_m \bar{u} A = \text{constant} \quad (3.7)$$

where  $\rho_m$  is the mean density, and  $A$  is the cross-sectional area of the channel.

### Conservation of Momentum

The forces present in the x-direction of a differential control volume of fluid are shown in Figure 3.1. Summing the forces in the x-direction, dividing by the cross-sectional area, and multiplying by the differential length ( $A dx$ ) yields

$$\rho g_x - \frac{dp}{dx} - \frac{1}{A} \frac{d\bar{F}}{dx} = \rho \frac{d\bar{u}}{dt} + \rho \bar{u} \frac{d\bar{u}}{dx} \quad (3.8)$$

where  $d\bar{F}$  is the force exerted to overcome friction. For a horizontal tube,  $g_x = 0$ . Therefore, the first term on the left-hand side can be neglected. The first term on the right-hand side can also be neglected due to the steady flow assumption. Making these substitutions, multiplying through by the cross-sectional area ( $A$ ), and noting that  $\rho_m \bar{u} A$  is the mass flow rate ( $\dot{m}$ ), the final form of the conservation of momentum equation

becomes

$$\dot{m} \frac{d\bar{u}}{dx} = -A \frac{dp}{dx} - \frac{d\bar{F}}{dx} \quad (3.9)$$

The term  $d\bar{F}$  is the total wall shear force and can be expressed in terms of the wall shear stress  $\tau_w$ . Or,

$$\frac{d\bar{F}}{dx} = \tau_w P \quad (3.10)$$

where  $P$  is the perimeter of the channel. Also,  $\tau_w$  may be expressed in terms of a friction factor,

$$\tau_w = f_{tp} \left( \frac{\rho_m \bar{u}^2}{2} \right) \quad (3.11)$$

As Collier (1981) notes, the total wall shear force ( $d\bar{F}$ ) can be expressed as a part of the overall static pressure gradient required to overcome friction, or

$$-\left( \frac{dp}{dx} \right)_F = \frac{1}{A} \frac{d\bar{F}}{dx} = \frac{\tau_w P}{A} = \frac{f_{tp} P}{A} \left( \frac{\rho_m \bar{u}^2}{2} \right) \quad (3.12)$$

This is the well-known Fanning friction equation. For a known geometry, equation (3.12) reduces to

$$-\left(\frac{dp_F}{dx}\right)_{tp} = \frac{2f_{tp} G^2 v_m}{D_h} \quad (3.13)$$

where  $G$  is the mass flux,  $v_m$  is the specific volume of the fluid mixture, and  $D_h$  is the hydraulic diameter.

The left-hand term of equation (3.9) involves the acceleration of the fluid through the control volume due to expansion of the gas phase as the local pressure drops. Putting this expression in terms of the static pressure gradient yields

$$\frac{\dot{m}}{A} \left( \frac{d\bar{u}}{dx} \right) = - \left( \frac{dp_a}{dx} \right)_{tp} \quad (3.14)$$

From Collier (1981),

$$-\left(\frac{dp_a}{dx}\right)_{tp} = G \frac{d\bar{u}}{dx} = G^2 \frac{dv_m}{dx} \quad (3.15)$$

where, neglecting the compressibility of the liquid phase,

$$\frac{dv_m}{dx} = v_{fg} \frac{d(\text{quality})}{dx} + x \frac{dv_g}{dp} \left( \frac{dp}{dx} \right) = x \frac{dv_g}{dp} \left( \frac{dp}{dx} \right) \quad (3.16)$$

Substituting equations (3.13), (3.15), and (3.16) into equation (3.9) yields, after simplifying

$$-\frac{dp}{dx} = -\left(\frac{dp}{dx}\right)_p = \frac{\frac{2f_p G^2 v_f}{D} \left[ 1 + x \left( \frac{v_{fg}}{v_f} \right) \right]}{1 + G^2 x \left( \frac{dv_g}{dp} \right)} \quad (3.17)$$

To solve (3.17), one must either use stepwise integration or some simplifying assumptions. The first assumption that can be made is that  $v_{fg}/v_f$  is approximately constant. This assumption is valid because of the large difference in specific volumes. A second assumption is that the compressibility of the gas can be neglected, or that

$$\left| G^2 x \left( \frac{dv_g}{dp} \right) \right| \ll 1 \quad (3.18)$$

This second assumption can be checked using some experimental data. For example, the following data is taken from data point 30 for water and nitrogen flowing together through five -  $134.64\mu\text{m} \times 121.83\mu\text{m}$  channels. We have;  $G = 466.128 \text{ kg/m}^2\text{-s}$ ,  $x = 0.03525$ ,  $dv_g = 0.8071 \text{ m}^3/\text{kg}$ , and  $dp = 432.7 \text{ psi} = 2.983351 \text{ MPa}$ . Putting these numbers into equation (3.18), we have

$$G^2 x \left( \frac{dv_g}{dp} \right) = (466.128 \text{ kg/m}^2\text{s})^2 (0.03525) \left( \frac{0.8071 \text{ m}^3/\text{kg}}{2.983351 \times 10^6 \text{ Pa}} \right) = 0.00207 \ll 1$$



Therefore, the second assumption is also valid. Employing these assumptions, equation (3.17) reduces to

$$-\left(\frac{dp}{dx}\right)_{tp} = \frac{2f_{tp} G^2 v_f}{D_h} \left[ 1 + x \left( \frac{v_{fg}}{v_f} \right) \right] \quad (3.19)$$

To evaluate the two-phase friction factor, Collier (1981) outlines two different approaches. The first approach assumes  $f_{tp}$  equal to the friction factor that would occur if the total flow was assumed to be all liquid. Denoting this friction factor as  $f_{fa}$  gives

$$-\left(\frac{dp_F}{dx}\right)_{tp} = \frac{2f_{fa} G^2 v_f}{D_h} \left[ 1 + x \left( \frac{v_{fg}}{v_f} \right) \right] = -\left(\frac{dp_F}{dz}\right)_{fa} \left[ 1 + x \left( \frac{v_{fg}}{v_f} \right) \right] \quad (3.20)$$

where  $-\left(\frac{dp_F}{dx}\right)_{fa}$  is the frictional pressure gradient, from the Fanning equation, for the flow assumed to be all liquid. Unfortunately, this method does not allow extrapolation to the correct value at a quality of 100%. To overcome this problem, a second method must be used to evaluate the two-phase friction factor. This method evaluates the two-phase friction factor by using a mean two-phase viscosity in the normal friction factor relationship. The most popular form of the two-phase viscosity equation, given as

$$\frac{1}{\mu_m} = \frac{x}{\mu_g} + \frac{(1-x)}{\mu_f} \quad (3.21)$$

was proposed by McAdams et al. (1942). The next assumption is that the friction factor may be expressed in terms of the Reynolds number, by the Blasius equation

$$f_{fa} = 0.079 \left[ \frac{GD}{\mu} \right]^{-\frac{1}{4}} \quad (3.22)$$

Using equations (3.21) and (3.22) in equation (3.20), one obtains Collier's (1981) result of

$$-\left( \frac{dp_F}{dx} \right)_{tp} = -\left( \frac{dp_F}{dx} \right)_{fa} \left[ 1 + x \left( \frac{v_{fg}}{v_f} \right) \right] \left[ 1 + x \left( \frac{\mu_{fg}}{\mu_f} \right) \right]^{-\frac{1}{4}} \quad (3.23)$$

Therefore, we have a two-phase pressure gradient expressed as a single-phase (liquid) pressure gradient multiplied by a term that accounts for two-phase effects. Or, defined in general,

$$-\left( \frac{dp_F}{dx} \right)_{tp} = -\left( \frac{dp_F}{dx} \right)_{fa} \phi_{fa}^2 \quad (3.24)$$

where  $\phi_{fa}^2$  is known as the two-phase friction multiplier and is defined, from above, as

$$\phi_{fa}^2 = \left[ 1 + x \left( \frac{v_{fg}}{v_f} \right) \right] \left[ 1 + x \left( \frac{\mu_{fg}}{\mu_f} \right) \right]^{-\frac{1}{4}} \quad (3.25)$$

Applying these results to equation (3.19) gives

$$-\left(\frac{dp}{dx}\right)_{tp} = -\left(\frac{dp}{dx}\right)_F \phi_{fa}^2 = \frac{2f_{fa} G^2 v_f}{D_h} \left[1 + x \left(\frac{v_{fg}}{v_f}\right)\right] \left[1 + x \left(\frac{\mu_{fg}}{\mu_f}\right)\right]^{-\frac{1}{4}} \quad (3.26)$$

Integration over the length of the channel gives the final result of

$$\Delta p_{tp} = \frac{2f_{fa} G^2 v_f L}{D_h} \left[1 + x \left(\frac{v_{fg}}{v_f}\right)\right] \left[1 + x \left(\frac{\mu_{fg}}{\mu_f}\right)\right]^{-\frac{1}{4}} \quad (3.27)$$

### Conservation of Energy

From the First Law of Thermodynamics

$$\dot{E}_{in} = \dot{E}_{out} \quad (3.28)$$

From Figure 3.1, assuming steady flow with no work done on the system, equation (3.28) becomes

$$dq = \dot{m} \left( dh_m + \frac{d\bar{u}^2}{2} \right) \quad (3.29)$$

where  $q$  is in watts and  $h_m$  is the mean enthalpy of the fluid. Integrating yields

$$q_{in} = \dot{m} \left( h_{m,out} - h_{m,in} + \frac{\bar{u}_{out}^2}{2} - \frac{\bar{u}_{in}^2}{2} \right) \quad (3.30)$$

Note, if kinetic effects can be neglected, this equation reduces to

$$q_{in} = \dot{m}(h_{m,out} - h_{m,in}) \quad (3.32)$$

Also, for constant properties, equation (3.32) further reduces to

$$q_{in} = \dot{m}c_{pm}(T_{out} - T_{in}) \quad (3.33)$$

where  $\dot{m}c_{pm}$  is the capacity rate of the fluid.

The main nondimensional parameter used for comparisons in convection heat transfer is the Nusselt number. The average Nusselt number is defined as

$$\overline{Nu} = \frac{\bar{h}D_h}{k_m} \quad (3.34)$$

where  $\bar{h}$  is the overall heat transfer coefficient,  $D_h$  is the hydraulic diameter, and  $k_m$  is the mean thermal conductivity of the fluid. The overall heat transfer coefficient is defined by Newton's law of cooling as

$$q = \bar{h}A(T_s - T_\infty) \quad (3.35)$$

where  $A$  is the cross-sectional area of the channel,  $T_s$  is the channel surface temperature, and  $T_\infty$  is the bulk fluid temperature. Solving equation (3.35) for the overall heat transfer coefficient and substituting into the definition for the average Nusselt number, we have

$$\overline{Nu} = \frac{\left( \frac{q}{A(T_s - T_\infty)} \right) D_h}{k_m} \quad (3.36)$$

Substituting the expressions for the heat transfer ( $q$ ), found in equations (3.30) and (3.33), we obtain the final expressions for the Nusselt number. Combining equation (3.30), with constant properties, and equation (3.36) yields

$$\overline{Nu} = \frac{D_h \dot{m} \left[ c_p (T_{out} - T_{in}) + \frac{1}{2} (\bar{u}_{out}^2 - \bar{u}_{in}^2) \right]}{A k_m (T_s - T_\infty)} \quad (3.37)$$

Similarly, combining equation (3.33) with (3.36) gives

$$\overline{Nu} = \frac{D_h \dot{m} [c_p (T_{out} - T_{in})]}{A k_m (T_s - T_\infty)} \quad (3.38)$$

### Separated Flow

The separated flow model, as mentioned previously, develops governing equations based on the individual behavior of each component. The assumptions for this model are similar to the ones used for the homogeneous model. Along with the one-dimensional assumption mentioned earlier, the assumptions used with the separated flow model are as follows:

- 1) Steady flow.
- 2) Constant properties.

- 3) Liquid and gas velocities not necessarily equal.
- 4) Thermodynamic equilibrium between phases.
- 5) The use of empirical correlations to relate the two-phase friction multiplier ( $\phi^2$ ) to the independent variables of the flow.

As before, the last three assumptions by Collier (1981) are used in the more general derivation of the two-phase flow equations and apply for this investigation. The first two assumptions are specific to this derivation.

### Conservation of Mass

Following the same procedure as for the homogeneous flow model, equations can be developed for each component of the fluid. From Figure 3.2, summing the mass flow rates in the x-direction for each component and simplifying gives

$$\dot{m}_g = \rho_g \bar{u}_g A_g = \text{constant} \quad (3.39)$$

$$\dot{m}_f = \rho_f \bar{u}_f A_f = \text{constant} \quad (3.40)$$

with the additional constraints

$$\dot{m}_{\text{total}} = \dot{m}_g + \dot{m}_f \quad (3.41)$$

$$A_{\text{total}} = A_g + A_f \quad (3.42)$$

### Conservation of Momentum

The momentum equation for each component of the fluid can be found by summing the forces in the x-direction of Figure 3.2. Neglecting gravity and acceleration of the flow

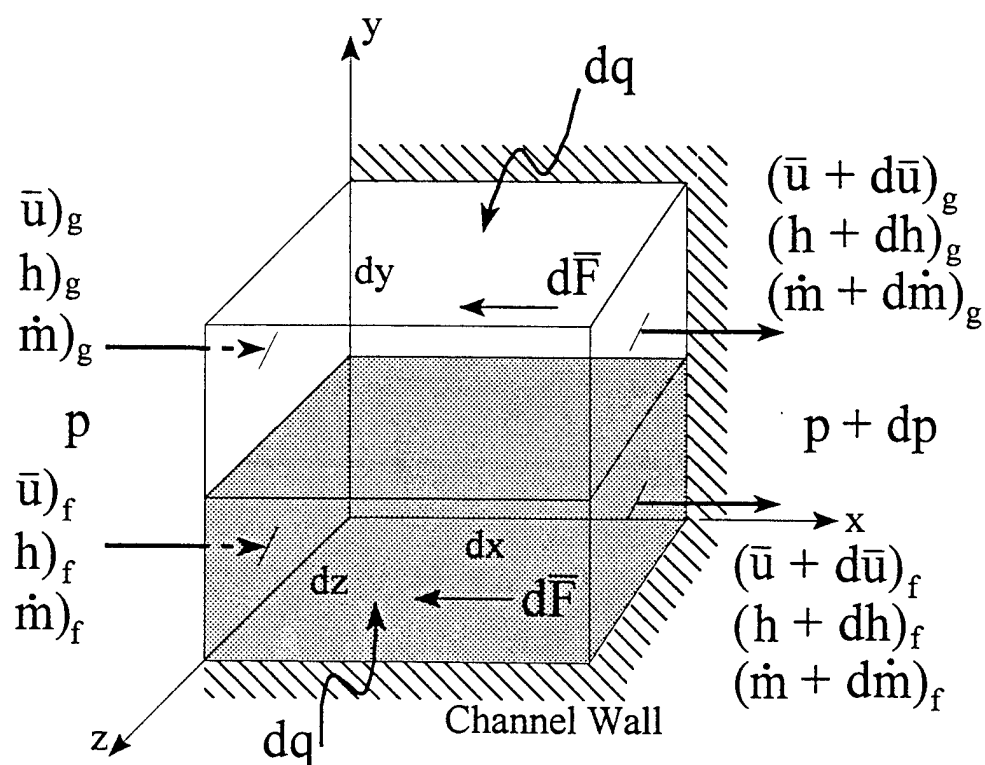


Figure 3.2: Separated flow model control volume.

with respect to time gives

$$-A_g dp - dF_g - I_F = \rho_g \bar{u}_g A_g d\bar{u}_g = \dot{m}_g d\bar{u}_g \quad (3.43)$$

$$-A_f dp - dF_f + I_F = \rho_f \bar{u}_f A_f d\bar{u}_f = \dot{m}_f d\bar{u}_f \quad (3.44)$$

where  $I_F$  is the interface friction force acting between the gas and liquid. Adding equations (3.43) and (3.44) gives

$$-Adp - dF_g - dF_f = d(\dot{m}_g \bar{u}_g + \dot{m}_f \bar{u}_f) \quad (3.45)$$

Using the area of each component to express the net friction force acting on each component, Collier (1981) gives

$$(dF_g + I_F) = -A_g \left( \frac{dp}{dx} F_g \right)_{\text{tp}} dx \quad (3.46)$$

$$(dF_f - I_F) = -A_f \left( \frac{dp}{dx} F_f \right)_{\text{tp}} dx \quad (3.47)$$

$$\text{or, } (dF_g + dF_f) = -A \left( \frac{dp}{dx} F \right)_{\text{tp}} dx \quad (3.48)$$

Substituting equation (3.48) into equation (3.45) and dividing by  $A dx$  yields

$$-\left( \frac{dp}{dx} \right)_{\text{tp}} = -\left( \frac{dp}{dx} F \right)_{\text{tp}} + \frac{1}{A} \frac{d}{dx} (\dot{m}_g \bar{u}_g + \dot{m}_f \bar{u}_f) \quad (3.49)$$



where the first and second terms on the right-hand side are the static pressure gradients due to friction and acceleration, respectively. In Collier's (1981) derivation, he considers the acceleration of the fluid and finds that

$$\frac{1}{A} \frac{d}{dx} (\dot{m}_g \bar{u}_g + \dot{m}_f \bar{u}_f) = G^2 \frac{d}{dx} \left[ \frac{x^2 v_g}{\alpha} + \frac{(1-x)^2 v_f}{1-\alpha} \right] \quad (3.50)$$

Therefore, equation (3.49) becomes

$$-\left( \frac{dp}{dx} \right)_{tp} = -\left( \frac{dp_F}{dx} \right)_{tp} + G^2 \frac{d}{dx} \left[ \frac{x^2 v_g}{\alpha} + \frac{(1-x)^2 v_f}{1-\alpha} \right] \quad (3.51)$$

It should be noted that the acceleration term is presented for completeness. In the final expression for the pressure drop, these terms drop out because of either the steady state assumption or through the use of simplifying assumptions.

As for homogeneous flow, the friction pressure gradient may be expressed in terms of a single-phase pressure gradient ( $f_{fa}$ ) with the total flow considered to be liquid.

$$-\left( \frac{dp_F}{dx} \right)_{tp} = -\left( \frac{dp_F}{dx} \right)_{fa} \phi_{fa}^2 = \left[ \frac{2 f_{fa} G^2 v_f}{D_h} \right] \phi_{fa}^2 \quad (3.52)$$

The fiction pressure gradient may also be expressed in terms a single-phase pressure gradient ( $f_f$ ) with the liquid phase considered to flow alone in the channel.

$$-\left( \frac{dp_F}{dx} \right)_{tp} = -\left( \frac{dp_F}{dx} \right)_f \phi_f^2 = \left[ \frac{2 f_f G^2 (1-x)^2 v_f}{D_h} \right] \phi_f^2 \quad (3.53)$$

This is the preferred form used in calculating pressure drop. Substituting equation (3.53) back into equation (3.51) and simplifying yields,

$$-\left(\frac{dp}{dx}\right)_{tp} = \frac{\left[\frac{2f_f G^2 (1-x)^2 v_f}{D_h}\right] \Phi_f^2}{1 + G^2 \left[ \frac{x^2}{\alpha} \left( \frac{dv_g}{dp} \right) + \frac{d\alpha}{dp} \left\{ \frac{(1-x)^2 v_f}{(1-\alpha)^2} - \frac{x^2 v_g}{\alpha^2} \right\} \right]} \quad (3.54)$$

As with the homogeneous model, equation (3.54) requires stepwise integration unless simplifying assumptions are made. These assumptions are similar to those made for the homogeneous flow model; 1) the specific volumes,  $v_g$  and  $v_f$ , along with the friction factor ( $f_f$ ) remain constant over the length of the channel, and 2) the second term in the denominator is much less than one. With these assumptions, equation (3.54) reduces to a form very similar to equation (3.26)

$$-\left(\frac{dp}{dx}\right)_{tp} = \left[ \frac{2f_f G^2 (1-x)^2 v_f}{D_h} \right] \Phi_f^2 \quad (3.55)$$

The difference with this model is that no expression has been derived for the two-phase multiplier ( $\Phi_f^2$ ). Therefore, to apply equation (3.55) one must develop an expression for the two-phase multiplier in terms of the independent variables. This expression was first developed by Martinelli et al.(1944). This material was presented in Chapter 2. As a brief

summary, expressions for  $\phi_f^2$  and  $\phi_g^2$  were given as

$$\phi_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (2.12)$$

$$\phi_g^2 = 1 + CX + X^2 \quad (3.56)$$

where the constant  $C$  is given in Table 2, pg.17, and the Martinelli parameter,  $X$ , was given by

$$X^2 = \frac{(\Delta p / \Delta L)_f}{(\Delta p / \Delta L)_g} = \frac{C_f (Re_G)^m \rho_G}{C_g (Re_f)^n \rho_f} \left( \frac{1-x}{x} \right)^2 \quad (2.10)$$

where the values of the coefficients  $C_f$ ,  $C_g$ ,  $m$ , and  $n$  were given in Table 1, pg. 17. The literature survey also discussed Martinelli and Nelson (1948) who developed an expression for boiling two-phase flow. Again, as a summary, only the pertinent equations are repeated here. From Barron (1985),

$$\Delta p_m = \frac{\phi_m (\dot{m}_f + \dot{m}_g)^2}{g_c \rho_f A^2} \quad (2.14)$$

with the momentum-pressure-drop parameter given by

$$\phi_m = \frac{(1-x_{out})^2}{\alpha_{f,out}} - \frac{(1-x_{in})^2}{\alpha_{f,in}} + \left( \frac{x_{out}^2}{1-\alpha_{f,out}} - \frac{x_{in}^2}{1-\alpha_{f,in}} \right) \left( \frac{\rho_f}{\rho_g} \right) \quad (2.15)$$

where  $\alpha_f$  is the volume fraction of liquid at the entrance and exit of the channel. Similar to before, the Martinelli parameter,  $X$ , and the momentum-pressure-drop parameter are related by

$$\phi_m = \frac{X}{(X^2 + CX + 1)^{1/2}} \quad (2.16)$$

where the coefficient  $C$  was given in Table 2.

To now obtain the final expression for the pressure drop, we must combine the above equations such that

$$\Delta p = \Delta p_f + \Delta p_m \quad (2.17)$$

Integrating equation (3.55) over the length of the channel, and combining with equation (2.14) gives

$$\Delta p_{tp} = \left[ \frac{2L f_f G^2 (1-x)^2 v_f}{D_h} \right] \phi_f^2 + \frac{\phi_m (\dot{m}_f + \dot{m}_g)^2}{g_c \rho_f A^2} \quad (3.57)$$

After simplification, the final result is obtained as

$$\Delta p_{tp} = G^2 v_f \left( \frac{2L f_f (1-x)^2 \phi_f^2}{D_h} + \phi_m \right) \quad (3.58)$$

where  $\phi_f^2$  and  $\phi_m$  are given in equations (2.12) and (2.16), respectively.

### Conservation of Energy

The analysis of the conservation of energy is virtually identical to the derivation for the homogeneous model. Each component of the fluid is considered separately and the resulting equations are then combined using the definition of quality. The results are the same equations as found for the homogenous flow model. This conclusion is only possible because of the assumption of thermodynamic equilibrium between the two phases. To help reduce redundancy, the final equations are simply restated. When considering kinetic effects, we have

$$\overline{Nu} = \frac{D_h \dot{m} \left[ c_p (T_{out} - T_{in}) + \frac{1}{2} (\bar{u}_{out}^2 - \bar{u}_{in}^2) \right]}{A k_m (T_s - T_\infty)} \quad (3.37)$$

When neglecting kinetic effects, we have

$$\overline{Nu} = \frac{D_h \dot{m} [c_p (T_{out} - T_{in})]}{A k_m (T_s - T_\infty)} \quad (3.38)$$

It should be noted that if phase change was present or thermodynamic equilibrium between the phases was not assumed, a detailed analysis would be necessary to account for the interaction between the phases.

## Two-Phase Two-Component Flow Regimes

### Macroscale

Though many types of two component flow geometries exist, the generally accepted macroscale flow regimes for two-phase two-component horizontal flow are shown graphically in Figure 3.3. A general description is as follows.

a) *Bubble Flow*. Here the main continuum is liquid with bubbles of various sizes flowing along with the liquid. For macroscale channels, the bubbles tend to flow at or near the top of the channel. This regime is characterized by a low quality. The bubble size will vary depending of the quality of the flow. As the quality and, hence, the bubble size increases, the bubbles will tend to coalesce into larger and larger bubbles which provides the transition to the next regime.

b) *Plug Flow*. In this regime the bubble size is large enough to occupy the upper part of the channel so that the liquid no longer surrounds the bubble. Hence the descriptive name changes from a bubble to a plug of gas. The liquid does, however, still separate each plug of gas. As the size of the plug (quality of the flow) continues to increase, the amount of liquid separating the plugs decreases until it no longer exists. This is the transition to the next regime.

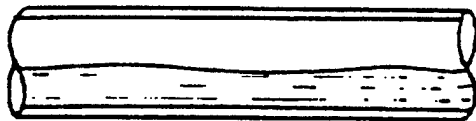
c) *Stratified Flow*. For this regime, the gas and liquid are flowing as two separate entities. Therefore, the flow rates are much more independent than in any other flow regime. However, for this regime to exist, the overall flow rate of both components must



Bubble Flow



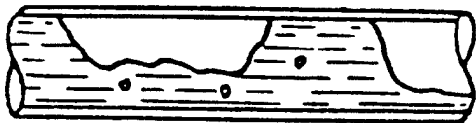
Plug Flow



Stratified Flow



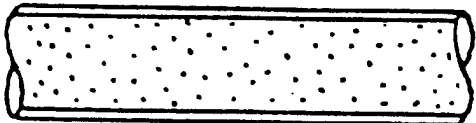
Wavy Flow



Slug Flow



Annular Flow



Mist Flow

Figure 3.3: Macroscale two-phase flow regimes (Barron, 1985).

be relatively low. As the gas flow rate increases, relative to the liquid flow rate, the viscous interaction between the two components causes the transition to the next regime.

d) *Wavy Flow*. Here the gas flow rate is large enough, relative to the liquid flow rate, to cause waves to form. As the flow rate of the gas continues to increase, the amplitude of the waves will increase. The size of these waves can vary from ripples up to the height of the channel. When the liquid waves reach the top of the channel, the next regime is attained.

e) *Slug Flow*. In this regime the slug of liquid, for the most part, is actually being pushed by the gas. Though this regime is easily mistaken for plug flow, it generally occurs at a much higher overall flow rate. As the quality and overall flow rate continue to increase, the gas will reach a point that its flow rate, relative to the liquid, becomes large enough to actually start pushing the liquid to all sides of the channel. At this point the next regime is reached.

f) *Annular Flow*. For this regime the flow of the liquid is mainly restricted to a thin layer around the perimeter of the channel. The gas flows through the center of the liquid and can contain some entrained droplets of liquid. This flow regime is characterized by high values of quality and gas flow rate. As the quality continues to increase, the thickness of the liquid layer decreases until it can no longer exist. This is the transition to the last regime.

g) *Mist Flow*. This regime exists only for the highest values of quality and flow rates. The gas flowing through the channel contains entrained droplets of liquid, as in the

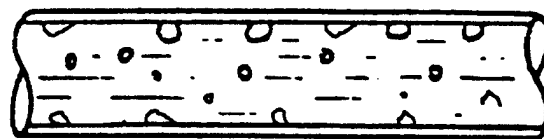


last regime. However, the liquid flow rate is so low that the droplets have virtually no chance to coalesce. The size of the droplets will vary but will decrease with increasing quality. This will continue until only gas is flowing thorough the channel.

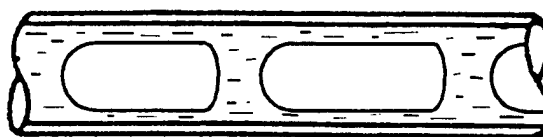
### Microscale

For microscale, the flow regimes are not as well defined. The regimes proposed below are based on literature reviews and experimental observation. One of the biggest differences between macroscale and microscale regimes is the role of surface tension. For macroscale, gravity dominates over surface tension even though they both play important roles. In microscale, however, surface tension is not only dominant but gravity has been shown [Suo and Griffith (1964)] not to be a factor. The flow regimes to be discussed are shown graphically in Figure 3.4.

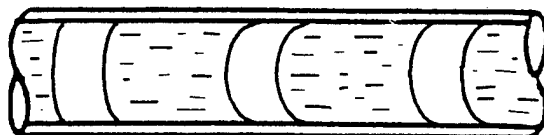
a) *Bubble Flow*. Like macroscale, this regime is made up of a continuum of liquid with bubbles of various size flowing along with the liquid. For microscale, however, the bubbles do not tend to flow near the top of the channel. Instead, they are present throughout the entire depth of the channel. Also, bubbles of various sizes will tend to adhere to the channel walls and be pushed through the channel by the liquid and other bubbles. As before, as the quality increases, the average bubble size increases. This will continue until the bubble size approaches the size of the channel. At this point, increasing the quality will only increase the bubbles length. And, depending on the flow rate of each component, one of the next two regimes will occur.



Bubble Flow



Slug Flow



Plug Flow



Annular Flow



Mist Flow

Figure 3.4: Microscale two-phase flow regimes.

b) *Slug Flow*. In this regime the gas forms long bubbles separated from the channel walls by a thin layer of liquid. The long bubbles are separated from each other by liquid filling the entire cross-section. It is easy to see, for this regime, that as the quality increases the bubble length increases. This can continue until the bubble length actually becomes longer than the channel itself. At this point we have transitioned to annular flow.

c) *Plug Flow*. For this regime the bubble occupies the entire cross section of the channel and is not separated from the channel wall by a thin layer of liquid. Therefore, the liquid and gas components are virtually completely separate at a given cross section. As with slug flow, the bubble length will increase with increasing quality. This can continue until either the bubble length becomes longer than the channel itself or the liquid plug becomes so thin that surface tension will not maintain a film across the channel cross-section. In the former case, one would have only gas flowing through the channel. In the latter case, the flow will have transitioned to mist flow. How and when this regime will occur, and how it will transition between the other regimes, is unclear at this point. However, one detail about the pressure drop in this unique regime is worth mentioning. As with the other regimes, the pressure drop will be dependent on the viscous interaction of each component with the channel wall. In addition, because the interface of the two components meets at the wall, the pressure drop will also be highly dependent on the surface tension produced by the two fluids.

d) *Annular Flow*. As with macroscale, this regime is characterized by the liquid flow being restricted to a thin layer around the perimeter of the channel with the gas

flowing through the center. Though possible, it is not expected that small liquid droplets will be entrained in the gas flow. For small channels, if any liquid is entrained it will not travel far before contacting and becoming part of the thin liquid layer. With increasing quality, the liquid layer will continue to decrease until surface tension is not able to maintain a continuous fluid around the entire perimeter of the channel. At this point, we have the transition to the next regime.

e) *Mist Flow*. Analogous to macroscale, this regime is made up of gas flowing through the channel with some entrained liquid droplets. Though some droplets may stay entrained in the gas, it is anticipated most of the droplets will adhere to the channel wall and be pushed through the channel by the gas while coalescing with other droplets. As before, the size of the droplets will decrease with increasing quality until only gas is flowing through the channel.

## CHAPTER 4

### DIMENSIONAL AND EMPIRICAL ANALYSIS

The empirical equations used to interpret the experimental data of this study will be derived in this chapter. A dimensional analysis will be the main source of this derivation. The first section of this chapter (Dimensional Analysis) will present the dimensional analysis for both single-phase and two-phase flow. As discussed in chapter two, single-phase flow is only being considered because of two interrelated reasons; one, the macroscale and microscale two-phase relations are based on single-phase coefficients, and two, there is no general agreement on the values of these coefficients in microscale flow. The second section (Empirical Relations) will discuss the form of the empirical equations and present the procedure to solve for the empirical coefficients. Also, the computational method used to determine the empirical coefficients, correlation coefficient, and the standard deviation will be presented.

#### Dimensional Analysis

The method used in this section is the Buckingham Pi Theorem. This method, like other methods, reduces a number of dimensional variables into smaller dimensionless groups (White, 1986). The MLT (mass, length, and time) system is used for the pressure drop analysis, while the MLTH (mass, length, time, and heat transfer) system is used for

the heat transfer analysis. Analysis of this type is mainly based on the homogeneous flow model, or average fluid properties. The separated flow model, which involves ratios of variables ( $\rho_g/\rho_f$ , for example) and quality, will be considered in the last part of this section.

### Pressure Drop

The following variables can be used to describe the pressure drop per unit length in two-phase flow.

$$\frac{\Delta p}{L} = f(\rho_m, \mu_m, \sigma, D_H, V, \epsilon) \quad (4.1)$$

From White (1986), for the MLT system,

|                 |           |                 |           |       |           |            |
|-----------------|-----------|-----------------|-----------|-------|-----------|------------|
| $\Delta p/L$    | $\rho_m$  | $\mu_m$         | $\sigma$  | $D_H$ | $V$       | $\epsilon$ |
| $ML^{-2}T^{-2}$ | $ML^{-3}$ | $ML^{-1}T^{-1}$ | $MT^{-2}$ | $L$   | $LT^{-1}$ | $L$        |

The maximum number of variables that can be combined and not form a pi group is three.

The combination that will be used here is  $(\mu_m V D_H)$ . Therefore, we have  $7 - 3 = 4$

dimensionless pi groups to be found. For the first pi group

$$\Pi_1 = [\mu_m D_H V] \rho_m = (ML^{-1}T^{-1})^a (L)^b (LT^{-1})^c (ML^{-3})^1 = M^0 L^0 T^0$$

$$M: 0 = a + 1 \quad (4.2)$$

$$L: 0 = -a + b + c - 3$$

$$T: 0 = -a - c$$

Solving gives,  $a = -1$ ,  $b = c = 1$ . Substituting the values of the coefficients into the above equation gives

$$\Pi_1 = \mu_m^{-1} D_H V \rho_m = \frac{\rho_m D_H V}{\mu_m} = \text{Re} \quad (4.3)$$

where Re is the Reynolds number based on average properties of the fluid. Using the same method for the other variables yields

$$\begin{aligned} \Pi_2 &= \frac{\text{We}}{\text{Re}} \\ \Pi_3 &= \frac{D_H^2 \Delta p}{\mu_m V L} \\ \Pi_4 &= \frac{\varepsilon}{D_H} \end{aligned} \quad (4.4)$$

For the third pi group, we can substitute in the definition of the friction factor

$$f = \frac{\Delta p D_H}{2 \rho_m V^2 L} \quad (4.5)$$

Making this substitution and simplifying gives

$$\Pi_3 = 2 f Re \quad (4.6)$$

Therefore, the friction factor may be described by

$$2 f Re = f \left\{ Re, \frac{We}{Re}, \frac{\varepsilon}{D_H} \right\} \quad (4.7)$$

Or, eliminating redundancy

$$f = f \left\{ Re, We, \frac{\varepsilon}{D_H} \right\} \quad (4.8)$$

For single-phase flow, the dimensional analysis follows exactly the same procedure. The only differences are that the fluid properties are based on a single component and surface tension need not be considered. The results are the same that are found for macroscale flow. From White (1988),

$$f = f \left\{ Re, \frac{\varepsilon}{D_H} \right\} \quad (4.9)$$

If the pressure term, at the start of the analysis, was taken as  $\Delta p$  instead of  $\Delta p/L$ , then a  $L/D_H$  pi group would be found. This applies to both single and two-phase.



Therefore, including the  $L/D_H$  term in the above analysis, the final description of pressure drop is

$$\text{Two-Phase: } f = f\left\{\text{Re}, \text{We}, \frac{\epsilon}{D_H}, \frac{L}{D_H}\right\} \quad (4.10)$$

$$\text{Single-Phase: } f = f\left\{\text{Re}, \frac{\epsilon}{D_H}, \frac{L}{D_H}\right\} \quad (4.11)$$

The  $L/D_H$  ratio was included for completeness and to help show if any entrance effects are present in the experimental data. Entrance effect pi groups will be discussed in more detail in the last part of this section.

### Heat Transfer

Using the MLT $\theta$  (mass, length, time, and temperature) system, the heat transfer of two-phase flow in an enclosed channel can be described by the following variables

$$q = f(h, k_m, C_{p_m}, \Delta T, D_H, \mu_m, V, \rho_m, \sigma, L, \epsilon) \quad (4.12)$$

For the MLT $\theta$  system, the basic units for these variables are

| q                                | h                              | k                               | C <sub>p</sub>                               | $\Delta T$ | $D_H$ | $\mu_m$                          | V                | $\rho_m$         | $\sigma$         | L | $\epsilon$ |
|----------------------------------|--------------------------------|---------------------------------|----------------------------------------------|------------|-------|----------------------------------|------------------|------------------|------------------|---|------------|
| ML <sup>-2</sup> T <sup>-2</sup> | MT <sup>-2</sup> $\theta^{-1}$ | MLT <sup>-3</sup> $\theta^{-1}$ | L <sup>2</sup> T <sup>-2</sup> $\theta^{-1}$ | $\theta$   | L     | ML <sup>-1</sup> T <sup>-1</sup> | LT <sup>-1</sup> | ML <sup>-3</sup> | MT <sup>-2</sup> | L | L          |

As Schenck (1968) describes, the MLT $\theta$  system can be changed to the MLTH (mass,

length, time, and heat transfer) system by making the substitution

$$H = \frac{q}{L\Delta T} = MLT^{-2}\theta^{-1} \quad (4.13)$$

Or,

$$\theta^{-1} = \frac{H}{MLT^{-2}} \quad (4.14)$$

Substituting for  $\theta^{-1}$ , the basic dimensions on each of the variables becomes

| h                                | k                | C <sub>p</sub>     | D <sub>H</sub> | $\mu_m$                          | V                | $\rho_m$         | $\sigma$         | $\epsilon$ |
|----------------------------------|------------------|--------------------|----------------|----------------------------------|------------------|------------------|------------------|------------|
| HL <sup>-1</sup> T <sup>-5</sup> | HT <sup>-5</sup> | HMLT <sup>-4</sup> | L              | ML <sup>-1</sup> T <sup>-1</sup> | LT <sup>-1</sup> | ML <sup>-3</sup> | MT <sup>-2</sup> | L          |

thereby eliminating  $\Delta T$ , L, and q from the analysis. We now have

$$h = f(k_m, C_{p_m}, D_H, \mu_m, V, \rho_m, \sigma, \epsilon) \quad (4.15)$$

Schenck (1968) mentions this substitution is done because the resulting system (MLTH) is more applicable to heat transfer systems and the pi groups are more easily found. The maximum number of variables that can be combined and not form a pi group is four. The combination that will be used here is ( $D_H$  V  $\rho_m$   $k_m$ ). Therefore, we have  $9 - 4 = 5$  dimensionless pi groups to be found. For the first pi group

$$\Pi_1 = [D_H V \rho_m k_m] h = (L)^a (L T^{-1})^b (M L^{-3})^c (H T^{-5})^d (H L^{-1} T^{-5})^1 = M^0 L^0 T^0$$

$$M: 0 = c$$

$$L: 0 = a + b + 3c - 1 \quad (4.16)$$

$$T: 0 = -b - 5d - 5$$

$$H: 0 = d + 1$$

Solving gives,  $a = 1$ ,  $b = c = 0$ , and  $d = -1$ . Substituting these values into equation (4.16)

yield

$$\Pi_1 = D_H k_m^{-1} h = \frac{h D_H}{k_m} = Nu \quad (4.17)$$

where  $Nu$  is the Nusselt number based on average fluid properties. Using the same method for the other variables yields

$$\Pi_2 = Re$$

$$\Pi_3 = We$$

$$\Pi_4 = RePr \quad (4.18)$$

$$\Pi_5 = \frac{\varepsilon}{D_H}$$

Therefore, the heat transfer between the channel and the fluid may be described by

$$Nu = f \left\{ Re, We, RePr, \frac{\varepsilon}{D_H} \right\} \quad (4.19)$$

As before, the dimensional analysis for single-phase flow follows exactly the same procedure. Basing the fluid's properties on a single component and neglecting surface tension, we have

$$\text{Nu} = f\left\{\text{Re}, \text{RePr}, \frac{\varepsilon}{D_H}\right\} \quad (4.20)$$

Reducing redundancy with regard to the Reynolds number, and including  $L/D_H$ , the final description of heat transfer becomes

$$\text{Two-Phase: } \text{Nu} = f\left\{\text{Re}, \text{We}, \text{Pr}, \frac{\varepsilon}{D_H}, \frac{L}{D_H}\right\} \quad (4.20)$$

$$\text{Single-Phase: } \text{Nu} = f\left\{\text{Re}, \text{Pr}, \frac{\varepsilon}{D_H}, \frac{L}{D_H}\right\} \quad (4.21)$$

### Separated Flow Model and Other Considerations

By definition, the separated flow model is concerned with the individual properties of each component. This has led to many researchers [Lockhart and Martinelli (1949), Martinelli et al. (1944), Martinelli and Nelson (1948), and Suo and Griffith (1964)] using the ratio of the fluid properties as pi groups. Though a dimensional analysis could be done with all properties of each fluid present, this would be exceedingly lengthy. One would soon find out that the ratios of specific properties do naturally fall out of such an analysis. However, by not including them directly in the analysis, many unnecessary terms are eliminated. For example, a Reynolds number type expression based on the density of the

liquid and the viscosity of the gas. The ratios to be used as pi groups in this analysis are based on the preceding analysis as well as the studies just mentioned. They are

$$\frac{k_f}{k_g}, \frac{Cp_f}{Cp_g}, \frac{\rho_f}{\rho_g} \text{ or } \frac{v_g}{v_f}, \text{ and } \frac{\mu_f}{\mu_g}$$

Another natural pi group that arises in the study of two-phase flow is quality. Quality itself is nondimensional and therefore can be used as a pi group. However, most often it is not. The term involving quality, used by Martinelli and Nelson (1948), is based on the ratio of the mass flow rates. Quality is defined as

$$x = \frac{\dot{m}_g}{\dot{m}_f + \dot{m}_g} \quad (4.22)$$

Solving this expression for the ratio of the mass flow rate of the gas to the mass flow rate of the liquid yields the pi group based on quality

$$\frac{\dot{m}_g}{\dot{m}_f} = \frac{1-x}{x} \quad (4.23)$$

This pi group applies to both pressure drop and heat transfer analysis.

When considering entrance effects in heat transfer, two other pi groups come about from the Seider-Tate equation. The Seider-Tate equation considers the thermal and velocity entry lengths, and has shown to be a good correlation. From Incropera and

DeWitt (1985), the Seider-Tate equation is given as

$$\overline{Nu}_D = 1.86 \left( \frac{Re_D Pr}{L/D} \right)^{1/3} \left( \frac{\mu}{\mu_s} \right)^{0.14} \quad (4.24)$$

The pi groups of interest are  $L/D$  and  $\mu/\mu_s$ , where  $\mu$  is evaluated at the mean fluid temperature and  $\mu_s$  is evaluated at the mean wall temperature. These pi groups can be used for two-phase flow if the following substitutions are made: 1) The channel hydraulic diameter ( $D_H$ ) replaces the tube inside diameter ( $D$ ), and 2) The viscosity terms are the mean values as found by the homogeneous flow model.

As will be discussed in Chapter 5, channel configurations with various aspect ratios were tested to determine the effect, if any, of the aspect ratio. The consideration of the aspect ratio applies for each flow model. To conclude this section, the various pi groups discussed above can be combined to give a final description of the pressure drop and heat transfer, in single- and two-phase flow, for each flow model. For two-phase flow we have:

Homogeneous Flow Model:

$$f = f \left\{ Re, We, \frac{\varepsilon}{D_H}, \frac{L}{D_H}, \frac{1-x}{x}, \alpha \right\} \quad (4.25)$$

$$Nu = f \left\{ Re, We, Pr, \frac{\mu_m}{\mu_{ms}}, \frac{\varepsilon}{D_H}, \frac{L}{D_H}, \frac{1-x}{x}, \alpha \right\} \quad (4.26)$$

Separated Flow Model:

$$f = f \left\{ \frac{k_f}{k_g}, \frac{Cp_f}{Cp_g}, \frac{v_g}{v_f}, \frac{\mu_f}{\mu_g}, \frac{\varepsilon}{D_H}, \frac{L}{D_H}, \frac{1-x}{x}, \alpha \right\} \quad (4.27)$$

$$Nu = f \left\{ \frac{k_f}{k_g}, \frac{Cp_f}{Cp_g}, \frac{v_g}{v_f}, \frac{\mu_f}{\mu_g}, \frac{\varepsilon}{D_H}, \frac{L}{D_H}, \frac{1-x}{x}, \alpha \right\} \quad (4.28)$$

Similarly, for single-phase flow, we have

$$f = f \left\{ Re, \frac{\varepsilon}{D_H}, \frac{L}{D_H}, \alpha \right\} \quad (4.29)$$

$$Nu = f \left\{ Re, Pr, \frac{\mu_m}{\mu_{ms}}, \frac{\varepsilon}{D_H}, \frac{L}{D_H}, \alpha \right\} \quad (4.30)$$

### Empirical Relations

The form that the empirical correlation equations will take is that of a multidimensional power equation. Or, an equation of the form

$$y = A x_1^b x_2^c x_3^d \dots \quad (4.31)$$

where the  $x_i$ 's are nondimensional parameters (Re, Nu, etc.) and A, b, c, etc. are empirical constants to be calculated. Putting equations (4.25) through (4.30) into this form gives:

Homogeneous Two-Phase Flow Model:

$$f = A (Re)^b (We)^c \left( \frac{\mu_m}{\mu_{ms}} \right)^d \left( \frac{\epsilon}{D_H} \right)^e \left( \frac{L}{D_H} \right)^f \left( \frac{1-x}{x} \right)^g (\alpha)^h \quad (4.32)$$

$$Nu = A (Re)^b (We)^c (Pr)^d \left( \frac{\mu_m}{\mu_{ms}} \right)^e \left( \frac{\epsilon}{D_H} \right)^f \left( \frac{L}{D_H} \right)^g \left( \frac{1-x}{x} \right)^h (\alpha)^i \quad (4.33)$$

Separated Two-Phase Flow Model:

$$f = A \left( \frac{k_f}{k_g} \right)^b \left( \frac{Cp_f}{Cp_g} \right)^c \left( \frac{v_g}{v_f} \right)^d \left( \frac{\mu_f}{\mu_g} \right)^d \left( \frac{\epsilon}{D_H} \right)^e \left( \frac{L}{D_H} \right)^f \left( \frac{1-x}{x} \right)^g (\alpha)^h \quad (4.34)$$

$$Nu = A \left( \frac{k_f}{k_g} \right)^b \left( \frac{Cp_f}{Cp_g} \right)^c \left( \frac{v_g}{v_f} \right)^d \left( \frac{\mu_f}{\mu_g} \right)^d \left( \frac{\epsilon}{D_H} \right)^e \left( \frac{L}{D_H} \right)^f \left( \frac{1-x}{x} \right)^g (\alpha)^h \quad (4.35)$$

Single-Phase:

$$f = A (Re)^b \left( \frac{\mu_m}{\mu_{ms}} \right)^c \left( \frac{\epsilon}{D_H} \right)^d \left( \frac{L}{D_H} \right)^e (\alpha)^f \quad (4.36)$$

$$Nu = A (Re)^b (Pr)^c \left( \frac{\mu_m}{\mu_{ms}} \right)^d \left( \frac{\epsilon}{D_H} \right)^e \left( \frac{L}{D_H} \right)^f (\alpha)^g \quad (4.37)$$

Solving for the empirical coefficients is accomplished by using multiple linear regression. The equation for multiple linear regression takes the form

$$y = a + bx_1 + cx_2 + dx_3 + \dots \quad (4.38)$$

Equations (4.32) through (4.37) can be put into this form by taking the natural log of the equation. For example, equation (4.36) can be put into the form of equation (4.38) by



making the following substitutions:

$$\begin{aligned}
 y &= \ln(f) \\
 x_1 &= \ln(\text{Re}) \\
 x_2 &= \ln\left(\frac{\mu_m}{\mu_{ms}}\right) \\
 x_3 &= \ln\left(\frac{\varepsilon}{D_H}\right) \\
 x_4 &= \ln\left(\frac{L}{D_H}\right) \\
 x_5 &= \ln(\alpha)
 \end{aligned} \tag{4.39}$$

Once these substitutions are made, the resulting equation can then be solved for the empirical coefficients using the standard numerical methods for multiple linear regression.

The method of solving a multiple linear regression equation, as outlined by Chapra and Canale (1985), is to minimize the sum of the square of the residuals. The sum of the

square of the residuals is given by the expression

$$S = \sum_{i=1}^n (y_i - a - bx_{1,i} - cx_{2,i} - dx_{3,i} - \dots)^2 \tag{4.40}$$

Differentiating equation (4.40) with respect to each of the coefficients (a, b, c, etc.) and setting each equation equal to zero, generates a system of equations. This system of equations, when solved, yields the coefficients that minimize the sum of the squares of the

residuals. For the general case of multiple linear regression, the matrix to be solved is given by Chapra and Canale (1985) as

$$\begin{bmatrix} n & \sum x_{1,i} & \sum x_{2,i} & \dots & \sum x_{m,i} \\ \sum x_{1,i} & \sum x_{1,i}^2 & \sum x_{2,i}x_{1,i} & \dots & \sum x_{1,i}x_{m,i} \\ \sum x_{2,i} & \sum x_{2,i}x_{1,i} & \sum x_{2,i}^2 & \dots & \sum x_{2,i}x_{m,i} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sum x_{m,i} & \sum x_{m,i}x_{1,i} & \sum x_{m,i}x_{2,i} & \dots & \sum x_{m,i}^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} = \begin{bmatrix} \sum y_i \\ \sum x_{1,i}y_i \\ \sum x_{2,i}y_i \\ \vdots \\ \sum x_{m,i}y_i \end{bmatrix} \quad (4.41)$$

where 'n' is the number of data points, 'i' is incremented from one to 'n', 'm' is the number of dimensionless numbers or ratios used in the correlation minus one,  $a_i$ 's are the coefficient values (a, b, c, d, etc.), and  $x_i$ 's and  $y_i$ 's are the natural logs of the dimensionless numbers or ratios as described in equation (4.39). The only post computational manipulation required is to calculate the correct value of the constant 'A.' Because the natural log of the original equation was taken before solving, the computed value of the constant 'a' is not equal to 'A.' The relationship is  $a = \ln(A)$ . Therefore, the correct value of 'A' is given by  $A = e^a$ .

An important issue when using empirical correlation is to know how well the resulting correlation fits the data points. The rating, or value, of the correlation is determined by using a correlation coefficient. From Holman (1984), the correlation coefficient (r) is defined as

$$r = \left[ 1 - \frac{\sigma_{y,x}^2}{\sigma_y^2} \right]^{1/2} \quad (4.42)$$

where  $\sigma_y$  is the standard deviation of  $y$  given as

$$\sigma_y = \left[ \frac{\sum_{i=1}^n (y_i - y_m)^2}{n-1} \right]^{1/2} \quad (4.43)$$

and

$$\sigma_{y,x} = \left[ \frac{\sum_{i=1}^n (y_i - y_{ic})^2}{n-2} \right]^{1/2} \quad (4.44)$$

In these equations,  $y_i$  are the measured values,  $y_m$  is the mean of the measured values, and  $y_{ic}$  are the values calculated using the correlation equation. The standard deviation is also helpful in evaluating the success of the correlation equation, as it is a measure of the variability of the data around the correlation equation. The coefficient of determination ( $r^2$ ) is a measure of how well the computed correlation explains the variability of the data. A value of  $r^2 = 1$  signifies that the computed correlation explains 100% of the variability and a value of  $r^2 = 0$  represents no improvement [Chapra and Canale (1985)].

The calculation methods described above are very easily incorporated into a computer program. For this study, a FORTRAN program was written that calculates the empirical coefficients, the standard deviation, and the correlation coefficient for a given

set of dimensionless numbers and ratios. The program, listed in Appendix A, also does these calculations for each unique combination of the given dimensionless numbers and ratios in the input data file. For example, if one wishes to correlate equation (4.36), the following procedure should be followed:

- 1) Generate a data file listing the values calculated for the dimensionless numbers and ratios shown in equation (4.36) ( $f$ ,  $Re$ ,  $\mu_m/\mu_{ms}$ ,  $\epsilon/D_H$ , and  $L/D_H$ ) for each data point. One data point per line.
- 2) Determine the number of dimensionless numbers (columns) and data points (rows). These will be the constants  $m$  and  $n$ , respectively, used in the computer program. For this example,  $m$  has a value of five.
- 3) Change the computer program to reflect the correct values of  $m$  and  $n$ .
- 4) Make sure the name and path of the file containing the data is listed correctly in the program. Also check the output file name.
- 5) Run the program.

The output file will list all the pertinent information for each unique combination on a separate line. Each line will list the following for each combination; correlation coefficient, standard deviation, value of coefficients  $A$ ,  $b$ ,  $c$ , etc. These results can easily be transferred into a spread sheet for further analysis. As will be discussed in chapter six, using this computer program along with a spreadsheet allows for a much more thorough analysis. Not only can one determine which particular correlation gives the best fit to the data, but one can also determine the relative importance of each dimensionless term.

## CHAPTER 5

### EXPERIMENTAL APPARATUS, PROCEDURE, AND CALCULATIONS

#### Experimental Apparatus

##### Test Section

The basic test section configuration was designed by the author and Darin Bailey (1996). Shown in Figure 5.1, the test section consisted of an aluminum blank in which the microchannels were machined and a glass cover plate (not shown) epoxied on top to seal the tops of the microchannels and the manifold areas. Detailed information on milling the aluminum blank to the dimensions shown in Figure 5.1, along with program listings of all CNC G-Code is given in Bailey (1996). The test section used in this study differed from Bailey's (1996) in that there were seven small thermocouples mounted in the aluminum just beneath the channels to measure the wall temperature along the channel length.

In this study, liquid water was used along with gaseous argon, helium, and nitrogen. Each fluid was tested as a single phase and then combinations of water and each gas were tested. The fluids were chosen to give a range of viscosity, density, specific heat, and surface tension. The channel sizes were chosen to range from approximate 254  $\mu\text{m}$  square down to 50  $\mu\text{m}$  square. This range was chosen to encompass macroscopic

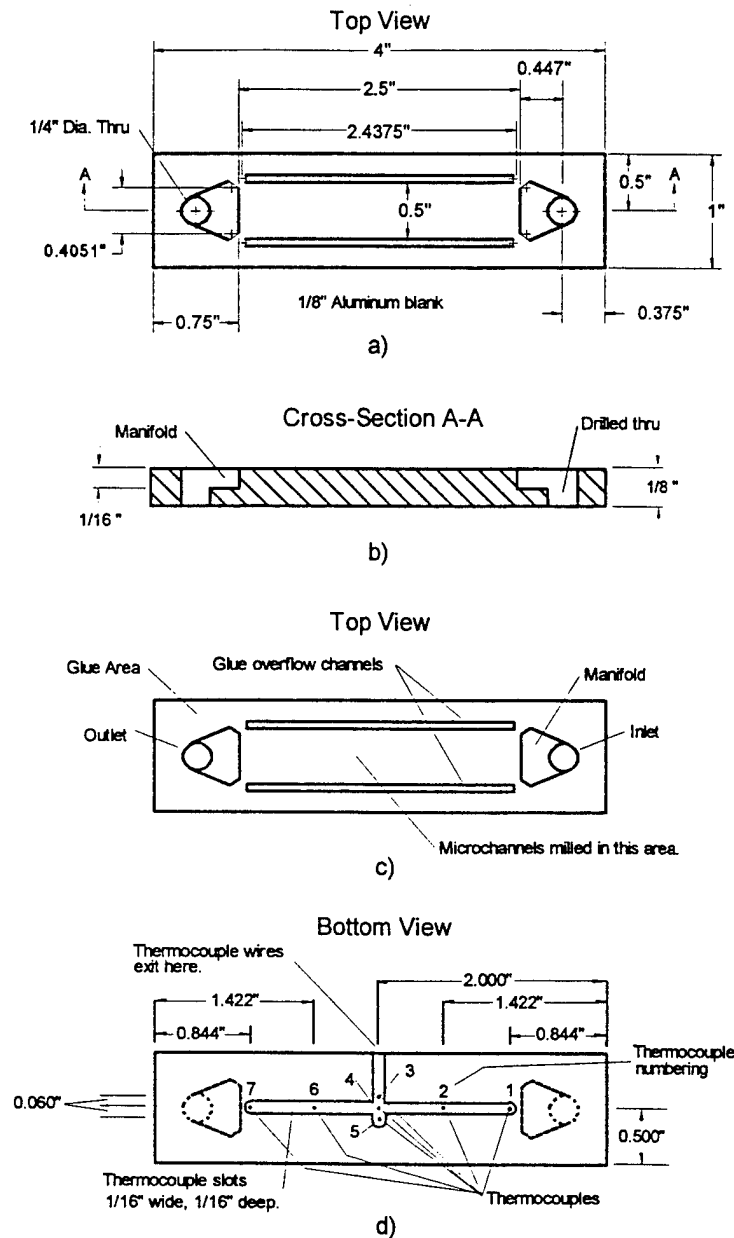


Figure 5.1: Test Section; a) Dimensions, b) Cross-section, c) Component description, and d) Thermocouple numbering and locations, approximately 0.01" beneath channels.

effects for the larger channels as well as microscopic effects for the smaller channels. Table 3, below, lists the measured channel height, width, aspect ratio, surface roughness, and number of channels for each configuration. A majority of the channels had an aspect ratio of approximately 1:1. However, for configurations C1-4, several aspect ratios were considered to determine the effect, if any, of the aspect ratio. Numbers in parentheses indicate the size of the end-mill used in cutting the channels. Variations from the size of the end-mill were caused by the end-mill being slightly out of round, build up of material on the end-mill during machining, and build up of material on the channel wall during machining. The channels were machined on the Ultra Precision Milling Machine of the Institute of Micromanufacturing using commercially available micro end-mills. The micro end-mills are available from McMaster-Carr and Mini Tool, Inc. A complete listing of companies and products mentioned in this study are given in Appendix B. The channel dimensions and surface characteristics were measured on a WYKO - RST surface profilometer. This device gave accurate and detailed information of depth and surface roughness using white light interferometry. Widths of the channel were measured using a microscope/video camera system with interpolating software. The system was calibrated using micrommeasurement slides from Edmond Scientific. The accuracy of all measurements will be discussed in the Error Analysis section of the next chapter.

Table 3: Measured Channel Dimensions

| Channel Designation | Avg. Roughness,nm | Avg. Depth, $\mu\text{m}$ | Avg. Width, $\mu\text{m}$ | Aspect Ratio | Hydraulic Diameter, $\mu\text{m}$ | Num. of Channels |
|---------------------|-------------------|---------------------------|---------------------------|--------------|-----------------------------------|------------------|
| A                   | 102.7             | 255.8                     | 258.0 (254)               | 0.991        | 256.9                             | 3                |
| B                   | 154.7             | 211.1                     | 208.9 (203)               | 1.010        | 210.1                             | 3                |
| C1                  | 290.4             | 134.6                     | 121.8 (127)               | 1.105        | 127.9                             | 5                |
| C2                  | 1,846.2           | 263.73                    | 170.4 (127)               | 1.548        | 170.4                             | 3                |
| C3                  | 156.5             | 71.3                      | 144.8 (127)               | 0.492        | 95.6                              | 7                |
| C4                  | 202.8             | 19.3                      | 150.7 (127)               | 0.128        | 34.2                              | 9                |
| D                   | 183.9             | 111.3                     | 112.4 (90)                | 1.010        | 111.9                             | 7                |
| E                   | 1,334.7           | 74.9                      | 85.8 (70)                 | 1.145        | 80.0                              | 9                |
| F                   | 427.6             | 54.1                      | 58.0 (50)                 | 1.073        | 56.0                              | 11               |

Channel spacing and the number of channels to be used in each configuration were given great consideration. The number of channels in each configuration was selected considering the desired range of Reynolds numbers, the available pressures and flow rates from the flow loop apparatus, and the pressure restriction on the channels themselves. Though a larger number of configurations would ensure an adequate range of Reynold number, machining time was an important limiting factor. The largest channels (configuration A) took only about one hour to machine. However, the smallest channels (configuration F) took over 33 hours of machine time, not including setup. Unfortunately, there is no set formula for determining which number of channels is best for the wide variation of fluid properties between liquid s and gases. However, as one will see in the



next chapter, the data for both the single- and two-phase flow experiments yield a good range of Reynolds numbers. These ranges will be discussed in detail in the next chapter. The channels were spaced five widths of the cutting end-mill (on center) apart. Assumptions of equal heat flux from each wall of the channel was used to determine this spacing. Details of how the channel spacing was calculated, and verification of the heat flux assumption using the macroscale fin theory is given at the end of this section.

Originally, the test sections were to be covered with a glass plate bonded directly on the aluminum blank. However, residual stresses in the aluminum from machining caused the blank to warp. Also, the glass plates were not perfectly flat and therefore made sealing the channels impossible. During the initial testing with water, one could see the water traveling between the glass and the aluminum even for very low flow rates. The problem was solved using a Loctite-UV cure adhesive. The following procedure was used to sealing the channels:

- 1) Thin the UV adhesive with acetone (~50/50 by volume).
- 2) Pour this mixture on the polished side of a clean 4" silicon wafer.
- 3) Allow the acetone to evaporate leaving a thin layer of adhesive.
- 4) Place wafer in direct sunlight for about one hour.
- 5) Carefully remove the thin layer of adhesive, being sure not to stretch the partially cured adhesive. The adhesive has a rubbery consistency at this point. One may need to use a small sharp knife around the edge of the wafer to start the removal.

- 6) Lay the side of the adhesive that was exposed to the atmosphere on top of the aluminum blank. This side will still be slightly tacky. Be sure that all the channels and the manifold areas are completely covered. Press only hard enough to ensure contact. Too much pressure can press the film into the channel or cause sagging in the manifold areas.
- 7) Tape the glass cover plate on top of the blank/adhesive combination and let cure in direct sunlight for 10 - 12 hours. The cover plate will keep the adhesive from curling up along its edges and possibly lifting off the channels and manifolds.
- 8) Carefully remove the glass cover plate and, using a sharp knife, remove the excess adhesive from around the channels and manifolds. Be sure to leave the channel and manifold completely covered.
- 9) Finally, clean the glass cover plate thoroughly and bond to the aluminum blank with epoxy. Lay the assembly flat and allow to dry using no pressure to maintain contact (i.e. do not clamp). When the glue is completely cured, the test section is ready for use. It is recommended that one install the seven thermocouples in the backside of the blank before sealing the channels.

The channels were covered and recovered several times, while perfecting the above procedure, before satisfactory results were achieved. Obviously, the more experience and practice one has using the above procedure the sooner satisfactory results will be achieved. In addition, two tips are worth noting. First, use an epoxy that will not soften in the

slightest for the temperatures that the test section will experience. And second, be sure the epoxy melt temperature is low enough so that the cover can be removed, if needed, without damaging the thermocouples installed in the back of the test section.

This method was successful because of the properties of the UV-adhesive. After one-hour of cure time, the adhesive was still tacky on the side exposed to the atmosphere. This side was placed against the aluminum blank before final cure. The initial one-hour of cure time allowed the adhesive to be stiff enough to handle, and not be pressed into the micro channels, but pliable enough to conform to any unflatness of the aluminum blank. When assembling the glass cover plate and the aluminum blank, two points were crucial. First, do not use the same UV adhesive to bond the cover plate. The uncured adhesive will slightly dissolve the cured adhesive and cause the channels to become clogged. Second, any pressure, due to clamping of the glass cover plate to the aluminum while bonding, has been seen to push the cured adhesive into the channels and partially or completely clog them. It should also be noted that the above method proved unsuccessful in sealing the shallow channels of configuration C4 (20  $\mu\text{m}$  depth). The problem seemed to be the adhesive film sagging into the manifold areas, even with no pressure applied during assembly. Many attempts were made without success. Also, the diffusion bonding machine at Louisiana Tech University was not operational during this study. Therefore, configuration C4 was not used in this study.

From the experiments run for this study, the maximum pressure restriction on the test section assemblies described above was approximately 600 psi. However, if necessary

in future studies, the apparatus is capable of providing up to 1000 psi liquid pressures and 1500 psi gas pressures. It is not recommended to run the test sections, previously described, above a pressure of 200 psi without wearing safety goggles. Though the single-phase tests can be run at maximum pressure indefinitely, the two-phase tests cannot. It was seen that the intense pressure fluctuation associated with two-phase flow would eventually fatigue the epoxy bonding the glass cover plate to the aluminum. On more than one occasion during the two-phase tests, the epoxy did not hold. The results were quite explosive. Therefore, it is recommended that high pressure ( $> 300$  psi) two-phase flows not be run for more than a few minutes at a time. This recommendation is restated for a lower maximum pressure if one uses an epoxy that softens (even slightly) at the operating temperature of the test section.

The seven small thermocouples placed beneath the microchannels are shown in Figure 5.1. The thermocouples were type-T (copper-constantan) and are constructed from 36-gage wire coated with Teflon<sup>®</sup>. Small channels were machined on the back of the aluminum so the thermocouple wires could be routed out of the test section without interfering with the heater. The thermocouples were glued in the channel with a high temperature, high thermal conductivity epoxy. Thermocouple locations were symmetrical about the center of the channels and the end thermocouples were placed as near the channel ends as possible without the thermocouple slot cutting into the manifold area. From Figure 5.1, the end thermocouples are located  $0.844'' - 0.75'' = 0.094$  inches (2.39 mm) from the end of the channels. The thermocouples were numbered, as shown in Figure

5.1. Note that thermocouple numbers three, four, and five were placed lateral to the direction of the microchannels. Though not expected, any lateral heat conduction present during testing would be indicated by thermocouples number three through five having unequal readings. Small holes were drilled in the bottom of the thermocouple slots to a depth of approximately 0.01 inches (254  $\mu\text{m}$ ) from the backside of the channels using a #70 (0.028" diameter) drill. The welded bead of the thermocouple was then carefully inserted into the small hole and glued in place with a high temperature, high thermal conductivity epoxy. Care was taken to assure that no air bubbles were left in the epoxy. The distance from the microchannel wall to the thermocouple was chosen so that an assumption of a constant wall temperature between the wall and the thermocouple would be valid. This assumption may be checked with a simple calculation. For 6060-T6 aluminum, the thermal conductivity at 300 K is approximately 177 W/m-K. In this study the maximum heat dissipated was about 100 W and the smallest area was for 11 - 50  $\mu\text{m}$  wide channels. The channels were spaced five channel widths apart (on center). For conduction through a solid

$$q = kA \frac{dT}{dx} \doteq kA \frac{\Delta T}{\Delta x} \quad (5.1)$$

Solving for  $\Delta T$  gives

$$\Delta T = \frac{q \Delta x}{kA} \quad (5.2)$$

For  $\Delta x = 0.01$  inches (0.25 mm) and a channel length of 2.5 inches (0.0635 m)

$$\Delta T = \frac{(100 \text{ W})(2.54 \times 10^{-4} \text{ m})}{(177 \text{ W/m-K})[(11)(5) + 1](5 \times 10^{-5} \text{ m})(6.35 \times 10^{-2} \text{ m})} = 0.81^\circ \text{C} \quad (5.3)$$

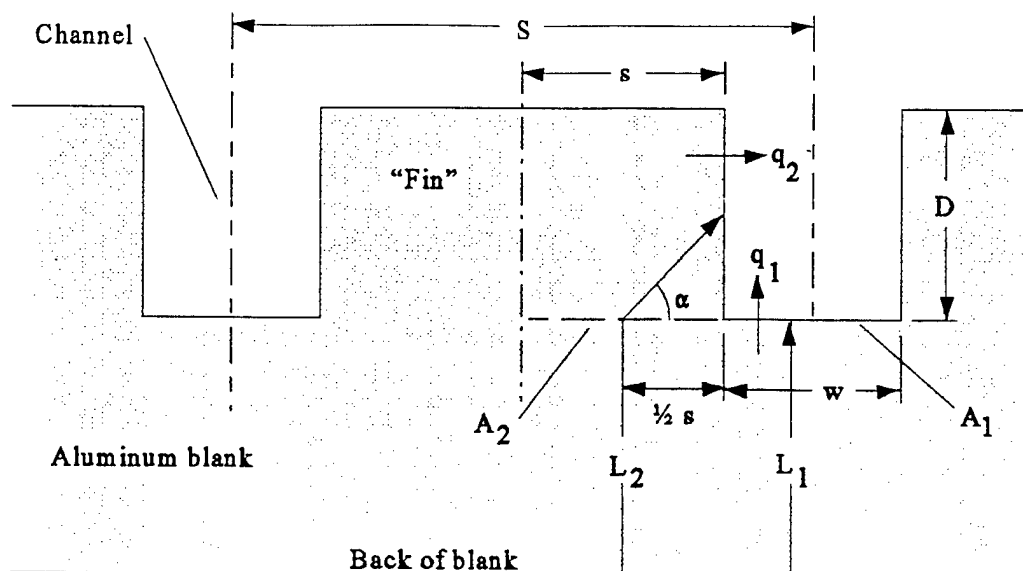
The accuracy of type-T thermocouples is  $\pm 1.0^\circ \text{C}$ . Therefore, the assumption of constant wall temperature is valid because the change in temperature within the aluminum wall is too small to be measured accurately.

The model for determining the spacing of the channels is shown in Figure 5.2. All variables used in the spacing model are defined in Figure 5.2. It is assumed that the heat transferred to area one and area two are equal. Or,

$$q_1 = q_2 \quad (5.4)$$

$$\frac{k_1 A_1 \Delta T_1}{L_1} = \frac{k_2 A_2 \Delta T_2}{L_2} \quad (5.5)$$

Since the blank material (aluminum) is homogeneous,  $k_1 = k_2$ . Also, assuming a constant wall temperature,  $\Delta T_1 = \Delta T_2$ . Define  $A_1 = wl$ ,  $A_2 = sl$ , and  $L_2 = L_1 + D/(2 \sin 45^\circ)$ . The angle of  $\alpha = 45^\circ$  is assumed and will be checked later in the analysis. Replacing the



Definition of variables:

$w$  = width of channel

$D$  = depth of channel

$s$  =  $\frac{1}{2}$  distance between edge of  
channels

$S = 2s + w$

$A_1$  = heat transfer area for bottom  
of channel

$A_2$  = horizontal heat transfer area  
for  $\frac{1}{2}$  width of "fin"

$L_1$  = thickness from back of blank to  
bottom of channel.

$L_2$  = distance from back of blank to  
center of side wall through angle  $\alpha$

$l$  = length of channel between manifolds

$q_1$  = heat transfer through bottom of  
channel

$q_2$  = heat transfer through side of channel

Figure 5.2: Model for determining channel spacing.

variables in equation (5.5) gives

$$sl = wl \left( \frac{L_1 + \frac{D}{2 \sin 45^\circ}}{L_1} \right) \quad (5.6)$$

Simplifying yields the final expression

$$s = w \left( 1 + \frac{D}{2 L_1 \sin 45^\circ} \right) \quad (5.7)$$

Because the area between the channels behaves as a fin, the worst case condition for this study is the channel configuration with the largest aspect ratio (configuration C2). However, to make sure, this analysis was also conducted for all other configurations. Configuration C2 was machined with a 127  $\mu\text{m}$  (0.005") diameter end-mill. Therefore, the expected dimensions are 127  $\mu\text{m}$  x 254  $\mu\text{m}$ . For the aluminum blanks,  $L_1 \approx 1/8" = 3,175 \mu\text{m}$ . Substituting these values into equation (5.7) yields

$$s = (1.25 \times 10^{-4} \text{m}) \left( 1 + \frac{2.5 \times 10^{-4} \text{m}}{2 (3.175 \times 10^{-4} \text{m}) \sin 45^\circ} \right) = 1.139 \times 10^{-4} \text{m} = 132 \mu\text{m} \quad (5.8)$$

Or, in terms of the channel width,

$$s = \frac{134}{127} w = 1.057 w \quad (5.9)$$



To add in a slight factor of safety, this number is rounded up to  $s = 1.5 w$ . Now, the spacing between the centers of the channels can be defined as

$$S = 2s + w \quad (5.10)$$

Substituting in the above expression for  $s$  gives

$$S = 2(1.5w)s + w = 4w \quad (5.11)$$

Or,

$$S \geq 4w \quad (5.12)$$

for the assumptions in this analysis to be valid. Again adding a slight factor of safety, the channel spacing was set at

$$S = 5w \quad (5.13)$$

Or, the spacing of the channels is five (5) widths of the end-mill used to machine the channels, on center. Using the actual dimensions of configuration C2, the assumed angle of  $\alpha = 45^\circ$  may be checked. For configuration C2,  $D = 263.7$  m,  $S = 5(127 \text{ m}) = 635$  m, and  $s = (S - 127 \text{ m})/2 = 254$  m. Then,

$$\alpha = \tan^{-1}\left(\frac{D}{s}\right) = \tan^{-1}\left(\frac{263.7}{254}\right) = 46.1^\circ$$

Therefore, the assumption of  $\alpha = 45^\circ$  is reasonable. The validity of the spacing can be checked using macroscale fin theory.

The analysis of the channel spacing using macroscale fin theory is based on two assumptions. First, a constant wall temperature. And second, equal heat fluxes from each wall of a given channel. For a given fin with an adiabatic tip, the temperature distribution is given by Incropera and DeWitt (1985) as

$$\frac{\theta}{\theta_b} = \frac{\cosh m(L-x)}{\cosh mL} \quad (5.14)$$

where  $\theta = T_{\text{fin}} - T_{\infty}$ ,  $\theta_b = T_{\text{wall}} - T_{\infty}$ ,  $m = hP/kA_c$ ,  $L$  = fin height (depth of channel),  $x = 0 \rightarrow L$  from base of fin,  $h$  = heat transfer coefficient,  $k$  = thermal conductivity of the fin material,  $P = 2w + 2t$  (perimeter of fin),  $A_c = wt$  (cross-sectional area of fin),  $w$  = width of fin (length of channel), and  $t$  = the thickness of the fin (distance between edges of channels). Again, the worst case scenario occurs for configuration C2. For the aluminum,  $k = 177 \text{ W/m-K}$ . The measured dimensions of configuration C2, based on the definitions above, are;  $L = 263.7 \text{ } \mu\text{m}$ ,  $t = 4(170.4) = 681.6 \text{ } \mu\text{m}$ , and  $w = 63,500 \text{ } \mu\text{m}$ . From the experimental data, the maximum values of  $h$  and  $\theta$  were found to be  $133,000 \text{ w/m}^2\text{-K}$  and  $10^\circ\text{C}$ , respectively. Substituting these values into the definitions above yield

$$P = 2(6.35 \times 10^{-2} \text{ m}) + 2(6.816 \times 10^{-4} \text{ m}) = 0.128363 \text{ m}$$

$$A_c = (6.35 \times 10^{-2} \text{ m})(6.816 \times 10^{-4} \text{ m}) = 4.32816 \times 10^{-5} \text{ m}^2$$

$$m = \left[ \frac{(133,000 \text{ W/m}^2\text{-K})(0.128363 \text{ m})}{(177 \text{ W/m-K})(4.32816 \times 10^{-5} \text{ m}^2)} \right]^{1/2} = 1,492.8 \text{ m}^{-1}$$

$$mL = (1,492.8 \frac{1}{\text{m}})(2.637 \times 10^{-4} \text{ m}) = 0.393657$$

The largest variation of the fin temperature from the base temperature will occur at the fin tip. Substituting into equation (5.14) at  $x = L$  (the tip of the fin) gives

$$\frac{\theta}{\theta_b} = \frac{\cosh(0)}{\cosh(0.393657)} = \frac{1}{1.078489} = 0.9272 \quad (5.15)$$

For  $\theta_b = 10^\circ\text{C}$ ,  $\theta$  becomes

$$\theta = 10^\circ\text{C}(0.9272) = 9.27^\circ\text{C} \quad (5.16)$$

Or, the maximum temperature drop within the fin is  $10 - 9.27 = 0.73^\circ\text{C}$ . As mentioned earlier, the wall temperature thermocouples have an accuracy of  $\pm 1.0^\circ\text{C}$ . Therefore the maximum temperature drop in the fin is too small to be measured accurately and hence, our assumption of constant wall temperature is valid.

The second assumption, constant heat flux from each wall of a given channel, can be examined by determining the heat flux for a given fin and comparing it to the heat flux from the channel bottom. Incropera and DeWitt (1985) give the heat transfer from a fin

with an adiabatic tip as

$$q_f = M \tanh mL \quad (5.17)$$

where  $M = [hPkA_c]^{1/2} \theta_b$ , and all other variables are defined below equation (5.14).

Substituting the values used in the temperature distribution yields

$$\begin{aligned} M &= [(133,000 \text{ W/m}^2\text{-K})(0.128363 \text{ m})(177 \text{ W/m-K})(4.32816 \times 10^{-5} \text{ m}^2)]^{1/2} (10 \text{ K}) \\ &= 114.36 \text{ W} \end{aligned}$$

and

$$q_f = (114.36 \text{ W}) \tanh (0.393657) = (114.36 \text{ W}) (0.3745) = 42.8 \text{ W} \quad (5.18)$$

Considering the heat loss though the bottom of the channel, for the same conditions give

$$\begin{aligned} q_b &= h A_b (T_b - T_\infty) \\ &= (133,000 \text{ W/m}^2\text{-K})(1.704 \times 10^{-4} \text{ m})(0.0635 \text{ m})(10 \text{ K}) \\ &= 14.39 \text{ W} \end{aligned} \quad (5.19)$$

where  $A_b$  is the channel width times its length. Equations (5.18) and (5.19) can seem deceiving until one puts them in terms of the wall area over which they occur. Considering the aspect ratio of configuration C2, one can see that a single vertical wall has an area 1.548 times that of the bottom wall. Also, the fin equation is based on the area of both sides of the fin. Therefore, the fin wall area is actually  $2(1.548) = 3.096$  times larger than the area of the wall bottom. Taking both these points under consideration, we find the

maximum difference in the heat transferred from each wall is

$$\frac{14.39 - \frac{42.8}{3.096}}{14.39} = \frac{14.39 - 13.82}{14.39} = 0.0396 = 3.96\% \quad (5.20)$$

Considering other inaccuracies, such as the accuracy of the thermocouples, a maximum difference of 4% in the amount heat flux from each wall is acceptable.

### Test Fixture

The test section will be held in a test fixture, shown in Figure 5.3. Inlet and outlet temperatures and pressures of the test section are measured, as well as the heater temperature. Also shown in Figure 5.3 is the position of a heater which will provide the necessary heating of the channels for heat transfer analysis. A OMEGA (1" x 2.5") Kapton heater, rated at 121 Ohms and a maximum heat flux of 6 Watts, was mounted between a piece of silicon wafer and a high temperature epoxy/fiberglass material. The silicon wafer helped distribute the heat evenly over the back of the test section and the epoxy/fiberglass material provided rigidity. The epoxy/fiberglass material also provided a location to mount the heater thermocouple without actually touching the heater. Teflon<sup>®</sup>, beneath the heater, provided high temperature thermal insulation for the heater while Lexan<sup>®</sup> (polycarbonate) insulated the entire test fixture from the surroundings. Note that the test section did not touch any metal which would conduct heat away and possibly affect the experiment. However, one must be careful when mounting the test section so as not to over compress the o-rings. This would allow the test section to come in contact

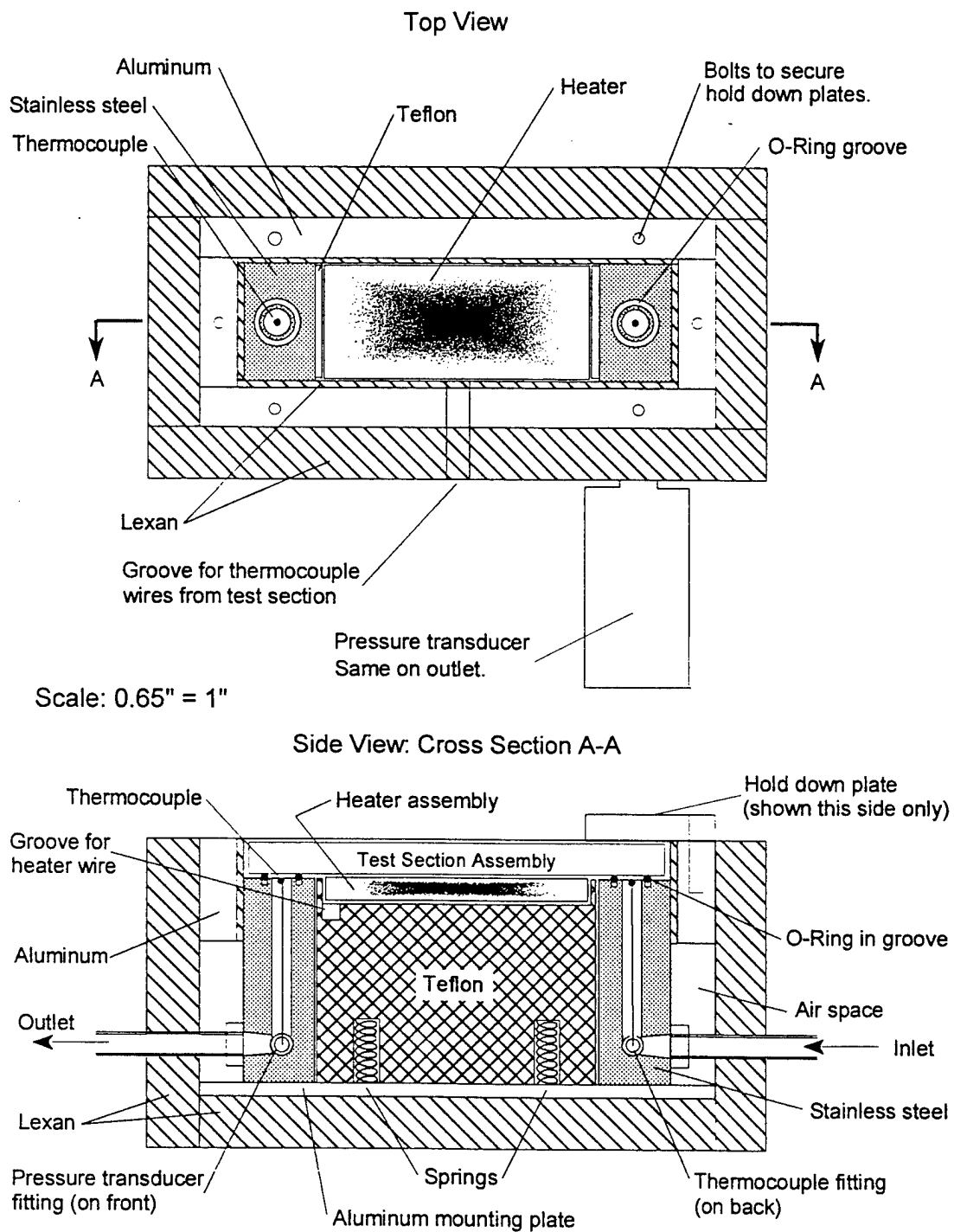


Figure 5.3: Test fixture assembly.

with the stainless steel. One must also be sure not to under compress the o-rings. The high inlet pressure can cause the o-rings to blow out of their grooves. Also note that the heater and test section maintain contact through the use of springs mounted in the lower part of the Teflon<sup>®</sup>.

One can see the location of the temperature and pressure measurements of the test fixture in Figure 5.3. The temperature is measured very near the entrance to the channels. Though the pressure is measured below the entrance to the channels, the pressure drop for the maximum flow rates of this study is negligible (less than 2%). The value of 2% was determined from the calculations of Bailey (1996) at a maximum water flow rate of 100 cc/min. More details on the layout of the test fixture will be given in the next section.

### Flow Loop

The apparatus on which the experimental study will be carried out was designed and built by the author and Darin Bailey. A schematic of the flow loop is given in Figure 5.4. The flow loop is designed to be a generic test bed for microscale fluid and heat transfer experiments here at Louisiana Tech University and the Institute for Micromanufacturing. For a thorough quantitative description of the apparatus and a complete list of components and manufacturers, please see Bailey (1996). The flow loop is mounted on a 4' x 6' air suspension table to dampen out any vibration from outside sources. Figure 5.5 and Figure 5.6 show the general layout of the actual system. All temperatures, pressures, and flow rates of the flow loop are monitored real time with a computer and data acquisition system. All wiring from the various components is routed

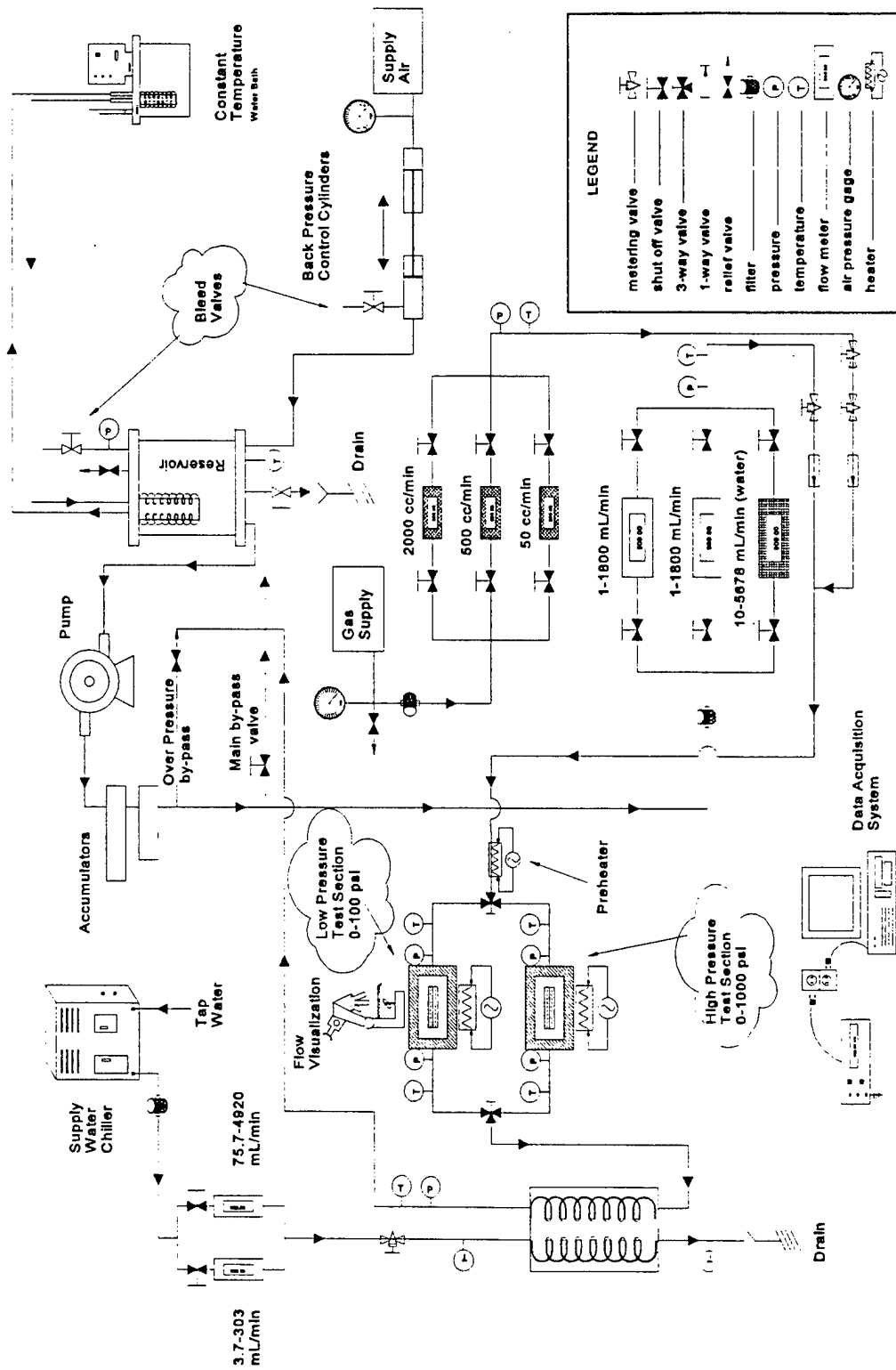


Figure 5.4: Schematic of experimental flow loop.



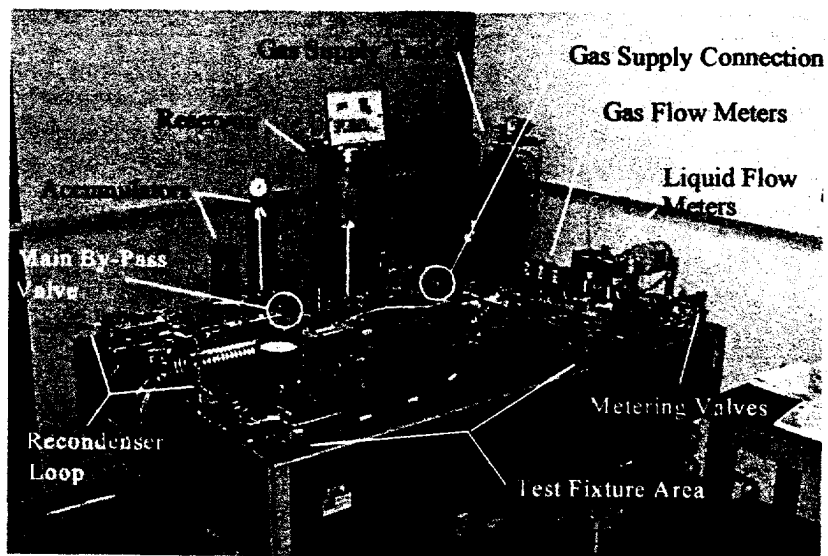


Figure 5.5: General layout of flow loop apparatus (flow loop components).

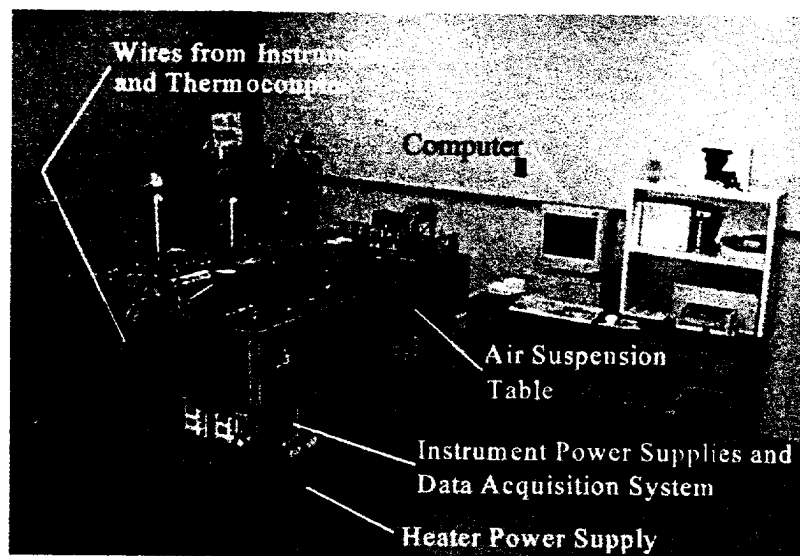


Figure 5.6: General layout of flow loop apparatus (entire apparatus).

off the table to the data acquisition chassis and power supplies underneath the air table. Shielded cable then connects the data acquisition chassis to the computer. The data acquisition system also monitors all temperatures and pressures of the test fixture and test section. Currently the data acquisition system is set up to measure all quantities 512 times each second. The data output to the screen, or written to a data file, is updated an average of every 250 readings. That is, the data screen is updated approximately twice per second. With only a click of a mouse button, the various information displayed on the computer screen can be stored to a spreadsheet or data file.

The test section and test fixture are incorporated into the flow loop as shown in Figures 5.7 and 5.8. In Figure 5.7, one can see the connections where the liquid and gas are mixed prior to entering the test fixture. Also shown in Figure 5.7 are the pressure transducers, test section thermocouple wires, the inlet and outlet thermocouple connections, and the test section being held in place by the aluminum cover plates. The bracket supporting the test fixture (seen more clearly in Figure 5.8) above the table can be removed. Removing the bracket will allow the test section to be mounted to the video/microscope system (used to measure the channel width) for flow visualization studies. Currently these studies are not being conducted pending the purchase of a high-speed video camera. Figures 5.9 and 5.10 show more detail of the test fixture with the test section removed. One can clearly see the o-ring grooves, heater, test section thermocouple wire slot, and the heater power wires and thermocouple. Also, one can see how the test fixture is bolted to the support bracket.

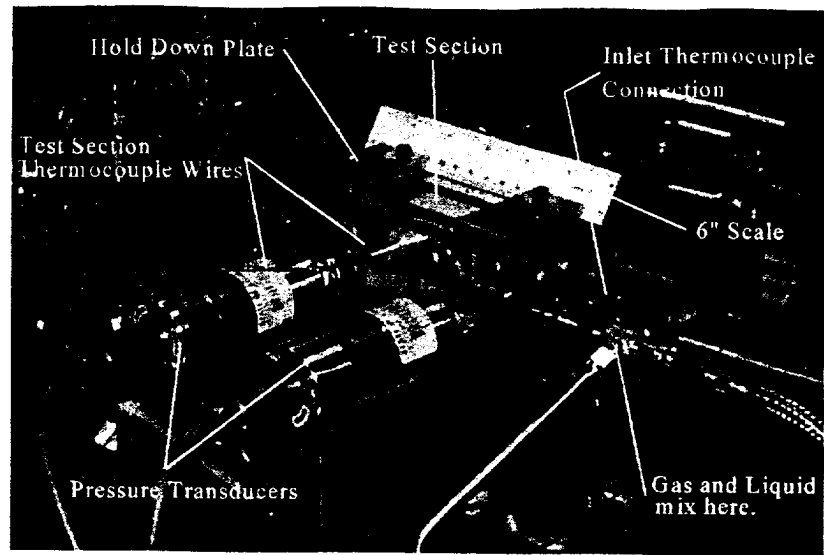


Figure 5.7: Test fixture components.

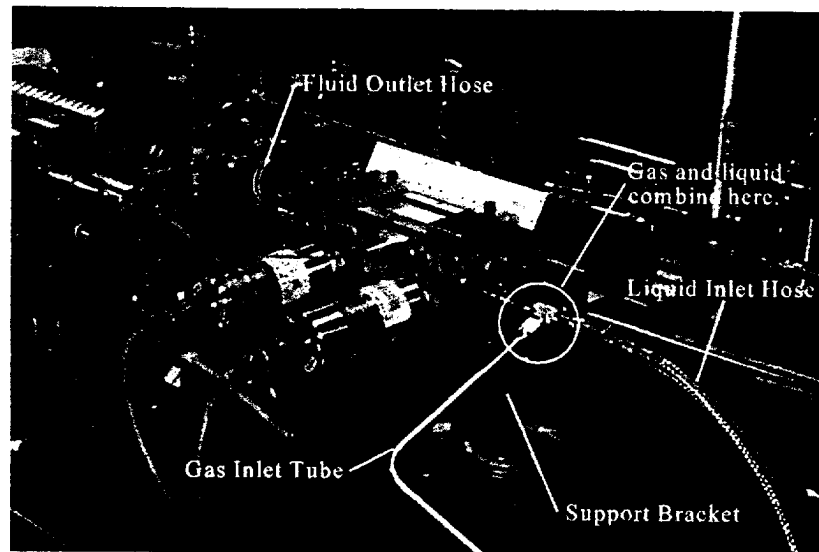


Figure 5.8: Test fixture.

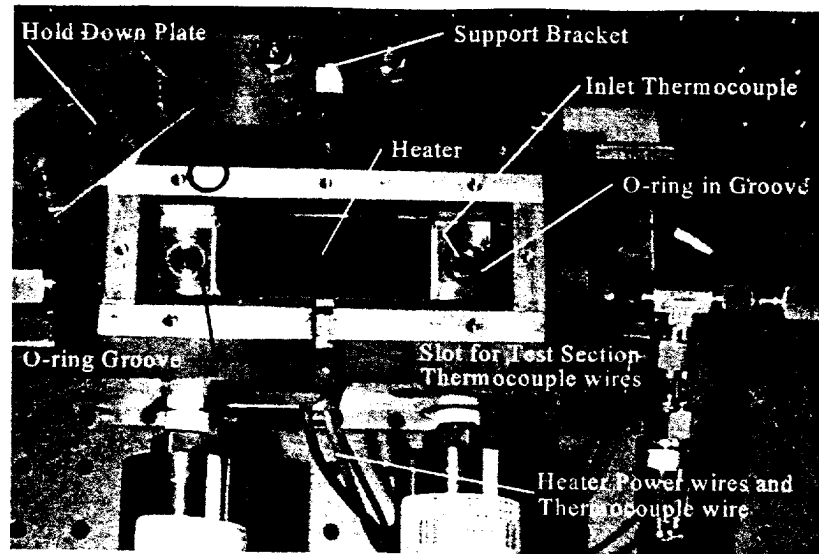


Figure 5.9: Detail of test fixture components without test section installed.

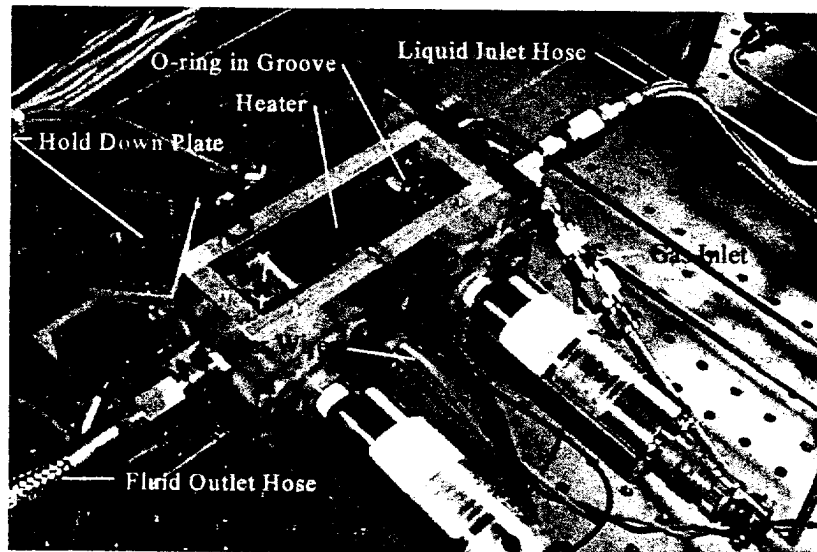


Figure 5.10: Detail of test fixture without test section installed.

The flow meters used for this study can also be seen in Figure 5.5. For the water, a flow meter from Max Machinery was used which has a flow rate range from approximately 5 cc/min to 4000 cc/min (based on the density of water at one atmosphere and 20°C). The upper end of the liquid flow meter (4000 cc/min) was well above the pressure restrictions of the test sections. For gases, the flow meters used were produced by Omega. A combination of three flow meters, with different ranges, allowed flow rates ranging from approximately 1 cc/min to approximately 2500 cc/min (based on the density of nitrogen at one atmosphere and 20°C). Though the gas flow meters were calibrated using nitrogen, a conversion factor could be used when the gas or pressure changed. This calibration factor will be discussed in the calculation section of this chapter. As can be seen in Figure 5.3, the gas was introduced from outside the main liquid flow path. The two components could be mixed at any point between the flow meters and the test section. Once through the test section, the gas was vented out the top of the reservoir.

### Experimental Procedure

Material in this section is a description of how the experimental apparatus used for this study was operated. The detailed instructions are applicable to both single- and two-phase flow experiments. One needs only to leave out the appropriate steps for their particular situation. Also included in this section is a discussion on the order of the fluids and channel configurations tested, along with information on the data files generated during the tests.

Start by turning on the computer, data acquisition system, and all power supplies. Allow approximately 30 minutes for the instruments to come up to operating temperature. During this wait, start the data acquisition program and monitor all pressures and temperatures. Monitoring of these values will help one determine if all instruments are functioning properly. Also, by not having the test section installed in the test fixture at this point, and making sure all pressure transducers are vented to atmosphere, one can determine if the pressure transducers have drifted since the previous calibration. Calibration (or signal conversion) of the transducers and the gas flow meters is conducted within the data acquisition program.

Next, install a test section into the test fixture. First, make sure the test section and test fixture are clean, dry, and free of debris. Second, coat the heater with a thin layer of Omegatherm high-thermal-conductivity grease. The grease will assure an even distribution of heat energy to the test section. Third, place new o-rings in the o-ring grooves of the test fixture. It is best to use new o-rings each time a test section is removed. Once o-rings are used, they develop ridges from being compressed between the test section and the test fixture and are unreliable. Fourth, lay the test section in the test fixture making sure the inlet and outlet holes of the manifolds are lined up with those of the test fixture and the thermocouple wires of the test section clear the test fixture. Fifth, press the test section down firmly and bolt on the hold down plates. Be sure to only finger tighten (as tight as possible with only your fingers) the bolts. Using any assistance such as an allen wrench or screw driver risks over compressing the o-rings and breaking the glass cover plates.

**The glass cover plates are very fragile.** Sixth, connect the test section thermocouples and check the data acquisition readout to make sure the thermocouples are functioning properly.

Now it is time to start the liquid flow loop. Before turning on the pump, make sure the main by-pass valve (see Figure 5.4) is open and the metering valve down stream of the liquid flow meter is closed. Also, make sure that the valves on the flow meters are set so that the liquid will flow only through the meter(s) you designate. This will prevent any unexpected flow through a flow meter not meant to handle the current liquid. Turn on the pump and let it run for a few minutes. Next, warm up the entire flow loop. For this next step, an additional by-pass line (a straight pipe between the multi-way valves) around the test fixtures was installed though it is not shown in the schematic of Figure 5.4. Switch the multi-way valves so that the liquid will go through the test section by-pass. Completely open the metering valve down stream of the liquid flow meters and slowly start closing the main by-pass valve. As the valve closes, the accumulators will slowly begin to fill and the flow rate and pressure to the flow meter will start to increase. For this system, the maximum flow rate and pressure from the pump is below the limits of the flow meter. Therefore, one does not have to worry about damaging the flow meter as long as no sudden changes are made. Continue to close the main by-pass valve until it is completely closed. During this time, however, monitor the pressure down stream of the liquid flow meter. If this pressure is higher than expected then the microfilter is becoming clogged and the element needs to be replaced. Note that there is an over pressure relief valve

installed, around the main by-pass valve, in case the flow is obstructed for any reason. With the main by-pass valve closed, let the system run for a few minutes while monitoring the system temperatures and pressures. Once the system has warmed up, slowly open the main by-pass valve and let the system return to normal.

The gas flow meters are ready to be prepared at this point. Start by connecting the air regulator and hose to the desired gas supply tank. Before opening the supply tank main valve, make sure the pressure regulator is set so that no gas will flow into the hose when the main valve is opened. Second, open the supply tank main valve and connect the gas supply hose to the apparatus. We use a quick disconnect fitting. Third, slowly open the valves upstream of the gas flow meters. The gas flow meters are very susceptible to sudden increases in pressure and flow. Also, flow rates beyond a given flow meters range will damage the flow meter. Fourth, open the valve down stream of the highest range flow meter (flow meter number 6). Opening this valve will allow all down stream piping to fill without running the risk of damaging the lower flow range meters. Fifth, very slowly start turning the pressure regulator knob to increase pressure and start the gas flowing. Monitor the data acquisition output to make sure one does not allow the flow to become greater than the range of each flow meter. Again, it is very easy to over range the flow meters and damage them. Proceed until the desired flow meter pressure is reached. Typically, this pressure will be 50 - 200 psi higher than the maximum pressure experienced at the inlet of the test section during maximum flow rate of a given gas. Sixth, once the pressure downstream of the flow meters has stabilized, open the remaining ball valves for



the other two flow meters. The gas flow meters can be used in any combination to achieve the desired flow range for testing. One final note. Be sure that the reservoir vent is open to allow the gas to escape. Having it closed will allow the pressure to build up in the test section and reservoir. At low flow meter pressures this will only result in a stoppage of the gas flow. However, for higher flow meter pressures the test section and, more easily, the reservoir can be damaged.

As with the gas, the maximum liquid pressure at the flow meter can now be set. Start by making sure the metering valve down stream of the liquid flow meter is closed and that the main by-pass valve is completely open. Next, while monitoring the pressure of the liquid at the flow meter, slowly start closing the main by-pass valve. Close the main by-pass valve until the desired pressure is achieved at the liquid flow meter. Just like the gas flow meters, this pressure will be approximately 50 - 200 psi higher than the maximum pressure to be experienced in the test section. However, be sure that the pressure at the flow meter does not go higher than approximately 1100 psi. Any higher risks tripping the over pressure safety relief valve.

Now one is ready to start running the fluid(s) through the test section. Before opening the metering valves, switch the multi-way valves so that the fluid flow will proceed through the test section. Due to the unsteady readout of the liquid flow meter at low flow rates, it was found to be easier to set the test section inlet pressure using the metering valve, and then measure the liquid flow rate. Adjustments of the liquid metering valve should proceed slowly because there is moderate lag time between adjusting the

valve and the test section inlet pressure stabilizing. Too large of an adjustment will very quickly result in excess pressure in the test section which may cause damage. For this particular apparatus, the inlet pressure could be controlled within  $\pm 0.5$  psi. A similar procedure is followed when adjusting the gas flow meters. Here, however, one monitors and controls the flow rate through the flow meters. As will be discussed in the Experimental Calculations section of this chapter, the gas flow meter reading on the screen is not the actual flow rate of the gas. Instead the reading is a relative flow rate based on the maximum range of the flow meter. For this particular apparatus, the gas flow rate could be controlled within  $\pm 1\%$  of the maximum range of the largest flow meter being used at a given time. While setting the gas flow rate, one should also monitor the inlet pressure of the test section. In two-phase flow, the gas and liquid flow meters tend to work against each other. That is, when one flow meter is adjusted, the flow rate from the other flow meter will change. This is not as big a problem as it may seem because the system equalizes fairly quickly. The worst case that may occur is that increasing the flow rate in one flow meter will actually stop the flow from the other flow meter. However, this only occurs when one or both of the flow meters are at the low end of their flow range and small adjustments will quickly fix the problem.

Once the fluid is flowing through the test section, the heater power supply may be turned on and the voltage output adjusted. It is very important to make sure fluid is flowing through the test section before turning on the heater. If no fluid is passing through the test section when the heater is turned on, damage to the test section, heater, or even

the test fixture may result. The heater for this study was powered by a 150 V, 35 Amp, DC power supply. It is recommend that one use a DC power supply and not an AC power supply. The AC power supply generates a slight induction voltage that will interfere with any thermocouple if its wires are located near the heater or heater wires. While adjusting the power supply, one must monitor the temperatures of the heater, test section wall, and test section inlet and outlet. To prevent any damage to any part of the test apparatus, the following maximum temperatures are recommended; 1) The heater temperature should not exceed  $160^{\circ}\text{C}$  ( $320^{\circ}\text{F}$ ), and 2) the test section wall, inlet, and outlet temperatures should not exceed  $60^{\circ}\text{C}$  ( $140^{\circ}\text{F}$ ). Once the heater is set, the system must be allowed to come to steady-state before the first data point is taken.

Typically the system takes ten to twenty minutes to come to steady-state for the first data point depending on how high one sets the heater voltage. During the initial time period, the channels as well as the entire test fixture are warming-up to operating temperature. The state of all test section and test fixture temperatures can be monitored on the computer screen. Once all temperatures have stabilized, the system data is ready to be recorded. The data is stored to computer disk using the data acquisition software. A virtual switch on the computer screen starts the data recording when it is triggered by "clicking" on it with the computers mouse. The data is recorded at a rate of approximately two measurements per second. As will be discussed in the next chapter, for statistical purposes, sixty data points are recorded for each fluid flow rate/heater setting. One stops the data recording after about 35 seconds by again "clicking" the virtual switch with the

computer's mouse. The fluid flow rates can now be adjusted for the next data point.

For the next data point, adjust the liquid and/or gas flow rate as described above. The heater voltage may also be adjusted. Reaching steady-state takes much less time, now that the test fixture is at its operating temperature. However, the amount of time required to reach steady-state depends on the magnitude of the changes in the flow rates and/or heater voltages. For the experiments run with this study, the time between taking data varied from three to seven minutes. One advantage of the data acquisition system was being able to view the temperature and pressure variations with respect to time. Continuous graphs show a history for a given number of data points up to the present, not just current tabulated numbers. When all desired data points have been taken, the system may be shut down.

Shutting down the flow loop is basically the reverse of the start up. However, precautions should be taken. First, with the fluid continuing to flow through the test section, turn the heater supply voltage off and allow the test section and fixture to cool. Second, when the test section and fixture are cool, close the liquid metering valve and slowly open the main by-pass valve. The increased pressure to the flow meter will be reduced to its starting value. Third, at this point the liquid pump can be turned off and the ball valves on either side of the flow meter closed. Fourth, as for the gas, it is best to turn off the gas supply tank main valve and allow the pressure to bleed down slowly through the test section. Slowly bleeding the pressure down eliminates the risk of damaging the flow meters by a quick pressure release at the quick disconnect. Fifth, when the flow has

completely stopped, close the gas metering valves and all the ball valves on both sides of the gas flow meters. Also, disconnect the gas supply hose from the flow loop. Sixth, switch the multi-way valves on either side of the test section so that no back flow of liquid will escape through the test fixture when the test section is removed. One may now either change test sections and/or gas supply tanks and start the process over. Finally, if done for the day, turn off the computer and all the power supplies.

In the experiments conducted for this study, the various fluids were tested in a relatively specific order. First, the gases were tested for a given test section. Next, water was tested. Finally, the two-phase tests were conducted with water and each of the three gases. Therefore, seven sets of data were generated for each test section. Test sections were changed in a similar manner. The largest test section (configuration A) was tested first. Subsequently, the various configurations B, C1, C2, ..., F were tested. Obviously the experiments did not go as well as the preceding statements suggest. On several occasions the test sections ruptured and the glass cover plates had to be replaced. Other times, certain configurations were reinstalled to collect additional data. The data files generated from these experiments are discussed in the next paragraph. The calculations used in converting the raw data and determining other fluid mechanic and heat transfer parameters are presented in the last section of this chapter.

The data files generated from the experiments of this study are given in appendices C and D. Appendix C contains the measured data and Appendix D contains the reduced data. Though the data acquisition system records all the pressures, temperatures and flow

rates shown in Figure 5.4, not all of these values are needed. Only the pressures and temperatures of the test section, test fixture, and flow meters are used in the calculations. The raw data files were copied into a spreadsheet to allow easy conversion (pressures and flow rates) of the data and parameter calculation. Each data file is listed on several pages. The first page lists the measured values as converted from the raw data. The second list all reduced or calculated fluid mechanic and heat transfer parameters.

### Experimental Calculations

The raw data collected from the data files discussed in the previous section, were used in determining all fluid properties, material properties, fluid mechanic parameters, and heat transfer parameters. The equations used in all of these conversions and calculations will be presented in this section. Raw data values stored by the data acquisition system were in the default units of the software. All temperatures were internally converted from millivolts and stored in units of degrees Celsius. Pressure and gas flow meter readings, however, were stored as the measured output voltages from the various instruments. The liquid flow meter has a pulsed output and its values were stored in hertz. The values recorded consisted of the following; 1) the fluid inlet and outlet temperatures of the test section, 2) the test section wall temperatures, 3) the gas and liquid flow meter temperatures, 4) the inlet and outlet pressures of the test section, 5) the gas and liquid flow meter pressures, and 6) the gas and liquid flow meter flow rates. All together, nineteen values were used for the calculations and described as follows.

All equations used to determine liquid and gas properties are given by Reid et al. (1987). Due to the extent of the equations, they will not be listed. The liquid and gas properties calculated for this study were the density, specific heat, absolute viscosity, thermal conductivity, Prandtl number, and surface tension. The calculated values were compared to tabulated values given by White (1986) (surface tension, viscosity, density), Barron (1985) (density, specific heat, absolute viscosity, thermal conductivity, Prandtl number), Incropera and DeWitt (1985) (thermal conductivity, Prandtl number, absolute viscosity), Hayduk (1981) (surface tension), and Sonntag and Van Wylen (1991) (density, specific heat). For a temperature range of 20 °C - 80 °C and a pressure range of 0 psig - 600 psig, all calculated fluid properties were found to be accurate to within 1%, or better, of the tabulated values. Thermal conductivity of the aluminum test section was curve-fit from the tabulated values given in Incropera and DeWitt (1985). The resulting equation was also accurate to within 1% for the temperature range considered.

Most of the measuring instruments used on this apparatus had output signals in volts or hertz, which required conversion of units. For example, the pressure transducers give an output of 0.0 vdc - 5 vdc or 0.5 vdc to 5.5 vdc depending on the model. The voltage signal was converted to the corresponding pressure by the equation

$$\text{Pressure (gage)} = \frac{\text{voltage} - \text{offset}}{5.0} (\text{max. pressure range}) \quad (5.21)$$

where *voltage* is the value recorded by the data acquisition system, *offset* is the calibration voltage measured with the transducer open to atmospheric pressure, and *max. pressure*

*range* is the maximum pressure range to which the transducer is calibrated (measured in gage pressure). The transducer was calibrated by measuring the output voltage when the transducer was open to the atmosphere and substituting this value into equation (5.21) for offset.

A similar equation was used for the gas flow meters which also had an output of 0.0 vdc - 5.0 vdc.

$$\text{Flow Rate (cc/min)} = \frac{\text{voltage} - \text{offset}}{5.0} (\text{max. flow range}) \quad (5.22)$$

where *voltage* is the value recorded by the data acquisition system, *offset* is the calibration voltage measured with no flow, and *max. flow range* is the maximum range of the given flow meter. Because the density of the gas was dependent on the pressure and temperature in the flow meter, the readout of the gas flow meters was actually a relative flow based on the maximum range of a given flow meter. That is, for a constant mass flow rate, as the temperature and density of the gas changed, so did the output voltage. To calculate the actual flow rate through a given flow meter, Omega gives the correction factor

$$CF = \frac{(\rho C_p)_{\text{calibration}}}{(\rho C_p)_{\text{flow meter}}} \quad (5.23)$$



where  $(\rho C_p)_{\text{calibration}}$  are the density and specific heat for the calibration gas at calibration conditions, and  $(\rho C_p)_{\text{actual}}$  are the density and specific heat of the actual gas flowing through the flow meter. The calibration gas for the three gas flow meters was nitrogen at one standard atmosphere and 20 °C. The properties for the actual gas were determined using the measured pressure and temperature at the flow meter. Therefore, multiplying equation (5.23) by (5.22) will give the actual flow rate (cc/min) of a given gas through the flow meters. The correction factor applied for all of the gas flow meters and this feature made them versatile. Any gas could be used with the flow meter without having to recalibrate. Equation (5.23) could be modified to yield the flow rate at the test section. From the continuity equation, the mass flow rate at the flow meter is simply the measured volumetric flow rate times the density of the gas at the flow meter. Assuming steady-flow, the mass flow rate at the flow meter is the same as at the test section. Therefore, by then dividing equation (5.23) by the density at the test section, one finds the volumetric flow rate at the test section. Or, in equation form

$$CF = \frac{(\rho C_p)_{\text{calibration}}}{(\rho C_p)_{\text{flow meter}}} * \frac{\rho_{\text{flow meter}}}{\rho_{\text{test section}}} = \frac{(\rho C_p)_{\text{calibration}}}{\rho_{\text{test section}} C_{p \text{ flow meter}}} \quad (5.24)$$

Now, equation (5.22) and (5.24) can be used to determine the volumetric flow rate at the test section directly. Note that the fluid properties in the test section are based on the average temperature and pressure of the test section. Because of the extremely small mass

flow rates, the liquid and gas flow rates are listed in Appendix C and D as the volumetric flow rates.

The liquid flow meter conversion was easier to carry out because of the incompressibility of the water and because the meter was calibrated using water. Max Machinery gave an equation for the flow rate based on an average K-factor times the hertz output of the flow meter. The accuracy of the equation was listed as +2%/-4% over the entire range of the flow meter (5 - 4,000 cc/min). However, for better accuracy, the calibration specifications that came with the flow meter were curve-fit. The resulting equations are

$$5 - 100 \text{ cc/min: Flow Rate, (cc/min)} = 87.596 (\text{output})^{3.118696\text{E}-04} \quad (5.25)$$

$$100 - 4000 \text{ cc/min: Flow Rate, (cc/min)} = 89.343 (\text{output})^{-2.400849\text{E}-06} \quad (5.26)$$

where the flow meter output is in hertz. Equations (5.25) and (5.26) agree with the tabulated calibration information to within  $\pm 1 \%$ .

For the analysis to be presented in the next chapter, several fluid mechanic and heat transfer parameters need to be calculated. The equations presented below are used in the calculation of all variables and parameters listed in Appendix C and D. Because the parameters are overall or average values, the fluid properties will be determined from the average temperature and pressure measured between the inlet and outlet of the test section. Any exceptions will be noted as needed.

In considering pressure drop in a channel, the relevant fluid mechanic parameters are the Reynold number and the Darcy-Weisbach friction factor. To calculate these parameters, one needs several fluid properties, channel dimensions, measured pressure drop, and velocity. Velocity is easily found from the continuity equation as

$$\bar{V} = \frac{\dot{V}}{A} \quad (5.27)$$

where  $\dot{V}$  is the measured volumetric flow rate, and  $A$  is the cross-sectional area of the channel {(width)(depth)}. Another variable that must be calculate at this point is the channel hydraulic diameter. White (1986) defines the hydraulic diameter as

$$D_h = \frac{4A}{P} \quad (5.28)$$

where  $A$  is the cross-sectional area of the channel and  $P$  is the wetted perimeter {2(width) + 2(depth)}. With equations (5.27) and (5.28), the Reynolds number can be calculated from

$$Re = \frac{\rho \bar{V} D_h}{\mu} \quad (5.29)$$

where  $\rho$  and  $\mu$  are the average fluid density and absolute viscosity, respectively. For the

Darcy-Weisbach friction factor, White (1986) gives

$$h_f = f \frac{L}{D_h} \frac{\bar{V}^2}{2g} \quad (5.30)$$

where  $h_f$  is the pipe-head loss,  $L$  is the length of the channel, and  $g$  is the local acceleration due to gravity. The pipe-head loss is also given as

$$h_f = \frac{\Delta p}{\rho g} \quad (5.31)$$

Combining equations (5.30) and (5.31) and solving for the friction factor yields

$$f = \frac{2 \Delta p D_h}{\rho L \bar{V}^2} \quad (5.32)$$

where  $\Delta p$  is the measured pressure drop of the fluid flowing through the channels.

When considering forced convection heat transfer inside channels, the most useful parameters are the Nusselt number, Reynolds number, and the Prandtl number. The Reynolds number is given in equation (5.29), and the Prandtl is a fluid property ( $\mu c_p/k$ ) calculated as previously discussed. In order to calculate the Nusselt number, one needs to know the heat transferred to the fluid and the overall heat transfer coefficient. For a fluid being heated as it flows through a channel, the amount of heat transferred to the fluid is given by Incropera and DeWitt (1985) as

$$q = \dot{m} C_p (T_{\text{outlet}} - T_{\text{inlet}}) \quad (5.33)$$

Or, in terms of volumetric flow rate,

$$q = \dot{V} \rho C_p (T_{\text{outlet}} - T_{\text{inlet}}) \quad (5.33)$$

Now, equating the amount of heat transferred to the fluid to the amount of heat transferred from the channels, one can determine the overall heat transfer coefficient. The heat transfer coefficient is defined by Newton's law of cooling as

$$q = h A_w (T_w - T_\infty) \quad (5.34)$$

where  $T_w$  is average channel wall temperature,  $T_\infty$  is the bulk fluid temperature, and  $A_w$  is the wall area of the channel over which the heat is transferred. Several correlations used in next chapter's comparisons contain fluid properties evaluated at the channel wall temperature. For these properties, the channel wall temperature was determined by averaging the test section wall thermocouple readings. Only the test section thermocouples numbered 1, 2, 4, 6, and 7 were averaged for this purpose. These thermocouples were used because they were located down the center of the channels. Because of the glass cover plate used in construction of the test section, the top channel wall was considered adiabatic. Therefore, the wall area over which heat energy is transferred to the fluid is given by

$$A_w = L (2 \text{ Depth} + \text{Width}) \quad (5.35)$$

Solving equation (5.34) for the heat transfer coefficient gives

$$h = \frac{q}{A_w (T_w - T_\infty)} \quad (5.36)$$

The Nusselt number can now be calculated from

$$Nu = \frac{h D_h}{k} \quad (5.37)$$

where  $k$  is the average thermal conductivity of the fluid. Another parameter that will be used in the comparisons of the next chapter is the heat flux. To determine the heat flux, one simply divides the amount of heat transferred from the channel wall by the channel wall area. Or,

$$q'' = \frac{q}{A_w} \quad (5.38)$$

For two-phase flow, the parameters presented above are essentially the same. The only difference is how one determines the fluid properties for a mixture of fluids. As mentioned in Chapter 3, average properties in two-component gas-liquid flows are

determined using the quality or mass fraction of gas in the mixture. The quality is defined by

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_f} \quad (5.39)$$

Putting equation into terms of the volumetric flow rate, gives

$$x = \frac{\dot{V}_g \rho_g}{\dot{V}_g \rho_g + \dot{V}_f \rho_f} \quad (5.40)$$

From basic thermodynamics, average properties of two-component gas-liquid mixtures take the form

$$v_{\text{mix}} = x v_g + (1 - x) v_f \quad (5.41)$$

where  $v_{\text{mix}}$  is the specific volume of the mixture,  $v_g$  is the specific volume of the gas, and  $v_f$  is the specific volume of the liquid. Other properties ( $\mu$ ,  $c_p$ ,  $k$ , etc.) take exactly the same form. Along with the fluid mechanic and heat transfer parameters discussed above, in two-phase flow another parameter arises when considering surface tension between the liquid and gas, the Weber number. The Weber number is the ratio of the liquid inertia to

the surface tension at the gas-liquid interface. White (1986) gives the Weber number as

$$We = \frac{\rho \bar{V}^2 L}{\Upsilon} \quad (5.42)$$

where  $\Upsilon$  is the surface tension.



## CHAPTER 6

### ANALYSIS OF RESULTS

In this chapter, the experimental data taken for both single- and two-phase flow will be presented and analyzed. The resulting empirical correlations based on the dimensional analysis of Chapter 4 will be presented along with the empirical solutions of the analytical flow models developed in Chapter 3. At the end of each respective single- and two-phase flow section, the new correlations will be compared with the correlations listed in chapter two. The two-phase data will then be compared to Baker's (1954) flow regime map. Also, comparisons will be made of other heat transfer quantities such as heat flux and forced convection heat transfer coefficient. Finally, in the last section, an analysis of the amount of uncertainty present in the experimental data will be developed and discussed.

As mentioned in Chapter 4, the empirical correlations presented in this chapter were chosen from a list of sometimes hundreds of correlations determined by the parameters derived using the dimensional analysis. The empirical correlations will most frequently be discussed and compared based on their correlation coefficients ( $r$ ) and the standard deviation ( $\sigma$ ) of the data. To follow the discussion, it is important that one understand the definition of the correlation coefficient. The correlation coefficient is a

description of the relative worth of the resulting empirical correlation. As Schenck (1968) states, a correlation coefficient value of 1.0 means that 100% of the variability is explained by the correlation. For a correlation coefficient value of 0.0, no improvement is seen. Also, there will virtually always be some combination of parameters that yield a higher correlation coefficient than those presented in this chapter. However, this can be likened to the number of terms used to estimate an infinite series. For example, five terms may give an estimate that is accurate to within 1% of the actual series value. An additional ten terms may increase the accuracy to within 0.75% but very little insight is gained using the extra terms. As with all empirical correlations, a large number of parameters can be correlated against experimental data to give a relatively high correlation coefficient. However, the larger the number of parameters correlated, the more difficult it becomes to understand which parameters are important to help to describe the behavior of the data. Now, all this is to say that the correlations presented in this chapter were not simply chosen based on how high their correlation coefficients were, but, more importantly, on how well they aided in describing the behavior of the fluid.

### Single-Phase Flow Results

For the single-phase experiments, liquid water and gaseous argon, helium, and nitrogen were tested in each of the channel configurations. The Reynolds numbers ranged from around 2 to just under 10,000 with most of the data between 100 and 5000. Figure 6.1 shows the friction factor data for all single-phase tests. For convenience, all figures are located together at the end of this chapter. As can be seen, there is a great deal of

scatter at the larger Reynolds numbers. The correlations presented in this section should help clarify the fluid's behavior in the various channel configurations. As will be shown, the friction factor for the gases has a strong, virtually complete, dependence on the Reynolds number. For the water, on the other hand, the friction factor will be shown also to be dependent on other parameters such as the ratio  $L/D_h$  and the viscosity ratio  $(\mu/\mu_s)$ .

As discussed in chapter four, the test section was electrically heated during all tests so that a heat transfer analysis could be conducted along with the fluid mechanic analysis. Figure 6.2 shows the resulting single-phase Nusselt number data. The laminar Nusselt number ( $Nu = 2.98$ ) and turbulent macroscale correlation are also shown for comparison. For this study, the turbulent macroscale correlation is given by the Dittus-Boelter equation, for the fluid being heated, as

$$Nu = 0.023 Re^{4/5} Pr^{0.4} \quad (6.1)$$

where the Reynolds number is based on the hydraulic diameter of the channel. As can be seen, there is even more scatter in these results than in the data for friction factor. The scatter is mainly due to inaccuracies in the temperature's measurement. However, considering the gas data separately did help in determining which parameters are important in single-phase heat transfer.

### Friction Factor

To analyze the friction factor data shown in Figure 6.1, one needs to break it down into several areas of consideration. The break down consists of considering the water and gases separately, and further breaking down the gases into two groups based on the channel's hydraulic diameter. The group with the largest hydraulic diameters is also broken down into two groups based on Reynolds number. Therefore, we have four groups to analyze. The reason for this particular break down is based on the fluid's behavior in the transition from laminar to turbulent regimes in the various channel configurations. The water showed virtually no transition in any size channel at any Reynolds number. For gases, transition did occur in the larger channels (configurations A - C2) but not in the smaller channels (configurations C3 - F).

The friction factor data for water in the various channel configurations are shown in Figure 6.3. As one can see there is a large amount of scatter associated with this data. For channel configuration C2, it is difficult to tell if the flow undergoes transition. All data points for channel C2 were well above both macroscale correlations. The increased pressure drop for this set of channels may be due to the very rough surface finish of these channels (see Table 3). However, pressure restriction did not allow higher Reynolds numbers data to be obtained for this set of channels which may have clarified the question of transition. Unlike what will be shown with gases, the friction factor for water is dependent on parameters in addition to Reynolds number. Correlating the data against the parameters discussed in Chapter 4, the empirical correlation which best describes the

fluid's behavior is

$$f = 3.9 \times 10^{11} \text{ Re}^{-1.862} \left( \frac{\mu}{\mu_s} \right)^{0.7845} \left( \frac{L}{D_h} \right)^{-2.762} \quad (6.2)$$

This correlation is a good fit to the data, as shown in Figure 6.4, with  $r = 0.983$  and  $\sigma = 0.033$ . The dependence on the Reynolds number was expected from classical fluid mechanics. Also, the various correlations of this data indicate that the Reynolds number is, by far, the parameter of primary importance. However, though the dependence of the friction factor on the other two terms was not expected, it does reveal some interesting fluid behavior. The viscosity term is important because the flow was also being heated. As the fluid flows through the channel and is warmed, the viscosity decreases which tends to also decrease the pressure drop. Because  $(\mu/\mu_s)$  was found to be important, it seems to emphasize that the change in the viscosity due to temperature increase is more important than the Reynold number alone considers. In addition, this particular viscosity ratio  $(\mu/\mu_s)$  is used in heat transfer analysis to take into account thermal and viscous boundary layer development [Incropera and DeWitt (1985)]. The final parameter, the  $L/D_h$  ratio, is an indication of entrance effects or viscous boundary layer development. Though for the smaller channels the entrance length may be no more than 10% of the channel's length, for the largest channel (configuration A) the entrance length can cover over 55% of the channel's length. The negative exponent on the  $L/D_h$  ratio is also an indication of the importance of this parameter as the channel size increases. Examination of the

different correlation combinations indicated that the viscosity ratio is the least important of the three parameters and that  $L/D_h$  ratio, though important, is less important than the Reynolds number.

For gases, the lack of transition was seen only in the smaller channel sizes. To show this difference, Figure 6.5 compares channel configurations B, E, and F with nitrogen gas as the fluid. As one can see, configuration B shows a well defined transition from laminar to turbulent regimes, configuration E shows a possible (slight) transition, and configuration F shows no transition. The transition behavior was seen to fall into several groups based on the channel's hydraulic diameter. Channels with hydraulic diameters greater than  $150\ \mu\text{m}$  (A - C2) show a definite predictable transition. Between the hydraulic diameters of  $80 - 150\ \mu\text{m}$ , suppression of the transition behavior is seen to take place in varying degrees. Below a hydraulic diameter of  $80\ \mu\text{m}$ , the transition behavior is almost completely suppressed.

For the larger channels (A - C2), transition was seen to occur between a Reynolds number of 1,500 and 2,000. Therefore, the data below a Reynolds number of 1,500 and above a Reynolds number of 2,000 were correlated separately. From the resulting correlations, both regions were found to be completely dependent on the Reynolds number. Also, the exponents on the Reynolds number were all found to be close to -1.0 for the laminar region and -0.25 for the turbulent. Both of these values are as macroscale theory predicts. Therefore, each region was re-correlated based on these exponents to determine the appropriate constants. The resulting expressions for the friction factor are

Laminar Region ( $Re < 1,500$ ):

$$f = \frac{74}{Re} \quad (6.3)$$

Turbulent Region ( $Re > 2000$ ):

$$f = \frac{0.39}{Re^{0.25}} \quad (6.4)$$

These correlations are shown in Figure 6.6. In both cases the correlation for the data of this study are above the macroscale correlations. From equations (6.3), the laminar constant of 74 is approximately 15% higher than the macroscale constant of 64. Similarly, for equation (6.4), the turbulent constant of 0.39 is approximately 23% higher than the macroscale constant of 0.316. Equations (6.3) and (6.4) have correlation coefficients of 0.994 and 0.516, respectively. As can be seen in Figure 6.6, equation (6.3) does only a fair job of reducing the data. This is due to the scatter associated with the transition region. More data taken at higher Reynolds numbers would help clarify the gases' behavior in the turbulent region. Unfortunately, the experimental apparatus described in Chapter 4 was not capable of higher gas flow rates. It should be noted that correlations were also calculated over the entire range of Reynolds numbers. However, due to the two distinct regions, no useful correlation was found.

For the channels with a hydraulic diameter less than 150  $\mu\text{m}$ , the resulting correlations also showed a complete dependence on the Reynolds number. Because little or no transition from the laminar to the turbulent region was seen, these correlations were

calculated for the entire range of Reynolds numbers. As with the channels that had a hydraulic diameter larger than 150  $\mu\text{m}$ , the Reynolds number exponent was approximately -1.0. Therefore, the data was re-correlated as before. The resulting expression for the friction factor is

$$f = \frac{66}{\text{Re}} \quad (6.5)$$

with a correlation coefficient value of 0.995. Note that the value of the constant in equation (6.5) (66) is close to the value of the macroscale constant (64). This almost insignificant difference can be entirely due to slight error in the data measurements. Equation (6.5) is shown in Figure 6.7. The macroscale correlation is not shown because one would have a hard time distinguishing it from equation (6.5). Of the most interest in this figure is the lack of the transition from laminar to turbulent regimes. Though it can be argued that the maximum Reynolds number in this figure is still in or near the transition region, the behavior of the gas is almost identical to that of the water which had Reynolds numbers as high as 10,000 with no transition. It is believed that this behavior can be explained by some ideas from the work of Yu (1995). Yu (1995) discusses how in microchannel flow, the size of the channel suppresses the formation of turbulent eddies. That is, the size of the channels is at, or below, the size of an eddie required for the fluid to transition from laminar to turbulent regions. These ideas are also based on the assumption that an eddie must be of a certain size to cause complete transition. Now, this suppression can clarify two points about the data taken for this study. First, as can be seen



in Figure 6.7, the behavior of the fluid does show some change in the area where transition is thought to start. What is possibly occurring at this point is that small eddies are forming and trying to develop into larger eddies; eddies large enough to cause the fluid to transition. However, the size of the channel restricts their growth and does not allow them to develop into a size that is large enough to cause the flow to transition to the turbulent region. This is why that even though the flow is seen to be less stable than turbulent flow, the friction factor is still a function of  $1/Re$ . Second, there is a noticeable difference between where the transition starts to be suppressed for liquids and gases. In this study, the water shows no transition, even at the largest channel size. For the gases, on the other hand, the suppression started at approximately  $150\text{ }\mu\text{m}$ . It is believed that because of the higher density and viscosity of a liquid, the size of an eddie required to cause transition is larger than for a gas. Therefore, a larger channel is required to have transition. A study of eddie formation and behavior on a very small scale may clarify this point.

A comparison between the experimentally measured friction factor data of this study and the friction factor correlations listed in Chapter 2, is shown in Figure 6.8. Note that the equations have been normalized and plotted as the ratio of the measured friction factors over the correlated friction factors ( $f_{\text{meas}}/f_{\text{corr}}$ ) versus Reynolds number. As one can see, most of the experimentally measured data is less than that predicted by the correlations. Note that all the correlations derived by considering microchannel flow give fairly good descriptions of the pressure drop, particularly the work by Yu (1995).

### Nusselt Number

To aid in the analysis of the Nusselt number, the gas data were analyzed in several steps. First, each channel configuration was correlated for all gases. Next, all channel configurations were correlated for all gases. Finally, all channel configurations were correlated with all single-phase data (both gas and water). The water was also correlated separately for all channel configurations. However, the maximum correlation coefficient was found to be less than 0.4 with a standard deviation on the order of 10.0. These correlations offered no insight into the behavior of the water in the microchannels and therefore will not be presented. However, the water data is included in the final analysis, as mentioned above, for completeness. The problem associated with the water data can be traced back to the inaccuracies of the temperature measurements. During the tests, the water dissipated much more heat than the gases, as would be expected. Unfortunately, even trying to compensate with higher heater powers, this higher heat dissipation of the water still usually resulted in a much lower change in temperature between the inlet and outlet of the channels. Also, the kinetic energy effects discussed in chapter three were found to effect the data by no more than 5%. As will be shown, this is considerably less than the error due to the thermocouples. Therefore, kinetic energy effects were not considered in the following gas correlations.

To start the analysis, each channel configuration was correlated against all the gas flow data taken for that particular channel. The correlation coefficients ranged from 0.826 to 0.998 with only one configuration (F) being below 0.95. The resulting correlations

revealed several interesting findings. First, as in most cases of the friction factor, no transition between laminar and turbulent regions was seen. This is evident in Figure 6.2 and will be seen in the graphs that follow. Even more interesting, the flow behaved slightly opposite to the friction factor. That is the Nusselt number data was which seen to be a function of the Reynolds number and Prandtl number (a turbulent flow profile) and not constant as macroscale laminar correlations predict. However, this finding agrees with the study by Choi (1991). Second, as with macroscale flow, the Reynolds number and the Prandtl number were found to be the most important parameters. For these correlations the Reynolds number was seen to be slightly more important than the Prandtl number. Third, the measured Nusselt number was considerably below the macroscale prediction. Fourth, and finally, the viscosity ratio ( $\mu/\mu_s$ ) was also found to be an important parameter. As mentioned in the previous section, the viscosity parameter is an indication of entrance effects. For each channel configuration, as the hydraulic diameter decreased, the importance of this viscosity parameter diminished. In fact, for the two smallest channels, the parameter vanished altogether. For a fixed length channel, these results were as would be expected. As the hydraulic diameter decreases so does the percentage of the channel with developing flow.

Next, the Nusselt number data for all channel configurations and gases were correlated. The resulting empirical correlation, seen in Figure 6.9, is

$$Nu = 3.47 \times 10^{-6} Re^{1.639} Pr^{-0.6858} \quad (6.6)$$

With a correlation coefficient of 0.925, equation (6.5) is a very good correlation for a Nusselt number. As one can see in Figure 6.7, the scatter in the Nusselt number data decreases as the Nusselt number, or temperature difference, increases. Again pointing towards the importance of the temperature measurement, the correlations computed for this set of data revealed two more interesting findings. First, the Reynolds number was, by far, the most important parameter. The Reynolds number combined with any other parameter(s) yielded a correlation of at least 0.85. Without the Reynolds number, the highest correlation coefficient achieved was 0.52. Second, the viscosity term ( $\mu/\mu_s$ ) and the term  $L/D_h$  indicated a slight dependence of the correlation on entrance effects. However, these effects were too small to include the terms in equation (6.5).

Finally, the Nusselt number data for all single-phase data (gases and water) were correlated for all channel configurations. The resulting empirical correlation is

$$Nu = 1.5 \times 10^{-8} Re^{1.812} Pr^{2.38} \quad (6.7)$$

Shown in Figure 6.10, with an correlation coefficient of only 0.616, equation (6.6) is not a very good correlation of the Nusselt number. However, as with the all gas correlations, ( $\mu/\mu_s$ ) and  $L/D_h$  again indicated the presence of entrance effects.

A comparison between the experimentally measured Nusselt number data of this study and the Nusselt number correlations listed in Chapter 2 are shown in Figure 6.11. As mentioned earlier, the equations have been normalized and plotted as the ratio of the

measured Nusselt number over the correlated Nusselt number ( $Nu_{meas}/Nu_{corr}$ ) versus the Reynolds number times the Prandtl number. As one can see, most of the experimental data is considerably less than that predicted by the correlations. However, between the values of  $Re \cdot Pr = 2,000$  to  $10,000$ , the correlations of Yu (1995) and Choi (1991) predict the observed Nusselt number well.

### Two-Phase Flow Results

For the two-phase experiments, a combination of water and each gas (argon, helium, and nitrogen) were tested in each of the channel configurations. The Reynolds numbers ranged from around 30 to just under 10,000 with the data distributed slightly more heavily near the lower Reynolds numbers. The quality ranged from very low values (on the order of 0.01%) up to approximately 45%. However, most of the data had a quality of less than 10%. Figure 6.12 shows the friction factor data for all two-phase tests. As one can see, this data is well behaved and the laminar and turbulent regions are well defined. As will be discussed, the friction factor of the two-phase tests showed no dependence on channel size. The heat transfer results are given in Figure 6.13. Here the data show a large amount of scatter, as with the single phase results. Also, the two-phase Nusselt number data show the same trend as the single-phase in that no transition is indicated. In the following sections it will be shown that neither the homogeneous flow model nor the separated flow model parameters correlate the heat transfer data well.

### Two-Phase Friction Factor

Homogeneous Flow Model. Because of the two distinct regions that are shown in Figure 6.12, the two-phase data was analyzed in each region separately. Discussed in Chapter 4 was the fact that the flow parameters are calculated based on average fluid properties. As with the single-phase data, the two-phase data for friction factor was correlated starting with each individual channel configuration. Then, more and more general correlations were performed until all two-phase data were correlated for all channel configurations. Though the specifics of each of these correlations need not be presented, several interesting details were found. First, the friction factor data show two distinct regions for all channel sizes. Or, in two-phase flow we did not see the suppression of the turbulent tendencies, as with the single-phase data. It is believed that this behavior is due to the intense pressure fluctuations associated with two-phase flow. These pressure fluctuations, present over almost the entire range of quality, provide enough induced turbulence to overcome any suppression tendencies. Second, there is virtually no scatter around the Reynolds number of 3,000. There is literally only one point, in the turbulent region, that has a Reynolds number less than 3,000. The lack of scatter is probably also due to the pressure fluctuations associated with two-phase flow. It is believed that the transition Reynolds number of 3,000 is dependent on the test section and test fixture. In other words, a different test section may show a similar definite transition Reynolds number, but the value of this number most likely will not be exactly 3,000. Third, as with single-phase correlations, all two-phase correlations showed a complete dependence on

the Reynolds number. For the laminar and turbulent regions, the Reynolds number exponent has values of approximately -1.0 and -0.25, respectively, just as macroscale theory predicts. Therefore, the resulting equations will have the same form as equations (6.3, 4 and 5). The resulting empirical correlations are

Laminar Region ( $Re < 3,000$ ):

$$f_{tp} = \frac{97}{Re} \quad (6.8)$$

Turbulent Region ( $Re > 3,000$ ):

$$f_{tp} = \frac{0.3384}{Re^{0.25}} \quad (6.9)$$

The correlation coefficients are 0.931 and 0.907 for the laminar and turbulent regions, respectively. Equations (6.8) and (6.9) are shown in Figure 6.14. As one can see, both correlations are exceptional, particularly in the turbulent regime. Equation (6.9) fits the data to within +2.4% to - 0.8%. Note the change in range of the error bars provided in Figure 6.14. There is a slight indication that entrance effects from the correlations are probably what is causing the scatter at the lower Reynolds numbers. As the error analysis will show, the uncertainty of the pressure measurements was very small and did not change with changing pressure. To better fit the laminar data at the higher Reynold numbers, the coefficient in Equation (6.7) can be changed to a value of 87. The resulting equation is shown in Figure 6.15. The fourth, and final detail that was learned from the empirical correlations was that the two smallest channels, configurations E and F, indicated a

dependence of the quality and surface tension parameters (  $(1-x)/x$  and  $We$ ), respectively. No other channel configurations showed this dependence. However, the quality for these channels also covered a larger range and was higher than the other channels (10 - 40%). The last point seems to indicate that the quality and surface tension parameters become more important as the quality increases.

Separated Flow Model. The parameters presented in Chapter 4 for the separated flow model were correlated in the same manner as the homogeneous parameters. However, the resulting correlations were very poor ( $r < 0.45$ ) in almost all cases. Also, the correlations provided no insight into which parameters were important. For the turbulent regime ( $Re > 3,000$ ), the empirical correlation

$$f_{tp} = 0.0487 \left( \frac{v_g}{v_f} \right)^{0.0644} \left( \frac{\mu_f}{\mu_g} \right)^{-0.0667} \left( \frac{\epsilon}{D_h} \right)^{-0.0189} \left( \frac{L}{D_h} \right)^{-0.0751} \left( \frac{1-x}{x} \right)^{0.00868} \alpha^{0.2809} \quad (6.10)$$

does, to some degree, reduce the scatter in the data. Equation (6.10) is shown in Figure 6.16. However, because so many parameters are contained in equation (6.10) it can really only be applied to this particular set of data. That is, because no insight can be determined from the parameters on the behavior of the fluid, there is no reason to believe that this equation would apply to data other than that of this study.



### Nusselt Number

The Nusselt number data taken during the two-phase tests is shown in Figure 6.13. As with the previous sections, the data was analyzed based on each channel configuration first and then by more general correlations. Unfortunately, the resulting correlations for both the homogeneous and separated flow models were very poor. However, the numerous empirical correlations did provide some insight into the dominant parameters in two-phase heat transfer. When each channel configuration was considered separately, the Reynolds number and the Prandtl number were found to be most important in describing the behavior of the flow. This agrees with the Dittus-Boelter equation. As one can see in Figure 6.13, the behavior of the data parallels that of the Dittus-Boelter equation. Also, as with the single-phase heat transfer results, no transition is seen to occur. Note the data in Figure 6.13 labeled channel D. The data appears to be in a transition to a higher Nusselt number. However, no other channel was seen to behave in this manner. Extensive physical inspection was conducted on channel configuration D, but nothing was found that would explain the jump in the Nusselt number. Based on the Reynolds number and the Prandtl number, the empirical correlation for the Nusselt number is

$$\text{Nu} = 0.00166 \text{Re}^{0.6268} \text{Pr}^{2.293} \quad (6.11)$$

Equation (6.11), with a correlation coefficient of only 0.434, is shown in Figure 6.17. As one can see, this correlation does not fit the data well and has a large standard deviation. Again, error in the measurement of the temperatures has made any analysis very difficult. Correlation of the separated flow parameters gave even less information about the behavior of the fluid. The best separated flow correlation had a correlation coefficient of 0.4 and a standard deviation on the order of 10.

### Analytical Models

This section presents empirical correlations based on the analytical equations developed in Chapter 3. It will be shown that the separated flow model can make use of the correlation derived from the homogeneous flow model.

Homogeneous Flow Model. Looking at equation (3.27), one can see that the two-phase pressure drop is a function of a friction factor ( $f_{fa}$ ) and frictional flow parameter ( $\Phi_{fa}^2$ ). For the homogeneous flow model, the parameter  $\Phi_{fa}^2$  is expressed quantitatively by equation (3.25). Therefore, the friction factor can be computed directly for each pressure measurement. Solving equation (3.37) for the friction factor gives

$$f_{fa} = \frac{\Delta P_{tp} D_h}{2 G^2 v_f L \Phi_{fa}^2} \quad (6.12)$$

The friction factor in equation (6.12) was correlated against both the homogeneous and separated flow model parameters. Both sets of parameters were utilized because of the

difficulty in finding an adequate correlation. As can be seen in Figure 6.18, there are two regimes which need to be considered. One for  $f_{fa}$  larger than 0.005 and the other for  $f_{fa}$  less than 0.005. The apparent jump in the friction factor does not appear to be due to the lack of data in that area. For channel configurations E and F, which makeup the data for  $f_{fa} < 0.005$ , several data points for these channels are above  $f_{fa} = 0.005$ . Also, inspecting the measured flow rates show no jumps in either the gas or liquid flow rates that might account for this jump in the data. Unfortunately, virtually no dimensionless combination of parameters gave a correlation coefficient greater than 0.4. The resulting empirical correlations are

$$(f_{fa} < 0.005): \quad f_{fa} = 43,940 \, G^{-3.885} \, \text{Re}^{2.732} \left( \frac{\dot{m}_f}{m_g} \right)^{-0.1137} \quad (6.13)$$

$$(f_{fa} > 0.005): \quad f_{fa} = 6,791 \, G^{-1.495} \, \text{Re}^{0.2466} \, x^{-1.571} \left( \frac{\dot{m}_f}{m_g} \right)^{-1.731} \quad (6.14)$$

As one can see, both equations are dimensional. This, unfortunately, could not be avoided. The correlations indicated that by far the most important parameter in determining  $f_{fa}$  was the mass velocity ( $G$ ). Even though dimensionless parameters containing  $G$  were tried, none were remotely successful. Only a correlation containing  $G$  gave reasonable results. On the positive side, however, in macroscale two-phase flow the mass velocity is a common and important parameter. Equations (6.13) and (6.14) are shown in Figures 6.19 and 6.20 for the different  $f_{fa}$  regimes. As one can see, the correlations give good results.

Equations (6.13) and (6.14) will be used in the next section to predict the two-phase friction coefficient. Comparisons will be made at that time.

Separated Flow Model. For the separated flow model, the pressure drop through a channel is given by equation (3.57). In equation (3.57), the pressure drop is a function of a friction factor ( $f_f$ ), a frictional pressure drop coefficient ( $\phi_f^2$ ), and a momentum pressure drop parameter ( $\phi_m$ ). The friction factor ( $f_f$ ) is based on a single phase pressure gradient with the liquid assumed to flow alone in the channel. The momentum pressure drop parameter is described by equation (2.15) and is particularly important in two-phase flow involving phase change. However, preliminary calculations indicated that the momentum pressure drop parameter changed the pressure calculation by less than 3% and was therefore neglected. Therefore, equation (3.57) was only a function of the liquid friction factor and the frictional pressure drop parameter. To solve equation (3.57), one can make use of the correlation of  $f_{fa}$  determined in the previous section. By using the Bausius equation (3.22), Collier (1981) showed that

$$f_f = f_{fa} (1 - x)^{-1/4} \quad (6.15)$$

Substituting this expression into equation (3.57) and neglecting the momentum pressure drop parameter, equation (3.57) becomes

$$\Delta P_{tp} = \frac{2 G^2 v_f L f_{fa} (1-x)^{-1.75}}{D_h} \phi_f^2 \quad (6.16)$$

Note that equation (6.16) is now a function  $\Phi_f^2$  and the friction factor ( $f_{fa}$ ) that was correlated in the last section. Therefore, values of  $\Phi_f^2$  can be determined for each pressure measurement directly and correlated against the homogeneous and separated flow parameters. Solving equation (6.16) for the frictional pressure drop parameter gives

$$\Phi_f^2 = \frac{D_h \Delta P_{tp}}{2 G^2 v_f L f_{fa} (1-x)^{-1/75}} \quad (6.17) \quad +1.75$$

The resulting empirical correlations of equation (6.17), over the two ranges of  $f_{fa}$ , yielded some interesting results. By far the most important parameters in predicting  $\Phi_f^2$  were found to be  $e/D_h$ ,  $L/D_h$ ,  $(1-x)/x$ , and  $\alpha$  (aspect ratio). Interestingly, the empirical correlation is dominated by the channel's physical dimensions more than any other parameter. Only one fluid parameter was shown to be important, the quality. Any correlation of parameters that contained these four parameters had a correlation coefficient of 0.91 or higher. To help reduce the standard deviation, the final correlation of  $\Phi_f^2$  also related some parameters which have been shown to be important in earlier correlations; Reynolds number, Weber number, Prandtl number, and the viscosity ratio ( $\mu/\mu_s$ ). The frictional pressure parameter is predicted well by the expressions

( $f_{fa} < 0.005$ ):

$$\Phi_f^2 = 0.011 \text{Re}^{0.325} \text{We}^{-0.0162} \text{Pr}^{-0.1803} \frac{\mu}{\mu_s}^{1.989} \frac{\epsilon}{D_h}^{0.231} \frac{L}{D_h}^{-0.113} \frac{1-x}{x}^{0.0541} \alpha^{7.94} \quad (6.18)$$

( $f_{fa} > 0.005$ ):

$$\Phi_f^2 = 1.0x^{-10} \text{Re}^{0.0834} \text{We}^{0.056} \text{Pr}^{2.932} \frac{\mu}{\mu_s}^{1.367} \frac{\epsilon}{D_h}^{-0.01795} \frac{L}{D_h}^{2.865} \frac{1-x}{x}^{0.0277} \alpha^{1.214} \quad (6.19)$$

Figures 6.21 and 6.22 show equations (6.18) and (6.19) which have correlations coefficients of 0.979 and 0.971, respectively.

The accuracy of the pressure drops predicted by empirical solution compared to the two analytical flow models can be seen in Figures 6.23 and 6.24. As one can see in Figure 6.23, the predicted pressure drop is reasonably accurate, particularly for the higher pressure drops where Martinelli's equations will be shown to fail. From Figure 6.24, one can see that the separated flow model does not provide a good estimate of the pressure drop. However, this could be for several reasons. First the separated flow model is essentially a correlation of a correlation. That is, the correlation for  $\Phi_f^2$  can not be expected to be any better than the correlation of  $f_{fa}$  on which it is based. Second, the separated flow model is not a good model for fluid flow at the scale of these experiments. For most macroscale developments, the correlation of  $\Phi_f^2$  is based on the assumption of a constant value for  $f_{fa}$ . As shown in these experiments,  $f_{fa}$  is definitely not a constant. Other reasons for the inaccuracy of the separated flow model can be seen when comparing the pressure prediction of Martinelli to the experimental data.

Figure 6.25 shows the data taken for this study plotted with the predicted pressure drop of Martinelli. As one can see, Martinelli's equations substantially over predict the measured pressure drop except at lower values of the measured pressure drop. This over prediction is due to two reasons. First, as Collier (1981) states, the semi-empirical equations developed by Martinelli are only good for low-to-moderate pressure drops over the length of the channel. For the data taken in this study, the calculated values of  $\Delta P/L$  were several orders of magnitude higher than Martinelli's equations would predict. Second, Martinelli's equations are based on the macroscale constants which predict the friction factor in laminar and turbulent regimes for the individual components. Not only have we shown that in some cases these constants are different, but also that there is no transition in the smaller channels for single-phase flow.

### Flow Regimes

To compare the flow regimes present for this study, the data of this study are plotted on Baker's (1954) flow regime map given in Figure 6.26. As one can see, the data extend past the regions given by Baker. The data are mainly concentrated in the mist flow and bubble flow regimes. Also, some data lie along the transition lines to annular and slug flow. The jump in the data about  $f_{fa} = 0.005$  is also seen in this figure. From what could be observed during the experimentation, the regimes predicted by Baker's flow regime map seem reasonable. Though the specific regimes could not be verified without a high-speed camera, the behavior of the two fluids in the manifold area of the test section indicated that the flow regimes were mainly slug flow with some annular flow. With such

low qualities seen during the experiments, it is also reasonable to believe that bubble flow occurred. However, this could not be confirmed. The large amount of data shown in the mist flow regime is not believed to have actually been mist flow. For mist flow to occur, the quality needs to be relatively high. The only data with high qualities are those points shown to have a  $f_{fa}$  value less than 0.005. These points can be seen to be the upper right grouping of data. Some of this contradiction is clarified by the flow regime map given by Suo and Griffith (1964) in Figure 6.27. Figure 6.27 shows the separation between bubbly-slug flow and slug flow. As can be seen, most of the data is in the region of bubbly-slug flow. It is believed that this figure is a better representation of what is actually occurring in the microchannels. For data points generated by this study, the mist flow regime on Baker's (1954) map are probably more like the bubbly-slug flow described by Suo and Griffith (1964).

#### Other Heat Transfer Comparisons

As some final comparisons, the heat flux data measured in this study, and the calculated heat transfer coefficients are compared with the information given in Chapter 2 for forced convection flow boiling. Figure 6.28 compares the measured heat flux in both the single- and two-phase data to the critical heat flux ranges given in Figure 3.3. As one can see, the heat flux dissipated by the water and all two-phase data approach the levels present in micro heat pipes for a lower temperature difference.

Figure 6.29 given the ranges of the calculated heat transfer coefficients for both the single- and two-phase flow data of this study. Typical ranges for the heat transfer



coefficient in various types of convection are listed on the left side of the graph. As can be seen the water and the two-component two-phase data have heat transfer coefficients on the order of, and higher, than convection involving phase change. It would therefore be expected to see higher heat transfer coefficients for microchannel flow boiling. The comparison indicates that heat transfer through microchannels does have advantages over macroscale channels.

### Error Analysis

For the results presented above to be used to their fullest, an uncertainty analysis of the experimental measurements must be considered. The uncertainty ( $\pm U$ ), or the 95% confidence limit, of the measurements are made up of the precision error (P) and the Bias error (B). Precision error is the lack of repeatability due to random error and unsteadiness. The Bias error is a measure of fixed or constant error. A list of the precision and bias limits for the equipments used in this error analysis is given in Table 4. For a detailed description of the experimental flow loop, please see the work by Bailey (1996).

For the experimental data taken during this study, only two expressions need to be analyzed. The friction factor, defined by

$$f = \frac{2 \Delta P D_h}{\rho L \bar{V}^2} \quad (6.20)$$

Table 4: Bias and precision error for measured experimental variables.

| Variable               | Bias Error | Precision Error |
|------------------------|------------|-----------------|
| Pressures              | 0.1 %      | 0.15 %          |
| Volumetric Flow Rates  | 0.25 %     | 1.0 %           |
| Thermocouples          | 0.1 °C     | 1.0 °C          |
| Channel Height (Depth) | 0.01 %     | 0.01 %          |
| Channel Length         | 0.04 %     | 0.04 %          |
| Channel Width          | 0.01 %     | 0.01 %          |
| Density                | 0.0        | 1.0 %           |
| Specific Heat          | 0.0        | 1.0 %           |
| Thermal Conductivity   | 0.0        | 1.0 %           |

and the Nusselt number, defined by

$$Nu = \frac{h D_h}{k} \quad (6.21)$$

To break these equations down into forms that contain only measured variables, requires the use of the equations

$$D_h = \frac{4 A}{P} = \frac{4 W H}{2 W + 2 H} \quad (6.22)$$

$$\bar{V} = \frac{\dot{V}}{A} = \frac{\dot{V}}{WH} \quad (6.23)$$

$$h = \frac{q}{A_w(T_w - T_\infty)} \quad (6.24)$$

$$A_w = L(W + 2H) \quad (6.25)$$

$$q = \dot{m} C_p (T_{in} - T_{out}) \quad (6.26)$$

Substituting equations (6.22) through (6.26) into equations (6.21) and (6.22) yield

$$f = \frac{2(P_{in} - P_{out})W^3H^3}{\rho L \bar{V}^2(W + H)} \quad (6.27)$$

$$Nu = \frac{2\rho \dot{V} C_p (T_{in} - T_{out})WH}{kL(T_w - T_\infty)(W + 2H)(W + H)} \quad (6.28)$$

Equations (6.27) and (6.29) can now be used to determine the experimental uncertainty due to the instruments used with the experimental flow loop.

Consider the friction factor. The square of the precision error for the friction factor can be found by summing the square of the partial derivative with respect to each variable multiplied by the square of the precision error for that variable. Or,

$$\begin{aligned}
 (P f)^2 = & \left( \frac{\partial f}{\partial P_{in}} \right)^2 (P_{P_i})^2 + \left( \frac{\partial f}{\partial P_{out}} \right)^2 (P_{P_o})^2 + \left( \frac{\partial f}{\partial W} \right)^2 (P_w)^2 + \left( \frac{\partial f}{\partial H} \right)^2 (P_H)^2 + \\
 & \left( \frac{\partial f}{\partial \rho} \right)^2 (P_\rho)^2 + \left( \frac{\partial f}{\partial L} \right)^2 (P_L)^2 + \left( \frac{\partial f}{\partial \dot{V}} \right)^2 (P_{\dot{V}})^2
 \end{aligned} \tag{6.29}$$

The bias error is determined using an equation of the same form by substituting the bias error for the precision error. Once the bias and precision error have been determined using equation (6.30), the uncertainty can be determined by the expression

$$U = (B^2 + P^2)^{1/2} \tag{6.30}$$

where  $U$  is the +/- percentage applied to the friction factor or Nusselt number for which it was calculated. The uncertainties for both the friction factor and the Nusselt number data are listed with the reduced data in Appendix D. Because of all the bias and precision error terms used in determining the friction factor being related as percentages, the final equations reduced down to the square root of the sum of the squares of the error terms. Therefore, the uncertainty calculated for the friction factor was a constant for all flow situations. The uncertainty of all friction factor measurements was found to be  $\pm 3.06\%$ . For the Nusselt number calculations, the bias and precision errors for the thermocouples were given a  $0.1^\circ\text{C}$  and  $1.0^\circ\text{C}$ , respectively. Therefore, the uncertainty of the Nusselt number measurements changed with each temperature measurement. Figures 6.30, 31, and 32 are samples of the uncertainty seen in the Nusselt number calculations. One can see in Figure 6.30 that the uncertainty in Nusselt number for gas flow is largest at the

lowest Reynolds numbers. Here the temperature differences are the smallest. Figure 6.30 also shows that the large error associated with the low Reynolds number quickly diminishes to a relatively constant value as Reynolds number increases. The ranges of the Nusselt number uncertainties are given for each channel configuration and flow combination in Table 5 and 6. A trend just opposite to Figure 6.30 can be seen in Figure 6.31 for water flows. Here the smaller temperature differences occur at the high end of the Reynolds numbers. Because of the temperature limitations on the test section and heater, the amount of power used to heat the channels was not adequate to maintain a larger temperature difference. A similar trend is seen in Figure 6.32 for two-phase flows. The uncertainty of the Nusselt number increases with average Reynolds number. Also, the Nusselt number is seen to be fairly constant within the different ranges of liquid and gas Reynolds numbers. As discussed through the previous sections, the medium to large amount of error in the Nusselt number measurements played a major role in the large amount of scatter observed in the various single- and two-phase tests conducted for this study.

Table 5: Single-phase Nusselt number uncertainty.

| Channel Configuration | Uncertainty ( $\pm U$ , %) |      |                     |       |                       |      |                    |      |
|-----------------------|----------------------------|------|---------------------|-------|-----------------------|------|--------------------|------|
|                       | Argon<br>Min. Max.         |      | Helium<br>Min. Max. |       | Nitrogen<br>Min. Max. |      | Water<br>Min. Max. |      |
| A                     | 7.82                       | 22.5 | 9.25                | 30.5  | 8.42                  | 14.5 | 12.6               | 21.3 |
| B                     | 7.32                       | 23.2 | 7.97                | 62.5  | 7.27                  | 16.1 | 14.7               | 42.4 |
| C1                    | 9.03                       | 172  | 10.2                | 136   | 8.77                  | 252  | 10.2               | 20.3 |
| C2                    | 12.1                       | 95.6 | 14.0                | 119   | 12.3                  | 196  | 13.0               | 31.2 |
| C3                    | 10.4                       | 186  | 11.9                | 73.7  | 11.0                  | 857  | 13.3               | 24.9 |
| D                     | 43.5                       | 11.7 | 17.9                | 91.3  | 14.6                  | 220  | 14.1               | 165  |
| E                     | 13.4                       | 122  | 15.7                | 9,329 | 25.7                  | 500  | 12.7               | 22.2 |
| F                     | 13.3                       | 113  | 12.5                | 303   | 13.8                  | 267  | 15.2               | 23.6 |

Table 6: Two-phase Nusselt number uncertainty.

| Channel Configuration | Uncertainty ( $\pm U$ , %) |      |                           |      |                             |      |
|-----------------------|----------------------------|------|---------------------------|------|-----------------------------|------|
|                       | Water-Argon<br>Min. Max.   |      | Water-Helium<br>Min. Max. |      | Water-Nitrogen<br>Min. Max. |      |
| A                     | 13.3                       | 16.3 | 15.8                      | 23.9 | 13.4                        | 19.6 |
| B                     | 7.90                       | 25.2 | 10.1                      | 17.7 | 11.2                        | 16.1 |
| C1                    | 10.1                       | 19.6 | 10.1                      | 17.9 | 11.3                        | 19.2 |
| C2                    | 10.1                       | 35.8 | 10.9                      | 19.4 | 25.3                        | 69.2 |
| C3                    | 13.8                       | 17.7 | 15.3                      | 17.8 | 13.9                        | 18.0 |
| D                     | 18.2                       | 123  | 22.4                      | 88.9 | 23.0                        | 494  |
| E                     | 33.4                       | 49.7 | 15.8                      | 25.1 | 16.2                        | 23.8 |
| F                     | 14.4                       | 19.3 | 14.0                      | 19.3 | 14.1                        | 19.3 |

### Final Summary of Equations

To conclude Chapter 6, the empirical relations developed in this chapter are summarized below with details for which flow regimes and conditions apply.

Single-Phase Flow:

Water: ( $50 \mu\text{m} < D_h < 250 \mu\text{m}$ )

$$(Re < 10,000) \quad f = 3.9 \times 10^{11} Re^{-1.862} \left( \frac{\mu}{\mu_s} \right)^{0.7845} \left( \frac{L}{D_h} \right)^{-2.762} \quad (6.2)$$

All Gases: ( $150 \mu\text{m} < D_h < 250 \mu\text{m}$ )

$$(Re < 1,500) \quad f = \frac{74}{Re} \quad (6.3)$$

$$(Re > 2000) \quad f = \frac{0.39}{Re^{0.25}} \quad (6.4)$$

All Gases: ( $50 \mu\text{m} < D_h < 150 \mu\text{m}$ )

$$(Re < 5,000) \quad f = \frac{66}{Re} \quad (6.5)$$

All Gases: ( $50 \mu\text{m} < D_h < 250 \mu\text{m}$ )

$$(Re < 5,000) \quad Nu = 3.47 \times 10^{-6} Re^{1.639} Pr^{-0.6858} \quad (6.6)$$

All Single-Phase: ( $50 \mu\text{m} < D_h < 250 \mu\text{m}$ )

$$(Re < 5,000) \quad Nu = 1.5 \times 10^{-8} Re^{1.812} Pr^{2.38} \quad (6.7)$$

Two-Phase Flow:

All Two-Phase: ( $50 \mu\text{m} < D_h < 250 \mu\text{m}$ )

$$(Re < 3,000) \quad f_{tp} = \frac{97}{Re} \quad (6.8)$$

$$(Re > 3,000) \quad f_{tp} = \frac{0.3384}{Re^{0.25}} \quad (6.9)$$

( $Re > 3,000$ )

$$f_{tp} = 0.0487 \left( \frac{v_g}{v_f} \right)^{0.0644} \left( \frac{\mu_f}{\mu_g} \right)^{-0.0667} \left( \frac{\epsilon}{D_h} \right)^{-0.0189} \left( \frac{L}{D_h} \right)^{-0.0751} \left( \frac{1-x}{x} \right)^{0.00868} \alpha^{0.00868} \quad (6.10)$$

$$(Re < 10,000) \quad Nu = 0.00166 Re^{0.6268} Pr^{2.293} \quad (6.11)$$

Homogeneous Flow Model:

$$(f_{fa} < 0.005): \quad f_{fa} = 43,940 G^{-3.885} Re^{2.732} \left( \frac{m_f}{m_g} \right)^{-0.1137} \quad (6.13)$$

$$(f_{fa} > 0.005): \quad f_{fa} = 6,791 G^{-1.495} Re^{0.2466} x^{-1.571} \left( \frac{m_f}{m_g} \right)^{-1.731} \quad (6.14)$$



Separated Flow Model:

$$(f_{fa} < 0.005)$$

$$\Phi_f^2 = 0.011 \text{Re}^{0.325} \text{We}^{-0.0162} \text{Pr}^{-0.1803} \frac{\mu}{\mu_s}^{1.989} \frac{\epsilon}{D_h}^{0.231} \frac{L}{D_h}^{-0.113} \frac{1-x}{x}^{0.0541} \alpha^{7.94} \quad (6.18)$$

$$(f_{fa} > 0.005)$$

$$\Phi_f^2 = 1.0x^{-10} \text{Re}^{0.0834} \text{We}^{0.056} \text{Pr}^{2.932} \frac{\mu}{\mu_s}^{1.367} \frac{\epsilon}{D_h}^{-0.01795} \frac{L}{D_h}^{2.865} \frac{1-x}{x}^{0.0277} \alpha^{1.214} \quad (6.19)$$

where  $f_{fa}$  and  $\Phi_f^2$  used in

$$\Delta p_{tp} = \frac{2f_{fa} G^2 v_f L}{D_h} \left[ 1 + x \left( \frac{v_{fg}}{v_f} \right) \right] \left[ 1 + x \left( \frac{\mu_{fg}}{\mu_f} \right) \right]^{-\frac{1}{4}} \quad (3.27)$$

$$\Delta P_{tp} = \frac{2 G^2 v_f L f_{fa} (1-x)^{-1/75}}{D_h} \Phi_f^2 \quad (6.16)$$

respectively.

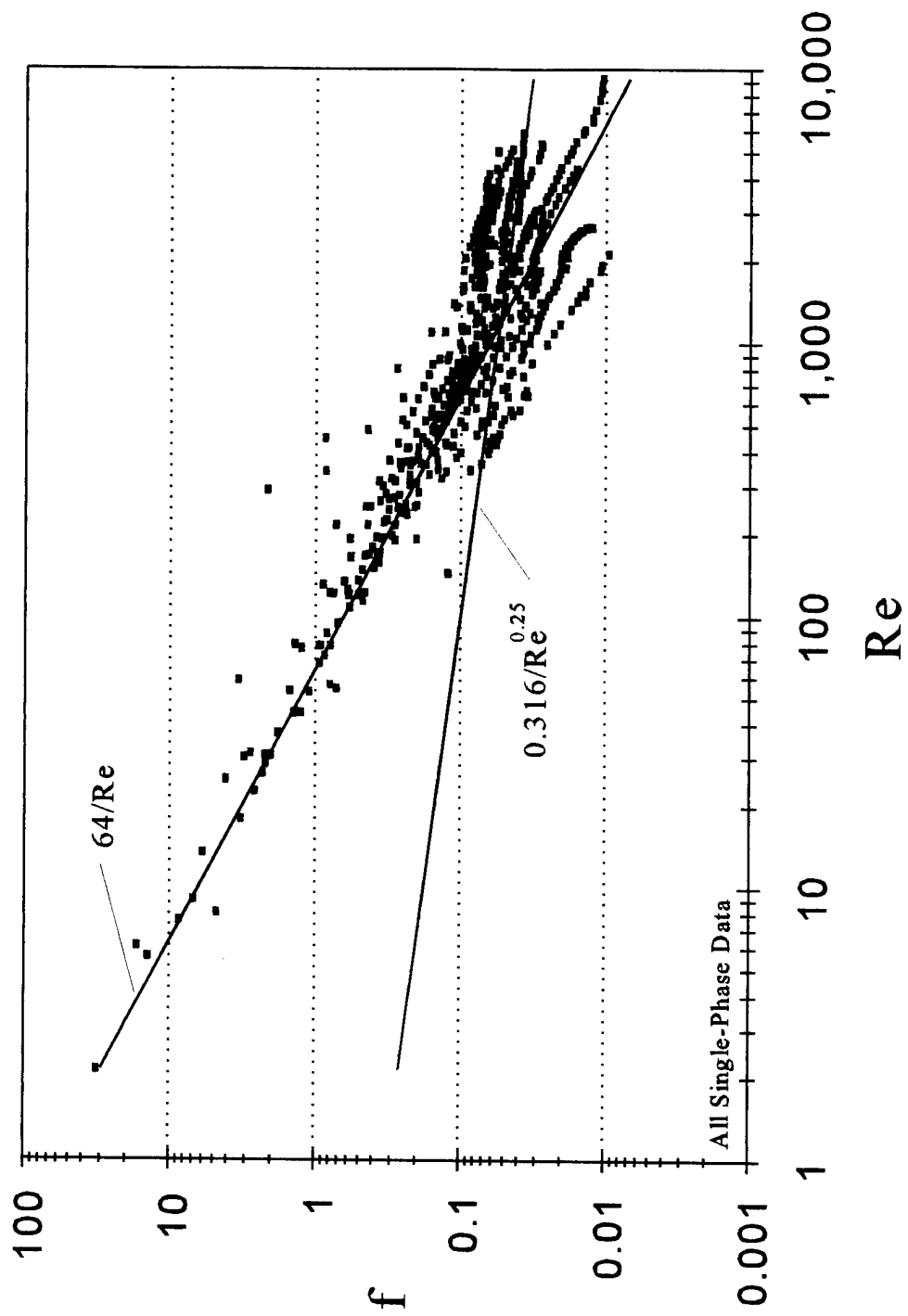


Figure 6.1: All single-phase friction factor data.

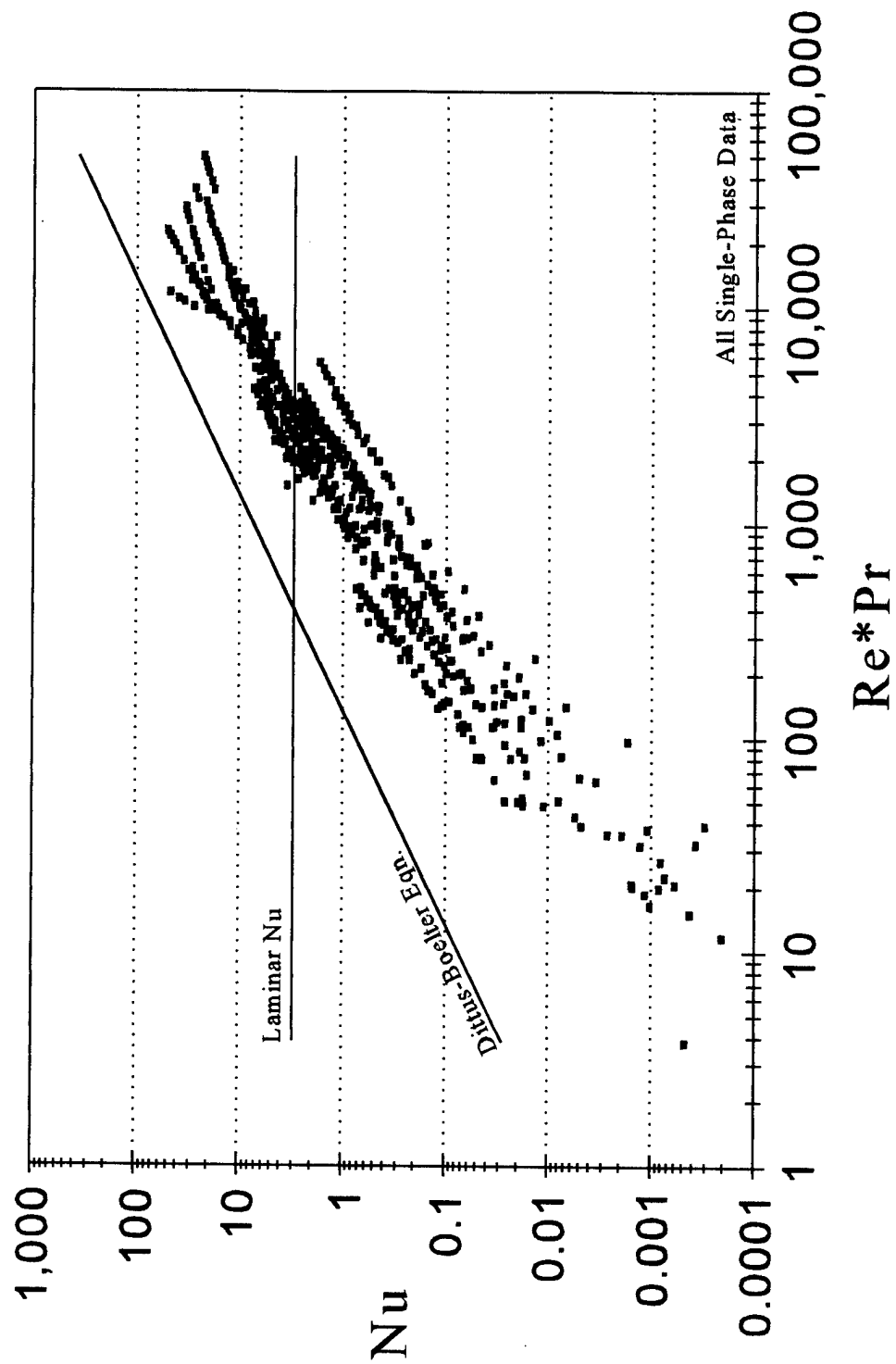


Figure 6.2: All single-phase Nusselt number data.

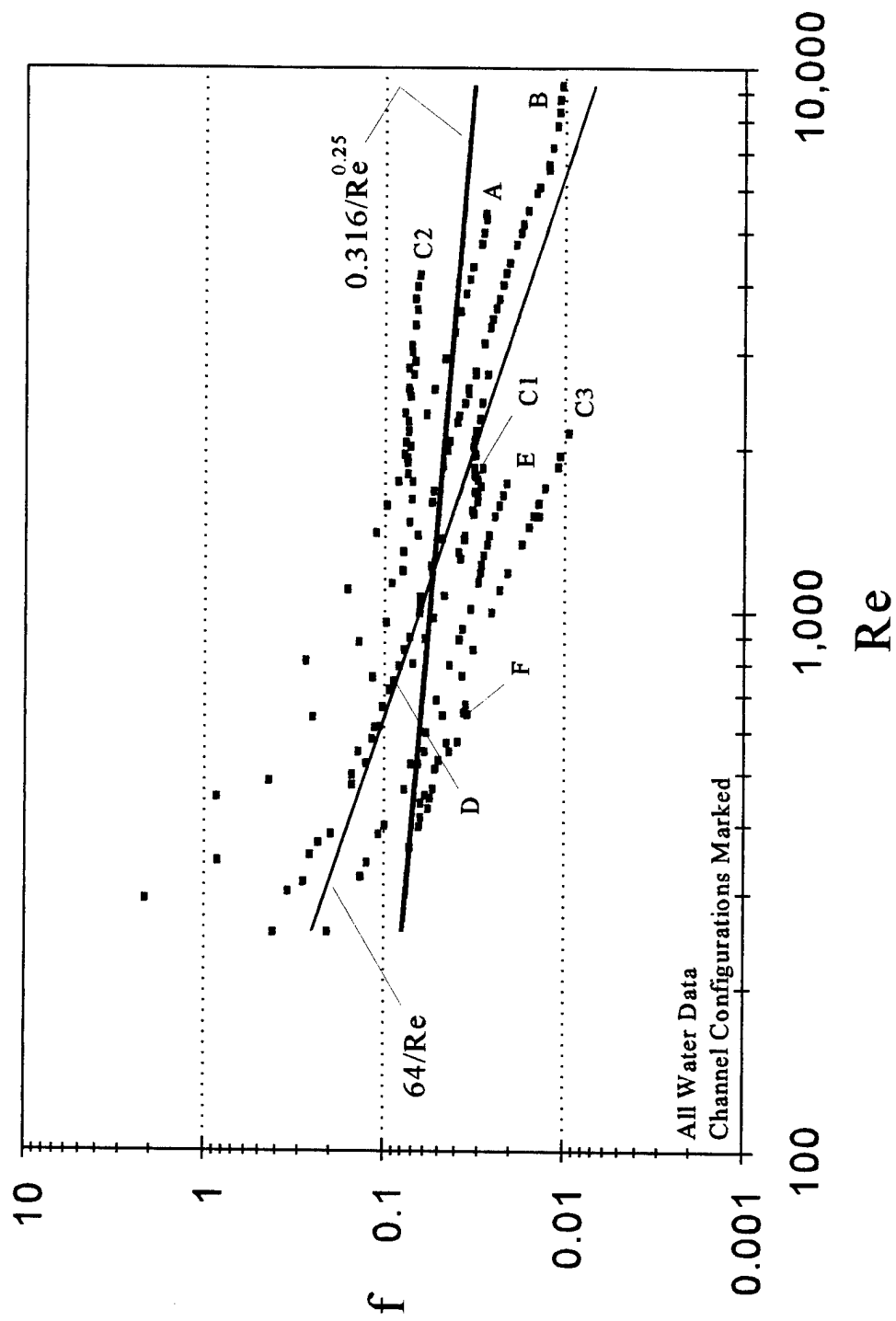


Figure 6.3: Water friction factor data with channel configurations indicated.

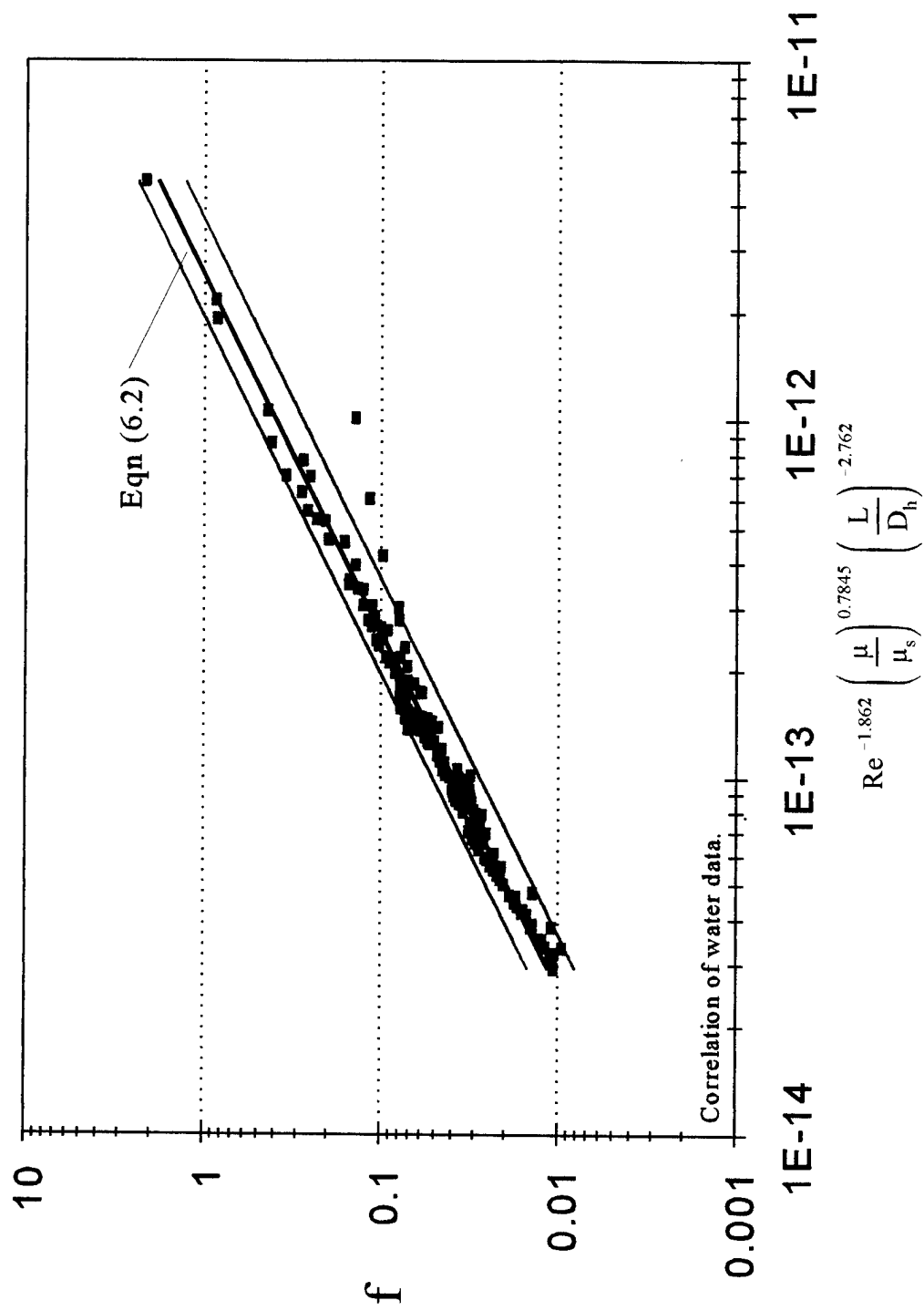


Figure 6.4: Friction factor correlation for water in all channel sizes.

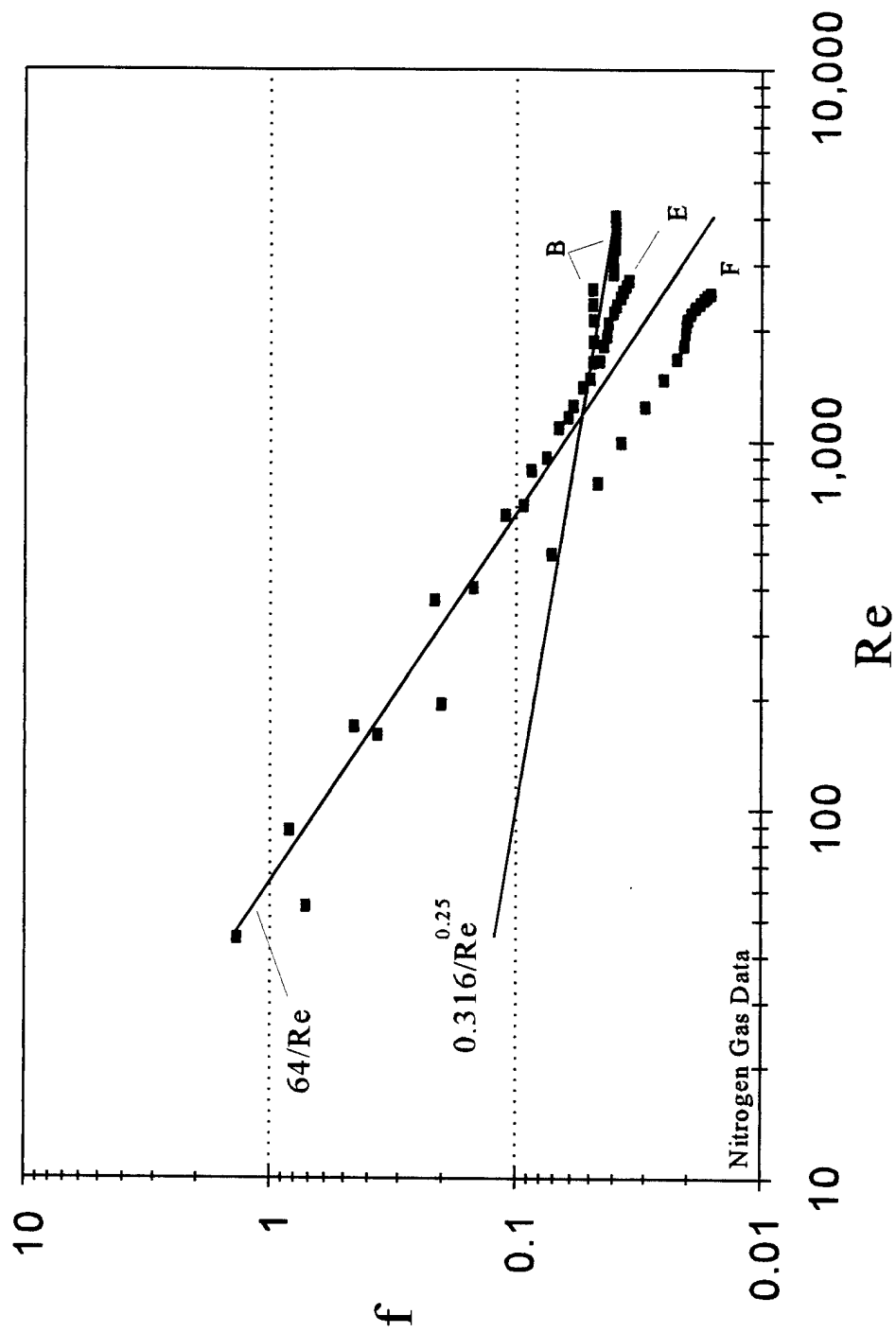


Figure 6.5: Nitrogen gas friction factor data for specified channels showing transition suppression.

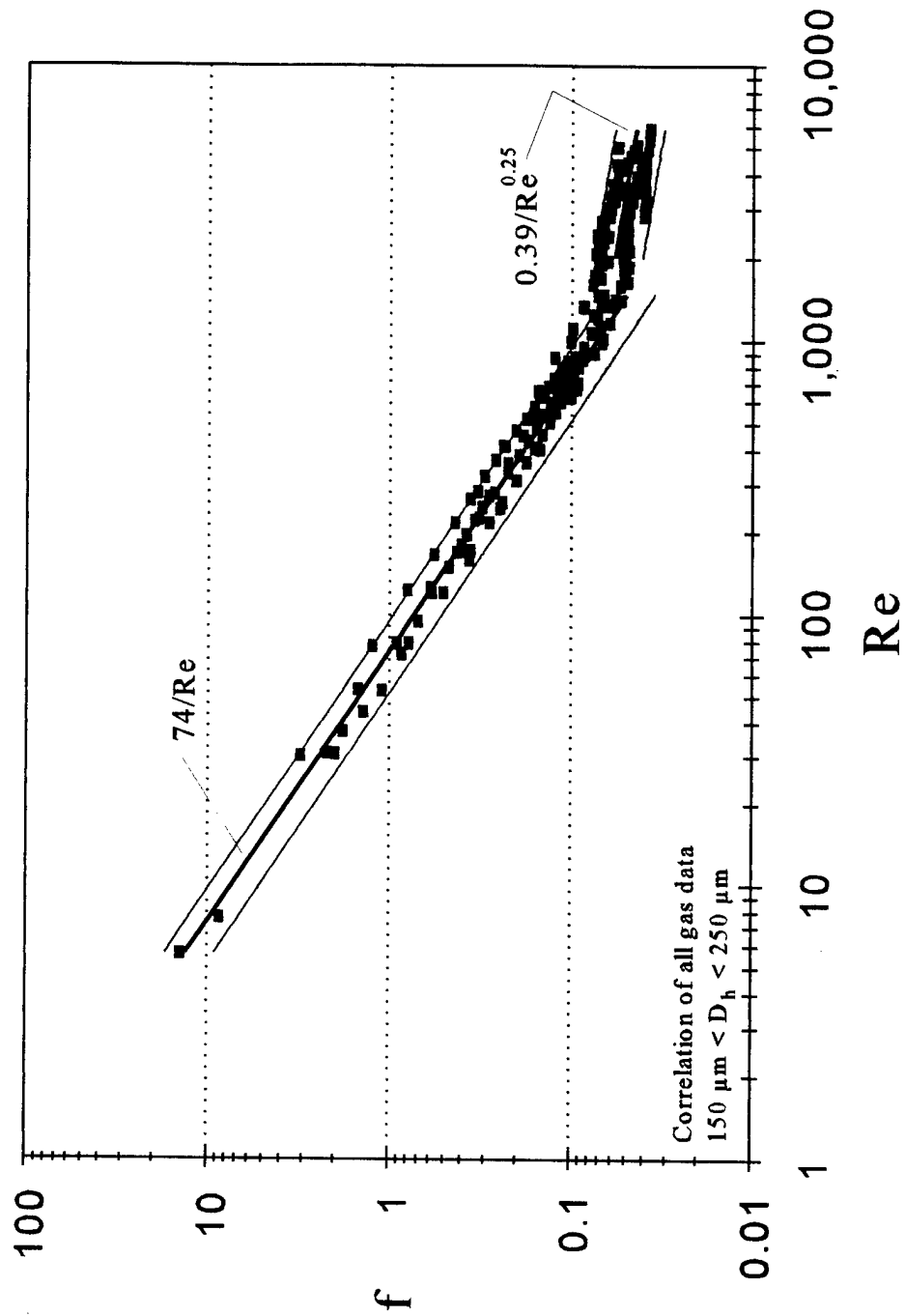


Figure 6.6: Friction factor correlation of all gas data for channels with hydraulic diameter between  $150 \mu m$  and  $250 \mu m$ .

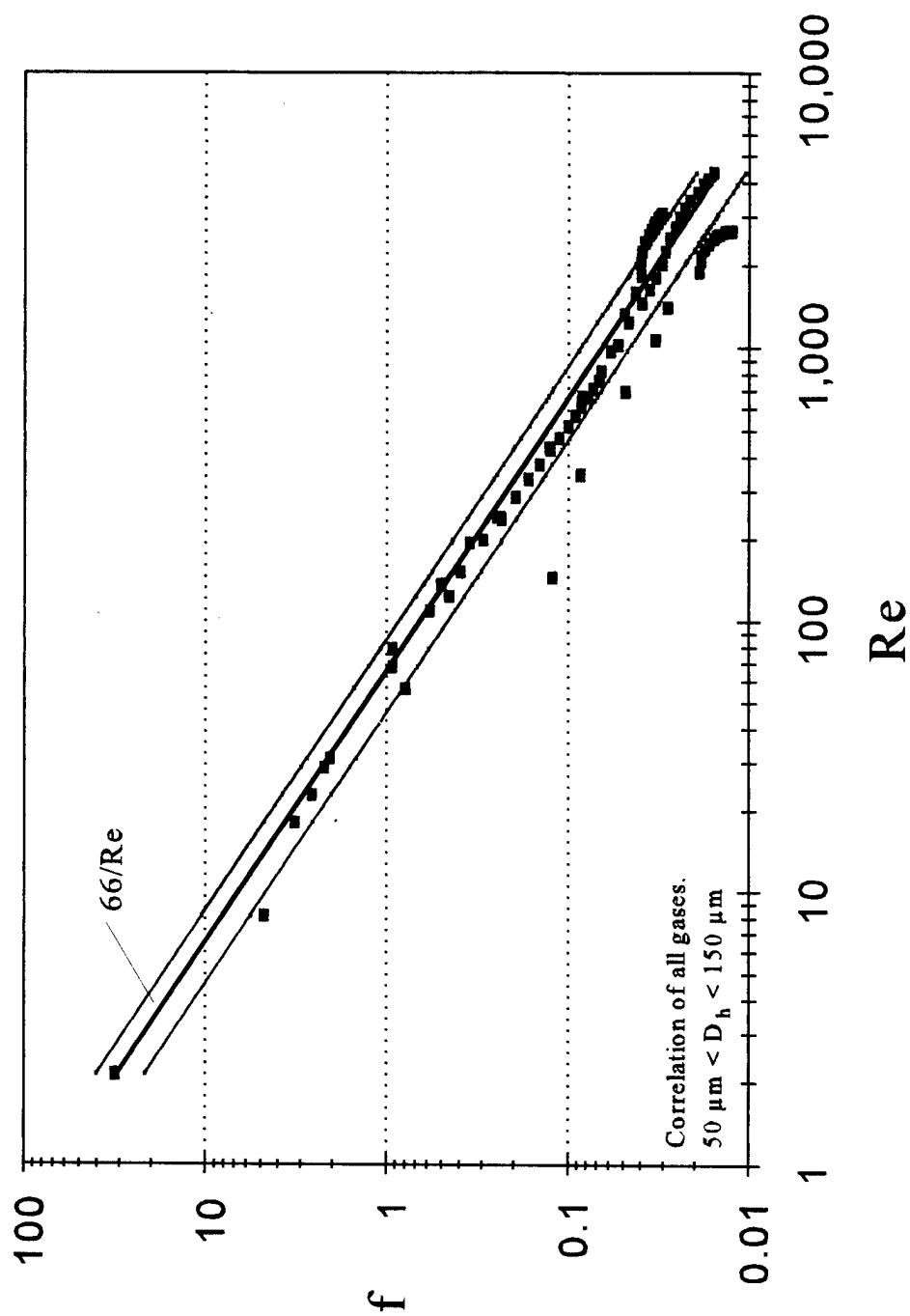


Figure 6.7: Friction factor correlation of all gas data for channel with hydraulic diameters between  $50 \mu\text{m}$  and  $150 \mu\text{m}$ .



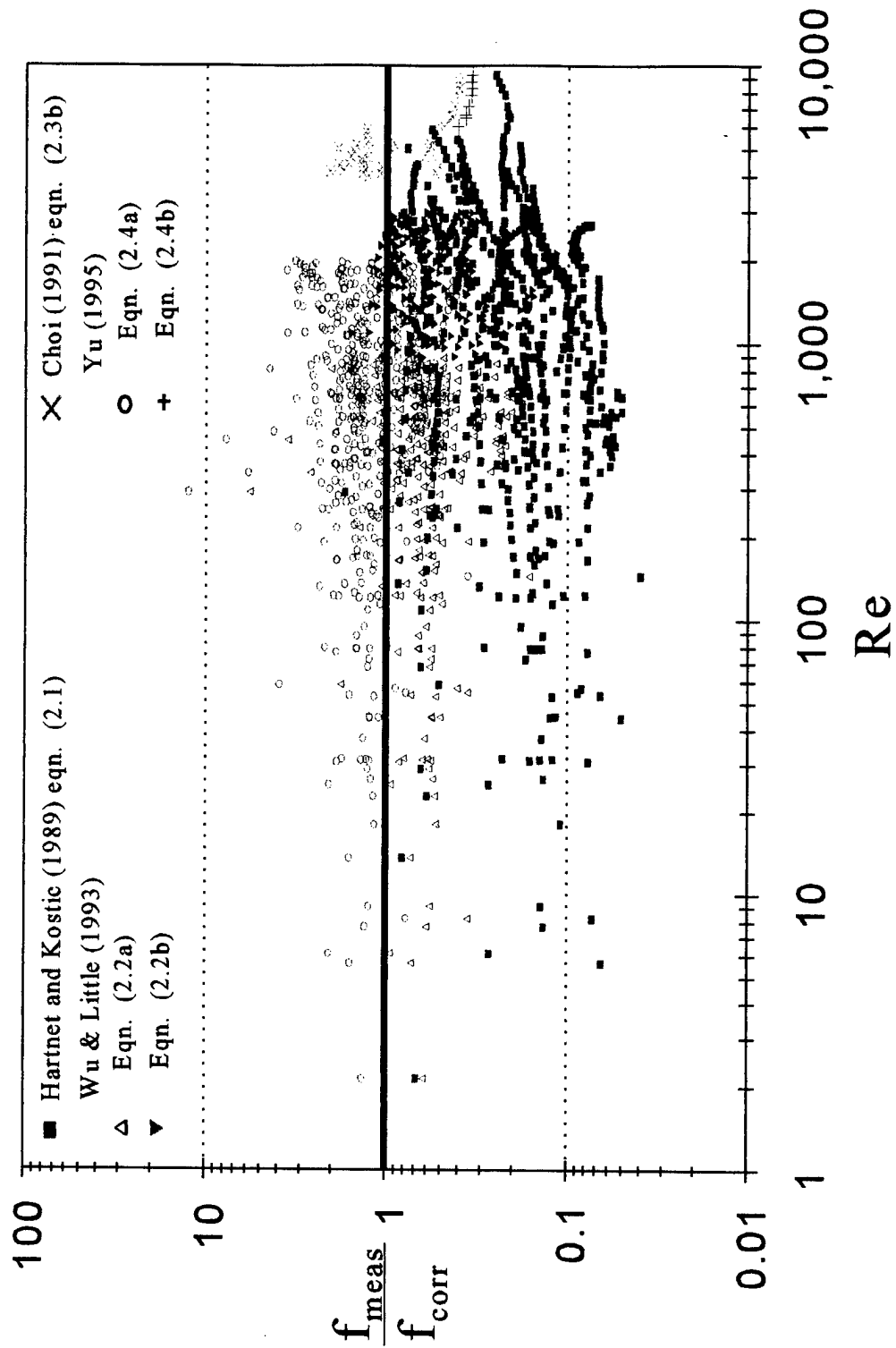


Figure 6.8: Comparison of friction factor data with correlations from Chapter 2.

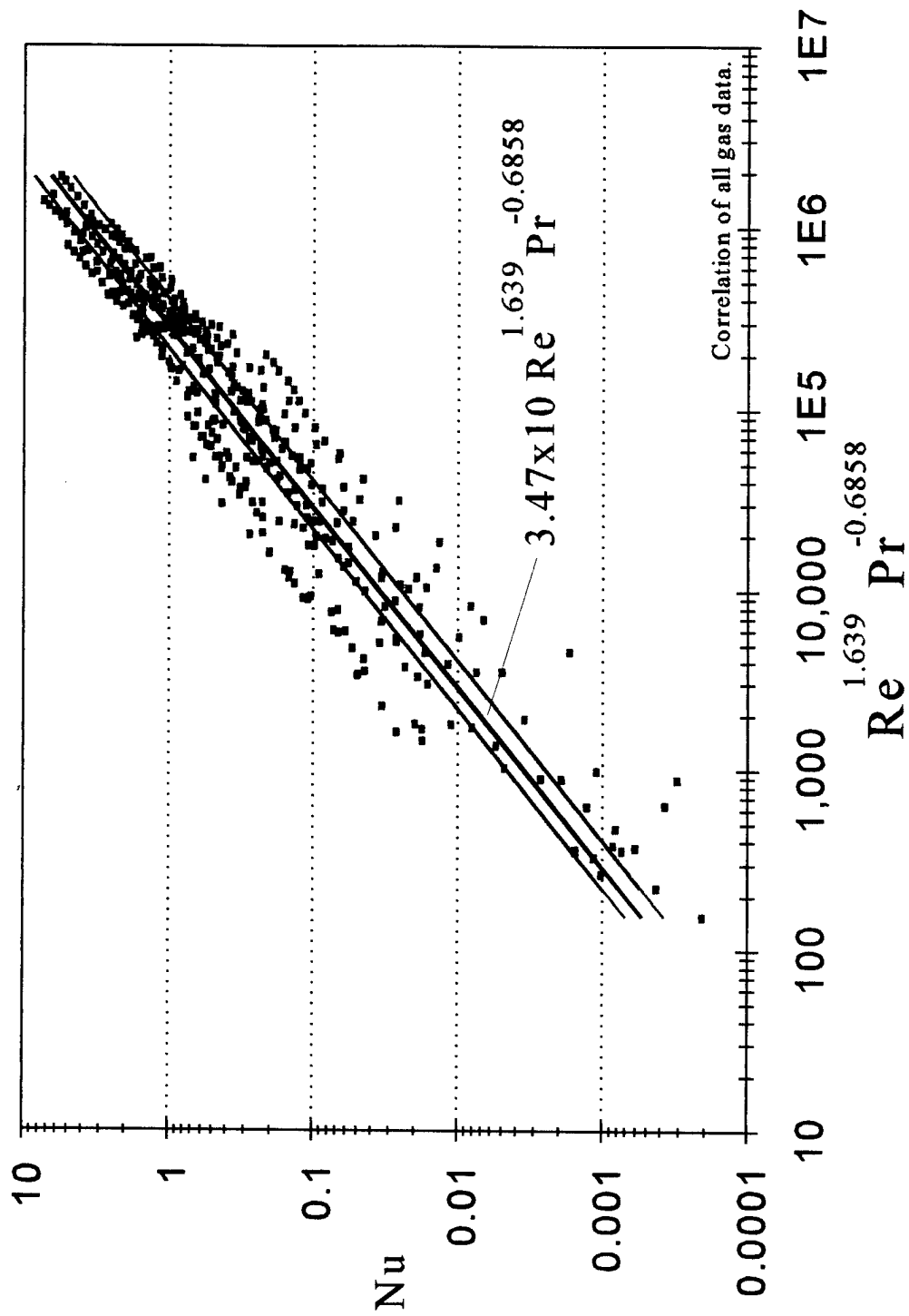


Figure 6.9: Nusselt number correlation of all gases for all channel sizes.

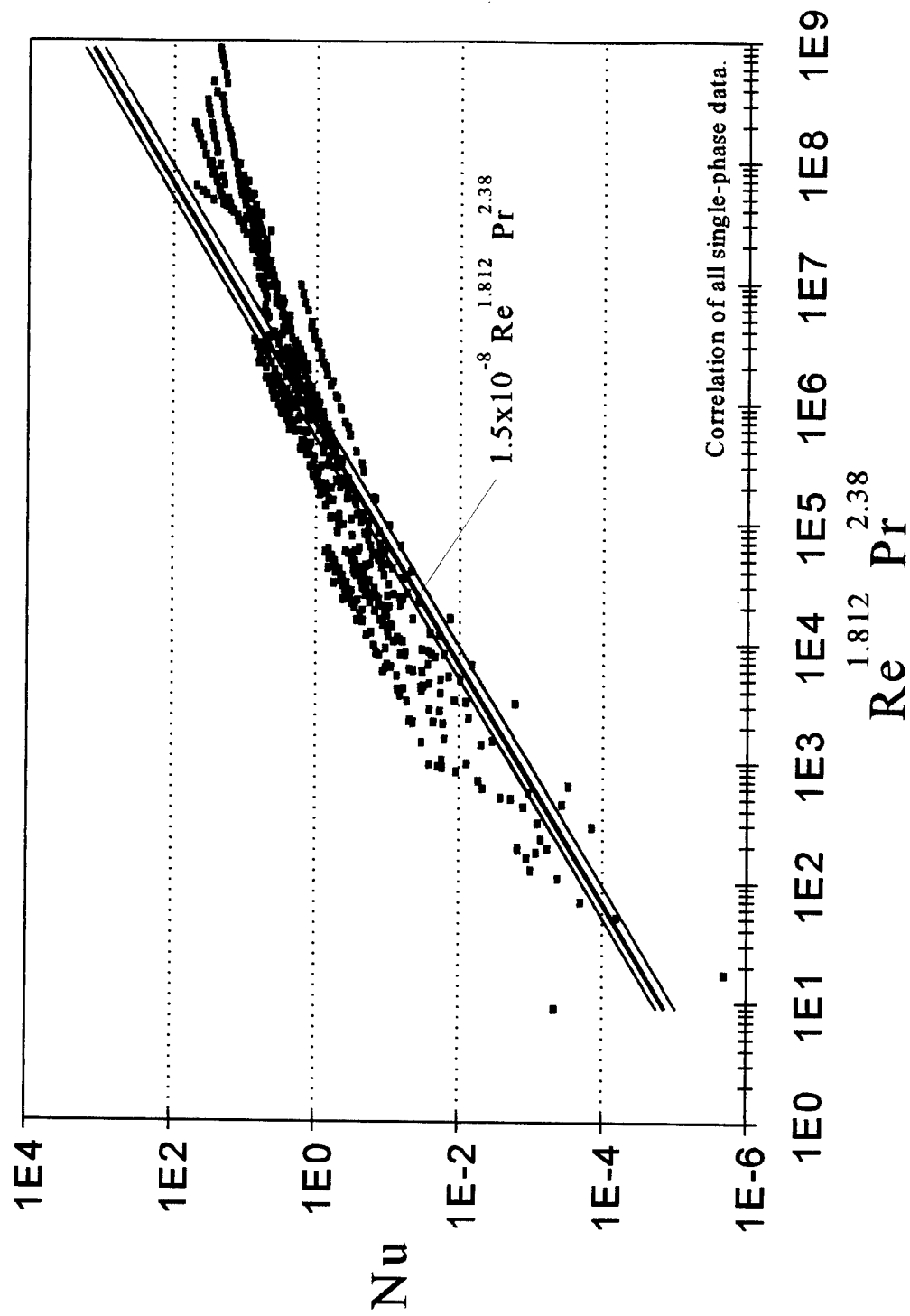


Figure 6.10: Correlation of Nusselt number data for all fluids and all channel sizes.

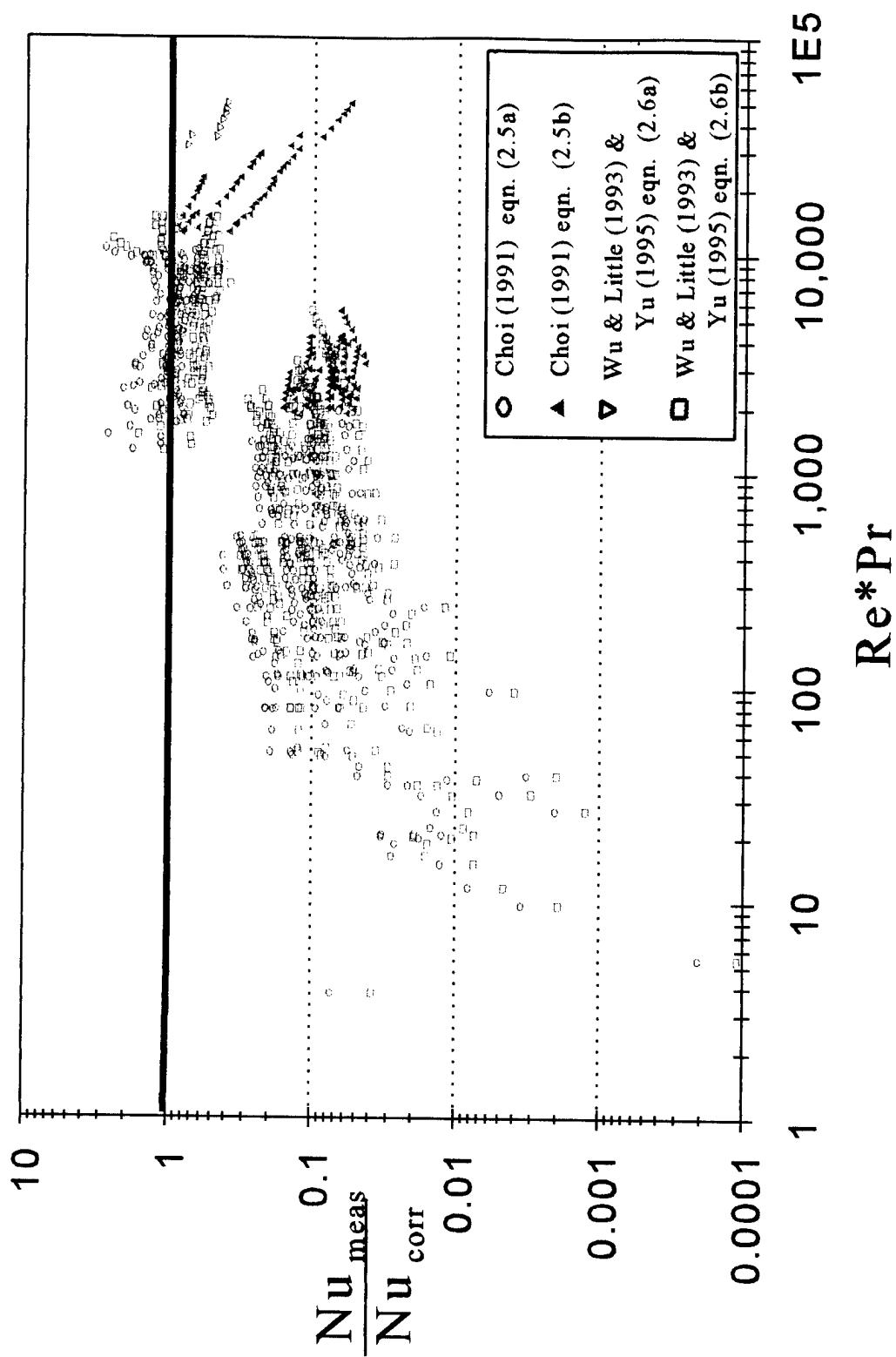


Figure 6.11: Comparison of Nusselt number data with correlations from Chapter 2.

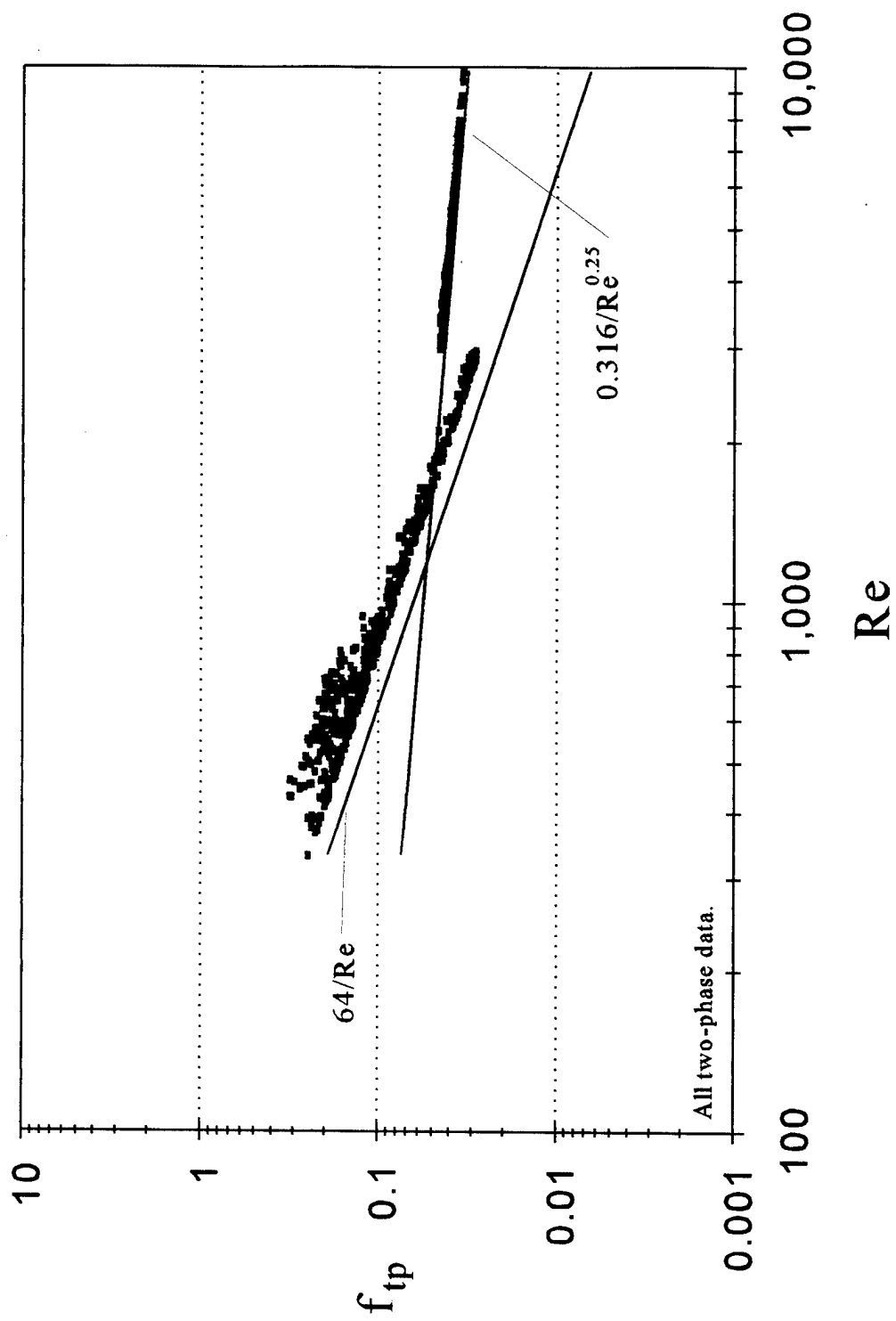


Figure 6.12: All two-phase friction factor data for all channel sizes.

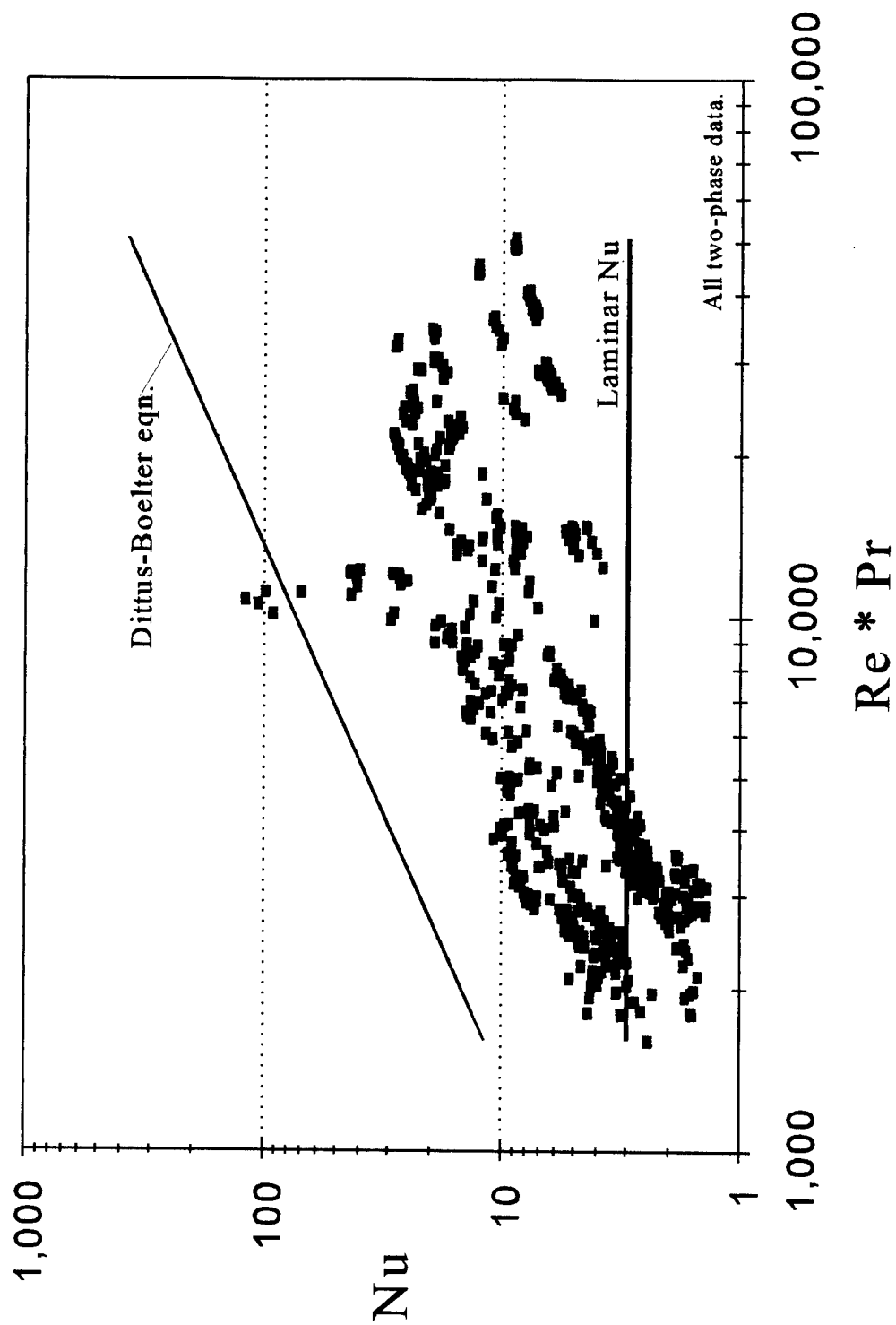


Figure 6.13: All two-phase Nusslet number data for all channel sizes.

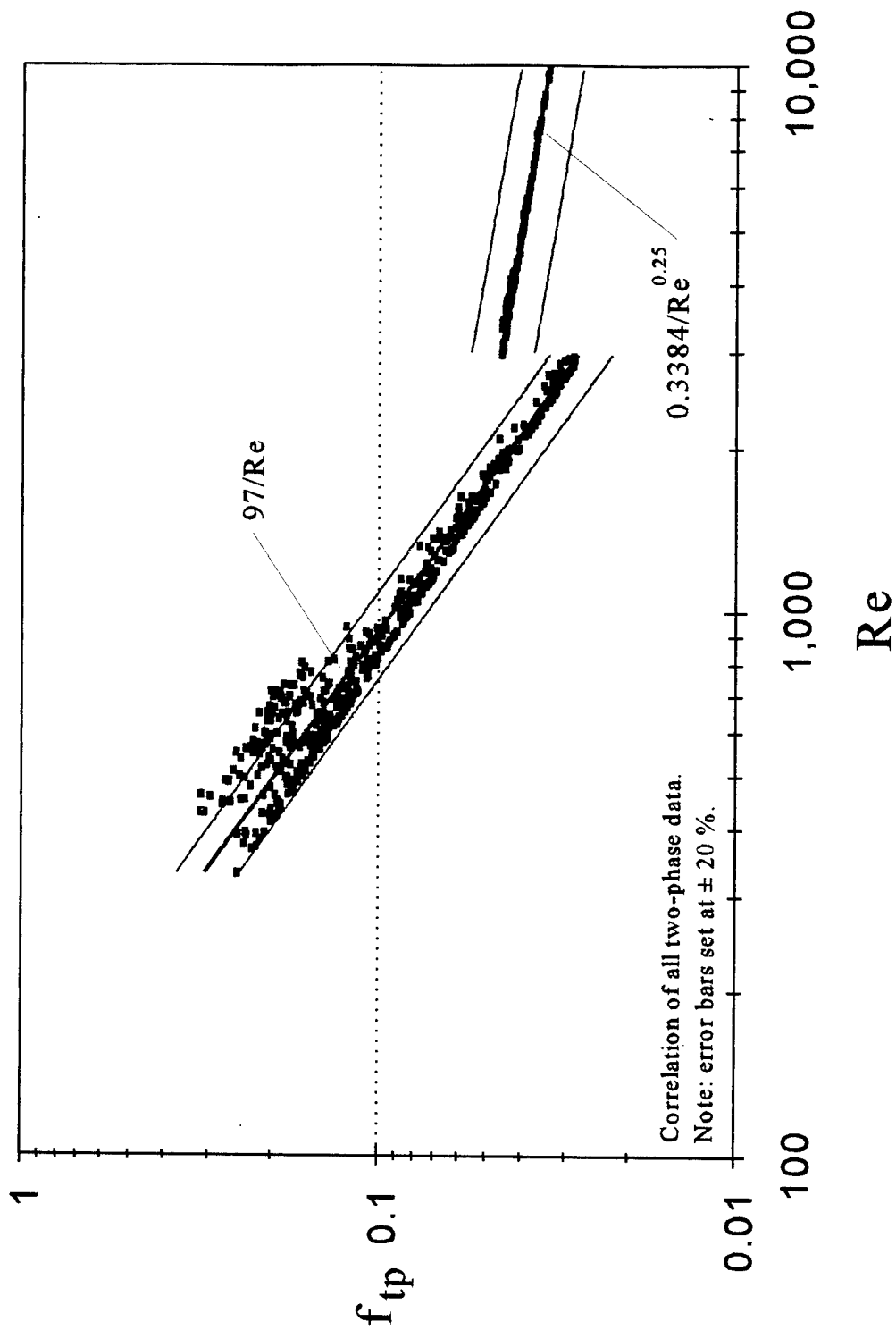


Figure 6.14: Correlation of all two-phase friction factor data for all channel sizes.

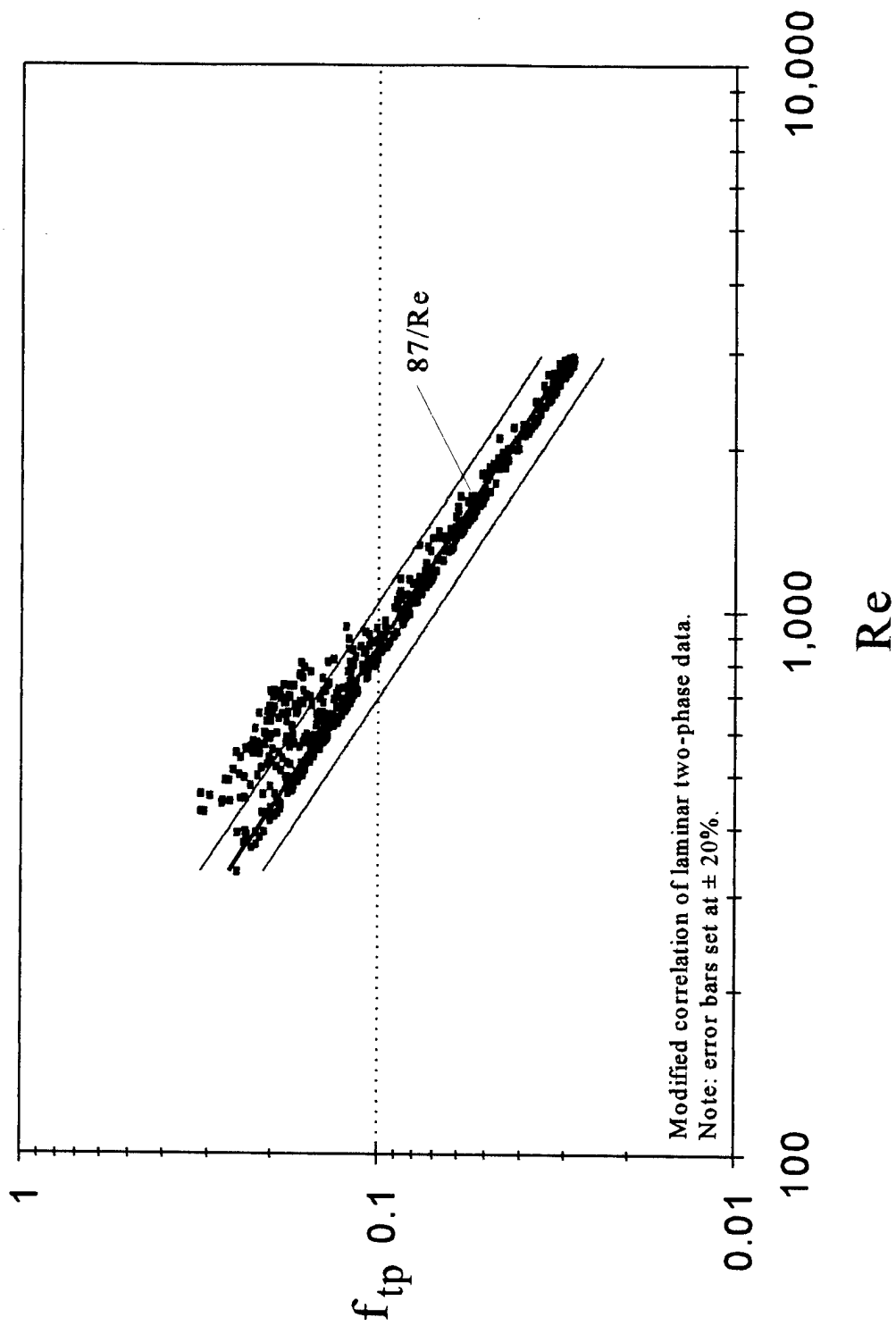


Figure 6.15: Modified correlation of laminar two-phase friction factor data for all channel sizes.



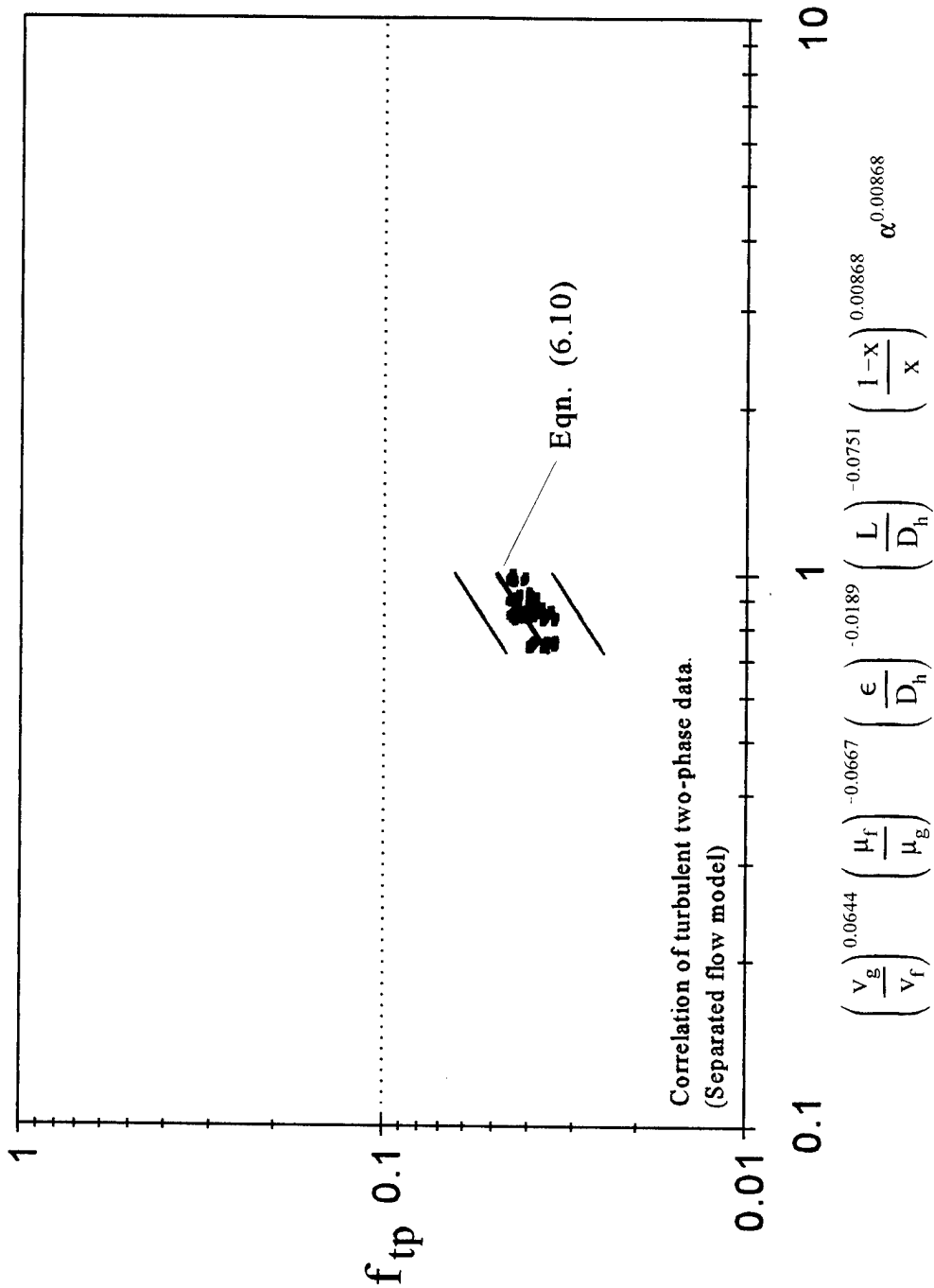


Figure 6.16: Correlation of turbulent two-phase friction factor data for all channel sizes using separated flow model parameters.

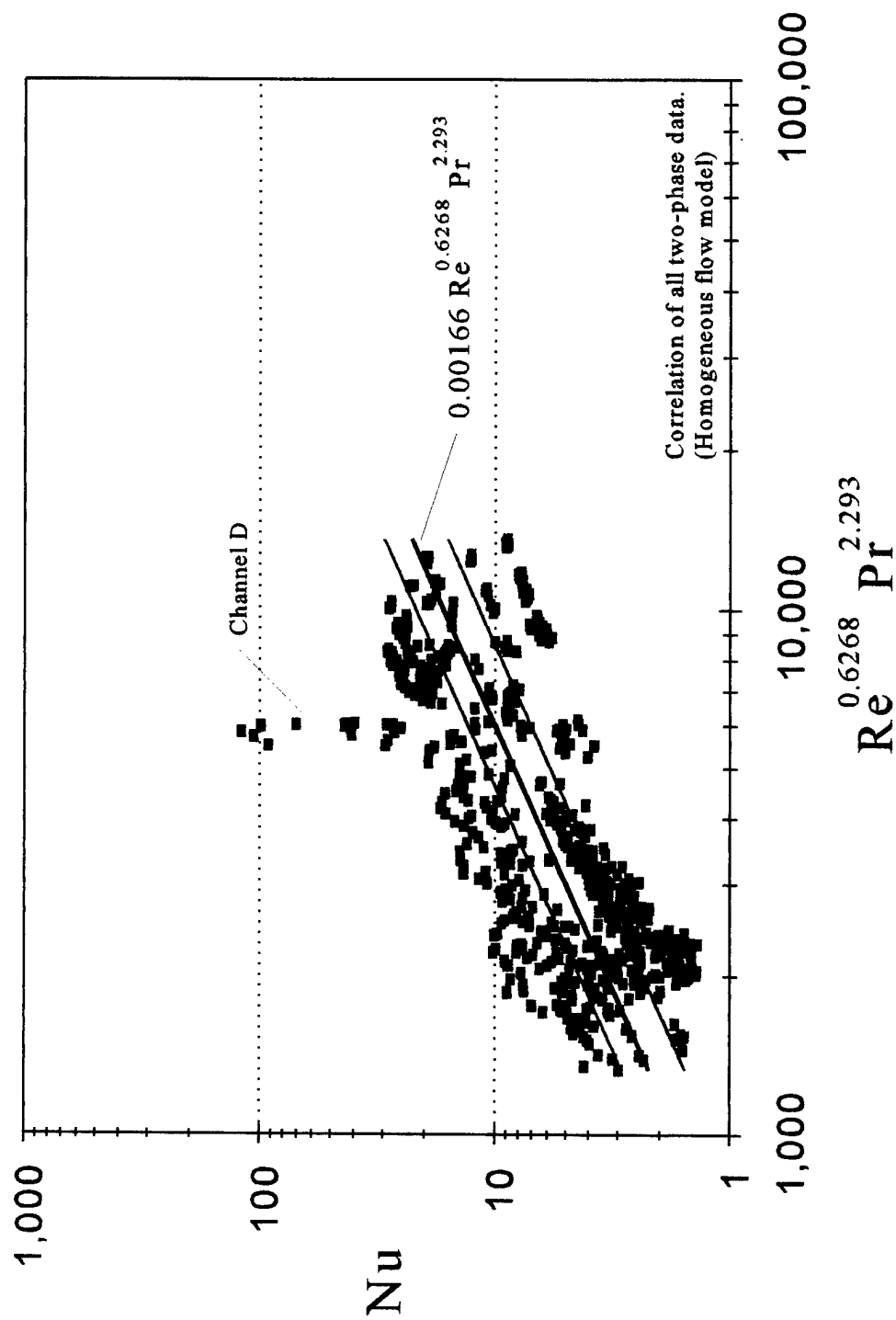


Figure 6.17: Correlation of two-phase Nusselt number data for all channel sizes using homogeneous flow model parameters.

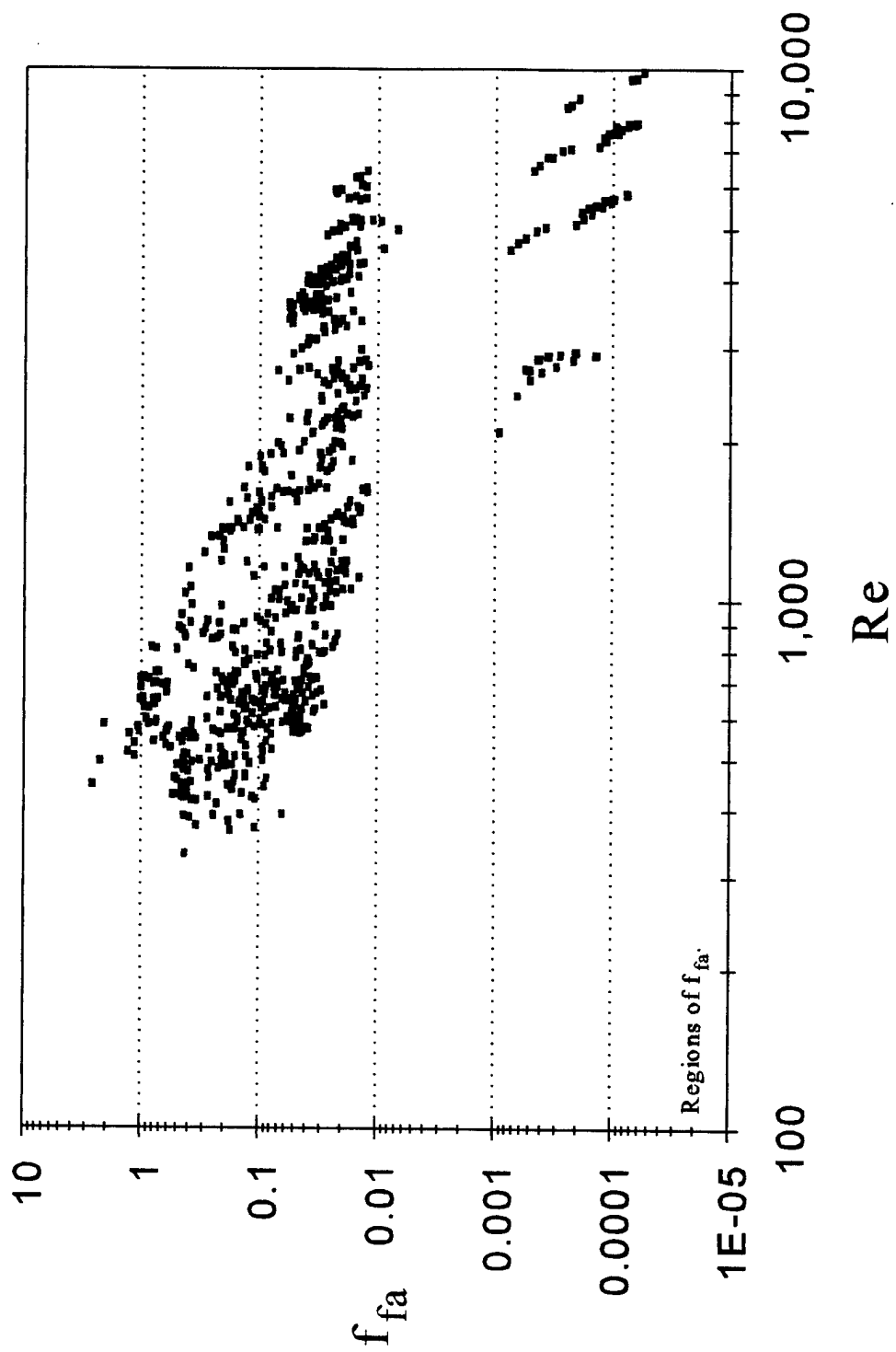


Figure 6.18: Regions of friction factor  $f_{fa}$  calculated by equation (6.12).

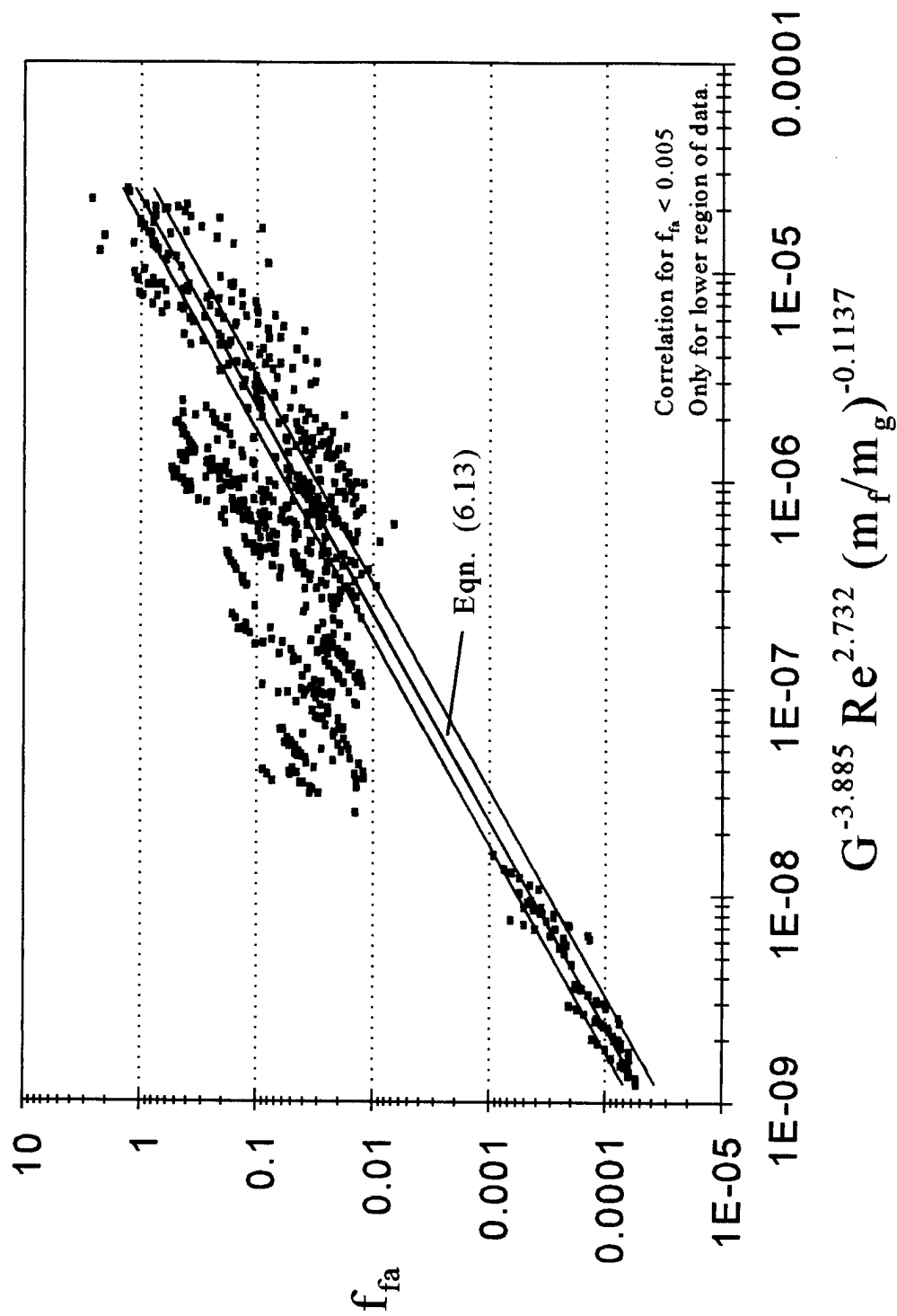


Figure 6.19: Correlation of  $f_{fa}$  data for  $f_{fa} < 0.005$ .

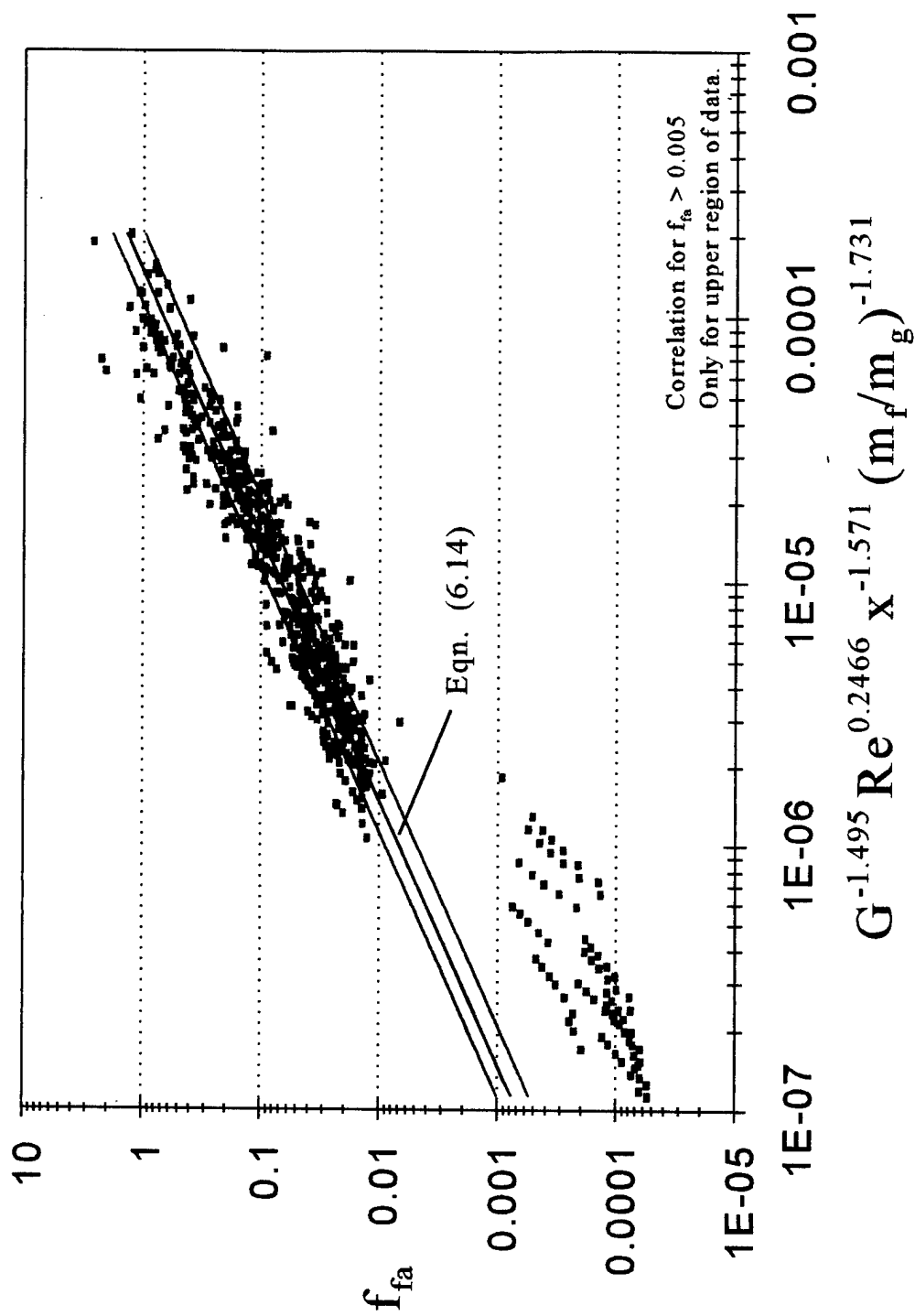


Figure 6.20: Correlation of  $f_{fa}$  data for  $f_{fa} > 0.005$ .

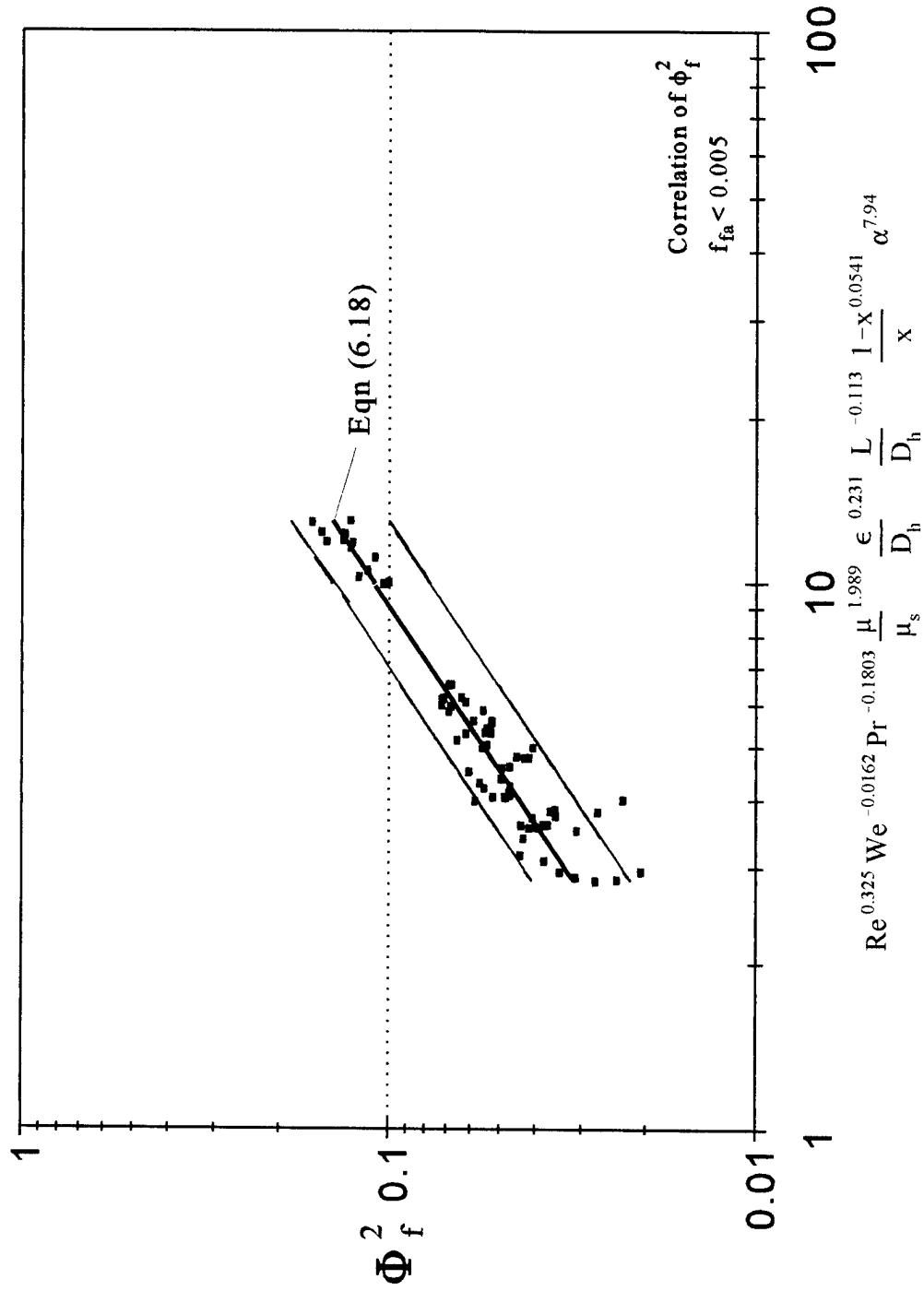
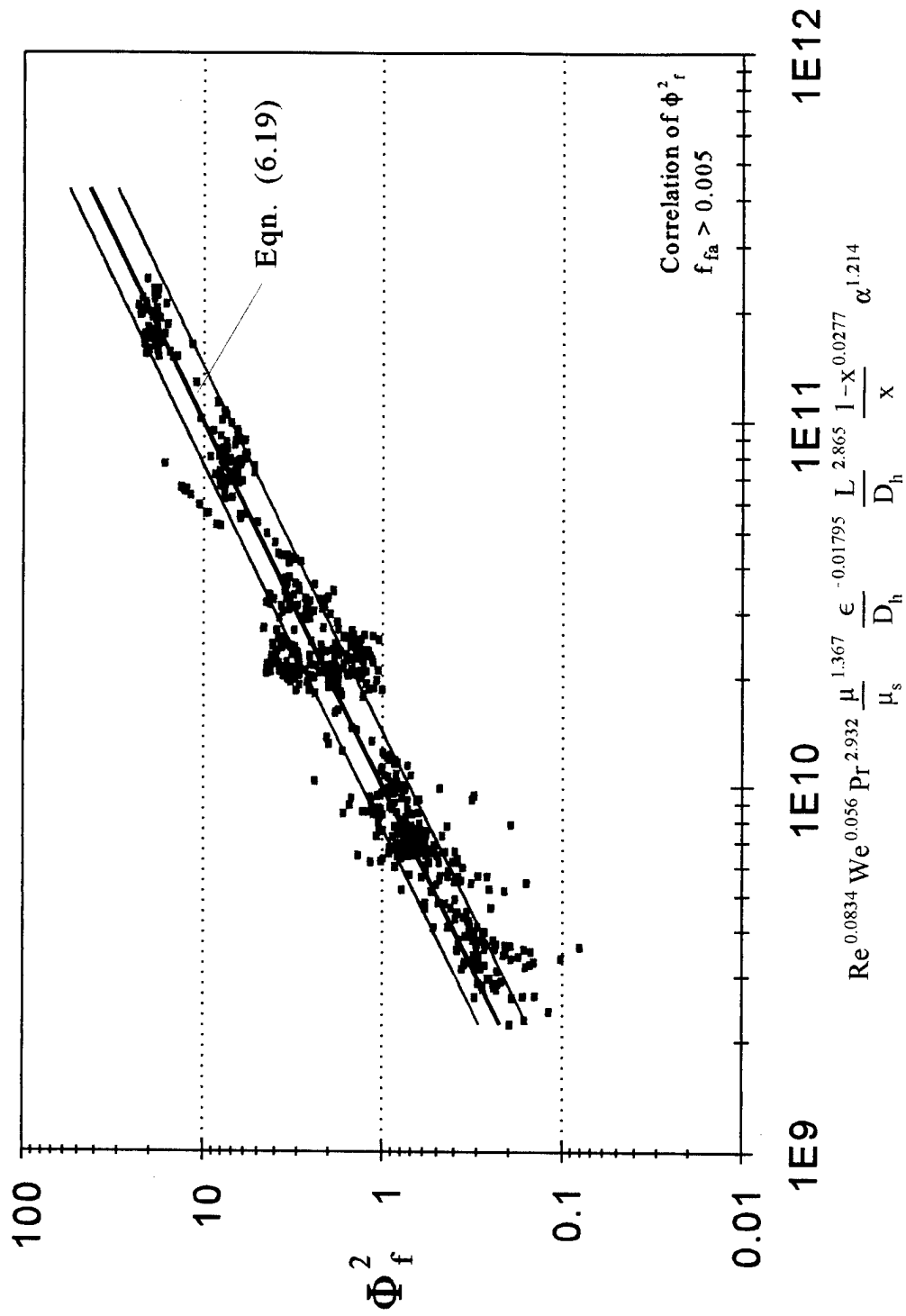


Figure 6.21: Correlation of  $\Phi_f^2$  over lower range of  $f_{fa}$ .

Figure 6.22: Correlation of  $\Phi_f^2$  over upper range of  $f_{fa}$ .

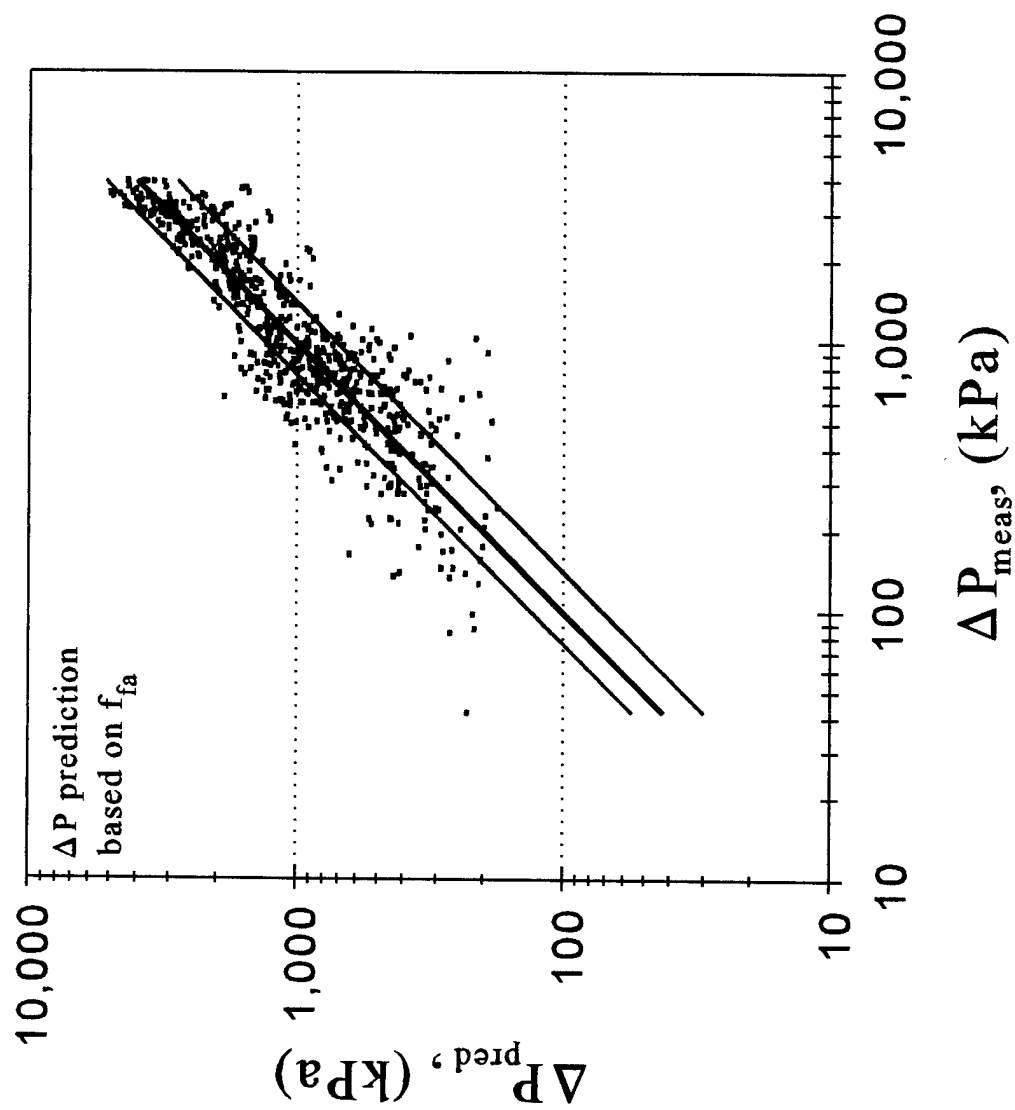


Figure 6.23: Pressure drop prediction based on  $f_{fa}$ .



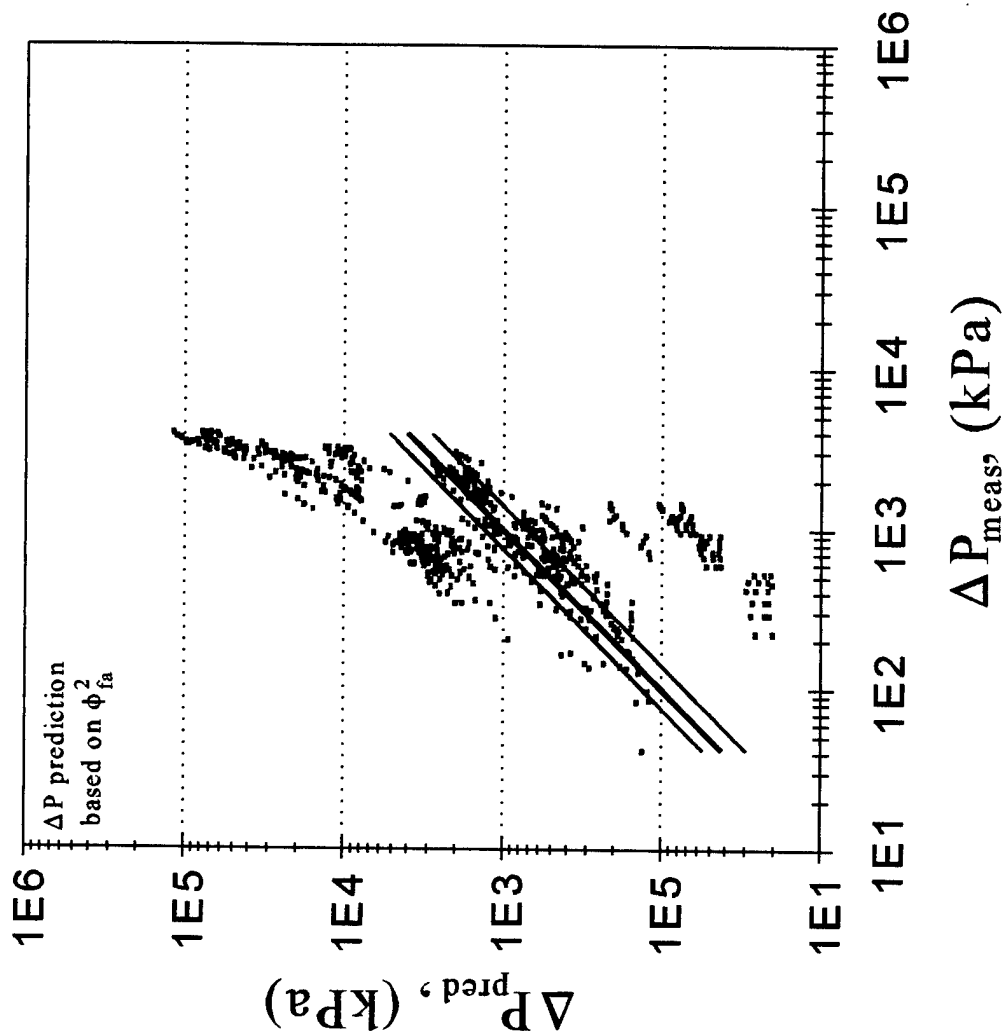


Figure 6.24: Pressure drop prediction based on  $\phi_f^2$ .

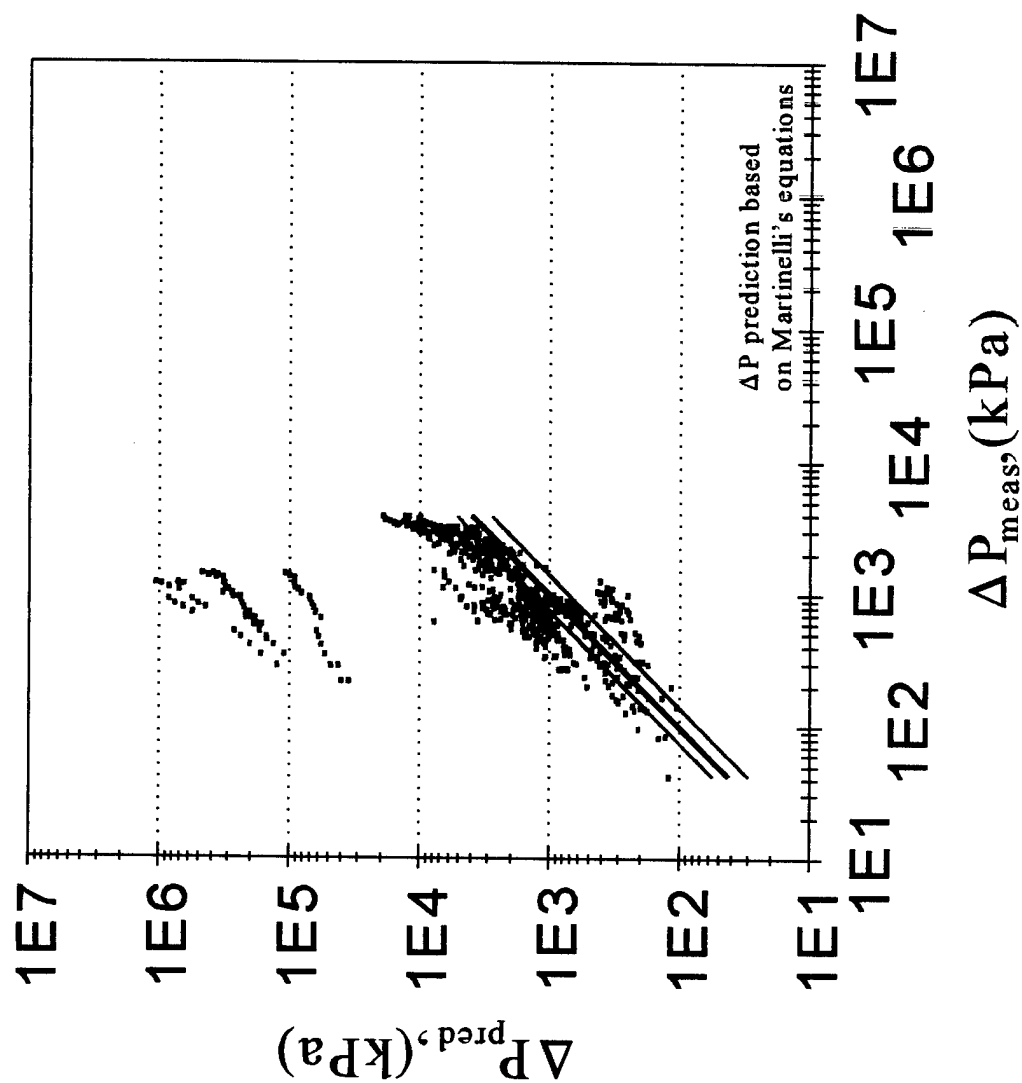


Figure 6.25: Pressure drop prediction based on Martinelli's equations.

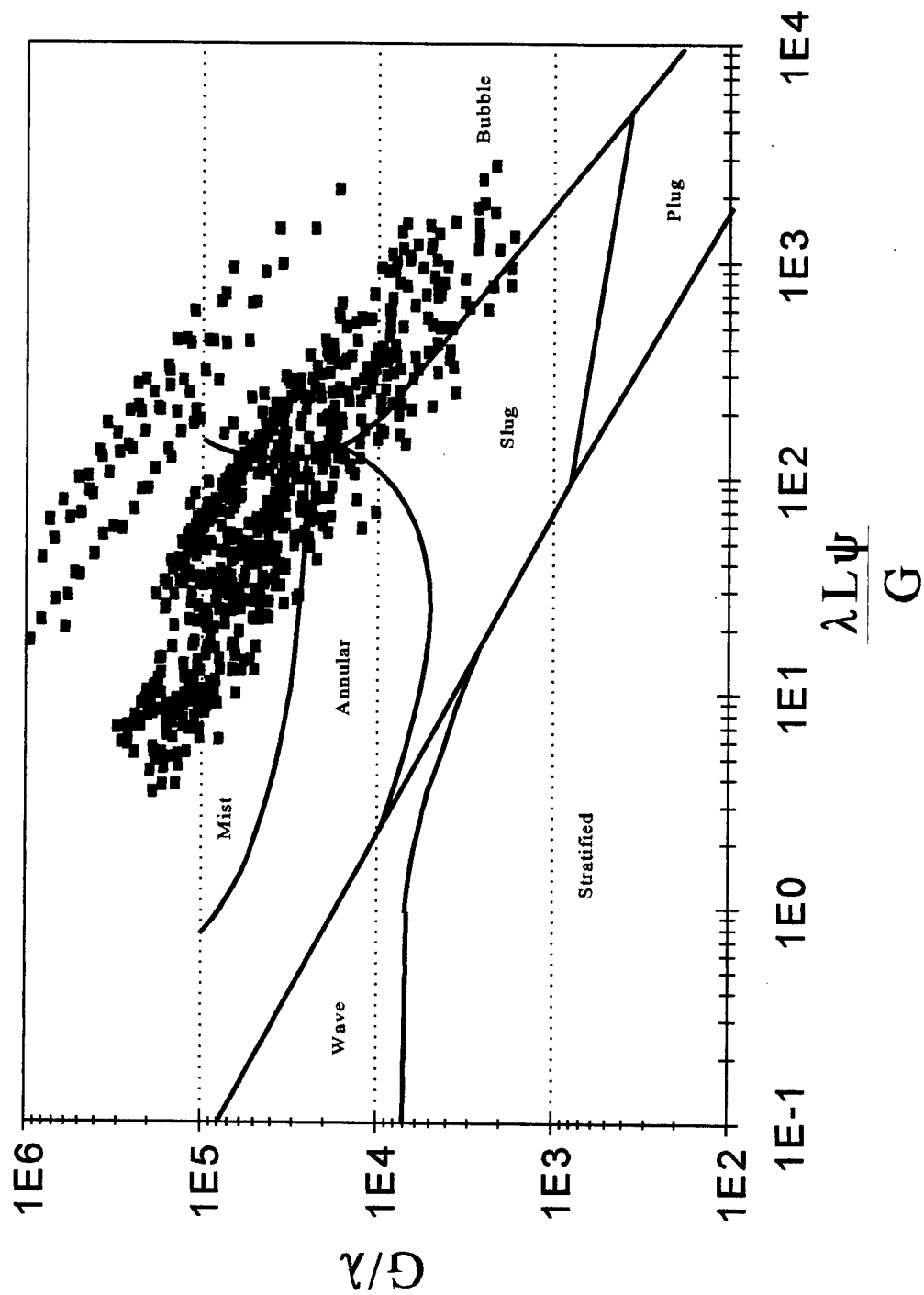


Figure 6.26: Flow regime map by Baker (1954) with two-phase data.

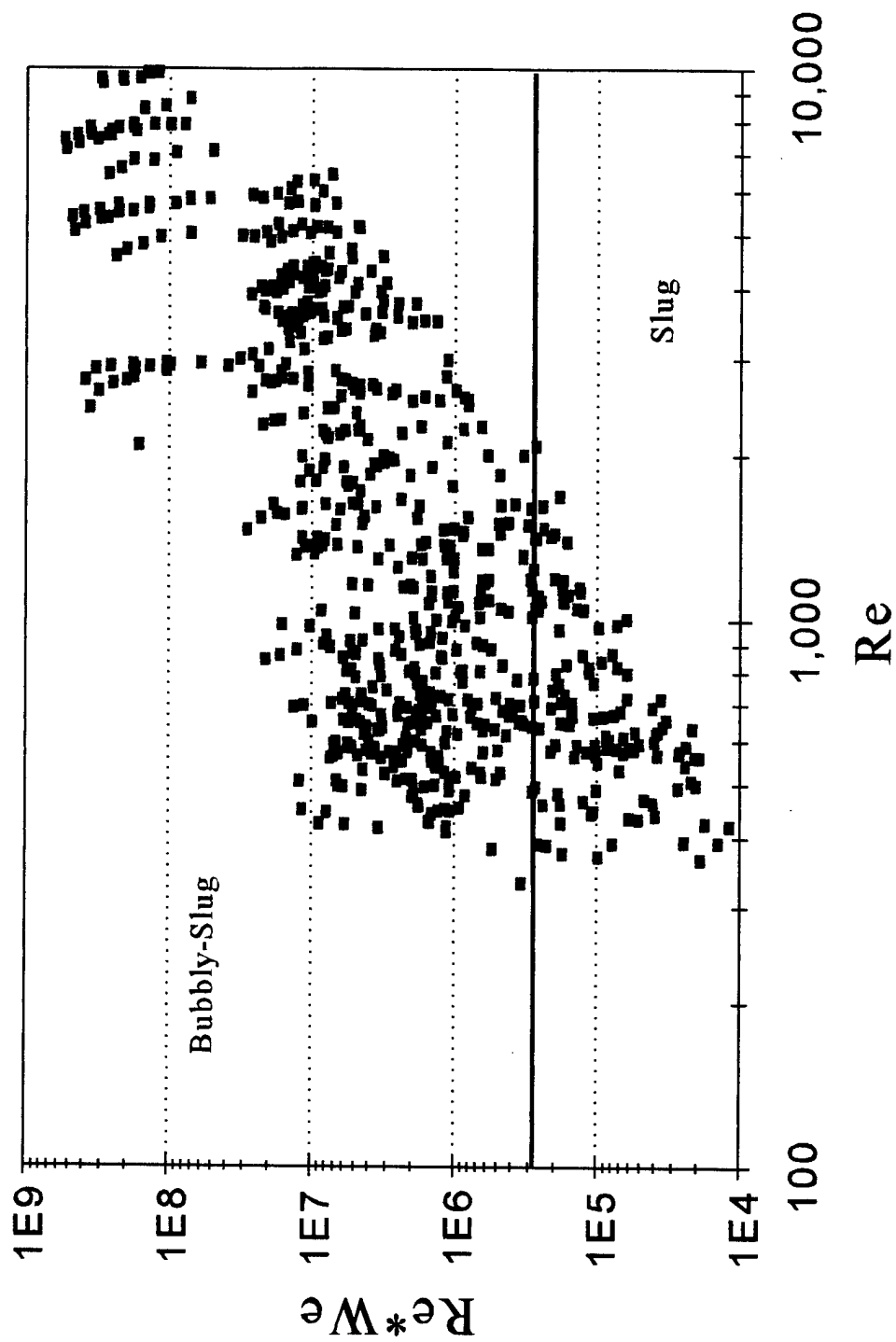


Figure 6.27: Flow regime map by Suo and Griffith (1964) with two-phase data.

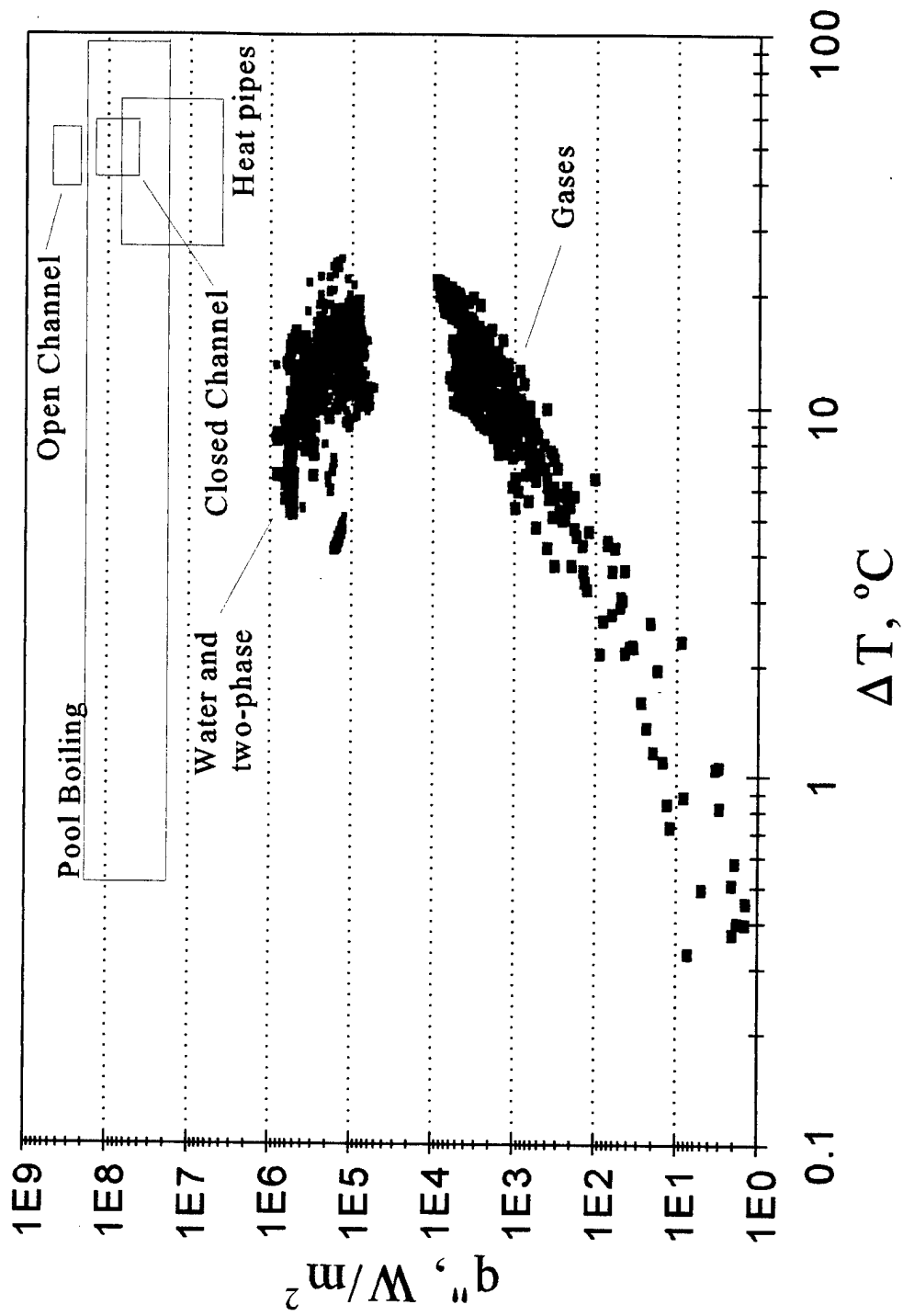


Figure 6.28: Heat flux comparisons with Figure 3.3.

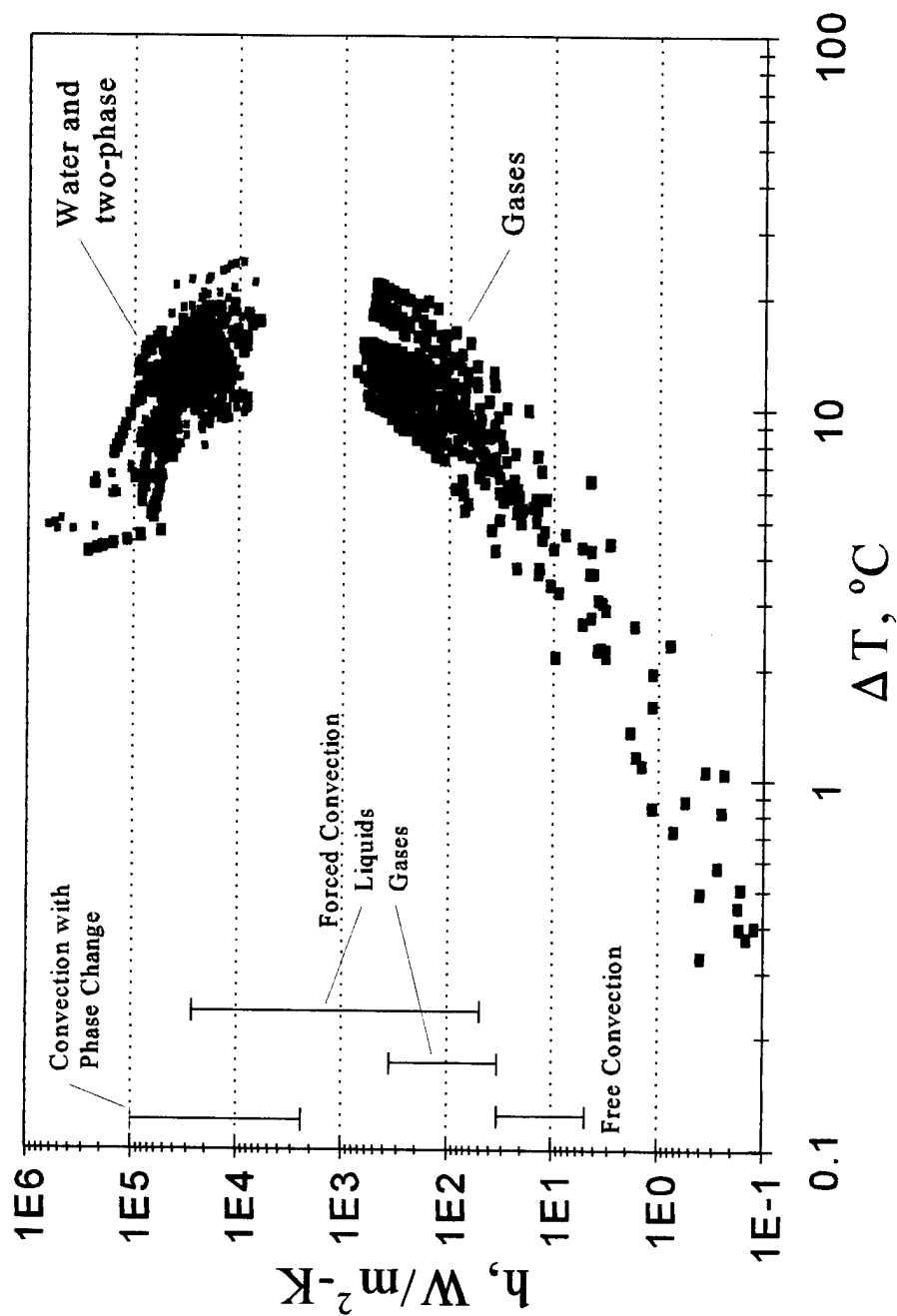


Figure 6.29: Heat transfer coefficient comparisons with typical values from Incropera and DeWitt (1985). Note: The temperature differences do not apply for the typical values.

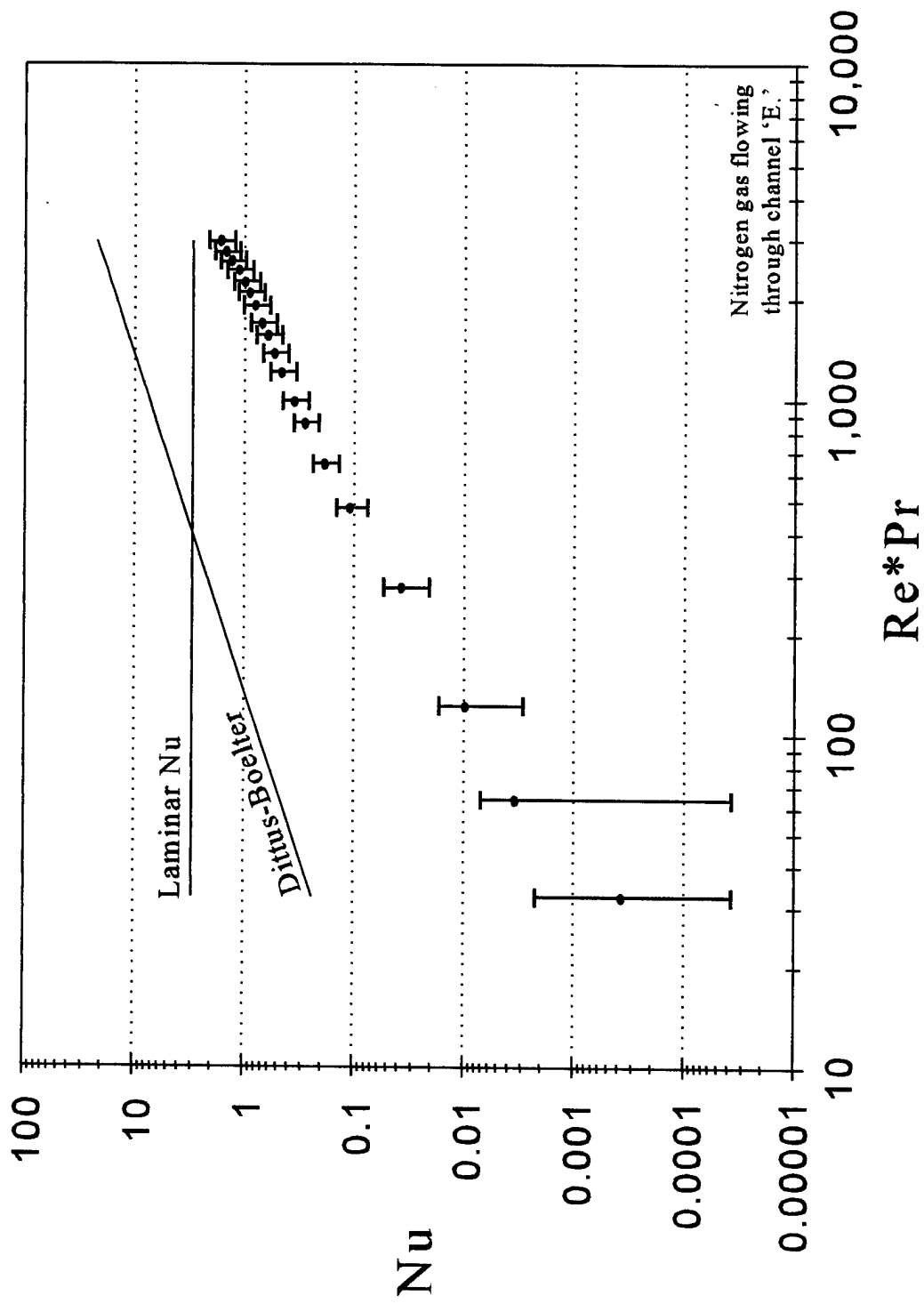


Figure 6.30: Typical Nusselt number uncertainty associated with gas flows.

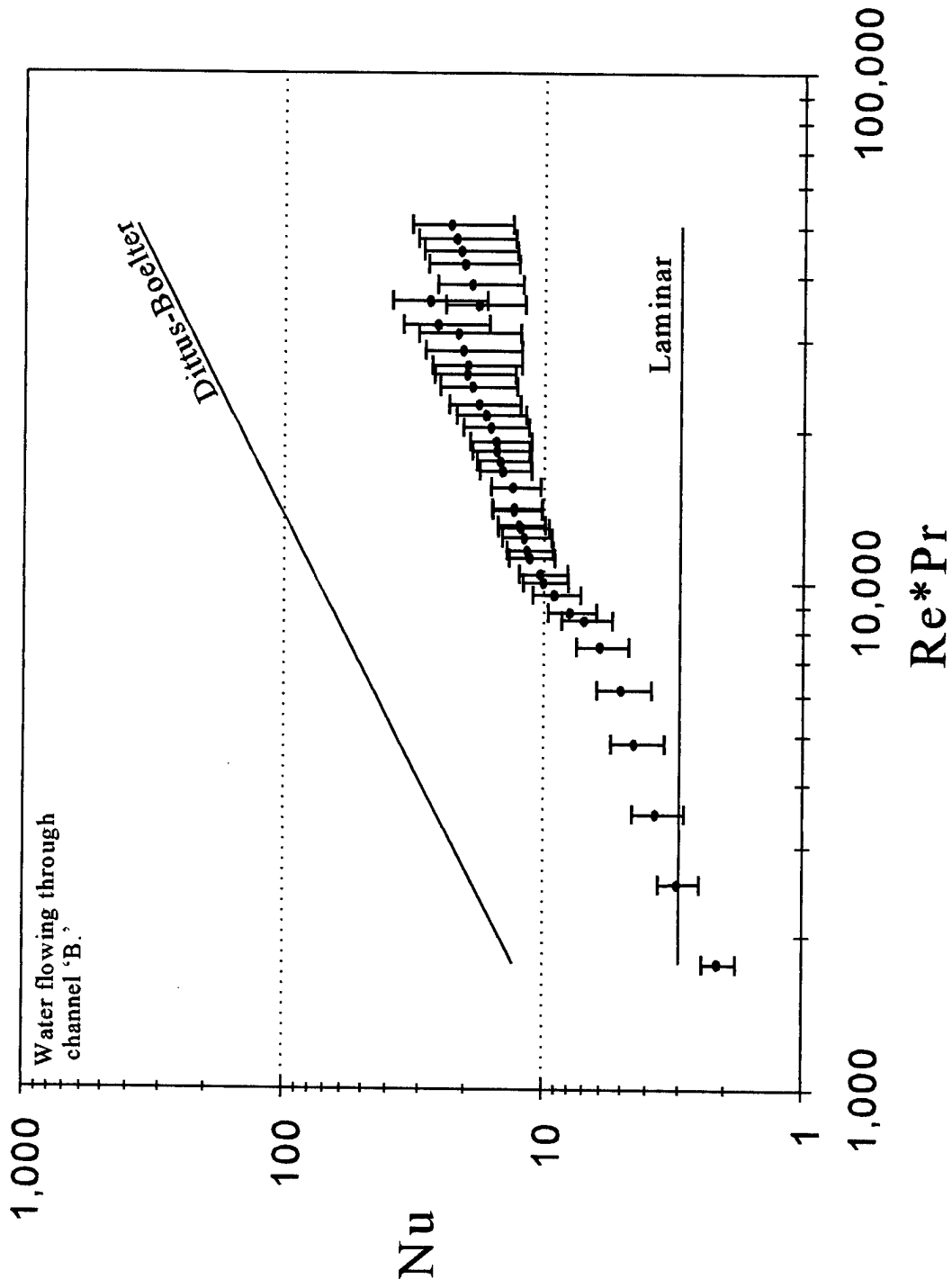


Figure 6.31: Typical Nusselt number uncertainty associated with water flows.



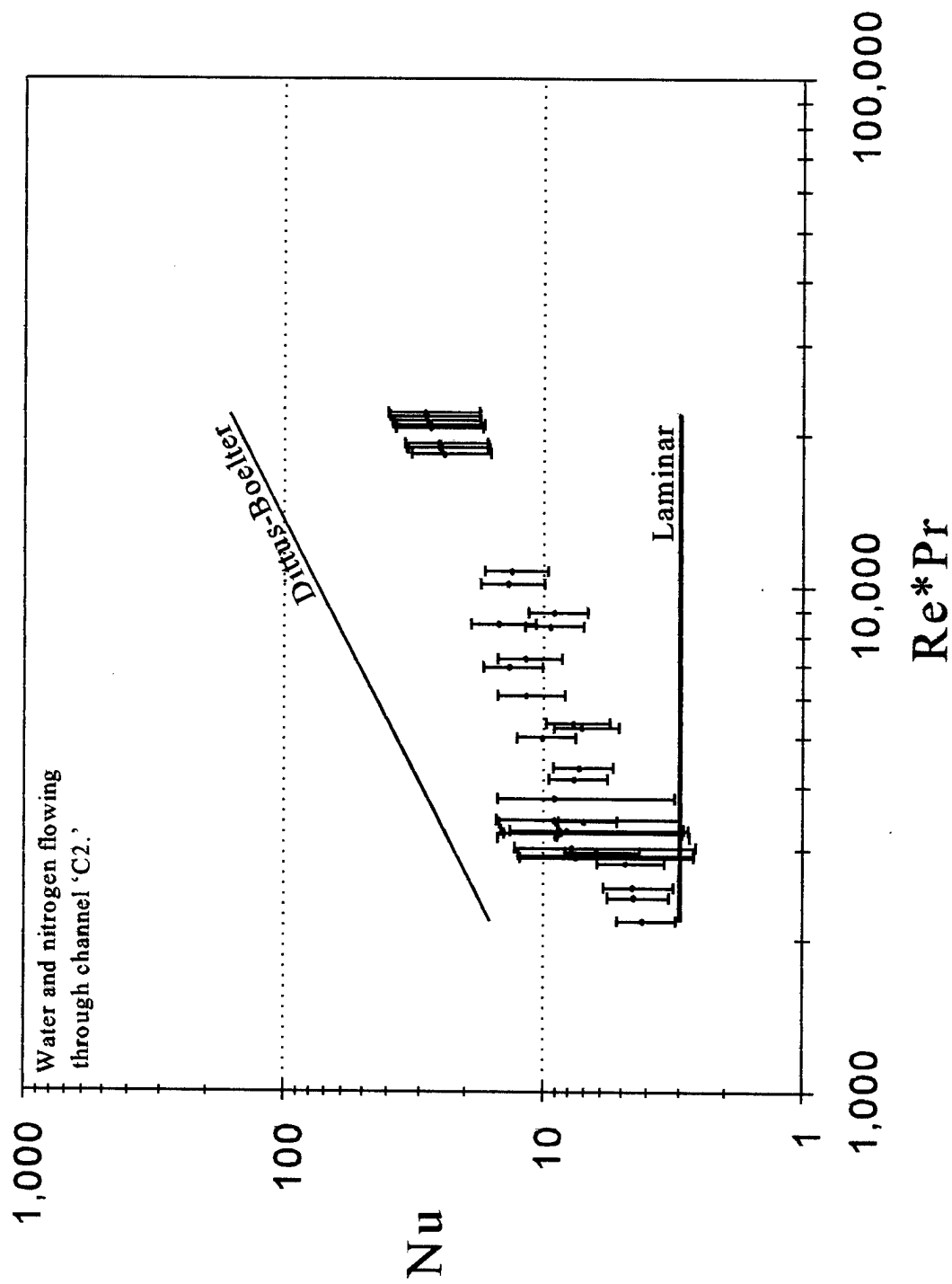


Figure 6.32: Typical Nusselt number uncertainty associated with two-phase flows.

## CHAPTER 7

### CONCLUSIONS AND RECOMMENDATIONS

#### Study Summary

The focus of the study was an empirical investigation of two-component two-phase flow being heated. Because of the dependence of existing two-phase relationships on single-phase equations, single-phase tests were also conducted. A dimensional analysis was used to determine the important pressure drop and heat transfer parameters. The resulting parameters were curve-fit against experimental data using multiple linear regression techniques. A FORTRAN program was developed to compute all of the necessary parameter coefficients. Governing equations based on the Conservation of Mass, Momentum, and Energy were considered for two flow models. The first of the flow models was the homogeneous flow model which consider the fluid properties to be averages based on the quality of the two components. Second, was the separated flow model which considered each component of the flow separately. Because neither of the flow models for pressure drop could be solved directly, they were solved empirically with the techniques mentioned above. Also, the flow regimes in macroscale and microscale two-phase flow were defined and discussed. Correlations of the single- and two-phase experimental data were presented and compared with other correlations and equations.

The flow experiments were conducted on an apparatus built by the author and Darin Bailey (1996). The hydraulic diameter of the microchannels tested varied from  $50\mu\text{m}$  to  $250\mu\text{m}$ . Most of the channels had an aspect ratio of approximately one, but several different aspect ratios were tested. Glass covers were used on the microchannels to allow flow visualization during the experiments. However, no available camera was found to be fast enough to provide any useful information. For the two-phase experiments, deionized water along with either argon, helium, or nitrogen were tested. Single-phase tests were conducted using the same four fluids separately. During the tests a data acquisition system was employed in the monitoring and storage of the flow information.

For both single- and two-phase tests, the Reynolds number was found to be the most important parameter in determining the friction factor. Considering heat transfer, the combination of Reynolds number and Prandtl were found to be the dominant parameters. These results are as were expected from macroscale theory. Other parameters also indicated the presence of entrance effects, particularly in the larger channels. However, what was found to be most interesting about the experimental results was not which flow parameters were important, but how the fluids behaved in microchannels. In single-phase flow, the transition from laminar to turbulence regimes was seen to be suppressed in certain situations. For gas flows, the suppression the did not occur above a hydraulic diameter of  $150\mu\text{m}$ . Between  $150\mu\text{m}$  and  $80\mu\text{m}$ , the suppression was seen in varying degrees. Below  $80\mu\text{m}$  the suppression seemed complete and no transition was seen. For

the water, no transition was seen even for the largest channels tested. These results indicate that the presence of laminar to turbulent transition is dependent on the fluid properties as well as the channel dimensions. A study of microscale turbulent eddy formation should help clarify these observations. For two-phase flow, a clear and well defined transition was seen for all channel sizes at a Reynolds number of 3,000. It is believed that the transition is caused by the intense pressure fluctuations associated with two-phase flows. Though some suppression tendencies may be present at the smaller channel sizes, the turbulence induced by the pressure fluctuations of two-phase flow is more than enough to ensure transition. It will be interesting to see in future research if two-phase flow sees any suppression tendencies in much smaller channels

The friction factor correlations developed for both single- and two-phase flows were seen to be in excellent agreement with the various flow situations considered. The analytical two-phase pressure drop models yielded mixed results. Pressure predictions based on the total flow assumed to be all liquid, gave reasonable results over the pressure ranges seen in the two-phase tests. However, pressure prediction based on the separated flow model were seen to give very poor result, particularly for the high pressure drops present in these tests.

Nusselt number data yielded very few reasonable correlations for either single- or two-phase data. The only Nusselt number correlation found to be useful was the correlation for gases only. All other combination of fluids could not be correlated well. Most of the problems associated with correlating the Nusselt number were traced back to

the inaccuracies associated with the thermocouple measurement. However, correlating the various fluid combinations did indicate several things. One, no transition from laminar to turbulent Nusselt values was seen. Two, opposite to the friction factor, the fluids paralleled the Nusselt predictions of turbulent flow correlations which is in agreement with the work of Choi (1991). Finally, the Reynolds number and the Prandtl number are the dominant flow parameters in closed channel forced convection heat transfer.

#### Recommendations for Future Research

Though this study may have helped understand the behavior of single and two-phase fluids in microchannels, much more research is needed in this area. In particular, studies of single- and two-phase flow using localized pressure and temperature measurements. On this scale, the only way to make sure that the inlet pressure, for example, is being accurately measured, is to have the pressure instrument in or very near the channel entrance. Temperature measurements are even more critical. As was seen in this study, the inaccuracies in the thermocouples themselves some times accounted for measurement uncertainties of well over 200%. The increasing number of fabrication techniques being used and developed today will allow localized instrumentation to become common place over the next few years. Along with the increasing need for heat dissipation from electronic components, micro refrigeration cycles, and other microfluidic devices, the need for basic research in the micro thermal fluids area will continue to have far reaching implication for all areas of micro technologies.

## APPENDIX A

# APPENDIX A: FORTRAN program to solve for correlation coefficients.

```

C Program to calculate empirical coefficients from experimental values.
C Program Name: 2-PHS-2.FOR
C By: Roger S. Stanley
C Written: 9/30/96; Modified: 10/18/96
C
C
C Define double precision variables, integers N and M, and dimension arrays
  INTEGER N, M, L2, L3, L4, L5, L6, L7, L8, L9, NC
  DIMENSION YMDATA(800), YC(800), X(800,11), XDATA(800,11)
  DIMENSION M1(11,11), A(11)
  DOUBLE PRECISION YMDATA, YC, X, A, YMEAN, XDATA, ST, SR, R
  DOUBLE PRECISION M1, SIGMAXY, SIGMAY
C
C N are the number of data points for the specified file.
C M are the number of coefficients to be found (order of multiple regression).
C Value of M should not exceed 10.
C
  N = 678
  M = 7
C
C Open input and output data files.
C
  OPEN (UNIT=1,FILE='c:\disert\correla\dph2-3.txt')
  OPEN (UNIT=2,FILE='c:\disert\correla\dph2-3.dat')
C
C Read in entire data file
C
  DO 10 I = 1,N
10  READ(1,*) YMDATA(I),(XDATA(I,J),J=2,M)
C
C Take natural log of X-values and YM-values (Entire data file.).
C
  DO 20 I=1,N
    YMDATA(I) = LOG(YMDATA(I))
  DO 30 J=2,M
    XDATA(I,J) = LOG(XDATA(I,J))
30  CONTINUE
20  CONTINUE
C
C Start coefficient selection here.

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

C Set NC (number of coefficients. currently being solved for) equal to 2.

C

NC = 2

C

C The following loops find all unique combinations of coefficients.

C

C Two Coefficients:

C

IF (M.LT.2) THEN

GOTO 999

ENDIF

L2 = 2

200 IF (L2.GT.M) THEN

GOTO 310

ENDIF

DO 210 I=1,N

210 X(I,2) = XDATA(I,L2)

GOTO 998

C

C Three Coefficients

C

310 NC = 3

IF (M.LT.3) THEN

GOTO 999

ENDIF

L3 = 2

320 L2 = L3+1

300 IF (L3.GT.M) THEN

GOTO 410

ENDIF

IF (L2.GT.M) THEN

L3 = L3 + 1

GOTO 320

ENDIF

DO 330 I=1,N

X(I,2) = XDATA(I,L3)

330 X(I,3) = XDATA(I,L2)

GOTO 998

C

C Four Coefficients



APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

C

```

410 NC = 4
    IF (M.LT.4) THEN
        GOTO 999
    ENDIF
    L4 = 2
420 L3 = L4+1
430 L2 = L3 +1
400 IF (L4.GT.M) THEN
    GOTO 510
    ENDIF
    IF (L3.GT.M) THEN
        L4 = L4 + 1
        GOTO 420
    ENDIF
    IF (L2.GT.M) THEN
        L3 = L3 + 1
        GOTO 430
    ENDIF
    DO 440 I=1,N
        X(I,2) = XDATA(I,L4)
        X(I,3) = XDATA(I,L3)
440   X(I,4) = XDATA(I,L2)
        GOTO 998

```

C

C Five Coefficients

C

```

510 NC = 5
    IF (M.LT.5) THEN
        GOTO 999
    ENDIF
    L5 = 2
520 L4 = L5 + 1
530 L3 = L4 + 1
540 L2 = L3 +1
500 IF (L5.GT.M) THEN
    GOTO 610
    ENDIF
    IF (L4.GT.M) THEN
        L5 = L5 + 1

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      GOTO 520
    ENDIF
    IF (L3.GT.M) THEN
      L4 = L4 + 1
      GOTO 530
    ENDIF
    IF (L2.GT.M) THEN
      L3 = L3 + 1
      GOTO 540
    ENDIF
    DO 550 I=1,N
      X(I,2) = XDATA(I,L5)
      X(I,3) = XDATA(I,L4)
      X(I,4) = XDATA(I,L3)
550    X(I,5) = XDATA(I,L2)
      GOTO 998
C
C Six Coefficients
C
610  NC = 6
      IF(M.LT.6) THEN
        GOTO 999
      ENDIF
      L6 = 2
620  L5 = L6 + 1
630  L4 = L5 + 1
640  L3 = L4 + 1
650  L2 = L3 + 1
600  IF (L6.GT.M) THEN
        GOTO 710
      ENDIF
      IF (L5.GT.M) THEN
        L6 = L6 + 1
        GOTO 620
      ENDIF
      IF (L4.GT.M) THEN
        L5 = L5 + 1
        GOTO 630
      ENDIF
      IF (L3.GT.M) THEN

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

        L4 = L4 + 1
        GOTO 640
    ENDIF
    IF (L2.GT.M) THEN
        L3 = L3 + 1
        GOTO 650
    ENDIF
    DO 660 I=1,N
        X(I,2) = XDATA(I,L6)
        X(I,3) = XDATA(I,L5)
        X(I,4) = XDATA(I,L4)
        X(I,5) = XDATA(I,L3)
660    X(I,6) = XDATA(I,L2)
        GOTO 998
C
C Seven Coefficients
C
710  NC = 7
        IF(M.LT.7) THEN
            GOTO 999
        ENDIF
        L7 = 2
720  L6 = L7 + 1
730  L5 = L6 + 1
740  L4 = L5 + 1
750  L3 = L4 + 1
760  L2 = L3 + 1
700  IF (L7.GT.M) THEN
            GOTO 810
        ENDIF
        IF (L6.GT.M) THEN
            L7 = L7 + 1
            GOTO 720
        ENDIF
        IF (L5.GT.M) THEN
            L6 = L6 + 1
            GOTO 730
        ENDIF
        IF (L4.GT.M) THEN
            L5 = L5 + 1

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      GOTO 740
    ENDIF
    IF (L3.GT.M) THEN
      L4 = L4 + 1
      GOTO 750
    ENDIF
    IF (L2.GT.M) THEN
      L3 = L3 + 1
      GOTO 760
    ENDIF
    DO 770 I=1,N
      X(I,2) = XDATA(I,L7)
      X(I,3) = XDATA(I,L6)
      X(I,4) = XDATA(I,L5)
      X(I,5) = XDATA(I,L4)
      X(I,6) = XDATA(I,L3)
770   X(I,7) = XDATA(I,L2)
      GOTO 998
C
C Eight Coefficients
C
810  NC = 8
      IF (M.LT.8) THEN
        GOTO 999
      ENDIF
      L8 = 2
820  L7 = L8 + 1
830  L6 = L7+1
840  L5 = L6 + 1
850  L4 = L5 + 1
860  L3 = L4 + 1
870  L2 = L3 +1
800  IF (L8.GT.M) THEN
        GOTO 910
      ENDIF
      IF (L7.GT.M) THEN
        L8 = L8 + 1
        GOTO 820
      ENDIF
      IF (L6.GT.M) THEN

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      L7 = L7 + 1
      GOTO 830
    ENDIF
    IF (L5.GT.M) THEN
      L6 = L6 + 1
      GOTO 840
    ENDIF
    IF (L4.GT.M) THEN
      L5 = L5 + 1
      GOTO 850
    ENDIF
    IF (L3.GT.M) THEN
      L4 = L4 + 1
      GOTO 860
    ENDIF
    IF (L2.GT.M) THEN
      L3 = L3 + 1
      GOTO 870
    ENDIF
    DO 880 I=1,N
      X(I,2) = XDATA(I,L8)
      X(I,3) = XDATA(I,L7)
      X(I,4) = XDATA(I,L6)
      X(I,5) = XDATA(I,L5)
      X(I,6) = XDATA(I,L4)
      X(I,7) = XDATA(I,L3)
880   X(I,8) = XDATA(I,L2)
      GOTO 998
    C
    C Nine Coefficients
    C
910   NC = 9
      IF(M.LT.9) THEN
        GOTO 999
      ENDIF
      L9 = 2
920   L8 = L9 + 1
930   L7 = L8 + 1
940   L6 = L7+1
950   L5 = L6 + 1

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```
960 L4 = L5 + 1
970 L3 = L4 + 1
980 L2 = L3 + 1
900 IF (L9.GT.M) THEN
      GOTO 1010
ENDIF
IF (L8.GT.M) THEN
      L9 = L9 + 1
      GOTO 920
ENDIF
IF (L7.GT.M) THEN
      L8 = L8 + 1
      GOTO 930
ENDIF
IF (L6.GT.M) THEN
      L7 = L7 + 1
      GOTO 940
ENDIF
IF (L5.GT.M) THEN
      L6 = L6 + 1
      GOTO 950
ENDIF
IF (L4.GT.M) THEN
      L5 = L5 + 1
      GOTO 960
ENDIF
IF (L3.GT.M) THEN
      L4 = L4 + 1
      GOTO 970
ENDIF
IF (L2.GT.M) THEN
      L3 = L3 + 1
      GOTO 980
ENDIF
DO 990 I=1,N
      X(I,2) = XDATA(I,L9)
      X(I,3) = XDATA(I,L8)
      X(I,4) = XDATA(I,L7)
      X(I,5) = XDATA(I,L6)
      X(I,6) = XDATA(I,L5)
```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

          X(I,7) = XDATA(I,L4)
          X(I,8) = XDATA(I,L3)
990      X(I,9) = XDATA(I,L2)
          GOTO 998
C
C Ten Coefficients
C
1010 NC = 10
      IF(M.LT.10) THEN
          GOTO 999
      ENDIF
      L10 = 2
1020 L9 = L10 + 1
1030 L8 = L9 + 1
1040 L7 = L8 + 1
1050 L6 = L7 + 1
1060 L5 = L6 + 1
1070 L4 = L5 + 1
1080 L3 = L4 + 1
1095 L2 = L3 + 1
1000 IF (L10.GT.M) THEN
      GOTO 999
  ENDIF
  IF (L9.GT.M) THEN
      L10 = L10 + 1
      GOTO 1020
  ENDIF
  IF (L8.GT.M) THEN
      L9 = L9 + 1
      GOTO 1030
  ENDIF
  IF (L7.GT.M) THEN
      L8 = L8 + 1
      GOTO 1040
  ENDIF
  IF (L6.GT.M) THEN
      L7 = L7 + 1
      GOTO 1050
  ENDIF
  IF (L5.GT.M) THEN

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      L6 = L6 + 1
      GOTO 1060
    ENDIF
    IF (L4.GT.M) THEN
      L5 = L5 + 1
      GOTO 1070
    ENDIF
    IF (L3.GT.M) THEN
      L4 = L4 + 1
      GOTO 1080
    ENDIF
    IF (L2.GT.M) THEN
      L3 = L3 + 1
      GOTO 1095
    ENDIF
    DO 1090 I=1,N
      X(I,2) = XDATA(I,L10)
      X(I,3) = XDATA(I,L9)
      X(I,4) = XDATA(I,L8)
      X(I,5) = XDATA(I,L7)
      X(I,6) = XDATA(I,L6)
      X(I,7) = XDATA(I,L5)
      X(I,8) = XDATA(I,L4)
      X(I,9) = XDATA(I,L3)
1090   X(I,10) = XDATA(I,L2)
      GOTO 998
    C
    C Start calculations of matrix (NC x NC+1) coefficients here.
    C
    998 CONTINUE
    C
    C Set J=1 values of X(I,J) equal to 1.0
    C
      DO 40 I = 1,N
        X(I,1) = 1.0
    40 CONTINUE
    C
    C Set matrix (M1) values equal to zero.
    C
      DO 50 J = 1,NC

```



APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      DO 60 K = 1,NC+1
        M1(J,K) = 0.0
60    CONTINUE
50    CONTINUE

C
C Calculate matrix coefficient values for M1.
C
      DO 70 J=1,NC
        DO 80 K=1,NC
          DO 90 I=1,N
            M1(J,K) = M1(J,K) + X(I,K)*X(I,J)
90    CONTINUE
80    CONTINUE
70    CONTINUE
C
C Calculate right hand side coefficients (M1 (I, NC + 1)).
C
      DO 95 J=1,NC
        K = NC + 1
        DO 97 I=1,N
          M1(J,K) = M1(J,K) + YMDATA(I)*X(I,J)
97    CONTINUE
95    CONTINUE
C
C Set A(J) values equal to zero.
C
      DO 85 J=1,M
        A(J) = 0.0
85    CONTINUE
C
C Solve matrix M1 (subroutine Gauss).
C
      CALL GAUSS(NC,M1,A)
C
C Find values for Y-calc (YC).
C
      DO 100 I=1,N
        YC(I) = 0.0
      DO 110 J=1,NC

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      YC(I) = YC(I) + A(J)*X(I,J)
110  CONTINUE
      YC(I) = EXP(YC(I))
100  CONTINUE
C
C Take exponential of YM(I) for computing error.
      DO 115 I=1,N
          YMDATA(I) = EXP(YMDATA(I))
115  CONTINUE
C
C Calculate mean of measured values.
C
      YMEAN = 0.0
      DO 120 I=1,N
          YMEAN = YMEAN + YC(I)
120  CONTINUE
      YMEAN = YMEAN/N
C
C Calculate ST and SR.
C
      ST = 0.0
      SR = 0.0
      DO 130 I=1,N
          ST = ST + (YMDATA(I) - YMEAN)**2
          SR = SR + (YMDATA(I) - YC(I))**2
130  CONTINUE
C
C Calculate standard error (standard deviation), SIGMAY.
C
      SIGMAY = (ST/(N-1))**(0.5)
C
C Calculate SIGMAXY.
C
      SIGMAXY = (SR/(N-2))**(0.5)
C
C Calculate correlation coefficient, (R).
C
      IF((1-(SIGMAXY**2)/(SIGMAY**2)).LT.0.0) THEN
          R = 0.0
          GOTO 140

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      ENDIF
C
      R = (1 - (SIGMAXY**2)/(SIGMAY**2))**(0.5)
C
140  CONTINUE
C
C Output data to file.
C
      A(1) = EXP(A(1))
2000 WRITE(2,145) R,SIGMAXY,A(1),(A(J),J=2,NC)
145  FORMAT (F6.4,"",F7.4,10("","E12.4))
C
C Get YMDATA ready for the next set.
      DO 150 I=1,N
          YMDATA(I) = LOG(YMDATA(I))
150  CONTINUE
C
C Determine next set of coefficients, if any, and send back to start.
C
      IF(NC.EQ.2) THEN
          L2 = L2 + 1
          GOTO 200
      ELSE IF(NC.EQ.3) THEN
          L2 = L2 + 1
          GOTO 300
      ELSE IF(NC.EQ.4) THEN
          L2 = L2 + 1
          GOTO 400
      ELSE IF(NC.EQ.5) THEN
          L2 = L2 + 1
          GOTO 500
      ELSE IF(NC.EQ.6) THEN
          L2 = L2 + 1
          GOTO 600
      ELSE IF(NC.EQ.7) THEN
          L2 = L2 + 1
          GOTO 700
      ELSE IF(NC.EQ.8) THEN
          L2 = L2 + 1
          GOTO 800

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```

      ELSE IF(NC.EQ.9) THEN
        L2 = L2 + 1
        GOTO 900
      ELSE IF(NC.EQ.10) THEN
        L2 = L2 + 1
        GOTO 1000
      ENDIF
C
C All possibilities have been calculated.
C
999 CONTINUE
      PRINT*, 'ALL POSSIBLE COMBINATIONS OF PARAMETERS HAVE'
      PRINT*, 'BEEN CALCULATED!!!'
C
C Close files
C
      CLOSE(UNIT=1)
      CLOSE(UNIT=2)
C
C Stop and end program
C
      PRINT *, 'PROGRAM IS FINISHED'
      STOP
      END
C
C Subroutine Gauss to solve matrix.
C
      SUBROUTINE GAUSS(N1,A1,X1)
      DIMENSION A1(11,11),X1(11)
      DOUBLE PRECISION A1,X1,QT1,SUM
C forward substitution
      M2 = N1 + 1
      L1 = N1 - 1
      DO 1140 K1=1,L1
        KK1 = K1 + 1
        DO 1100 I1=KK1,N1
          QT1 = A1(I1,K1)/A1(K1,K1)
          DO 1090 J1=KK1,M2
            A1(I1,J1) = A1(I1,J1) - QT1*A1(K1,J1)
          1090 CONTINUE

```

APPENDIX A: FORTRAN program to solve for correlation coefficients (continued).

```
1100 CONTINUE
      DO 1130 I1=KK1,N1
        A1(I1,K1)=0.0
1130 CONTINUE
1140 CONTINUE
C
C Back substitution
C
      X1(N1) = A1(N1,M2)/ A1(N1,N1)
      DO 1240 NN1=1,L1
        SUM = 0.0
        I1 = N1 - NN1
        II1 = I1 + 1
        DO 1220 J1=II1,N1
          SUM = SUM + A1(I1,J1)*X1(J1)
1220 CONTINUE
        X1(I1) = (A1(I1,M2) - SUM)/ A1(I1,I1)
1240 CONTINUE
C
      RETURN
      END
```

## APPENDIX B

APPENDIX B: Manufacturers addresses and products.

| Manufactures addresses:                                                                                                                                              | Manufactures products:                                                                                                                                                                                             |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>Capital Valve &amp; Fitting Co.<br/>(Swagelok Companies)<br/>224 North Service Highway<br/>Sulphur, LA. 70669<br/>TEL: (318) 625-5136<br/>FAX: (318) 625-2419</p> | <p>All valves, filters, and fittings for flow loop and test fixture.</p>                                                                                                                                           |
| <p>Max Machinery, Inc.<br/>1420 Healdsburg Ave.<br/>Healdsburg, CA. 95548-3298<br/>TEL: (707) 433-7281<br/>FAX: (707) 433-0571</p>                                   | <p>Liquid Flow Meters</p>                                                                                                                                                                                          |
| <p>McMaster - Carr, Inc.<br/>P.O. Box 740100<br/>Atlanta, Ga. 30374-0100<br/>TEL: (404) 346-7000<br/>FAX: (404) 349-9091</p>                                         | <p>Miniature end mills, aluminum and Lexan<sup>®</sup> for test sections and test fixture, electrical wiring, glass cover plates, Teflon<sup>®</sup>, epoxy/fiberglass, Loctite-UV cure adhesive, and o-rings.</p> |
| <p>Mini Tool, Inc.<br/>634 University Ave.<br/>Los Gatos, CA. 95030<br/>TEL: (408) 395-1585<br/>FAX: (408) 395-1605</p>                                              | <p>Micro end mills</p>                                                                                                                                                                                             |

## APPENDIX B: Manufacturers addresses and products (continued).

|                                                                                                                                                       |                                                                                                                                                            |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| National Instrument, Inc.<br>Corporate Headquarters<br>6504 Bridge Point Pkwy.<br>Austin TX. 78730-5039<br>TEL: (512) 795-8284<br>FAX: (512) 794-5678 | Data acquisition system                                                                                                                                    |
| OMEGA Engineering, Inc.<br>World Wide Headquarters<br>One OMEGA Dr.<br>Stamford, CT. 06907-0047<br>TEL: (800) 826-6342<br>FAX: (203) 359-7700         | Gas flow meters, pressure transducers,<br>thermocouple wire and fittings, Omega-<br>therm high thermal conductivity paste,<br>Kapton <sup>®</sup> heaters. |

For a complete list and description of all products used in the construction of the experimental flow loop, please Bailey (1996).



## APPENDIX C

### Appendix C: Single- and two-phase measured data.

Channel A: Argon gas tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80      Hyd. Diameter ( $\mu\text{m}$ ): 256.91Width ( $\mu\text{m}$ ): 258.03      Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          |                          |        |                                                  |        |        |        |        |        |        |
| 2          |                          |        |                                                  |        |        |        |        |        |        |
| 3          | 30.16                    | 34.82  | 46.87                                            | 47.87  | 48.45  | 50.14  | 49.97  | 50.03  | 49.44  |
| 4          | 30.23                    | 35.67  | 46.85                                            | 47.84  | 48.43  | 50.12  | 49.96  | 50.02  | 49.44  |
| 5          | 30.16                    | 36.30  | 47.01                                            | 48.01  | 48.61  | 50.30  | 50.14  | 50.21  | 49.65  |
| 6          | 30.39                    | 39.98  | 52.78                                            | 54.19  | 55.04  | 56.70  | 56.46  | 56.56  | 55.79  |
| 7          | 30.74                    | 41.33  | 54.69                                            | 56.18  | 57.07  | 58.72  | 58.48  | 58.60  | 57.82  |
| 8          | 30.89                    | 42.51  | 55.43                                            | 56.94  | 57.87  | 59.52  | 59.28  | 59.40  | 58.62  |
| 9          | 30.83                    | 43.47  | 55.98                                            | 57.52  | 58.47  | 60.12  | 59.87  | 60.01  | 59.25  |
| 10         | 30.75                    | 43.69  | 56.33                                            | 57.90  | 58.86  | 60.51  | 60.26  | 60.41  | 59.63  |
| 11         | 30.76                    | 44.64  | 56.61                                            | 58.18  | 59.16  | 60.80  | 60.56  | 60.70  | 59.91  |
| 12         | 30.98                    | 45.67  | 56.78                                            | 58.37  | 59.38  | 61.02  | 60.77  | 60.94  | 60.16  |
| 13         | 30.40                    | 47.76  | 56.28                                            | 57.92  | 58.98  | 60.63  | 60.38  | 60.59  | 59.86  |
| 14         | 30.13                    | 50.33  | 55.64                                            | 57.32  | 58.45  | 60.09  | 59.85  | 60.11  | 59.43  |
| 15         | 29.98                    | 50.97  | 55.05                                            | 56.77  | 57.96  | 59.60  | 59.36  | 59.66  | 59.04  |
| 16         | 29.83                    | 51.36  | 54.49                                            | 56.24  | 57.49  | 59.13  | 58.89  | 59.24  | 58.65  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          |                              |             |                           |        |                          |         |         |
| 2          |                              |             |                           |        |                          |         |         |
| 3          | 23.94                        | 800.748     | 18.684                    | 3.865  | 0.00                     | 248.76  | 0.00    |
| 4          | 23.96                        | 780.606     | 27.785                    | 3.931  | 0.00                     | 367.59  | 0.00    |
| 5          | 23.97                        | 765.438     | 38.127                    | 4.010  | 0.00                     | 483.28  | 0.00    |
| 6          | 23.95                        | 755.786     | 49.660                    | 4.168  | 0.00                     | 581.35  | 0.00    |
| 7          | 23.95                        | 1,017.780   | 62.672                    | 4.370  | 0.00                     | 0.00    | 647.10  |
| 8          | 23.98                        | 1,007.156   | 78.116                    | 4.458  | 0.00                     | 0.00    | 726.47  |
| 9          | 23.96                        | 999.854     | 93.422                    | 4.686  | 0.00                     | 0.00    | 792.78  |
| 10         | 23.94                        | 994.339     | 110.972                   | 4.860  | 0.00                     | 0.00    | 849.29  |
| 11         | 23.96                        | 990.202     | 126.846                   | 4.998  | 0.00                     | 0.00    | 887.29  |
| 12         | 23.97                        | 987.444     | 143.614                   | 5.337  | 0.00                     | 0.00    | 932.41  |
| 13         | 23.91                        | 983.194     | 200.978                   | 6.022  | 0.00                     | 0.00    | 1063.20 |
| 14         | 23.93                        | 984.686     | 259.828                   | 6.687  | 0.00                     | 0.00    | 1159.02 |
| 15         | 23.96                        | 986.065     | 314.840                   | 7.471  | 0.00                     | 261.17  | 976.83  |
| 16         | 24.00                        | 983.488     | 375.162                   | 8.163  | 0.00                     | 270.10  | 1024.29 |

## Appendix C: Single- and two-phase measured data (continued).

Channel A: Helium gas tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          |                          |        |                                                  |        |        |        |        |        |        |
| 2          |                          |        |                                                  |        |        |        |        |        |        |
| 3          |                          |        |                                                  |        |        |        |        |        |        |
| 4          | 36.76                    | 40.16  | 49.46                                            | 50.46  | 51.07  | 52.75  | 52.59  | 52.66  | 52.11  |
| 5          | 37.09                    | 42.08  | 50.64                                            | 51.69  | 52.33  | 54.00  | 53.83  | 53.90  | 53.34  |
| 6          | 37.09                    | 42.81  | 50.74                                            | 51.81  | 52.45  | 54.13  | 53.96  | 54.03  | 53.46  |
| 7          | 37.64                    | 44.27  | 55.34                                            | 56.80  | 57.67  | 59.32  | 59.09  | 59.18  | 58.42  |
| 8          | 38.22                    | 45.16  | 57.16                                            | 58.69  | 59.62  | 61.26  | 61.01  | 61.12  | 60.34  |
| 9          | 38.57                    | 46.16  | 57.91                                            | 59.48  | 60.43  | 62.07  | 61.83  | 61.96  | 61.18  |
| 10         | 38.82                    | 47.89  | 58.41                                            | 60.00  | 60.98  | 62.61  | 62.36  | 62.51  | 61.74  |
| 11         | 39.02                    | 49.35  | 58.77                                            | 60.39  | 61.39  | 63.03  | 62.78  | 62.94  | 62.19  |
| 12         | 39.10                    | 49.96  | 58.94                                            | 60.58  | 61.60  | 63.24  | 62.99  | 63.17  | 62.44  |
| 13         | 38.59                    | 52.30  | 58.69                                            | 60.39  | 61.48  | 63.11  | 62.87  | 63.10  | 62.41  |
| 14         | 37.99                    | 53.99  | 58.30                                            | 60.07  | 61.23  | 62.86  | 62.62  | 62.92  | 62.30  |
| 15         | 37.36                    | 54.49  | 57.72                                            | 59.55  | 60.77  | 62.41  | 62.17  | 62.53  | 61.96  |
| 16         | 36.75                    | 54.32  | 57.03                                            | 58.88  | 60.17  | 61.80  | 61.56  | 61.96  | 61.46  |

| Data Point | Gas Flow Meter               |              | Test Fixture Press., (Pa) |          | Gas Flow Rates, (cc/min) |         |          |
|------------|------------------------------|--------------|---------------------------|----------|--------------------------|---------|----------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa)  | Inlet                     | Outlet   | F.M. #4                  | F.M. #5 | F.M. #6  |
| 1          |                              |              |                           |          |                          |         |          |
| 2          |                              |              |                           |          |                          |         |          |
| 3          |                              |              |                           |          |                          |         |          |
| 4          | 23.93                        | 1,184,653.07 | 23,373.15                 | 3,779.67 | 0.00                     | 383.51  | 0.00     |
| 5          | 23.94                        | 1,158,453.08 | 30,697.39                 | 3,838.44 | 0.00                     | 491.01  | 0.00     |
| 6          | 23.94                        | 1,140,526.78 | 39,093.14                 | 3,913.04 | 0.00                     | 602.48  | 0.00     |
| 7          | 24.00                        | 1,132,253.10 | 45,895.19                 | 3,994.42 | 0.00                     | 0.00    | 723.44   |
| 8          | 23.99                        | 1,125,358.36 | 52,251.91                 | 4,014.77 | 0.00                     | 0.00    | 807.31   |
| 9          | 24.00                        | 1,118,463.63 | 59,539.98                 | 4,096.15 | 0.00                     | 0.00    | 907.09   |
| 10         | 24.00                        | 1,112,947.84 | 66,629.12                 | 4,175.27 | 0.00                     | 0.00    | 1,003.78 |
| 11         | 24.01                        | 1,108,811.00 | 72,877.33                 | 4,267.95 | 0.00                     | 0.00    | 1,088.79 |
| 12         | 23.99                        | 1,106,053.11 | 79,607.04                 | 4,299.60 | 0.00                     | 0.00    | 1,177.65 |
| 13         | 24.00                        | 1,097,101.26 | 99,215.21                 | 4,645.47 | 0.00                     | 0.00    | 1,443.36 |
| 14         | 24.01                        | 1,089,505.75 | 119,766.04                | 4,955.17 | 0.00                     | 0.00    | 1,701.12 |
| 15         | 24.00                        | 1,085,368.91 | 140,032.03                | 5,576.82 | 0.00                     | 398.66  | 1,506.98 |
| 16         | 23.99                        | 1,081,232.07 | 159,262.69                | 5,992.77 | 0.00                     | 434.03  | 1,667.99 |

Appendix C: Single- and two-phase measured data (continued).

Channel A: Nitrogen gas tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80

Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          |                          |        |                                                  |        |        |        |        |        |        |
| 2          |                          |        |                                                  |        |        |        |        |        |        |
| 3          |                          |        |                                                  |        |        |        |        |        |        |
| 4          |                          |        |                                                  |        |        |        |        |        |        |
| 5          | 36.39                    | 44.41  | 52.71                                            | 53.72  | 54.33  | 56.00  | 55.83  | 55.90  | 55.35  |
| 6          | 35.85                    | 44.38  | 52.54                                            | 53.57  | 54.19  | 55.86  | 55.69  | 55.77  | 55.22  |
| 7          | 35.29                    | 44.41  | 52.32                                            | 53.36  | 54.00  | 55.67  | 55.50  | 55.59  | 55.05  |
| 8          | 34.83                    | 44.51  | 52.03                                            | 53.08  | 53.73  | 55.40  | 55.24  | 55.33  | 54.81  |
| 9          | 34.48                    | 44.54  | 51.76                                            | 52.82  | 53.48  | 55.15  | 54.99  | 55.09  | 54.58  |
| 10         | 34.16                    | 44.71  | 51.51                                            | 52.57  | 53.24  | 54.92  | 54.75  | 54.87  | 54.37  |
| 11         | 34.02                    | 47.04  | 55.74                                            | 57.17  | 58.09  | 59.73  | 59.50  | 59.65  | 58.99  |
| 12         | 34.09                    | 48.54  | 57.30                                            | 58.81  | 59.79  | 61.43  | 61.19  | 61.36  | 60.67  |
| 13         | 33.94                    | 49.62  | 57.18                                            | 58.74  | 59.77  | 61.41  | 61.17  | 61.36  | 60.67  |
| 14         | 33.82                    | 51.10  | 56.89                                            | 58.50  | 59.58  | 61.22  | 60.98  | 61.22  | 60.57  |
| 15         | 33.55                    | 52.03  | 56.50                                            | 58.16  | 59.30  | 60.94  | 60.70  | 60.99  | 60.38  |
| 16         | 33.06                    | 52.36  | 55.86                                            | 57.56  | 58.76  | 60.40  | 60.17  | 60.50  | 59.94  |

| Data Point | Gas Flow Meter               |              | Test Fixture Press., (Pa) |          | Gas Flow Rates, (cc/min) |         |          |
|------------|------------------------------|--------------|---------------------------|----------|--------------------------|---------|----------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa)  | Inlet                     | Outlet   | F.M. #4                  | F.M. #5 | F.M. #6  |
| 1          |                              |              |                           |          |                          |         |          |
| 2          |                              |              |                           |          |                          |         |          |
| 3          |                              |              |                           |          |                          |         |          |
| 4          |                              |              |                           |          |                          |         |          |
| 5          | 23.93                        | 1,450,405.50 | 23,282.04                 | 3,899.48 | 0.00                     | 370.21  | 0.00     |
| 6          | 23.95                        | 1,424,589.80 | 28,959.01                 | 3,942.43 | 0.00                     | 451.98  | 0.00     |
| 7          | 23.97                        | 1,406,663.50 | 35,645.77                 | 4,030.59 | 0.00                     | 0.00    | 533.93   |
| 8          | 23.92                        | 1,397,010.90 | 41,563.94                 | 4,078.07 | 0.00                     | 0.00    | 610.47   |
| 9          | 23.91                        | 1,388,918.00 | 46,939.57                 | 4,179.79 | 0.00                     | 0.00    | 674.55   |
| 10         | 23.93                        | 1,383,877.00 | 53,020.50                 | 4,286.04 | 0.00                     | 0.00    | 741.77   |
| 11         | 23.92                        | 1,379,152.40 | 60,432.90                 | 4,399.07 | 0.00                     | 0.00    | 803.31   |
| 12         | 23.91                        | 1,376,326.70 | 67,906.34                 | 4,460.10 | 0.00                     | 0.00    | 859.98   |
| 13         | 23.91                        | 1,368,053.00 | 101,283.60                | 4,835.36 | 0.00                     | 0.00    | 1,022.14 |
| 14         | 23.97                        | 1,362,537.20 | 136,690.90                | 5,018.46 | 0.00                     | 0.00    | 1,137.21 |
| 15         | 23.99                        | 1,358,400.30 | 170,809.70                | 5,353.03 | 0.00                     | 258.51  | 970.86   |
| 16         | 23.96                        | 1,352,884.60 | 209,069.80                | 5,633.34 | 0.00                     | 271.86  | 1,037.14 |

# Appendix C: Single- and two-phase measured data (continued).

Channel A: Water tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80Hyd. Diameter ( $\mu\text{m}$ ): 256.91Width ( $\mu\text{m}$ ): 258.03

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 24.64                    | 40.38  | 36.84                                            | 39.97  | 43.06  | 44.60  | 44.26  | 45.52  | 45.72  |
| 2          | 24.30                    | 36.96  | 34.86                                            | 38.04  | 41.26  | 42.74  | 42.33  | 43.20  | 43.10  |
| 3          | 24.45                    | 34.68  | 34.03                                            | 37.67  | 41.63  | 42.99  | 42.41  | 42.95  | 42.45  |
| 4          | 25.11                    | 34.53  | 34.13                                            | 38.07  | 42.46  | 43.76  | 43.08  | 43.27  | 42.32  |
| 5          | 25.65                    | 36.08  | 34.53                                            | 38.75  | 44.52  | 45.64  | 44.75  | 45.00  | 44.02  |
| 6          | 26.06                    | 37.58  | 35.27                                            | 39.93  | 46.69  | 47.69  | 46.61  | 46.64  | 45.52  |
| 7          | 26.54                    | 37.24  | 34.73                                            | 38.99  | 45.31  | 46.25  | 45.14  | 44.78  | 43.96  |
| 8          | 26.82                    | 38.47  | 35.60                                            | 40.09  | 47.03  | 47.75  | 46.42  | 46.10  | 45.47  |
| 9          | 26.81                    | 37.95  | 35.20                                            | 39.40  | 46.14  | 46.85  | 45.54  | 45.19  | 44.69  |
| 10         | 26.95                    | 36.97  | 34.49                                            | 38.32  | 44.81  | 45.50  | 44.22  | 43.78  | 43.40  |
| 11         | 27.11                    | 37.77  | 35.21                                            | 39.39  | 46.76  | 47.24  | 45.71  | 45.10  | 44.78  |
| 12         | 27.36                    | 38.13  | 35.68                                            | 40.02  | 48.26  | 48.50  | 46.71  | 45.88  | 45.62  |
| 13         | 27.49                    | 37.26  | 35.11                                            | 39.08  | 47.21  | 47.41  | 45.62  | 44.68  | 44.51  |
| 14         | 27.77                    | 37.28  | 35.17                                            | 39.22  | 47.85  | 47.92  | 45.99  | 44.90  | 44.76  |
| 15         | 27.82                    | 36.64  | 34.73                                            | 38.56  | 47.04  | 47.10  | 45.18  | 44.03  | 43.93  |
| 16         | 27.63                    | 36.11  | 34.34                                            | 38.01  | 46.43  | 46.48  | 44.57  | 43.33  | 43.27  |
| 17         | 27.64                    | 35.59  | 33.92                                            | 37.46  | 45.84  | 45.86  | 43.96  | 42.67  | 42.65  |
| 18         | 27.62                    | 35.01  | 33.48                                            | 36.96  | 45.15  | 45.17  | 43.29  | 41.92  | 41.94  |
| 19         | 27.51                    | 34.51  | 33.04                                            | 36.41  | 44.50  | 44.51  | 42.66  | 41.26  | 41.31  |
| 20         | 27.50                    | 34.10  | 32.66                                            | 35.91  | 43.97  | 43.98  | 42.14  | 40.71  | 40.80  |
| 21         | 27.57                    | 33.76  | 32.32                                            | 35.46  | 43.54  | 43.54  | 41.70  | 40.26  | 40.38  |

# Appendix C: Single- and two-phase measured data (continued).

## Channel A: Water tests (continued).

| Data Point | Liquid Flow Meter |              | Test Fixture Press., (Pa) |            | liquid Flow Rate   |
|------------|-------------------|--------------|---------------------------|------------|--------------------|
|            | Temp.(°C)         | Press.(Pa)   | Inlet                     | Outlet     | F. M. #1, (cc/min) |
| 1          | 24.10             | 2,788,887.96 | 116,374.06                | 100,862.04 | 10.69              |
| 2          | 24.27             | 2,734,136.99 | 133,757.83                | 99,290.94  | 17.17              |
| 3          | 24.90             | 2,681,171.88 | 169,406.99                | 98,832.05  | 31.52              |
| 4          | 25.96             | 2,647,376.38 | 201,122.76                | 98,253.34  | 42.51              |
| 5          | 26.63             | 2,636,796.92 | 239,348.97                | 98,526.87  | 52.86              |
| 6          | 27.11             | 2,638,854.04 | 271,788.12                | 99,180.17  | 58.31              |
| 7          | 27.49             | 2,633,315.65 | 307,595.53                | 99,128.18  | 64.65              |
| 8          | 27.76             | 2,627,935.49 | 343,222.08                | 99,177.91  | 70.28              |
| 9          | 27.95             | 2,634,468.54 | 380,634.49                | 99,914.86  | 74.16              |
| 10         | 28.17             | 2,585,775.90 | 446,010.12                | 98,920.21  | 85.77              |
| 11         | 28.43             | 2,552,251.67 | 511,182.31                | 98,823.00  | 94.29              |
| 12         | 28.62             | 2,532,607.33 | 613,631.26                | 99,139.48  | 106.80             |
| 13         | 28.72             | 2,524,491.89 | 726,320.59                | 99,706.89  | 120.56             |
| 14         | 28.79             | 2,503,152.13 | 827,322.78                | 99,695.58  | 130.90             |
| 15         | 28.85             | 2,492,233.58 | 933,840.76                | 100,095.70 | 142.14             |
| 16         | 28.88             | 2,501,162.83 | 1,042,980.99              | 101,092.61 | 152.24             |
| 17         | 28.89             | 2,436,985.29 | 1,165,707.25              | 99,984.94  | 161.25             |
| 18         | 28.89             | 2,449,124.54 | 1,314,949.96              | 101,241.81 | 178.93             |
| 19         | 28.87             | 2,388,676.95 | 1,447,396.66              | 100,529.73 | 188.83             |
| 20         | 28.87             | 2,391,706.11 | 1,601,047.49              | 100,755.79 | 200.92             |
| 21         | 28.84             | 2,326,036.60 | 1,733,109.88              | 99,573.51  | 205.93             |

# Appendix C: Single- and two-phase measured data (continued).

Channel A: Water and argon tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 24.83                    | 39.90  | 34.16                                            | 38.34  | 42.33  | 43.83  | 43.37  | 44.94  | 45.10  |
| 2          | 25.02                    | 41.10  | 33.59                                            | 37.45  | 41.53  | 42.97  | 42.50  | 44.33  | 45.04  |
| 3          | 24.65                    | 41.46  | 33.68                                            | 37.44  | 41.51  | 42.91  | 42.40  | 44.26  | 44.99  |
| 4          | 24.73                    | 41.59  | 33.86                                            | 37.58  | 41.66  | 43.04  | 42.51  | 44.39  | 45.06  |
| 5          | 24.82                    | 41.73  | 34.08                                            | 37.79  | 41.86  | 43.24  | 42.73  | 44.59  | 45.19  |
| 6          | 24.97                    | 42.01  | 34.57                                            | 38.34  | 42.40  | 43.79  | 43.27  | 45.07  | 45.52  |
| 7          | 24.67                    | 37.23  | 32.53                                            | 36.81  | 42.13  | 43.22  | 42.44  | 43.40  | 43.97  |
| 8          | 24.94                    | 37.98  | 32.60                                            | 36.64  | 41.85  | 42.93  | 42.12  | 43.11  | 43.89  |
| 9          | 26.74                    | 39.74  | 34.21                                            | 38.08  | 42.83  | 44.03  | 43.33  | 44.37  | 44.96  |
| 10         | 25.12                    | 37.99  | 32.95                                            | 37.02  | 42.34  | 43.39  | 42.53  | 43.77  | 44.41  |
| 11         | 25.14                    | 37.30  | 33.10                                            | 37.24  | 42.66  | 43.70  | 42.83  | 44.19  | 44.82  |
| 12         | 25.10                    | 38.80  | 33.22                                            | 37.45  | 42.98  | 43.99  | 43.11  | 44.61  | 45.21  |
| 13         | 25.83                    | 34.59  | 32.84                                            | 36.76  | 43.76  | 44.21  | 42.79  | 42.60  | 43.85  |
| 14         | 25.94                    | 35.52  | 33.03                                            | 37.04  | 44.12  | 44.55  | 43.13  | 43.04  | 44.22  |
| 15         | 25.98                    | 35.77  | 33.20                                            | 37.27  | 44.43  | 44.86  | 43.42  | 43.45  | 44.58  |
| 16         | 25.96                    | 36.30  | 33.35                                            | 37.56  | 44.84  | 45.27  | 43.82  | 44.04  | 45.09  |
| 17         | 25.93                    | 36.57  | 33.57                                            | 37.96  | 45.45  | 45.85  | 44.36  | 44.86  | 45.85  |
| 18         | 25.85                    | 36.74  | 33.77                                            | 38.32  | 46.05  | 46.46  | 44.93  | 45.74  | 46.65  |
| 19         | 26.18                    | 34.73  | 33.15                                            | 37.08  | 45.81  | 45.78  | 43.84  | 43.18  | 44.83  |
| 20         | 26.19                    | 34.96  | 33.26                                            | 37.31  | 46.14  | 46.09  | 44.14  | 43.64  | 45.22  |
| 21         | 26.12                    | 35.34  | 33.39                                            | 37.57  | 46.55  | 46.49  | 44.50  | 44.15  | 45.68  |
| 22         | 26.12                    | 35.99  | 33.48                                            | 37.79  | 46.92  | 46.85  | 44.82  | 44.70  | 46.12  |
| 23         | 26.08                    | 36.56  | 33.70                                            | 38.25  | 47.63  | 47.56  | 45.46  | 45.67  | 47.01  |
| 24         | 26.01                    | 37.03  | 33.71                                            | 38.36  | 47.96  | 47.88  | 45.73  | 46.28  | 47.68  |

# Appendix C: Single- and two-phase measured data (continued).

## Channel A: Water and argon tests (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |           | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|-----------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet    | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 23.82          | 1,529,390  | 24.00             | 1,998,789  | 200,558                   | 113,543.8 | 0.00                            | 0.00    | 210.68  | 14.27   |
| 2          | 24.17          | 1,517,070  | 24.41             | 1,962,868  | 295,705                   | 124,489.5 | 0.00                            | 0.00    | 382.10  | 14.82   |
| 3          | 24.14          | 1,515,600  | 24.37             | 1,904,274  | 374,079                   | 131,978.8 | 0.00                            | 0.00    | 504.21  | 13.33   |
| 4          | 24.12          | 1,511,124  | 24.36             | 1,892,180  | 455,889                   | 140,797.2 | 0.00                            | 0.00    | 597.35  | 12.74   |
| 5          | 24.08          | 1,510,062  | 24.36             | 1,900,138  | 539,643                   | 149,672.2 | 0.00                            | 142.34  | 529.95  | 11.98   |
| 6          | 24.06          | 1,510,740  | 24.34             | 1,903,528  | 621,679                   | 157,719.8 | 0.00                            | 153.68  | 581.78  | 9.80    |
| 7          | 23.99          | 1,536,284  | 25.66             | 1,871,835  | 326,132                   | 111,719.5 | 0.00                            | 0.00    | 163.90  | 47.20   |
| 8          | 23.96          | 1,521,116  | 25.98             | 1,845,748  | 445,309                   | 121,849.2 | 0.00                            | 0.00    | 306.69  | 42.30   |
| 9          | 25.15          | 2,460,179  | 27.79             | 3,280,102  | 406,315                   | 130,055.0 | 0.00                            | 0.00    | 485.60  | 35.72   |
| 10         | 23.94          | 1,515,035  | 26.17             | 1,849,908  | 641,075                   | 140,937.4 | 0.00                            | 0.00    | 483.30  | 37.72   |
| 11         | 23.94          | 1,513,340  | 26.17             | 1,855,175  | 732,288                   | 148,892.3 | 0.00                            | 117.19  | 436.43  | 35.41   |
| 12         | 23.92          | 1,516,278  | 26.10             | 1,860,713  | 825,944                   | 156,458.5 | 0.00                            | 127.16  | 481.47  | 32.45   |
| 13         | 23.94          | 1,536,284  | 27.34             | 1,775,784  | 716,578                   | 113,301.9 | 0.00                            | 0.00    | 110.20  | 101.44  |
| 14         | 23.91          | 1,523,806  | 27.42             | 1,785,029  | 779,941                   | 120,922.3 | 0.00                            | 0.00    | 168.84  | 99.65   |
| 15         | 23.92          | 1,516,979  | 27.43             | 1,784,962  | 842,582                   | 127,566.1 | 0.00                            | 0.00    | 221.67  | 95.38   |
| 16         | 23.94          | 1,518,358  | 27.34             | 1,779,242  | 935,694                   | 136,913.6 | 0.00                            | 0.00    | 305.58  | 89.27   |
| 17         | 23.98          | 1,515,035  | 27.25             | 1,780,893  | 1,040,788                 | 147,635.5 | 0.00                            | 0.00    | 390.94  | 82.00   |
| 18         | 24.01          | 1,515,691  | 27.14             | 1,788,918  | 1,149,951                 | 158,624.1 | 0.00                            | 99.99   | 378.51  | 74.49   |
| 19         | 23.98          | 1,538,296  | 27.64             | 1,705,277  | 1,067,260                 | 112,978.7 | 0.00                            | 0.00    | 80.26   | 140.78  |
| 20         | 24.00          | 1,523,580  | 27.62             | 1,703,649  | 1,111,951                 | 119,868.9 | 0.00                            | 0.00    | 129.16  | 137.60  |
| 21         | 24.03          | 1,521,116  | 27.57             | 1,695,059  | 1,146,651                 | 125,807.4 | 0.00                            | 0.00    | 173.79  | 131.03  |
| 22         | 24.10          | 1,520,619  | 27.51             | 1,718,433  | 1,223,510                 | 136,850.3 | 0.00                            | 0.00    | 247.05  | 123.35  |
| 23         | 24.16          | 1,518,223  | 27.42             | 1,724,876  | 1,299,533                 | 148,573.6 | 0.00                            | 0.00    | 332.86  | 111.96  |
| 24         | 24.12          | 1,523,603  | 27.31             | 1,739,456  | 1,365,542                 | 157,812.5 | 0.00                            | 85.02   | 320.90  | 103.54  |



Appendix C: Single- and two-phase measured data (continued).

Channel A: Water and helium tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 25.62                    | 34.75  | 31.74                                            | 35.17  | 38.46  | 39.91  | 39.49  | 40.34  | 40.15  |
| 2          | 25.96                    | 35.22  | 31.30                                            | 34.60  | 37.95  | 39.40  | 38.99  | 39.98  | 40.04  |
| 3          | 26.11                    | 35.21  | 30.81                                            | 33.90  | 37.19  | 38.63  | 38.23  | 39.26  | 39.55  |
| 4          | 25.99                    | 34.85  | 30.56                                            | 33.53  | 36.76  | 38.19  | 37.80  | 38.80  | 39.12  |
| 5          | 25.65                    | 34.67  | 30.25                                            | 33.11  | 36.27  | 37.70  | 37.31  | 38.28  | 38.65  |
| 6          | 25.57                    | 34.41  | 30.11                                            | 32.94  | 36.09  | 37.51  | 37.12  | 38.06  | 38.44  |
| 7          | 26.10                    | 36.91  | 32.80                                            | 37.21  | 42.60  | 43.67  | 42.90  | 43.83  | 44.40  |
| 8          | 26.14                    | 37.08  | 32.45                                            | 36.60  | 41.75  | 42.81  | 42.03  | 42.75  | 43.45  |
| 9          | 26.41                    | 37.18  | 32.32                                            | 36.37  | 41.45  | 42.50  | 41.71  | 42.47  | 43.33  |
| 10         | 26.31                    | 37.27  | 32.24                                            | 36.24  | 41.29  | 42.32  | 41.54  | 42.36  | 43.26  |
| 11         | 26.04                    | 37.32  | 32.13                                            | 36.09  | 41.10  | 42.13  | 41.36  | 42.21  | 43.10  |
| 12         | 26.03                    | 37.28  | 32.21                                            | 36.19  | 41.21  | 42.24  | 41.47  | 42.32  | 43.15  |
| 13         | 26.48                    | 34.69  | 31.99                                            | 35.69  | 41.97  | 42.47  | 41.25  | 41.08  | 42.48  |
| 14         | 26.51                    | 34.84  | 31.95                                            | 35.70  | 42.04  | 42.53  | 41.30  | 41.24  | 42.56  |
| 15         | 26.80                    | 36.08  | 32.76                                            | 36.97  | 44.11  | 44.43  | 43.03  | 43.03  | 44.50  |
| 16         | 26.76                    | 36.24  | 32.75                                            | 36.97  | 44.15  | 44.47  | 43.06  | 43.14  | 44.56  |
| 17         | 26.49                    | 36.50  | 32.71                                            | 36.94  | 44.18  | 44.48  | 43.05  | 43.24  | 44.62  |
| 18         | 26.41                    | 36.88  | 32.65                                            | 36.91  | 44.20  | 44.49  | 43.05  | 43.38  | 44.67  |
| 19         | 26.61                    | 34.76  | 32.28                                            | 35.98  | 44.04  | 44.04  | 42.30  | 41.86  | 43.51  |
| 20         | 26.61                    | 35.09  | 32.26                                            | 36.03  | 44.17  | 44.17  | 42.42  | 42.09  | 43.70  |
| 21         | 26.85                    | 35.22  | 32.27                                            | 36.07  | 44.23  | 44.25  | 42.47  | 42.30  | 43.85  |

# Appendix C: Single- and two-phase measured data (continued).

## Channel A: Water and helium (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.06          | 1,707,274  | 26.22             | 1,876,650  | 207,995                   | 109,432 | 0.00                            | 0.00    | 222.88  | 28.54   |
| 2          | 24.08          | 1,687,969  | 26.14             | 1,872,084  | 249,341                   | 120,511 | 0.00                            | 0.00    | 415.60  | 27.30   |
| 3          | 24.09          | 1,675,558  | 26.06             | 1,867,631  | 287,341                   | 129,913 | 0.00                            | 0.00    | 583.54  | 26.80   |
| 4          | 24.10          | 1,667,284  | 25.96             | 1,863,856  | 315,078                   | 138,797 | 0.00                            | 0.00    | 745.18  | 26.13   |
| 5          | 24.06          | 1,666,335  | 25.85             | 1,870,637  | 354,887                   | 146,826 | 0.00                            | 182.43  | 685.84  | 25.55   |
| 6          | 24.03          | 1,667,058  | 25.77             | 1,874,684  | 383,799                   | 153,655 | 0.00                            | 204.85  | 784.96  | 25.05   |
| 7          | 24.06          | 1,725,200  | 26.26             | 1,816,045  | 284,312                   | 108,864 | 0.00                            | 0.00    | 193.59  | 48.80   |
| 8          | 24.07          | 1,696,242  | 26.36             | 1,815,683  | 341,594                   | 120,943 | 0.00                            | 0.00    | 358.26  | 46.54   |
| 9          | 24.08          | 1,683,832  | 26.39             | 1,820,114  | 390,739                   | 130,674 | 0.00                            | 0.00    | 501.23  | 46.60   |
| 10         | 24.07          | 1,678,316  | 26.37             | 1,818,667  | 434,956                   | 138,711 | 0.00                            | 0.00    | 634.19  | 45.52   |
| 11         | 24.08          | 1,674,224  | 26.34             | 1,835,192  | 478,201                   | 147,421 | 0.00                            | 155.36  | 583.82  | 44.56   |
| 12         | 24.08          | 1,675,558  | 26.30             | 1,813,535  | 500,512                   | 153,314 | 0.00                            | 177.81  | 681.28  | 42.29   |
| 13         | 24.11          | 1,737,859  | 27.05             | 1,732,019  | 621,001                   | 109,977 | 0.00                            | 0.00    | 118.75  | 98.64   |
| 14         | 24.14          | 1,710,032  | 27.06             | 1,737,851  | 683,980                   | 123,009 | 0.00                            | 0.00    | 234.41  | 97.01   |
| 15         | 24.18          | 1,692,874  | 27.01             | 1,743,412  | 731,927                   | 132,417 | 0.00                            | 0.00    | 343.05  | 94.26   |
| 16         | 24.19          | 1,685,211  | 26.93             | 1,746,849  | 775,465                   | 141,381 | 0.00                            | 0.00    | 436.14  | 91.35   |
| 17         | 24.19          | 1,678,452  | 26.85             | 1,767,329  | 828,634                   | 150,592 | 0.00                            | 109.31  | 410.99  | 89.16   |
| 18         | 24.17          | 1,679,695  | 26.73             | 1,773,501  | 872,918                   | 157,546 | 0.00                            | 122.52  | 468.92  | 87.28   |
| 19         | 24.17          | 1,745,884  | 27.02             | 1,669,040  | 964,336                   | 110,992 | 0.00                            | 0.00    | 88.06   | 136.17  |
| 20         | 24.16          | 1,712,790  | 26.99             | 1,675,776  | 1,019,516                 | 124,218 | 0.00                            | 0.00    | 179.10  | 132.29  |
| 21         | 24.18          | 1,697,825  | 26.96             | 1,680,026  | 1,065,655                 | 134,246 | 0.00                            | 0.00    | 261.70  | 128.19  |

# Appendix C: Single- and two-phase measured data (continued).

Channel A: Water and nitrogen tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 25.62                    | 34.75  | 31.74                                            | 35.17  | 38.46  | 39.91  | 39.49  | 40.34  | 40.15  |
| 2          | 25.96                    | 35.22  | 31.30                                            | 34.60  | 37.95  | 39.40  | 38.99  | 39.98  | 40.04  |
| 3          | 26.11                    | 35.21  | 30.81                                            | 33.90  | 37.19  | 38.63  | 38.23  | 39.26  | 39.55  |
| 4          | 25.99                    | 34.85  | 30.56                                            | 33.53  | 36.76  | 38.19  | 37.80  | 38.80  | 39.12  |
| 5          | 25.65                    | 34.67  | 30.25                                            | 33.11  | 36.27  | 37.70  | 37.31  | 38.28  | 38.65  |
| 6          | 25.57                    | 34.41  | 30.11                                            | 32.94  | 36.09  | 37.51  | 37.12  | 38.06  | 38.44  |
| 7          | 26.10                    | 36.91  | 32.80                                            | 37.21  | 42.60  | 43.67  | 42.90  | 43.83  | 44.40  |
| 8          | 26.14                    | 37.08  | 32.45                                            | 36.60  | 41.75  | 42.81  | 42.03  | 42.75  | 43.45  |
| 9          | 26.41                    | 37.18  | 32.32                                            | 36.37  | 41.45  | 42.50  | 41.71  | 42.47  | 43.33  |
| 10         | 26.31                    | 37.27  | 32.24                                            | 36.24  | 41.29  | 42.32  | 41.54  | 42.36  | 43.26  |
| 11         | 26.04                    | 37.32  | 32.13                                            | 36.09  | 41.10  | 42.13  | 41.36  | 42.21  | 43.10  |
| 12         | 26.03                    | 37.28  | 32.21                                            | 36.19  | 41.21  | 42.24  | 41.47  | 42.32  | 43.15  |
| 13         | 26.48                    | 34.69  | 31.99                                            | 35.69  | 41.97  | 42.47  | 41.25  | 41.08  | 42.48  |
| 14         | 26.51                    | 34.84  | 31.95                                            | 35.70  | 42.04  | 42.53  | 41.30  | 41.24  | 42.56  |
| 15         | 26.80                    | 36.08  | 32.76                                            | 36.97  | 44.11  | 44.43  | 43.03  | 43.03  | 44.50  |
| 16         | 26.76                    | 36.24  | 32.75                                            | 36.97  | 44.15  | 44.47  | 43.06  | 43.14  | 44.56  |
| 17         | 26.49                    | 36.50  | 32.71                                            | 36.94  | 44.18  | 44.48  | 43.05  | 43.24  | 44.62  |
| 18         | 26.41                    | 36.88  | 32.65                                            | 36.91  | 44.20  | 44.49  | 43.05  | 43.38  | 44.67  |
| 19         | 26.61                    | 34.76  | 32.28                                            | 35.98  | 44.04  | 44.04  | 42.30  | 41.86  | 43.51  |
| 20         | 26.61                    | 35.09  | 32.26                                            | 36.03  | 44.17  | 44.17  | 42.42  | 42.09  | 43.70  |
| 21         | 26.85                    | 35.22  | 32.27                                            | 36.07  | 44.23  | 44.25  | 42.47  | 42.30  | 43.85  |

Appendix C: Single- and two-phase measured data (continued).

Channel A: Water and nitrogen (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.06          | 1,707,274  | 26.22             | 1,876,650  | 207,995                   | 109,432 | 0.00                            | 0.00    | 222.88  | 28.54   |
| 2          | 24.08          | 1,687,969  | 26.14             | 1,872,084  | 249,341                   | 120,511 | 0.00                            | 0.00    | 415.60  | 27.30   |
| 3          | 24.09          | 1,675,558  | 26.06             | 1,867,631  | 287,341                   | 129,913 | 0.00                            | 0.00    | 583.54  | 26.80   |
| 4          | 24.10          | 1,667,284  | 25.96             | 1,863,856  | 315,078                   | 138,797 | 0.00                            | 0.00    | 745.18  | 26.13   |
| 5          | 24.06          | 1,666,335  | 25.85             | 1,870,637  | 354,887                   | 146,826 | 0.00                            | 182.43  | 685.84  | 25.55   |
| 6          | 24.03          | 1,667,058  | 25.77             | 1,874,684  | 383,799                   | 153,655 | 0.00                            | 204.85  | 784.96  | 25.05   |
| 7          | 24.06          | 1,725,200  | 26.26             | 1,816,045  | 284,312                   | 108,864 | 0.00                            | 0.00    | 193.59  | 48.80   |
| 8          | 24.07          | 1,696,242  | 26.36             | 1,815,683  | 341,594                   | 120,943 | 0.00                            | 0.00    | 358.26  | 46.54   |
| 9          | 24.08          | 1,683,832  | 26.39             | 1,820,114  | 390,739                   | 130,674 | 0.00                            | 0.00    | 501.23  | 46.60   |
| 10         | 24.07          | 1,678,316  | 26.37             | 1,818,667  | 434,956                   | 138,711 | 0.00                            | 0.00    | 634.19  | 45.52   |
| 11         | 24.08          | 1,674,224  | 26.34             | 1,835,192  | 478,201                   | 147,421 | 0.00                            | 155.36  | 583.82  | 44.56   |
| 12         | 24.08          | 1,675,558  | 26.30             | 1,813,535  | 500,512                   | 153,314 | 0.00                            | 177.81  | 681.28  | 42.29   |
| 13         | 24.11          | 1,737,859  | 27.05             | 1,732,019  | 621,001                   | 109,977 | 0.00                            | 0.00    | 118.75  | 98.64   |
| 14         | 24.14          | 1,710,032  | 27.06             | 1,737,851  | 683,980                   | 123,009 | 0.00                            | 0.00    | 234.41  | 97.01   |
| 15         | 24.18          | 1,692,874  | 27.01             | 1,743,412  | 731,927                   | 132,417 | 0.00                            | 0.00    | 343.05  | 94.26   |
| 16         | 24.19          | 1,685,211  | 26.93             | 1,746,849  | 775,465                   | 141,381 | 0.00                            | 0.00    | 436.14  | 91.35   |
| 17         | 24.19          | 1,678,452  | 26.85             | 1,767,329  | 828,634                   | 150,592 | 0.00                            | 109.31  | 410.99  | 89.16   |
| 18         | 24.17          | 1,679,695  | 26.73             | 1,773,501  | 872,918                   | 157,546 | 0.00                            | 122.52  | 468.92  | 87.28   |
| 19         | 24.17          | 1,745,884  | 27.02             | 1,669,040  | 964,336                   | 110,992 | 0.00                            | 0.00    | 88.06   | 136.17  |
| 20         | 24.16          | 1,712,790  | 26.99             | 1,675,776  | 1,019,516                 | 124,218 | 0.00                            | 0.00    | 179.10  | 132.29  |
| 21         | 24.18          | 1,697,825  | 26.96             | 1,680,026  | 1,065,655                 | 134,246 | 0.00                            | 0.00    | 261.70  | 128.19  |

## Appendix C: Single- and two-phase measured data (continued).

Channel B: Argon gas tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.14 Hyd. Diameter ( $\mu\text{m}$ ): 210.05Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 30.56                    | 34.95  | 55.12                                            | 56.54  | 57.39  | 59.11  | 58.71  | 59.01  | 58.26  |
| 2          | 31.01                    | 38.56  | 56.15                                            | 57.57  | 58.43  | 60.15  | 59.75  | 60.05  | 59.30  |
| 3          | 30.75                    | 40.90  | 57.24                                            | 58.64  | 59.50  | 61.21  | 60.81  | 61.12  | 60.37  |
| 4          | 32.10                    | 45.26  | 58.66                                            | 60.03  | 60.87  | 62.58  | 62.17  | 62.46  | 61.69  |
| 5          | 32.50                    | 46.69  | 59.18                                            | 60.58  | 61.44  | 63.15  | 62.74  | 63.05  | 62.28  |
| 6          | 31.57                    | 47.51  | 59.42                                            | 60.86  | 61.76  | 63.47  | 63.05  | 63.38  | 62.62  |
| 7          | 31.80                    | 47.72  | 59.47                                            | 60.92  | 61.83  | 63.56  | 63.13  | 63.46  | 62.68  |
| 8          | 31.39                    | 48.36  | 59.41                                            | 60.90  | 61.86  | 63.59  | 63.16  | 63.52  | 62.77  |
| 9          | 31.51                    | 49.00  | 59.30                                            | 60.81  | 61.80  | 63.53  | 63.10  | 63.48  | 62.75  |
| 10         | 31.49                    | 49.59  | 59.11                                            | 60.63  | 61.64  | 63.37  | 62.94  | 63.34  | 62.64  |
| 11         | 31.41                    | 51.45  | 58.81                                            | 60.35  | 61.39  | 63.12  | 62.69  | 63.12  | 62.44  |
| 12         | 31.23                    | 51.66  | 58.56                                            | 60.12  | 61.19  | 62.93  | 62.49  | 62.95  | 62.29  |
| 13         | 31.08                    | 51.97  | 58.33                                            | 59.92  | 61.02  | 62.76  | 62.32  | 62.80  | 62.17  |
| 14         | 31.04                    | 52.36  | 58.16                                            | 59.76  | 60.89  | 62.64  | 62.20  | 62.71  | 62.11  |
| 15         | 30.87                    | 52.49  | 57.82                                            | 59.44  | 60.60  | 62.35  | 61.90  | 62.45  | 61.87  |
| 16         | 30.72                    | 52.55  | 57.51                                            | 59.15  | 60.33  | 62.09  | 61.64  | 62.21  | 61.66  |
| 17         | 30.65                    | 52.58  | 57.24                                            | 58.88  | 60.08  | 61.83  | 61.38  | 61.97  | 61.44  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.92                        | 1,199.822   | 20,194                    | 3,472  | 0.00                     | 127.76  | 0.00    |
| 2          | 23.88                        | 1,043.840   | 46,751                    | 3,560  | 0.00                     | 314.41  | 0.00    |
| 3          | 23.82                        | 1,028.832   | 66,088                    | 3,633  | 0.00                     | 427.89  | 0.00    |
| 4          | 23.76                        | 1,015,043   | 98,457                    | 3,859  | 0.00                     | 0.00    | 539.87  |
| 5          | 23.74                        | 994,358     | 127,001                   | 4,001  | 0.00                     | 0.00    | 626.06  |
| 6          | 23.71                        | 989,069     | 175,678                   | 4,320  | 0.00                     | 0.00    | 690.27  |
| 7          | 23.69                        | 983,779     | 205,047                   | 4,514  | 0.00                     | 0.00    | 722.48  |
| 8          | 23.68                        | 976,025     | 247,686                   | 4,831  | 0.00                     | 0.00    | 770.98  |
| 9          | 23.68                        | 982,920     | 282,076                   | 5,242  | 0.00                     | 0.00    | 808.80  |
| 10         | 23.67                        | 983,327     | 313,597                   | 5,511  | 0.00                     | 0.00    | 838.94  |
| 11         | 23.68                        | 984,706     | 349,563                   | 5,837  | 0.00                     | 0.00    | 869.38  |
| 12         | 23.70                        | 985,226     | 362,575                   | 6,097  | 0.00                     | 0.00    | 931.54  |
| 13         | 23.76                        | 986,062     | 397,584                   | 6,402  | 0.00                     | 0.00    | 946.50  |
| 14         | 23.84                        | 985,135     | 426,377                   | 6,748  | 0.00                     | 207.01  | 769.11  |
| 15         | 23.90                        | 987,464     | 468,284                   | 7,157  | 0.00                     | 209.22  | 783.04  |
| 16         | 23.90                        | 988,504     | 503,040                   | 7,408  | 0.00                     | 211.10  | 794.77  |
| 17         | 23.94                        | 994,517     | 529,387                   | 7,573  | 0.00                     | 212.55  | 803.83  |

## Appendix C: Single- and two-phase measured data (continued).

Channel B: Helium gas tests.                      Number of channels:                      3  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):                      211.14                      Hyd. Diameter ( $\mu\text{m}$ ):                      210.05  
Width ( $\mu\text{m}$ ):                      208.97                      Channel Length (m):                      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 33.40                    | 35.00  | 55.76                                            | 57.02  | 57.68  | 59.44  | 59.04  | 59.27  | 58.47  |
| 2          | 34.06                    | 40.97  | 57.87                                            | 59.18  | 59.85  | 61.63  | 61.23  | 61.47  | 60.68  |
| 3          | 33.83                    | 45.53  | 58.42                                            | 59.76  | 60.46  | 62.24  | 61.83  | 62.09  | 61.29  |
| 4          | 34.69                    | 46.57  | 58.71                                            | 60.07  | 60.77  | 62.55  | 62.14  | 62.39  | 61.57  |
| 5          | 35.10                    | 48.65  | 58.97                                            | 60.36  | 61.09  | 62.87  | 62.46  | 62.72  | 61.91  |
| 6          | 35.31                    | 50.35  | 59.24                                            | 60.67  | 61.42  | 63.21  | 62.79  | 63.07  | 62.28  |
| 7          | 35.24                    | 51.79  | 59.34                                            | 60.81  | 61.61  | 63.39  | 62.98  | 63.30  | 62.54  |
| 8          | 35.14                    | 51.48  | 59.34                                            | 60.87  | 61.72  | 63.50  | 63.08  | 63.45  | 62.73  |
| 9          | 35.04                    | 50.18  | 59.34                                            | 60.91  | 61.81  | 63.59  | 63.17  | 63.59  | 62.92  |
| 10         | 34.88                    | 50.69  | 59.18                                            | 60.78  | 61.71  | 63.49  | 63.06  | 63.50  | 62.85  |
| 11         | 34.63                    | 51.48  | 58.90                                            | 60.52  | 61.49  | 63.27  | 62.84  | 63.30  | 62.66  |
| 12         | 34.44                    | 52.26  | 58.77                                            | 60.43  | 61.44  | 63.21  | 62.78  | 63.27  | 62.67  |
| 13         | 34.32                    | 52.74  | 58.57                                            | 60.25  | 61.29  | 63.07  | 62.63  | 63.16  | 62.59  |
| 14         | 34.19                    | 52.98  | 58.31                                            | 60.02  | 61.10  | 62.88  | 62.44  | 63.00  | 62.45  |
| 15         | 33.99                    | 53.44  | 58.06                                            | 59.79  | 60.90  | 62.68  | 62.24  | 62.83  | 62.31  |
| 16         | 33.89                    | 53.69  | 57.77                                            | 59.52  | 60.65  | 62.44  | 62.00  | 62.61  | 62.12  |
| 17         | 33.96                    | 53.96  | 57.44                                            | 59.19  | 60.34  | 62.13  | 61.68  | 62.32  | 61.86  |

| Data Point | Gas Flow Meter              |            | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|-----------------------------|------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp.( $^{\circ}\text{C}$ ) | Press.(Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.67                       | 1,119,119  | 19,167                    | 3,988  | 0.00                     | 0.00    | 133.85  |
| 2          | 24.35                       | 1,051,930  | 39,557                    | 4,015  | 0.00                     | 0.00    | 315.67  |
| 3          | 24.30                       | 1,031,590  | 55,443                    | 4,103  | 0.00                     | 0.00    | 457.78  |
| 4          | 24.27                       | 1,013,935  | 72,490                    | 4,227  | 0.00                     | 0.00    | 608.86  |
| 5          | 24.24                       | 1,004,667  | 86,795                    | 4,517  | 0.00                     | 0.00    | 733.79  |
| 6          | 24.21                       | 999,083    | 98,579                    | 4,453  | 0.00                     | 0.00    | 836.84  |
| 7          | 24.19                       | 992,957    | 113,487                   | 4,471  | 0.00                     | 0.00    | 962.24  |
| 8          | 24.18                       | 987,532    | 126,680                   | 4,600  | 0.00                     | 0.00    | 1065.42 |
| 9          | 24.17                       | 984,954    | 138,555                   | 4,673  | 0.00                     | 0.00    | 1153.04 |
| 10         | 24.16                       | 984,367    | 150,730                   | 4,885  | 0.00                     | 0.00    | 1241.82 |
| 11         | 24.14                       | 981,948    | 163,389                   | 5,315  | 0.00                     | 0.00    | 1329.82 |
| 12         | 24.15                       | 981,903    | 174,534                   | 5,681  | 0.00                     | 0.00    | 1404.29 |
| 13         | 24.14                       | 981,948    | 185,491                   | 5,495  | 0.00                     | 0.00    | 1478.67 |
| 14         | 24.14                       | 981,948    | 197,296                   | 5,613  | 0.00                     | 323.60  | 1213.30 |
| 15         | 24.09                       | 981,948    | 210,667                   | 6,180  | 0.00                     | 337.74  | 1277.48 |
| 16         | 24.03                       | 982,445    | 220,632                   | 5,830  | 0.00                     | 349.01  | 1328.83 |
| 17         | 23.96                       | 983,327    | 233,406                   | 6,370  | 0.00                     | 362.00  | 1389.52 |

## Appendix C: Single- and two-phase measured data (continued).

Channel B: Nitrogen gas tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.14 Hyd. Diameter ( $\mu\text{m}$ ): 210.05Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 37.88                    | 44.36  | 62.52                                            | 63.73  | 64.37  | 66.10  | 65.70  | 65.94  | 65.17  |
| 2          | 37.53                    | 47.57  | 63.89                                            | 65.16  | 65.84  | 67.57  | 67.16  | 67.42  | 66.64  |
| 3          | 37.04                    | 49.70  | 64.39                                            | 65.70  | 66.42  | 68.15  | 67.73  | 68.00  | 67.23  |
| 4          | 36.61                    | 51.84  | 64.45                                            | 65.79  | 66.55  | 68.28  | 67.86  | 68.16  | 67.41  |
| 5          | 36.24                    | 52.47  | 64.45                                            | 65.81  | 66.58  | 68.32  | 67.89  | 68.21  | 67.45  |
| 6          | 36.00                    | 54.86  | 64.33                                            | 65.70  | 66.51  | 68.25  | 67.81  | 68.15  | 67.42  |
| 7          | 35.78                    | 55.45  | 64.23                                            | 65.63  | 66.44  | 68.19  | 67.75  | 68.10  | 67.37  |
| 8          | 35.91                    | 55.13  | 64.04                                            | 65.45  | 66.30  | 68.05  | 67.60  | 67.96  | 67.23  |
| 9          | 35.77                    | 55.08  | 63.67                                            | 65.10  | 65.98  | 67.73  | 67.28  | 67.66  | 66.94  |
| 10         | 35.59                    | 55.49  | 63.37                                            | 64.83  | 65.75  | 67.49  | 67.04  | 67.45  | 66.76  |
| 11         | 35.23                    | 55.71  | 63.13                                            | 64.62  | 65.58  | 67.33  | 66.88  | 67.32  | 66.65  |
| 12         | 35.10                    | 55.60  | 62.76                                            | 64.28  | 65.27  | 67.02  | 66.57  | 67.04  | 66.40  |
| 13         | 34.89                    | 55.57  | 62.34                                            | 63.88  | 64.89  | 66.65  | 66.19  | 66.69  | 66.07  |
| 14         | 34.74                    | 55.61  | 61.93                                            | 63.49  | 64.55  | 66.30  | 65.84  | 66.36  | 65.76  |
| 15         | 34.54                    | 55.61  | 61.58                                            | 63.16  | 64.24  | 66.00  | 65.54  | 66.07  | 65.50  |
| 16         | 34.28                    | 55.58  | 61.19                                            | 62.79  | 63.90  | 65.66  | 65.20  | 65.76  | 65.21  |
| 17         | 33.96                    | 55.46  | 60.61                                            | 62.24  | 63.39  | 65.15  | 64.68  | 65.28  | 64.76  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.84                        | 1,073,704   | 12,962                    | 3,653  | 0.00                     | 94.98   | 0.00    |
| 2          | 23.84                        | 935,845     | 26,614                    | 3,663  | 0.00                     | 227.52  | 0.00    |
| 3          | 23.83                        | 906,106     | 41,782                    | 3,734  | 0.00                     | 358.57  | 0.00    |
| 4          | 23.79                        | 895,074     | 56,675                    | 3,850  | 0.00                     | 0.00    | 458.12  |
| 5          | 23.79                        | 885,535     | 71,983                    | 3,979  | 0.00                     | 0.00    | 558.73  |
| 6          | 23.79                        | 880,991     | 86,736                    | 4,092  | 0.00                     | 0.00    | 644.17  |
| 7          | 23.79                        | 877,103     | 101,895                   | 4,137  | 0.00                     | 0.00    | 715.23  |
| 8          | 23.79                        | 871,723     | 122,310                   | 4,311  | 0.00                     | 0.00    | 764.32  |
| 9          | 23.81                        | 870,253     | 147,672                   | 4,413  | 0.00                     | 0.00    | 812.20  |
| 10         | 23.81                        | 867,744     | 171,121                   | 4,551  | 0.00                     | 0.00    | 843.05  |
| 11         | 23.83                        | 866,772     | 194,782                   | 4,589  | 0.00                     | 0.00    | 874.12  |
| 12         | 23.83                        | 864,466     | 193,823                   | 4,842  | 0.00                     | 0.00    | 960.88  |
| 13         | 23.82                        | 864,737     | 212,704                   | 5,321  | 0.00                     | 0.00    | 984.45  |
| 14         | 23.84                        | 861,980     | 236,706                   | 5,129  | 0.00                     | 215.20  | 803.93  |
| 15         | 23.86                        | 861,414     | 256,502                   | 5,224  | 0.00                     | 218.51  | 821.38  |
| 16         | 23.86                        | 861,980     | 278,778                   | 5,550  | 0.00                     | 221.43  | 837.81  |
| 17         | 23.90                        | 871,632     | 308,348                   | 5,816  | 0.00                     | 224.42  | 856.46  |

## Appendix C: Single- and two-phase measured data (continued).

Channel B: Water tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.14      Hyd. Diameter ( $\mu\text{m}$ ): 210.05Width ( $\mu\text{m}$ ): 208.97      Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 24.33                    | 41.75  | 41.46                                            | 45.41  | 49.01  | 51.39  | 50.05  | 52.37  | 53.11  |
| 2          | 25.03                    | 39.39  | 38.67                                            | 42.12  | 45.35  | 47.75  | 46.43  | 48.35  | 48.90  |
| 3          | 24.57                    | 35.43  | 35.37                                            | 38.41  | 41.21  | 43.67  | 42.39  | 43.83  | 43.98  |
| 4          | 25.14                    | 35.17  | 35.31                                            | 38.94  | 42.16  | 44.85  | 43.31  | 44.92  | 45.15  |
| 5          | 25.57                    | 35.20  | 36.27                                            | 40.16  | 43.61  | 46.55  | 44.69  | 46.16  | 45.84  |
| 6          | 25.78                    | 35.75  | 36.92                                            | 41.04  | 44.49  | 47.76  | 45.65  | 47.25  | 46.97  |
| 7          | 26.47                    | 36.84  | 37.63                                            | 41.77  | 45.53  | 49.18  | 46.71  | 48.57  | 48.68  |
| 8          | 26.64                    | 37.82  | 37.89                                            | 41.38  | 45.76  | 49.62  | 46.73  | 49.07  | 49.87  |
| 9          | 27.65                    | 38.99  | 38.40                                            | 41.87  | 46.61  | 50.83  | 47.50  | 49.43  | 49.29  |
| 10         | 27.80                    | 39.94  | 39.04                                            | 42.64  | 47.60  | 52.17  | 48.38  | 50.16  | 50.44  |
| 11         | 28.14                    | 39.46  | 38.51                                            | 41.92  | 46.77  | 51.29  | 47.51  | 49.21  | 49.65  |
| 12         | 27.98                    | 40.27  | 39.10                                            | 42.60  | 47.88  | 52.75  | 48.44  | 50.34  | 51.08  |
| 13         | 28.00                    | 39.82  | 38.70                                            | 42.09  | 47.34  | 52.21  | 47.88  | 49.75  | 50.54  |
| 14         | 28.26                    | 39.24  | 38.15                                            | 41.43  | 46.58  | 51.38  | 47.11  | 48.95  | 49.76  |
| 15         | 28.16                    | 38.78  | 37.72                                            | 40.97  | 46.07  | 50.87  | 46.60  | 48.39  | 49.24  |
| 16         | 28.13                    | 39.62  | 38.42                                            | 41.95  | 47.53  | 52.73  | 47.93  | 49.87  | 50.86  |
| 17         | 28.12                    | 39.05  | 37.91                                            | 41.37  | 46.89  | 52.09  | 47.30  | 49.19  | 50.20  |
| 18         | 28.14                    | 38.85  | 37.75                                            | 41.18  | 46.67  | 51.88  | 47.08  | 48.95  | 49.98  |
| 19         | 29.47                    | 40.02  | 38.81                                            | 42.55  | 48.65  | 54.32  | 48.92  | 51.29  | 53.98  |
| 20         | 29.32                    | 39.51  | 38.35                                            | 41.96  | 47.81  | 53.53  | 48.10  | 49.99  | 51.35  |
| 21         | 29.33                    | 38.98  | 37.94                                            | 41.38  | 47.11  | 52.81  | 47.41  | 49.23  | 50.64  |
| 22         | 29.37                    | 38.59  | 37.54                                            | 40.93  | 46.59  | 52.28  | 46.90  | 48.68  | 50.13  |
| 23         | 29.62                    | 38.18  | 37.17                                            | 40.44  | 46.02  | 51.70  | 46.36  | 48.08  | 49.59  |
| 24         | 29.60                    | 37.58  | 36.43                                            | 39.61  | 45.03  | 50.68  | 45.39  | 47.15  | 48.78  |
| 25         | 29.62                    | 37.18  | 35.86                                            | 38.91  | 44.32  | 49.93  | 44.61  | 46.52  | 48.26  |
| 26         | 29.55                    | 36.95  | 35.44                                            | 38.43  | 43.79  | 49.31  | 43.97  | 46.00  | 47.88  |
| 27         | 29.59                    | 36.45  | 34.77                                            | 37.69  | 42.94  | 48.43  | 43.04  | 45.17  | 47.23  |
| 28         | 29.58                    | 36.11  | 34.31                                            | 37.17  | 42.31  | 47.81  | 42.40  | 44.59  | 46.77  |
| 29         | 29.80                    | 35.67  | 33.90                                            | 36.60  | 41.56  | 47.03  | 41.64  | 43.87  | 46.15  |
| 30         | 29.73                    | 35.23  | 33.56                                            | 36.12  | 40.93  | 46.33  | 40.91  | 43.18  | 45.54  |
| 31         | 29.67                    | 34.87  | 33.33                                            | 35.77  | 40.49  | 45.80  | 40.41  | 42.55  | 45.06  |
| 32         | 28.37                    | 34.61  | 33.14                                            | 35.40  | 39.93  | 45.33  | 39.84  | 42.13  | 44.73  |
| 33         | 28.30                    | 34.00  | 32.81                                            | 34.79  | 39.06  | 44.43  | 38.97  | 41.15  | 43.85  |
| 34         | 27.75                    | 34.41  | 33.38                                            | 35.83  | 40.76  | 45.91  | 41.26  | 43.56  | 43.65  |
| 35         | 27.89                    | 34.07  | 33.19                                            | 35.46  | 40.24  | 45.38  | 40.78  | 42.97  | 43.11  |
| 36         | 27.98                    | 33.82  | 33.05                                            | 35.18  | 39.88  | 45.01  | 40.43  | 42.58  | 42.75  |
| 37         | 28.03                    | 33.64  | 32.96                                            | 35.01  | 39.66  | 44.80  | 40.21  | 42.34  | 42.59  |
| 38         | 28.03                    | 33.46  | 32.81                                            | 34.77  | 39.37  | 44.53  | 39.93  | 42.02  | 42.27  |
| 39         | 28.03                    | 33.29  | 32.68                                            | 34.57  | 39.12  | 44.28  | 39.69  | 41.76  | 42.05  |



# Appendix C: Single- and two-phase measured data (continued).

## Channel B: Water tests (continued).

| Data Point | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | liquid Flow Rate   |
|------------|-------------------|------------|---------------------------|---------|--------------------|
|            | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F. M. #1, (cc/min) |
| 1          | 23.19             | 2,718,923  | 120,945                   | 92,025  | 10.20              |
| 2          | 23.83             | 2,832,133  | 141,322                   | 95,025  | 14.60              |
| 3          | 24.49             | 2,882,114  | 175,076                   | 96,131  | 20.02              |
| 4          | 25.48             | 2,881,159  | 204,380                   | 95,834  | 27.64              |
| 5          | 26.33             | 2,859,915  | 238,189                   | 95,211  | 35.26              |
| 6          | 26.93             | 2,861,317  | 271,921                   | 95,667  | 42.95              |
| 7          | 27.40             | 2,888,037  | 310,186                   | 96,413  | 48.53              |
| 8          | 27.60             | 2,885,550  | 342,784                   | 96,359  | 50.37              |
| 9          | 27.78             | 2,910,552  | 376,450                   | 97,198  | 54.76              |
| 10         | 27.89             | 2,926,082  | 411,448                   | 97,763  | 57.96              |
| 11         | 27.98             | 2,936,933  | 446,119                   | 98,084  | 60.27              |
| 12         | 28.03             | 2,937,453  | 489,752                   | 98,228  | 64.86              |
| 13         | 28.06             | 2,887,788  | 521,176                   | 96,696  | 67.13              |
| 14         | 28.11             | 2,891,247  | 554,696                   | 97,080  | 70.98              |
| 15         | 28.13             | 2,885,120  | 590,714                   | 96,850  | 74.28              |
| 16         | 28.17             | 2,886,545  | 616,154                   | 97,033  | 75.17              |
| 17         | 28.20             | 2,891,224  | 661,508                   | 97,421  | 80.48              |
| 18         | 28.23             | 2,864,459  | 682,475                   | 96,707  | 81.45              |
| 19         | 29.29             | 2,874,292  | 762,331                   | 97,525  | 89.72              |
| 20         | 29.42             | 2,885,731  | 839,959                   | 98,323  | 96.44              |
| 21         | 29.49             | 2,871,308  | 907,709                   | 98,339  | 100.54             |
| 22         | 29.54             | 2,860,277  | 967,704                   | 98,176  | 105.57             |
| 23         | 29.58             | 2,833,941  | 1,030,797                 | 97,670  | 110.11             |
| 24         | 29.65             | 2,813,076  | 1,140,276                 | 97,749  | 117.52             |
| 25         | 29.70             | 2,795,353  | 1,243,946                 | 97,749  | 124.02             |
| 26         | 29.88             | 2,751,272  | 1,326,162                 | 96,786  | 130.06             |
| 27         | 29.94             | 2,744,626  | 1,450,584                 | 97,290  | 140.99             |
| 28         | 29.94             | 2,709,474  | 1,534,813                 | 96,843  | 148.58             |
| 29         | 29.93             | 2,675,995  | 1,633,758                 | 96,488  | 154.87             |
| 30         | 29.94             | 2,712,142  | 1,766,363                 | 98,378  | 165.15             |
| 31         | 29.93             | 2,670,935  | 1,855,684                 | 98,470  | 178.25             |
| 32         | 29.93             | 2,657,029  | 1,958,918                 | 98,296  | 185.20             |
| 33         | 29.92             | 2,673,418  | 2,175,594                 | 100,729 | 205.77             |
| 34         | 29.24             | 4,135,622  | 2,084,419                 | 103,394 | 134.52             |
| 35         | 29.45             | 4,128,049  | 2,424,228                 | 104,280 | 147.70             |
| 36         | 29.64             | 4,093,959  | 2,777,329                 | 104,737 | 161.82             |
| 37         | 29.78             | 4,037,332  | 3,092,294                 | 104,775 | 172.04             |
| 38         | 29.86             | 4,011,449  | 3,445,213                 | 104,673 | 181.40             |
| 39         | 29.93             | 4,009,640  | 3,811,290                 | 105,510 | 192.81             |

# Appendix C: Single- and two-phase measured data (continued).

Channel B: Water and argon tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.14 Hyd. Diameter ( $\mu\text{m}$ ): 210.05

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 28.71                    | 50.87  | 46.87                                            | 52.31  | 56.80  | 59.35  | 57.71  | 60.45  | 60.99  |
| 2          | 29.09                    | 54.08  | 46.92                                            | 52.42  | 57.11  | 59.65  | 57.96  | 61.02  | 61.87  |
| 3          | 29.29                    | 54.03  | 45.81                                            | 50.91  | 55.65  | 58.19  | 56.45  | 59.69  | 60.84  |
| 4          | 29.51                    | 53.99  | 45.84                                            | 50.80  | 55.55  | 58.07  | 56.33  | 59.52  | 60.46  |
| 5          | 29.93                    | 53.78  | 46.08                                            | 50.88  | 55.55  | 58.08  | 56.32  | 59.40  | 60.04  |
| 6          | 29.01                    | 49.63  | 41.82                                            | 46.04  | 50.57  | 53.15  | 51.39  | 54.54  | 55.45  |
| 7          | 27.44                    | 39.30  | 37.78                                            | 42.68  | 47.10  | 50.23  | 48.01  | 50.27  | 50.75  |
| 8          | 28.08                    | 41.49  | 36.73                                            | 40.35  | 44.38  | 47.56  | 45.37  | 47.65  | 48.99  |
| 9          | 28.33                    | 40.08  | 35.34                                            | 38.43  | 42.36  | 45.46  | 43.26  | 45.59  | 46.97  |
| 10         | 28.37                    | 40.17  | 35.19                                            | 38.18  | 42.17  | 45.23  | 42.99  | 45.50  | 46.91  |
| 11         | 28.09                    | 40.52  | 35.31                                            | 38.27  | 42.38  | 45.42  | 43.13  | 45.85  | 47.29  |
| 12         | 28.04                    | 39.62  | 34.54                                            | 37.20  | 41.24  | 44.26  | 41.94  | 44.74  | 46.30  |
| 13         | 28.54                    | 38.89  | 36.75                                            | 39.60  | 44.13  | 48.21  | 44.87  | 47.11  | 48.95  |
| 14         | 28.95                    | 40.36  | 36.60                                            | 39.62  | 44.28  | 48.35  | 44.96  | 47.50  | 49.56  |
| 15         | 28.67                    | 40.08  | 36.15                                            | 38.98  | 43.66  | 47.70  | 44.28  | 46.92  | 49.00  |
| 16         | 28.62                    | 39.78  | 35.63                                            | 38.17  | 42.91  | 46.91  | 43.42  | 46.33  | 48.57  |
| 17         | 28.55                    | 39.78  | 35.27                                            | 37.69  | 42.40  | 46.36  | 42.84  | 45.92  | 48.32  |
| 18         | 28.41                    | 40.02  | 35.13                                            | 37.58  | 42.32  | 46.24  | 42.67  | 45.89  | 48.42  |
| 19         | 29.04                    | 38.12  | 36.29                                            | 38.33  | 43.90  | 49.44  | 44.19  | 47.00  | 50.43  |
| 20         | 29.11                    | 39.40  | 36.43                                            | 38.60  | 44.36  | 49.90  | 44.51  | 47.64  | 51.16  |
| 21         | 28.91                    | 40.04  | 36.47                                            | 38.68  | 44.43  | 49.96  | 44.41  | 47.74  | 51.56  |
| 22         | 28.89                    | 39.96  | 36.29                                            | 38.40  | 43.92  | 49.33  | 43.56  | 46.93  | 51.06  |
| 23         | 25.92                    | 34.31  | 31.46                                            | 33.76  | 37.55  | 41.42  | 38.38  | 35.55  | 42.56  |
| 24         | 26.37                    | 31.79  | 30.76                                            | 32.33  | 35.58  | 37.00  | 36.59  | 35.74  | 40.44  |
| 25         | 26.53                    | 31.90  | 30.67                                            | 32.18  | 35.32  | 39.22  | 36.23  | 33.08  | 40.37  |
| 26         | 25.42                    | 35.31  | 33.48                                            | 36.16  | 41.10  | 45.58  | 41.84  | 38.48  | 44.86  |
| 27         | 25.77                    | 36.33  | 33.95                                            | 36.62  | 41.74  | 46.11  | 42.23  | 39.49  | 45.83  |
| 28         | 26.71                    | 37.46  | 34.81                                            | 37.57  | 42.48  | 46.96  | 43.23  | 40.87  | 47.17  |
| 29         | 27.09                    | 40.15  | 40.48                                            | 44.69  | 50.16  | 53.35  | 50.01  | 50.10  | 54.66  |
| 30         | 27.80                    | 36.21  | 34.29                                            | 37.45  | 42.98  | 48.22  | 43.41  | 46.20  | 46.85  |
| 31         | 27.78                    | 36.26  | 34.23                                            | 37.39  | 42.93  | 48.16  | 43.35  | 46.15  | 46.84  |
| 32         | 27.75                    | 36.58  | 34.30                                            | 37.55  | 43.18  | 48.41  | 43.58  | 46.43  | 47.15  |
| 33         | 27.68                    | 36.78  | 34.29                                            | 37.60  | 43.27  | 48.48  | 43.65  | 46.55  | 47.29  |
| 34         | 27.62                    | 37.13  | 34.40                                            | 37.79  | 43.55  | 48.78  | 43.89  | 46.87  | 47.62  |
| 35         | 27.99                    | 37.44  | 34.68                                            | 38.01  | 43.72  | 48.92  | 44.07  | 47.05  | 47.83  |
| 36         | 27.94                    | 37.77  | 34.75                                            | 38.17  | 43.96  | 49.13  | 44.29  | 47.35  | 48.13  |
| 37         | 27.85                    | 37.78  | 34.71                                            | 38.18  | 43.99  | 49.14  | 44.31  | 47.40  | 48.17  |
| 38         | 27.77                    | 37.94  | 34.73                                            | 38.27  | 44.13  | 49.26  | 44.43  | 47.59  | 48.37  |

## Appendix C: Single- and two-phase measured data (continued).

## Channel B: Water and argon (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press.. (Pa) |          | Flow Meter/Flow rates. (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|----------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet   | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.87          | 2,154,550  | 24.71             | 2,441,499  | 145,400                   | 103188.2 | 0.00                            | 0.00    | 64.36   | 8.86    |
| 2          | 24.88          | 2,065,800  | 24.74             | 2,403,950  | 261,073                   | 114371.2 | 0.00                            | 0.00    | 294.24  | 8.06    |
| 3          | 24.87          | 2,029,947  | 24.77             | 2,397,485  | 402,607                   | 125479.6 | 0.00                            | 0.00    | 419.11  | 8.06    |
| 4          | 24.87          | 2,014,756  | 24.84             | 2,399,000  | 548,934                   | 136425.3 | 0.00                            | 0.00    | 505.95  | 8.06    |
| 5          | 24.86          | 2,014,010  | 24.83             | 2,383,967  | 666,845                   | 145203.1 | 0.00                            | 122.57  | 455.49  | 8.06    |
| 6          | 24.86          | 2,018,486  | 24.86             | 2,379,762  | 847,917                   | 153741.2 | 0.00                            | 125.61  | 475.69  | 8.51    |
| 7          | 24.82          | 2,185,814  | 26.45             | 2,408,539  | 270,409                   | 106038.7 | 0.00                            | 0.00    | 50.37   | 34.59   |
| 8          | 25.31          | 2,068,558  | 27.22             | 2,403,476  | 456,680                   | 115250.6 | 0.00                            | 0.00    | 216.18  | 33.47   |
| 9          | 25.33          | 2,028,636  | 27.45             | 2,365,182  | 674,441                   | 126413.2 | 0.00                            | 0.00    | 300.23  | 34.66   |
| 10         | 25.33          | 2,009,241  | 27.57             | 2,387,494  | 843,531                   | 138430.4 | 0.00                            | 0.00    | 379.40  | 32.70   |
| 11         | 25.34          | 2,006,505  | 27.61             | 2,378,994  | 963,906                   | 147447.8 | 0.00                            | 94.91   | 353.06  | 30.70   |
| 12         | 25.39          | 2,010,100  | 27.66             | 2,384,736  | 1,121,129                 | 155549.7 | 0.00                            | 101.54  | 384.39  | 31.60   |
| 13         | 25.36          | 2,192,618  | 28.61             | 2,398,751  | 527,571                   | 107248.1 | 0.00                            | 32.92   | 0.00    | 63.81   |
| 14         | 25.38          | 2,053,389  | 28.70             | 2,396,174  | 712,870                   | 117551.8 | 0.00                            | 0.00    | 160.18  | 60.69   |
| 15         | 25.42          | 2,033,836  | 28.67             | 2,417,288  | 903,300                   | 130816.8 | 0.00                            | 0.00    | 245.29  | 58.44   |
| 16         | 25.44          | 2,012,496  | 28.66             | 2,380,938  | 1,087,040                 | 140731.7 | 0.00                            | 0.00    | 313.26  | 59.45   |
| 17         | 25.45          | 2,007,183  | 28.60             | 2,381,706  | 1,221,204                 | 149651.9 | 0.00                            | 79.05   | 293.97  | 57.58   |
| 18         | 25.45          | 2,007,274  | 28.51             | 2,388,353  | 1,320,262                 | 159731.8 | 0.00                            | 91.01   | 345.18  | 53.60   |
| 19         | 25.37          | 2,190,629  | 29.08             | 2,372,958  | 1,007,987                 | 108448.5 | 0.00                            | 0.00    | 22.04   | 105.46  |
| 20         | 25.37          | 2,070,118  | 29.10             | 2,328,244  | 1,130,691                 | 119342.2 | 0.00                            | 0.00    | 112.70  | 97.16   |
| 21         | 25.39          | 2,032,728  | 29.07             | 2,328,131  | 1,235,921                 | 132080.5 | 0.00                            | 0.00    | 197.08  | 91.10   |
| 22         | 25.39          | 2,012,699  | 28.98             | 2,283,960  | 1,284,930                 | 141111.5 | 0.00                            | 0.00    | 276.96  | 88.01   |
| 23         | 24.50          | 1,938,349  | 27.51             | 2,131,891  | 1,705,260                 | 154107.5 | 0.00                            | 61.68   | 230.12  | 86.16   |
| 24         | 24.42          | 1,905,842  | 28.15             | 2,100,786  | 1,583,347                 | 105955.1 | 0.00                            | 18.58   | 0.00    | 130.09  |
| 25         | 24.40          | 1,919,948  | 28.31             | 2,050,488  | 1,726,125                 | 119536.6 | 0.00                            | 18.09   | 63.33   | 129.17  |
| 26         | 23.52          | 2,746,706  | 27.10             | 1,950,955  | 1,203,911                 | 109350.5 | 0.00                            | 18.86   | 0.00    | 86.08   |
| 27         | 23.57          | 2,722,359  | 27.38             | 1,927,739  | 1,251,428                 | 114583.7 | 0.00                            | 73.78   | 0.00    | 80.18   |
| 28         | 24.24          | 2,685,286  | 28.20             | 1,885,467  | 1,243,335                 | 120897.5 | 0.00                            | 0.00    | 127.67  | 78.76   |
| 29         | 24.21          | 2,646,337  | 28.28             | 1,850,043  | 927,217                   | 296229.4 | 0.00                            | 0.00    | 269.74  | 111.88  |
| 30         | 24.06          | 4,016,783  | 29.04             | 4,060,111  | 1,617,725                 | 118679.8 | 0.00                            | 0.00    | 87.55   | 100.89  |
| 31         | 24.10          | 3,985,090  | 29.02             | 4,072,092  | 1,700,982                 | 122075.2 | 0.00                            | 0.00    | 107.52  | 101.57  |
| 32         | 24.08          | 3,980,795  | 28.94             | 4,014,538  | 1,760,412                 | 126033.5 | 0.00                            | 0.00    | 139.63  | 98.78   |
| 33         | 24.04          | 3,985,113  | 28.84             | 3,966,003  | 1,826,692                 | 129135   | 0.00                            | 0.00    | 164.99  | 96.70   |
| 34         | 24.01          | 3,944,739  | 28.75             | 3,930,738  | 1,919,059                 | 134065.3 | 0.00                            | 0.00    | 214.33  | 93.43   |
| 35         | 24.50          | 3,952,199  | 29.18             | 3,927,438  | 2,014,342                 | 136549.6 | 0.00                            | 0.00    | 211.35  | 93.67   |
| 36         | 24.49          | 3,970,171  | 29.10             | 3,854,489  | 2,109,150                 | 141186.1 | 0.00                            | 53.38   | 179.01  | 90.27   |
| 37         | 24.51          | 3,953,013  | 29.01             | 3,840,135  | 2,196,136                 | 145564.8 | 0.00                            | 58.00   | 196.37  | 89.52   |
| 38         | 24.52          | 3,943,699  | 28.92             | 3,836,224  | 2,271,843                 | 150131.1 | 0.00                            | 62.38   | 214.19  | 87.63   |

# Appendix C: Single- and two-phase measured data (continued).

Channel B: Water and helium tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.14 Hyd. Diameter ( $\mu\text{m}$ ): 210.05

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 24.95                    | 40.90  | 38.12                                            | 42.63  | 46.29  | 48.98  | 47.51  | 49.86  | 50.15  |
| 2          | 25.15                    | 42.90  | 38.45                                            | 43.05  | 46.80  | 49.41  | 48.00  | 50.45  | 50.58  |
| 3          | 25.09                    | 43.68  | 38.20                                            | 42.61  | 46.50  | 49.09  | 47.64  | 50.33  | 50.69  |
| 4          | 25.19                    | 43.53  | 38.30                                            | 42.38  | 46.15  | 48.73  | 47.27  | 49.93  | 50.29  |
| 5          | 24.02                    | 34.55  | 34.70                                            | 38.87  | 42.43  | 45.43  | 43.66  | 45.45  | 45.17  |
| 6          | 24.40                    | 37.14  | 34.84                                            | 39.33  | 43.19  | 46.18  | 44.39  | 46.37  | 46.35  |
| 7          | 24.63                    | 39.45  | 35.45                                            | 39.70  | 43.57  | 46.51  | 44.68  | 46.93  | 47.29  |
| 8          | 25.17                    | 42.44  | 37.14                                            | 41.45  | 45.56  | 48.46  | 46.58  | 49.34  | 49.86  |
| 9          | 24.57                    | 34.26  | 34.58                                            | 38.46  | 42.10  | 45.59  | 43.23  | 44.14  | 44.59  |
| 10         | 24.96                    | 37.00  | 34.90                                            | 38.88  | 42.62  | 46.10  | 43.73  | 45.17  | 46.07  |
| 11         | 25.23                    | 40.22  | 36.28                                            | 40.54  | 44.72  | 48.17  | 45.73  | 47.86  | 48.89  |
| 12         | 25.52                    | 44.60  | 38.73                                            | 43.63  | 48.58  | 51.96  | 49.39  | 52.26  | 53.34  |
| 13         | 25.13                    | 34.21  | 33.75                                            | 36.47  | 39.79  | 43.52  | 40.95  | 42.36  | 43.27  |
| 14         | 25.40                    | 35.71  | 34.01                                            | 37.09  | 40.76  | 44.48  | 41.88  | 43.57  | 44.62  |
| 15         | 25.56                    | 37.32  | 34.54                                            | 38.01  | 42.02  | 45.71  | 43.06  | 45.04  | 46.07  |
| 16         | 23.67                    | 31.90  | 32.00                                            | 34.96  | 39.25  | 44.29  | 40.05  | 41.39  | 42.24  |
| 17         | 24.08                    | 32.62  | 32.46                                            | 35.49  | 39.85  | 44.92  | 40.63  | 41.99  | 42.88  |
| 18         | 24.38                    | 33.12  | 32.79                                            | 35.87  | 40.28  | 45.36  | 41.06  | 42.45  | 43.35  |
| 19         | 24.55                    | 33.45  | 32.92                                            | 36.01  | 40.47  | 45.54  | 41.22  | 42.65  | 43.63  |
| 20         | 24.69                    | 33.63  | 33.05                                            | 36.15  | 40.65  | 45.71  | 41.38  | 42.83  | 43.82  |
| 21         | 24.91                    | 32.56  | 32.93                                            | 35.59  | 40.03  | 45.50  | 40.75  | 41.95  | 43.14  |
| 22         | 25.08                    | 32.65  | 32.86                                            | 35.49  | 39.94  | 45.39  | 40.65  | 41.85  | 43.08  |
| 23         | 25.11                    | 32.85  | 32.94                                            | 35.63  | 40.15  | 45.61  | 40.84  | 42.07  | 43.31  |
| 24         | 25.16                    | 33.09  | 33.04                                            | 35.80  | 40.40  | 45.85  | 41.06  | 42.33  | 43.58  |
| 25         | 25.09                    | 33.22  | 33.04                                            | 35.85  | 40.50  | 45.95  | 41.14  | 42.45  | 43.71  |
| 26         | 25.21                    | 31.98  | 32.52                                            | 34.83  | 39.14  | 44.61  | 39.89  | 40.93  | 42.22  |
| 27         | 25.26                    | 32.16  | 32.56                                            | 34.91  | 39.27  | 44.75  | 40.00  | 41.07  | 42.39  |
| 28         | 25.28                    | 32.25  | 32.57                                            | 34.94  | 39.33  | 44.80  | 40.04  | 41.14  | 42.46  |
| 29         | 25.24                    | 32.33  | 32.56                                            | 35.01  | 39.45  | 44.91  | 40.14  | 41.29  | 42.62  |
| 30         | 25.20                    | 32.27  | 32.48                                            | 34.92  | 39.37  | 44.82  | 40.05  | 41.21  | 42.54  |

## Appendix C: Single- and two-phase measured data (continued).

Channel A: Water and helium (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 23.36          | 1,016,919  | 23.64             | 1,208,652  | 251,414                   | 111,249 | 0.00                            | 55.58   | 0.00    | 15.54   |
| 2          | 23.41          | 988,797    | 23.70             | 1,185,549  | 370,659                   | 124,449 | 0.00                            | 0.00    | 298.01  | 11.54   |
| 3          | 23.45          | 984,683    | 23.69             | 1,171,805  | 518,229                   | 140,960 | 0.00                            | 0.00    | 521.33  | 12.47   |
| 4          | 23.46          | 979,122    | 23.66             | 1,151,392  | 670,297                   | 156,386 | 0.03                            | 152.05  | 583.36  | 10.93   |
| 5          | 23.42          | 1,025,080  | 24.09             | 1,064,134  | 388,630                   | 103,195 | 0.00                            | 42.68   | 0.00    | 32.95   |
| 6          | 23.44          | 994,358    | 24.46             | 1,048,875  | 504,190                   | 115,404 | 0.00                            | 0.00    | 254.98  | 28.05   |
| 7          | 23.48          | 985,497    | 24.62             | 1,039,426  | 631,686                   | 131,113 | 0.00                            | 0.00    | 471.80  | 22.84   |
| 8          | 23.51          | 981,292    | 24.63             | 1,041,416  | 770,644                   | 145,126 | 0.00                            | 135.39  | 517.73  | 15.33   |
| 9          | 23.49          | 1,031,590  | 25.72             | 970,140    | 587,221                   | 97,399  | 0.00                            | 31.73   | 0.00    | 50.20   |
| 10         | 23.46          | 997,320    | 25.89             | 974,164    | 687,251                   | 110,499 | 0.00                            | 0.00    | 207.04  | 41.76   |
| 11         | 23.46          | 988,278    | 25.90             | 987,388    | 791,011                   | 127,424 | 0.01                            | 0.01    | 406.06  | 32.90   |
| 12         | 23.43          | 987,712    | 25.75             | 1,004,365  | 892,420                   | 142,459 | 0.08                            | 124.20  | 475.82  | 21.44   |
| 13         | 23.40          | 1,208,050  | 26.53             | 1,348,333  | 812,668                   | 96,176  | 0.00                            | 26.29   | 0.00    | 61.57   |
| 14         | 23.41          | 1,157,323  | 26.64             | 1,370,215  | 916,563                   | 111,652 | 0.00                            | 0.00    | 164.45  | 55.23   |
| 15         | 23.40          | 1,134,220  | 26.62             | 1,396,687  | 1,036,306                 | 129,305 | 0.00                            | 0.00    | 326.95  | 47.59   |
| 16         | 22.45          | 4,589,069  | 25.00             | 3,803,988  | 1,499,926                 | 117,889 | 0.00                            | 0.00    | 65.19   | 105.87  |
| 17         | 22.51          | 4,145,161  | 25.49             | 3,822,502  | 1,615,644                 | 130,112 | 0.00                            | 0.00    | 155.62  | 103.02  |
| 18         | 22.48          | 4,110,484  | 25.76             | 3,820,468  | 1,678,330                 | 137,160 | 0.00                            | 0.00    | 216.78  | 101.46  |
| 19         | 22.42          | 4,076,304  | 25.96             | 3,832,358  | 1,842,876                 | 149,623 | 0.00                            | 59.61   | 211.55  | 100.30  |
| 20         | 22.40          | 4,036,315  | 26.07             | 3,850,194  | 1,926,630                 | 156,440 | 0.00                            | 69.51   | 252.23  | 98.16   |
| 21         | 22.32          | 4,208,728  | 26.50             | 3,784,118  | 2,141,882                 | 120,167 | 0.00                            | 0.00    | 59.07   | 128.55  |
| 22         | 22.32          | 4,126,218  | 26.64             | 3,830,573  | 2,346,531                 | 131,974 | 0.00                            | 0.00    | 112.84  | 132.61  |
| 23         | 22.27          | 4,084,917  | 26.68             | 3,828,244  | 2,421,898                 | 140,551 | 0.00                            | 0.00    | 164.54  | 132.26  |
| 24         | 22.25          | 4,084,623  | 26.70             | 3,825,305  | 2,510,128                 | 150,246 | 0.00                            | 45.61   | 161.36  | 127.41  |
| 25         | 22.22          | 4,027,770  | 26.68             | 3,840,655  | 2,600,302                 | 158,172 | 0.00                            | 53.74   | 194.77  | 124.86  |
| 26         | 22.17          | 4,401,057  | 26.94             | 3,774,510  | 2,771,156                 | 121,313 | 0.00                            | 0.00    | 43.44   | 153.17  |
| 27         | 22.24          | 4,083,402  | 26.99             | 3,834,529  | 2,898,607                 | 134,832 | 0.00                            | 0.00    | 99.99   | 154.23  |
| 28         | 22.25          | 4,071,625  | 26.99             | 3,836,721  | 2,981,999                 | 142,117 | 0.00                            | 0.00    | 136.60  | 150.69  |
| 29         | 22.23          | 4,070,517  | 26.97             | 3,847,482  | 3,083,092                 | 153,269 | 0.00                            | 39.14   | 139.29  | 148.14  |
| 30         | 22.21          | 4,029,262  | 26.95             | 3,844,046  | 3,214,341                 | 159,370 | 0.00                            | 43.87   | 159.28  | 149.82  |

Appendix C: Single- and two-phase measured data (continued).

Channel B: Water and nitrogen tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.14 Hyd. Diameter ( $\mu\text{m}$ ): 210.05

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 25.10                    | 38.06  | 36.55                                            | 40.67  | 43.98  | 26.57  | 45.23  | 46.81  | 47.26  |
| 2          | 25.23                    | 40.73  | 36.42                                            | 40.51  | 44.16  | 26.58  | 45.32  | 47.34  | 48.34  |
| 3          | 25.50                    | 42.26  | 36.69                                            | 40.59  | 44.39  | 26.57  | 45.46  | 47.93  | 49.19  |
| 4          | 25.52                    | 42.90  | 37.04                                            | 40.94  | 44.80  | 26.56  | 45.83  | 48.36  | 49.54  |
| 5          | 25.56                    | 42.70  | 36.88                                            | 40.74  | 44.61  | 26.61  | 45.62  | 48.13  | 49.25  |
| 6          | 24.53                    | 32.54  | 32.93                                            | 36.08  | 39.13  | 25.61  | 40.38  | 41.30  | 41.93  |
| 7          | 25.05                    | 36.92  | 33.74                                            | 37.03  | 40.54  | 25.69  | 41.71  | 43.67  | 45.09  |
| 8          | 25.21                    | 38.86  | 34.64                                            | 38.25  | 42.11  | 45.28  | 43.17  | 45.40  | 46.73  |
| 9          | 25.21                    | 40.15  | 35.36                                            | 39.21  | 43.30  | 46.46  | 44.28  | 46.69  | 47.96  |
| 10         | 25.24                    | 41.51  | 36.21                                            | 40.28  | 44.56  | 47.66  | 45.46  | 48.03  | 49.21  |
| 11         | 24.93                    | 33.46  | 32.95                                            | 35.58  | 38.80  | 42.35  | 40.00  | 41.51  | 42.93  |
| 12         | 25.28                    | 36.13  | 33.66                                            | 36.74  | 40.34  | 43.86  | 41.44  | 43.25  | 44.72  |
| 13         | 25.30                    | 38.03  | 34.59                                            | 38.12  | 42.08  | 45.57  | 43.10  | 45.17  | 46.47  |
| 14         | 25.41                    | 39.07  | 35.18                                            | 38.94  | 43.10  | 46.56  | 44.05  | 46.28  | 47.54  |
| 15         | 25.30                    | 33.40  | 33.01                                            | 35.54  | 38.90  | 42.69  | 40.01  | 41.47  | 43.00  |
| 16         | 25.39                    | 35.67  | 33.79                                            | 36.83  | 40.55  | 44.33  | 41.60  | 43.30  | 44.69  |
| 17         | 25.38                    | 37.69  | 34.79                                            | 38.36  | 42.54  | 46.28  | 43.48  | 45.54  | 46.90  |
| 18         | 27.44                    | 35.20  | 35.30                                            | 37.85  | 42.28  | 47.69  | 42.97  | 44.12  | 45.40  |
| 19         | 27.44                    | 35.45  | 35.32                                            | 37.93  | 42.41  | 47.79  | 43.08  | 44.28  | 45.56  |
| 20         | 27.39                    | 35.41  | 35.23                                            | 37.83  | 42.35  | 47.75  | 43.00  | 44.22  | 45.52  |
| 21         | 27.36                    | 35.41  | 35.12                                            | 37.72  | 42.25  | 47.62  | 42.88  | 44.13  | 45.43  |
| 22         | 27.90                    | 35.79  | 34.08                                            | 37.09  | 42.55  | 47.82  | 42.98  | 45.79  | 46.36  |
| 23         | 27.99                    | 36.31  | 34.27                                            | 37.37  | 42.93  | 48.26  | 43.30  | 46.25  | 46.84  |
| 24         | 27.96                    | 36.52  | 34.31                                            | 37.45  | 43.02  | 48.30  | 43.39  | 46.37  | 46.97  |
| 25         | 27.87                    | 36.77  | 34.27                                            | 37.45  | 43.08  | 48.32  | 43.44  | 46.46  | 47.12  |
| 26         | 27.76                    | 37.04  | 34.32                                            | 37.63  | 43.34  | 48.56  | 43.70  | 46.77  | 47.46  |

## Appendix C: Single- and two-phase measured data (continued).

Channel B: Water and nitrogen (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 23.62          | 1,216,369  | 25.43             | 1,326,157  | 237,671                   | 100,731 | 0.00                            | 42.61   | 0.00    | 22.58   |
| 2          | 23.61          | 1,214,990  | 25.39             | 1,315,668  | 415,329                   | 111,249 | 0.00                            | 0.00    | 243.71  | 18.38   |
| 3          | 23.59          | 1,202,195  | 25.30             | 1,309,609  | 589,121                   | 124,105 | 0.00                            | 0.00    | 365.99  | 17.00   |
| 4          | 23.56          | 1,196,883  | 25.16             | 1,316,527  | 671,677                   | 130,966 | 0.00                            | 89.09   | 332.00  | 13.22   |
| 5          | 23.59          | 1,195,526  | 25.06             | 1,332,871  | 787,735                   | 138,657 | 0.00                            | 97.06   | 369.18  | 14.94   |
| 6          | 23.51          | 1,226,722  | 25.67             | 1,323,987  | 415,148                   | 103,952 | 0.00                            | 30.09   | 0.00    | 46.43   |
| 7          | 23.56          | 1,220,754  | 25.92             | 1,308,276  | 629,043                   | 113,361 | 0.00                            | 0.00    | 190.18  | 36.81   |
| 8          | 23.54          | 1,205,270  | 25.94             | 1,319,827  | 785,045                   | 127,168 | 0.00                            | 0.00    | 301.20  | 31.49   |
| 9          | 23.54          | 1,201,200  | 25.89             | 1,323,015  | 865,046                   | 132,942 | 0.00                            | 74.77   | 278.81  | 27.89   |
| 10         | 23.58          | 1,195,798  | 25.83             | 1,334,363  | 952,010                   | 140,680 | 0.00                            | 85.50   | 325.70  | 24.22   |
| 11         | 23.55          | 1,232,916  | 26.49             | 1,305,043  | 623,323                   | 100,561 | 0.00                            | 23.94   | 0.00    | 63.56   |
| 12         | 23.56          | 1,221,885  | 26.60             | 1,294,305  | 793,838                   | 114,147 | 0.00                            | 0.00    | 163.97  | 56.00   |
| 13         | 23.57          | 1,206,083  | 26.54             | 1,302,285  | 930,128                   | 127,681 | 0.00                            | 0.00    | 274.60  | 42.82   |
| 14         | 23.59          | 1,201,472  | 26.45             | 1,314,221  | 993,763                   | 133,758 | 0.00                            | 68.23   | 254.69  | 37.35   |
| 15         | 23.50          | 1,236,126  | 26.88             | 1,298,307  | 802,835                   | 101,701 | 0.00                            | 19.51   | 0.00    | 74.00   |
| 16         | 23.52          | 1,225,343  | 26.86             | 1,294,238  | 928,523                   | 115,339 | 0.00                            | 0.00    | 143.88  | 61.24   |
| 17         | 23.53          | 1,207,281  | 26.70             | 1,301,268  | 1,040,624                 | 128,794 | 0.00                            | 0.00    | 255.47  | 48.91   |
| 18         | 24.24          | 4,288,956  | 29.03             | 3,886,883  | 2,273,764                 | 116,051 | 0.00                            | 0.00    | 42.86   | 135.46  |
| 19         | 24.20          | 3,934,363  | 29.03             | 3,888,262  | 2,379,898                 | 124,435 | 0.00                            | 0.00    | 81.73   | 132.77  |
| 20         | 24.18          | 3,929,661  | 29.01             | 3,885,097  | 2,577,223                 | 131,106 | 0.00                            | 0.00    | 111.28  | 134.30  |
| 21         | 24.15          | 3,905,360  | 29.00             | 3,874,224  | 2,822,291                 | 139,995 | 0.00                            | 30.79   | 106.53  | 131.93  |
| 22         | 23.92          | 4,604,034  | 29.50             | 4,067,186  | 1,447,165                 | 112,454 | 0.00                            | 0.00    | 47.59   | 101.24  |
| 23         | 24.09          | 3,724,741  | 29.48             | 4,083,508  | 1,677,178                 | 125,333 | 0.00                            | 0.00    | 124.06  | 100.68  |
| 24         | 24.08          | 3,711,810  | 29.37             | 4,091,397  | 1,765,928                 | 130,604 | 0.00                            | 0.00    | 152.60  | 99.76   |
| 25         | 24.05          | 3,740,316  | 29.21             | 4,048,898  | 1,926,993                 | 138,076 | 0.00                            | 42.01   | 145.15  | 98.58   |
| 26         | 24.06          | 3,697,885  | 29.01             | 4,015,532  | 2,006,475                 | 144,154 | 0.00                            | 50.57   | 178.35  | 93.37   |

# Appendix C: Single- and two-phase measured data (continued).

Channel C1: Argon gas tests.                      Number of channels:                      5  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):                      134.64                      Hyd. Diameter ( $\mu\text{m}$ ):                      127.92  
Width ( $\mu\text{m}$ ):                      121.83                      Channel Length (m):                      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 32.79                    | 33.37  | 39.13                                            | 39.37  | 39.40  | 41.18  | 41.13  | 41.15  | 40.84  |
| 2          | 32.13                    | 34.42  | 42.01                                            | 42.41  | 42.49  | 44.26  | 44.17  | 44.17  | 43.67  |
| 3          | 31.86                    | 37.64  | 48.79                                            | 49.56  | 49.73  | 51.48  | 51.31  | 51.30  | 50.43  |
| 4          | 31.87                    | 40.47  | 51.56                                            | 52.41  | 52.63  | 54.37  | 54.19  | 54.20  | 53.27  |
| 5          | 31.77                    | 43.86  | 52.51                                            | 53.42  | 53.66  | 55.40  | 55.22  | 55.25  | 54.32  |
| 6          | 31.73                    | 45.13  | 52.92                                            | 53.86  | 54.14  | 55.87  | 55.69  | 55.74  | 54.82  |
| 7          | 31.78                    | 45.10  | 53.18                                            | 54.16  | 54.47  | 56.20  | 56.01  | 56.08  | 55.17  |
| 8          | 31.93                    | 44.51  | 53.47                                            | 54.49  | 54.83  | 56.56  | 56.37  | 56.46  | 55.56  |
| 9          | 31.80                    | 44.57  | 53.61                                            | 54.66  | 55.03  | 56.77  | 56.58  | 56.68  | 55.79  |
| 10         | 31.70                    | 45.10  | 53.68                                            | 54.77  | 55.16  | 56.89  | 56.70  | 56.82  | 55.94  |
| 11         | 31.63                    | 45.55  | 53.66                                            | 54.77  | 55.20  | 56.93  | 56.74  | 56.88  | 56.01  |
| 12         | 31.56                    | 47.79  | 53.50                                            | 54.64  | 55.09  | 56.83  | 56.64  | 56.80  | 55.95  |
| 13         | 31.55                    | 48.69  | 53.32                                            | 54.48  | 54.96  | 56.69  | 56.50  | 56.68  | 55.85  |
| 14         | 31.66                    | 49.09  | 53.11                                            | 54.29  | 54.80  | 56.53  | 56.34  | 56.54  | 55.72  |
| 15         | 31.59                    | 49.30  | 52.98                                            | 54.19  | 54.72  | 56.45  | 56.26  | 56.47  | 55.66  |
| 16         | 31.51                    | 49.51  | 52.76                                            | 53.99  | 54.54  | 56.27  | 56.08  | 56.30  | 55.51  |
| 17         | 31.39                    | 49.52  | 52.46                                            | 53.71  | 54.29  | 56.02  | 55.84  | 56.07  | 55.29  |
| 18         | 31.29                    | 49.46  | 52.06                                            | 53.33  | 53.93  | 55.66  | 55.48  | 55.73  | 54.96  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.78                        | 1,216,866   | 17,972                    | 3,538  | 26.96                    | 0.00    | 0.00    |
| 2          | 23.76                        | 1,184,065   | 62,053                    | 3,520  | 0.00                     | 104.62  | 0.00    |
| 3          | 23.75                        | 1,189,016   | 131,000                   | 3,585  | 0.00                     | 216.51  | 0.00    |
| 4          | 23.65                        | 1,179,137   | 191,674                   | 3,723  | 0.00                     | 295.15  | 0.00    |
| 5          | 23.61                        | 1,184,676   | 270,274                   | 3,997  | 0.00                     | 0.00    | 349.69  |
| 6          | 23.54                        | 1,187,841   | 335,084                   | 4,137  | 0.00                     | 0.00    | 390.93  |
| 7          | 23.49                        | 1,183,387   | 424,716                   | 4,365  | 0.00                     | 0.00    | 407.25  |
| 8          | 23.52                        | 1,181,895   | 510,210                   | 4,551  | 0.00                     | 0.00    | 418.16  |
| 9          | 23.50                        | 1,178,708   | 591,568                   | 4,700  | 0.00                     | 0.00    | 432.75  |
| 10         | 23.50                        | 1,175,000   | 673,152                   | 4,994  | 0.00                     | 0.00    | 446.74  |
| 11         | 23.51                        | 1,178,550   | 739,952                   | 5,240  | 0.00                     | 0.00    | 458.40  |
| 12         | 23.54                        | 1,177,012   | 824,339                   | 5,561  | 0.00                     | 0.00    | 471.21  |
| 13         | 23.60                        | 1,178,595   | 895,682                   | 5,875  | 0.00                     | 0.00    | 480.14  |
| 14         | 23.64                        | 1,425,313   | 976,226                   | 6,006  | 0.00                     | 0.00    | 487.01  |
| 15         | 23.64                        | 1,427,687   | 1,033,826                 | 6,352  | 0.00                     | 105.73  | 393.36  |
| 16         | 23.64                        | 1,431,259   | 1,113,850                 | 6,264  | 0.00                     | 106.32  | 398.19  |
| 17         | 23.63                        | 1,430,496   | 1,195,616                 | 6,647  | 0.00                     | 106.49  | 401.29  |
| 18         | 23.68                        | 1,427,777   | 1,288,298                 | 6,958  | 0.00                     | 106.62  | 404.40  |



## Appendix C: Single- and two-phase measured data (continued).

Channel C1: Helium gas tests.      Number of channels:      5  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):      134.64      Hyd. Diameter ( $\mu\text{m}$ ):      127.92  
Width ( $\mu\text{m}$ ):      121.83      Channel Length (m):      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 31.14                    | 30.87  | 43.55                                            | 44.68  | 45.06  | 40.68  | 46.63  | 46.64  | 45.50  |
| 2          | 32.10                    | 32.83  | 47.44                                            | 48.64  | 49.02  | 44.61  | 50.56  | 50.57  | 49.41  |
| 3          | 30.43                    | 32.60  | 39.35                                            | 39.91  | 40.09  | 35.88  | 41.78  | 41.84  | 41.34  |
| 4          | 31.02                    | 37.20  | 46.55                                            | 47.66  | 48.03  | 43.73  | 49.58  | 49.63  | 48.61  |
| 5          | 31.81                    | 39.21  | 49.89                                            | 51.11  | 51.52  | 47.34  | 53.05  | 53.12  | 52.04  |
| 6          | 32.73                    | 40.59  | 51.38                                            | 52.62  | 53.03  | 54.76  | 54.55  | 54.62  | 53.54  |
| 7          | 33.05                    | 41.73  | 52.57                                            | 53.87  | 54.32  | 56.05  | 55.84  | 55.93  | 54.84  |
| 8          | 33.58                    | 42.98  | 53.25                                            | 54.57  | 55.03  | 56.77  | 56.55  | 56.65  | 55.56  |
| 9          | 33.89                    | 43.89  | 53.73                                            | 55.08  | 55.55  | 57.28  | 57.07  | 57.18  | 56.09  |
| 10         | 34.10                    | 44.98  | 54.22                                            | 55.59  | 56.08  | 57.81  | 57.59  | 57.71  | 56.62  |
| 11         | 34.16                    | 45.97  | 54.53                                            | 55.94  | 56.44  | 58.17  | 57.95  | 58.09  | 57.01  |
| 12         | 33.98                    | 45.98  | 52.86                                            | 54.16  | 54.65  | 56.38  | 56.18  | 56.33  | 55.37  |
| 13         | 33.74                    | 46.14  | 52.29                                            | 53.59  | 54.09  | 55.82  | 55.63  | 55.78  | 54.85  |
| 14         | 33.45                    | 46.45  | 52.07                                            | 53.37  | 53.88  | 55.61  | 55.42  | 55.58  | 54.66  |
| 15         | 33.20                    | 46.88  | 51.79                                            | 53.11  | 53.64  | 55.38  | 55.19  | 55.36  | 54.45  |
| 16         | 32.95                    | 47.00  | 51.53                                            | 52.88  | 53.45  | 55.18  | 54.99  | 55.20  | 54.33  |
| 17         | 32.82                    | 47.11  | 51.46                                            | 52.84  | 53.44  | 55.18  | 54.99  | 55.22  | 54.38  |
| 18         | 32.60                    | 47.24  | 51.29                                            | 52.68  | 53.32  | 55.05  | 54.86  | 55.12  | 54.30  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.64                        | 1,235,561   | 20,684                    | 3,757  | 32.72                    | 0.00    | 0.00    |
| 2          | 24.10                        | 1,069,364   | 63,432                    | 3,549  | 0.00                     | 111.63  | 0.00    |
| 3          | 24.06                        | 1,042,622   | 126,863                   | 3,626  | 0.00                     | 223.11  | 0.00    |
| 4          | 24.00                        | 1,023,316   | 177,884                   | 3,721  | 0.00                     | 307.99  | 0.00    |
| 5          | 23.97                        | 1,012,285   | 217,874                   | 3,825  | 0.00                     | 0.00    | 394.83  |
| 6          | 23.94                        | 1,006,769   | 251,873                   | 3,888  | 0.00                     | 0.00    | 458.17  |
| 7          | 23.90                        | 1,002,700   | 286,798                   | 4,001  | 0.00                     | 0.00    | 521.29  |
| 8          | 23.89                        | 1,001,253   | 315,847                   | 4,135  | 0.00                     | 0.00    | 579.36  |
| 9          | 23.88                        | 999,874     | 346,116                   | 4,220  | 0.00                     | 0.00    | 632.78  |
| 10         | 23.87                        | 999,852     | 372,316                   | 4,408  | 0.00                     | 0.00    | 681.42  |
| 11         | 23.83                        | 1,000,869   | 397,137                   | 4,758  | 0.00                     | 0.00    | 725.73  |
| 12         | 23.81                        | 999,874     | 423,337                   | 4,982  | 0.00                     | 0.00    | 768.19  |
| 13         | 23.81                        | 999,874     | 448,158                   | 5,202  | 0.00                     | 0.00    | 808.93  |
| 14         | 23.81                        | 1,001,253   | 472,979                   | 5,274  | 0.00                     | 0.00    | 850.85  |
| 15         | 23.82                        | 1,002,632   | 496,421                   | 5,186  | 0.00                     | 184.87  | 693.43  |
| 16         | 23.83                        | 1,004,011   | 522,621                   | 5,480  | 0.00                     | 191.43  | 723.99  |
| 17         | 23.83                        | 1,005,390   | 543,305                   | 5,450  | 0.00                     | 197.14  | 750.71  |
| 18         | 23.85                        | 1,006,769   | 565,368                   | 5,627  | 0.00                     | 202.66  | 777.16  |

## Appendix C: Single- and two-phase measured data (continued).

Channel C1: Nitrogen gas tests.      Number of channels:      5  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      134.64      Hyd. Diameter ( $\mu\text{m}$ ):      127.92  
 Width ( $\mu\text{m}$ ):      121.83      Channel Length (m):      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 32.18                    | 32.58  | 39.83                                            | 40.18  | 40.25  | 42.03  | 41.95  | 41.95  | 41.49  |
| 2          | 31.77                    | 34.04  | 41.76                                            | 42.19  | 42.27  | 44.04  | 43.95  | 43.95  | 43.43  |
| 3          | 31.29                    | 34.92  | 42.19                                            | 42.64  | 42.74  | 44.51  | 44.42  | 44.43  | 43.91  |
| 4          | 31.16                    | 37.47  | 48.46                                            | 49.29  | 49.50  | 51.25  | 51.08  | 51.08  | 50.19  |
| 5          | 31.28                    | 40.72  | 51.31                                            | 52.25  | 52.51  | 54.25  | 54.06  | 54.09  | 53.13  |
| 6          | 31.37                    | 42.85  | 52.40                                            | 53.37  | 53.66  | 55.40  | 55.21  | 55.25  | 54.28  |
| 7          | 31.45                    | 44.81  | 53.00                                            | 54.01  | 54.32  | 56.05  | 55.86  | 55.92  | 54.97  |
| 8          | 31.45                    | 45.92  | 53.32                                            | 54.36  | 54.69  | 56.43  | 56.24  | 56.32  | 55.39  |
| 9          | 31.52                    | 46.51  | 53.63                                            | 54.71  | 55.08  | 56.81  | 56.62  | 56.72  | 55.79  |
| 10         | 31.54                    | 44.62  | 53.76                                            | 54.88  | 55.28  | 57.01  | 56.82  | 56.93  | 56.02  |
| 11         | 31.55                    | 45.82  | 53.83                                            | 54.98  | 55.42  | 57.15  | 56.96  | 57.10  | 56.19  |
| 12         | 31.44                    | 47.90  | 53.76                                            | 54.95  | 55.42  | 57.14  | 56.95  | 57.12  | 56.25  |
| 13         | 31.31                    | 47.47  | 53.78                                            | 55.00  | 55.51  | 57.23  | 57.04  | 57.22  | 56.36  |
| 14         | 31.21                    | 48.73  | 53.63                                            | 54.88  | 55.41  | 57.14  | 56.95  | 57.16  | 56.32  |
| 15         | 31.29                    | 49.24  | 53.51                                            | 54.78  | 55.34  | 57.06  | 56.87  | 57.11  | 56.29  |
| 16         | 31.14                    | 49.50  | 53.42                                            | 54.72  | 55.30  | 57.03  | 56.84  | 57.09  | 56.29  |
| 17         | 31.05                    | 49.53  | 53.10                                            | 54.41  | 55.02  | 56.75  | 56.56  | 56.84  | 56.06  |
| 18         | 30.93                    | 49.72  | 52.90                                            | 54.24  | 54.89  | 56.62  | 56.43  | 56.72  | 55.97  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |          | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|----------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet   | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.67                        | 1470095     | 13789.47                  | 3447.367 | 0.00                     | 21.51   | 0.00    |
| 2          | 23.66                        | 1311516.2   | 44126.29                  | 3510.663 | 0.00                     | 87.59   | 0.00    |
| 3          | 23.68                        | 1282942.6   | 86873.64                  | 3503.881 | 0.00                     | 177.41  | 0.00    |
| 4          | 23.66                        | 1267389.9   | 128762                    | 3585.261 | 0.00                     | 249.42  | 0.00    |
| 5          | 23.60                        | 1261761.1   | 175126.2                  | 3711.853 | 0.00                     | 0.00    | 308.54  |
| 6          | 23.54                        | 1257737.2   | 213736.7                  | 3813.579 | 0.00                     | 0.00    | 360.26  |
| 7          | 23.54                        | 1252221.5   | 248210.4                  | 3885.917 | 0.00                     | 0.00    | 400.52  |
| 8          | 23.56                        | 1253600.4   | 288199.9                  | 3998.945 | 0.00                     | 0.00    | 437.51  |
| 9          | 23.56                        | 1250842.5   | 330947.2                  | 4132.319 | 0.00                     | 0.00    | 460.10  |
| 10         | 23.57                        | 1250842.5   | 384726.1                  | 4161.706 | 0.00                     | 0.00    | 469.21  |
| 11         | 23.56                        | 1249463.6   | 439884                    | 4412.629 | 0.00                     | 0.00    | 479.66  |
| 12         | 23.60                        | 1249463.6   | 495041.8                  | 4532.439 | 0.00                     | 0.00    | 491.80  |
| 13         | 23.64                        | 1250842.5   | 540547.1                  | 4690.679 | 0.00                     | 0.00    | 502.12  |
| 14         | 23.72                        | 1249463.6   | 588810.2                  | 4803.708 | 0.00                     | 0.00    | 513.94  |
| 15         | 23.80                        | 1250842.5   | 631557.6                  | 4857.961 | 0.00                     | 111.41  | 415.73  |
| 16         | 23.86                        | 1249802.6   | 678600                    | 5088.539 | 0.00                     | 112.58  | 422.94  |
| 17         | 23.91                        | 1252198.8   | 729462.8                  | 5348.505 | 0.00                     | 113.34  | 428.67  |
| 18         | 23.94                        | 1252221.5   | 780325.6                  | 5506.744 | 0.00                     | 114.10  | 434.49  |

**Appendix C: Single- and two-phase measured data (continued).**

Channel C1: Water tests.

Number of channels: 5

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 134.64

Hyd. Diameter ( $\mu\text{m}$ ): 127.92

Width ( $\mu\text{m}$ ): 121.83

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.75                    | 43.76  | 40.53                                            | 43.47  | 46.13  | 47.85  | 47.50  | 49.24  | 49.48  |
| 2          | 26.49                    | 41.80  | 38.45                                            | 41.04  | 43.44  | 45.17  | 44.85  | 46.36  | 46.49  |
| 3          | 26.33                    | 38.92  | 35.87                                            | 38.07  | 40.13  | 41.89  | 41.59  | 42.80  | 42.74  |
| 4          | 26.47                    | 40.39  | 37.45                                            | 40.40  | 42.96  | 44.72  | 44.27  | 45.71  | 45.33  |
| 5          | 26.55                    | 42.35  | 39.62                                            | 43.45  | 46.55  | 48.32  | 47.69  | 49.38  | 48.62  |
| 6          | 26.45                    | 41.48  | 39.17                                            | 42.90  | 45.90  | 47.69  | 47.06  | 48.63  | 47.71  |
| 7          | 26.61                    | 40.44  | 38.53                                            | 42.12  | 44.95  | 46.76  | 46.14  | 47.57  | 46.55  |
| 8          | 26.75                    | 39.58  | 37.99                                            | 41.46  | 44.15  | 45.97  | 45.36  | 46.65  | 45.48  |
| 9          | 26.96                    | 41.74  | 40.09                                            | 44.50  | 47.76  | 49.61  | 48.78  | 50.20  | 48.51  |
| 10         | 27.13                    | 41.22  | 39.75                                            | 44.11  | 47.31  | 49.17  | 48.33  | 49.57  | 47.66  |
| 11         | 27.38                    | 40.52  | 39.50                                            | 43.80  | 46.86  | 48.74  | 47.91  | 48.88  | 46.95  |
| 12         | 27.52                    | 43.01  | 41.35                                            | 46.50  | 50.10  | 52.03  | 50.95  | 51.87  | 48.94  |
| 13         | 27.49                    | 42.84  | 41.09                                            | 46.21  | 49.92  | 51.86  | 50.76  | 51.59  | 48.60  |
| 14         | 27.61                    | 42.44  | 40.73                                            | 45.80  | 49.46  | 51.42  | 50.33  | 51.06  | 47.95  |
| 15         | 27.68                    | 42.13  | 40.55                                            | 45.49  | 49.08  | 51.04  | 49.96  | 50.62  | 47.50  |
| 16         | 27.68                    | 42.13  | 40.55                                            | 45.50  | 49.08  | 51.04  | 49.96  | 50.62  | 47.50  |
| 17         | 27.79                    | 41.61  | 39.91                                            | 44.59  | 47.89  | 49.85  | 48.77  | 49.26  | 46.65  |
| 18         | 27.89                    | 41.29  | 39.54                                            | 44.11  | 47.45  | 49.38  | 48.27  | 48.68  | 46.22  |
| 19         | 25.18                    | 36.95  | 36.38                                            | 41.64  | 45.36  | 46.96  | 46.27  | 48.03  | 46.77  |
| 20         | 25.48                    | 36.18  | 35.15                                            | 39.58  | 42.36  | 44.05  | 43.43  | 44.25  | 43.47  |
| 21         | 25.80                    | 36.00  | 34.49                                            | 38.32  | 40.52  | 42.21  | 41.64  | 42.61  | 42.03  |
| 22         | 26.05                    | 35.69  | 33.74                                            | 37.05  | 39.45  | 41.06  | 40.48  | 41.87  | 41.41  |
| 23         | 26.28                    | 35.68  | 33.34                                            | 36.39  | 38.87  | 40.46  | 39.86  | 41.12  | 40.06  |
| 24         | 26.46                    | 35.28  | 33.05                                            | 36.00  | 38.41  | 40.02  | 39.42  | 40.59  | 39.60  |
| 25         | 26.62                    | 35.01  | 32.90                                            | 35.78  | 38.12  | 39.73  | 39.14  | 40.25  | 39.29  |
| 26         | 26.77                    | 34.50  | 32.59                                            | 35.34  | 37.57  | 39.19  | 38.61  | 39.64  | 38.70  |

# Appendix C: Single- and two-phase measured data (continued).

## Channel C1: Water tests (continued).

| Data Point | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | liquid Flow Rate   |
|------------|-------------------|------------|---------------------------|---------|--------------------|
|            | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F. M. #1, (cc/min) |
| 1          | 25.20             | 2,258,019  | 227,526                   | 95,035  | 8.71               |
| 2          | 25.26             | 2,231,771  | 267,945                   | 93,716  | 10.41              |
| 3          | 25.37             | 2,225,893  | 351,044                   | 93,628  | 15.89              |
| 4          | 25.61             | 2,190,063  | 423,789                   | 92,708  | 18.32              |
| 5          | 25.89             | 2,194,313  | 484,010                   | 93,092  | 23.56              |
| 6          | 26.28             | 2,188,911  | 548,097                   | 92,875  | 26.49              |
| 7          | 26.66             | 2,179,574  | 617,859                   | 92,652  | 29.16              |
| 8          | 27.02             | 2,181,632  | 685,540                   | 92,166  | 32.25              |
| 9          | 27.28             | 2,200,100  | 748,361                   | 92,686  | 36.96              |
| 10         | 27.57             | 2,214,658  | 837,201                   | 93,377  | 38.00              |
| 11         | 27.78             | 2,198,088  | 897,287                   | 92,604  | 40.35              |
| 12         | 27.97             | 2,202,592  | 954,760                   | 92,311  | 43.90              |
| 13         | 28.14             | 2,185,994  | 1,030,525                 | 91,858  | 46.39              |
| 14         | 28.28             | 2,213,754  | 1,113,556                 | 93,307  | 48.00              |
| 15         | 28.39             | 2,194,823  | 1,165,486                 | 92,222  | 49.71              |
| 16         | 28.39             | 2,194,878  | 1,165,504                 | 92,220  | 49.63              |
| 17         | 28.54             | 2,239,751  | 1,318,296                 | 93,886  | 51.16              |
| 18         | 28.58             | 2,217,190  | 1,376,573                 | 93,217  | 53.90              |
| 19         | 26.68             | 4,734,604  | 1,055,228                 | 103,758 | 43.43              |
| 20         | 27.01             | 4,706,460  | 1,396,641                 | 103,780 | 52.23              |
| 21         | 27.37             | 4,680,599  | 1,719,021                 | 103,692 | 56.38              |
| 22         | 27.67             | 4,649,381  | 2,084,487                 | 103,317 | 61.27              |
| 23         | 27.94             | 4,644,724  | 2,429,405                 | 103,464 | 65.28              |
| 24         | 28.18             | 4,623,950  | 2,775,294                 | 103,209 | 71.40              |
| 25         | 28.41             | 4,605,029  | 3,130,475                 | 103,170 | 76.75              |
| 26         | 28.71             | 4,571,504  | 3,812,804                 | 103,281 | 87.08              |

## Appendix C: Single- and two-phase measured data (continued).

Channel C1: Water and argon tests. Number of channels: 5

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 134.64 Hyd. Diameter ( $\mu\text{m}$ ): 127.92Width ( $\mu\text{m}$ ): 121.83 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.97                    | 39.98  | 36.53                                            | 39.72  | 42.24  | 44.05  | 43.63  | 45.05  | 44.81  |
| 2          | 27.16                    | 41.60  | 38.01                                            | 41.57  | 44.19  | 46.00  | 45.55  | 46.98  | 46.44  |
| 3          | 27.44                    | 43.24  | 39.77                                            | 43.59  | 46.27  | 48.08  | 47.62  | 49.03  | 48.25  |
| 4          | 27.53                    | 43.14  | 39.80                                            | 43.66  | 46.34  | 48.15  | 47.69  | 49.03  | 48.09  |
| 5          | 28.38                    | 46.47  | 43.26                                            | 47.46  | 50.25  | 52.03  | 51.52  | 52.89  | 51.75  |
| 6          | 26.88                    | 38.17  | 35.67                                            | 39.07  | 41.64  | 43.49  | 42.97  | 44.15  | 43.11  |
| 7          | 27.01                    | 39.26  | 36.44                                            | 40.09  | 42.78  | 44.63  | 44.09  | 45.33  | 44.12  |
| 8          | 27.00                    | 40.57  | 37.54                                            | 41.51  | 44.32  | 46.16  | 45.60  | 46.87  | 45.55  |
| 9          | 27.16                    | 41.91  | 38.66                                            | 42.86  | 45.74  | 47.58  | 47.00  | 48.25  | 46.85  |
| 10         | 26.90                    | 40.87  | 37.97                                            | 42.33  | 45.47  | 47.35  | 46.65  | 48.01  | 46.32  |
| 11         | 27.09                    | 42.08  | 38.73                                            | 43.30  | 46.57  | 48.44  | 47.72  | 49.11  | 47.36  |
| 12         | 27.56                    | 43.28  | 39.73                                            | 44.58  | 47.92  | 49.79  | 49.06  | 50.42  | 48.61  |
| 13         | 27.67                    | 44.71  | 40.85                                            | 45.95  | 49.39  | 51.25  | 50.49  | 51.86  | 50.05  |
| 14         | 27.79                    | 46.12  | 41.97                                            | 47.32  | 50.87  | 52.73  | 51.95  | 53.37  | 51.54  |
| 15         | 26.39                    | 37.36  | 34.80                                            | 37.52  | 39.44  | 41.17  | 40.93  | 42.04  | 41.74  |
| 16         | 26.37                    | 37.39  | 34.98                                            | 37.73  | 39.61  | 41.36  | 41.12  | 42.18  | 41.76  |
| 17         | 26.23                    | 37.03  | 34.80                                            | 37.50  | 39.34  | 41.08  | 40.84  | 41.84  | 41.30  |
| 18         | 25.85                    | 35.87  | 33.59                                            | 36.13  | 37.95  | 39.66  | 39.40  | 40.41  | 39.89  |
| 19         | 25.60                    | 35.09  | 32.99                                            | 35.45  | 37.16  | 38.89  | 38.65  | 39.56  | 39.02  |
| 20         | 25.54                    | 34.96  | 32.99                                            | 35.40  | 37.07  | 38.80  | 38.56  | 39.45  | 38.89  |
| 21         | 25.51                    | 35.03  | 33.11                                            | 35.53  | 37.20  | 38.93  | 38.69  | 39.58  | 38.98  |
| 22         | 25.64                    | 33.05  | 31.36                                            | 34.21  | 36.45  | 38.04  | 37.53  | 38.78  | 38.27  |
| 23         | 25.93                    | 33.76  | 31.88                                            | 34.76  | 37.06  | 38.65  | 38.14  | 39.38  | 38.89  |
| 24         | 26.12                    | 33.92  | 32.04                                            | 34.91  | 37.22  | 38.82  | 38.30  | 39.53  | 39.06  |
| 25         | 26.22                    | 34.36  | 32.32                                            | 35.27  | 37.60  | 39.20  | 38.67  | 39.92  | 39.40  |
| 26         | 26.35                    | 34.57  | 32.50                                            | 35.53  | 37.90  | 39.50  | 38.96  | 40.21  | 39.64  |
| 27         | 26.39                    | 35.07  | 32.83                                            | 35.97  | 38.43  | 40.02  | 39.47  | 40.77  | 40.14  |
| 28         | 26.43                    | 35.55  | 33.14                                            | 36.38  | 38.93  | 40.52  | 39.96  | 41.30  | 40.65  |
| 29         | 26.45                    | 36.35  | 33.65                                            | 37.10  | 39.80  | 41.40  | 40.82  | 42.26  | 41.53  |

Appendix C: Single- and two-phase measured data (continued).

Channel C1: Water and argon (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.89          | 1,321,508  | 26.34             | 1,245,070  | 499,088                   | 92,826  | 0.00                            | 38.75   | 0.00    | 16.29   |
| 2          | 24.86          | 1,305,458  | 26.24             | 1,223,391  | 608,296                   | 94,069  | 0.00                            | 102.79  | 0.00    | 15.41   |
| 3          | 24.85          | 1,297,546  | 26.12             | 1,201,328  | 693,588                   | 97,672  | 0.00                            | 148.09  | 0.00    | 12.91   |
| 4          | 24.90          | 1,303,265  | 26.12             | 1,227,799  | 868,985                   | 104,888 | 0.00                            | 0.00    | 172.41  | 11.07   |
| 5          | 24.89          | 1,308,238  | 26.01             | 1,233,293  | 1,049,763                 | 114,570 | 0.00                            | 0.00    | 234.71  | 7.77    |
| 6          | 24.85          | 1,316,218  | 26.20             | 1,580,742  | 713,051                   | 94,810  | 0.00                            | 31.58   | 0.00    | 25.60   |
| 7          | 24.89          | 1,308,012  | 26.33             | 1,624,054  | 823,163                   | 97,657  | 0.00                            | 74.42   | 0.00    | 23.24   |
| 8          | 24.93          | 1,301,705  | 26.39             | 1,645,892  | 925,070                   | 102,872 | 0.00                            | 117.25  | 0.00    | 22.17   |
| 9          | 24.91          | 1,310,002  | 26.38             | 1,634,476  | 1,048,813                 | 110,210 | 0.00                            | 0.00    | 149.65  | 19.12   |
| 10         | 24.82          | 1,324,831  | 26.68             | 1,692,957  | 774,765                   | 100,907 | 0.00                            | 28.20   | 0.00    | 28.68   |
| 11         | 24.81          | 1,307,379  | 26.78             | 1,690,832  | 849,205                   | 101,023 | 0.00                            | 60.60   | 0.00    | 26.32   |
| 12         | 24.82          | 1,306,000  | 26.82             | 1,690,470  | 932,055                   | 104,572 | 0.00                            | 96.45   | 0.00    | 24.45   |
| 13         | 24.88          | 1,304,395  | 26.79             | 1,701,253  | 1,016,238                 | 109,091 | 0.00                            | 0.00    | 121.38  | 22.58   |
| 14         | 24.94          | 1,307,967  | 26.75             | 1,684,525  | 1,081,117                 | 112,097 | 0.00                            | 0.00    | 147.28  | 20.48   |
| 15         | 23.38          | 3,885,919  | 26.15             | 4,471,398  | 843,435                   | 123,976 | 0.00                            | 54.31   | 195.25  | 11.45   |
| 16         | 23.33          | 3,731,070  | 26.01             | 4,412,691  | 966,681                   | 127,652 | 0.00                            | 61.37   | 223.20  | 9.60    |
| 17         | 23.38          | 3,798,978  | 25.85             | 4,396,890  | 1,097,116                 | 131,154 | 0.00                            | 66.52   | 244.68  | 11.33   |
| 18         | 23.36          | 3,733,919  | 25.73             | 4,337,912  | 1,261,844                 | 134,526 | 0.00                            | 68.03   | 252.71  | 11.96   |
| 19         | 23.36          | 3,827,823  | 25.63             | 4,292,972  | 1,411,697                 | 137,436 | 0.00                            | 69.75   | 261.60  | 12.76   |
| 20         | 23.34          | 3,739,140  | 25.57             | 4,303,370  | 1,525,923                 | 140,987 | 0.00                            | 72.77   | 275.57  | 12.53   |
| 21         | 23.35          | 3,755,688  | 25.47             | 4,283,568  | 1,673,764                 | 146,657 | 0.00                            | 75.59   | 289.62  | 10.29   |
| 22         | 23.32          | 4,567,074  | 27.10             | 4,430,595  | 2,510,830                 | 110,510 | 0.00                            | 11.23   | 0.00    | 66.80   |
| 23         | 23.22          | 4,305,458  | 27.43             | 4,385,022  | 2,762,861                 | 119,340 | 0.00                            | 38.35   | 0.00    | 63.70   |
| 24         | 23.44          | 4,360,183  | 27.69             | 4,442,254  | 2,923,344                 | 122,556 | 0.00                            | 13.93   | 49.39   | 64.47   |
| 25         | 23.35          | 4,283,576  | 27.89             | 4,389,882  | 3,094,916                 | 127,512 | 0.00                            | 18.71   | 67.36   | 63.80   |
| 26         | 23.33          | 4,389,958  | 28.04             | 4,364,926  | 3,411,373                 | 135,686 | 0.00                            | 25.33   | 93.26   | 62.22   |
| 27         | 23.33          | 4,264,858  | 28.06             | 4,324,597  | 3,405,111                 | 140,702 | 0.00                            | 30.70   | 114.64  | 59.23   |
| 28         | 23.32          | 4,344,611  | 28.06             | 4,266,704  | 3,400,341                 | 143,652 | 0.00                            | 34.94   | 131.91  | 55.12   |
| 29         | 23.36          | 4,284,344  | 28.01             | 4,205,149  | 3,382,144                 | 149,394 | 0.00                            | 41.90   | 160.98  | 47.42   |

## Appendix C: Single- and two-phase measured data (continued).

Channel C1: Water and helium tests. Number of channels: 5

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 134.64 Hyd. Diameter ( $\mu\text{m}$ ): 127.92Width ( $\mu\text{m}$ ): 121.83 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.28                    | 44.08  | 39.00                                            | 42.92  | 45.87  | 47.62  | 47.17  | 49.05  | 48.98  |
| 2          | 27.77                    | 46.14  | 41.31                                            | 45.32  | 48.20  | 49.97  | 49.50  | 51.25  | 50.98  |
| 3          | 27.70                    | 46.12  | 41.43                                            | 45.45  | 48.29  | 50.06  | 49.60  | 51.25  | 50.83  |
| 4          | 27.84                    | 46.22  | 42.22                                            | 46.36  | 49.18  | 50.95  | 50.46  | 52.01  | 51.33  |
| 5          | 27.93                    | 46.13  | 42.75                                            | 46.94  | 49.76  | 51.53  | 51.03  | 52.49  | 51.51  |
| 6          | 26.84                    | 42.48  | 37.87                                            | 41.70  | 44.70  | 46.50  | 46.00  | 47.72  | 47.58  |
| 7          | 26.79                    | 41.70  | 37.62                                            | 41.46  | 44.37  | 46.18  | 45.67  | 47.25  | 46.84  |
| 8          | 27.07                    | 42.20  | 38.19                                            | 42.20  | 45.14  | 46.95  | 46.44  | 48.01  | 47.46  |
| 9          | 26.97                    | 42.47  | 38.83                                            | 43.01  | 45.94  | 47.75  | 47.21  | 48.68  | 47.75  |
| 10         | 27.14                    | 43.34  | 39.88                                            | 44.27  | 47.28  | 49.08  | 48.52  | 49.98  | 48.77  |
| 11         | 26.37                    | 39.76  | 36.60                                            | 40.45  | 43.38  | 45.22  | 44.65  | 46.15  | 45.59  |
| 12         | 26.69                    | 40.70  | 37.24                                            | 41.34  | 44.36  | 46.20  | 45.61  | 47.11  | 46.25  |
| 13         | 26.85                    | 41.36  | 37.86                                            | 42.11  | 45.16  | 46.99  | 46.39  | 47.88  | 46.86  |
| 14         | 27.04                    | 42.52  | 39.03                                            | 43.61  | 46.76  | 48.58  | 47.95  | 49.41  | 48.11  |
| 15         | 27.43                    | 43.81  | 40.24                                            | 45.10  | 48.37  | 50.19  | 49.54  | 51.04  | 49.54  |
| 16         | 26.62                    | 39.36  | 37.11                                            | 41.16  | 44.08  | 45.95  | 45.28  | 46.53  | 45.14  |
| 17         | 26.81                    | 39.59  | 37.12                                            | 41.38  | 44.40  | 46.27  | 45.59  | 46.86  | 45.29  |
| 18         | 26.84                    | 39.29  | 36.98                                            | 41.27  | 44.26  | 46.14  | 45.45  | 46.65  | 44.99  |
| 19         | 26.96                    | 40.44  | 37.74                                            | 42.31  | 45.42  | 47.29  | 46.58  | 47.80  | 46.01  |
| 20         | 27.07                    | 41.84  | 38.85                                            | 43.73  | 46.98  | 48.85  | 48.11  | 49.42  | 47.53  |
| 21         | 24.19                    | 34.43  | 32.97                                            | 36.54  | 33.52  | 40.74  | 40.05  | 41.64  | 40.70  |
| 22         | 24.54                    | 34.90  | 33.12                                            | 36.63  | 33.70  | 40.92  | 40.25  | 41.97  | 41.09  |
| 23         | 24.79                    | 35.50  | 33.07                                            | 36.48  | 33.80  | 41.05  | 40.39  | 42.46  | 41.62  |
| 24         | 24.99                    | 35.74  | 33.22                                            | 36.63  | 34.44  | 41.27  | 40.60  | 42.68  | 41.86  |
| 25         | 25.10                    | 36.02  | 33.37                                            | 36.85  | 34.59  | 41.53  | 40.86  | 42.97  | 42.14  |
| 26         | 25.26                    | 35.82  | 33.54                                            | 36.87  | 34.79  | 41.67  | 40.92  | 43.04  | 42.28  |
| 27         | 25.42                    | 36.00  | 33.62                                            | 36.98  | 34.52  | 41.84  | 41.09  | 43.20  | 42.45  |
| 28         | 25.59                    | 36.26  | 33.74                                            | 37.20  | 34.81  | 42.17  | 41.40  | 43.50  | 42.73  |
| 29         | 25.61                    | 36.25  | 33.67                                            | 37.14  | 34.75  | 42.13  | 41.36  | 43.42  | 42.70  |
| 30         | 25.66                    | 36.32  | 33.70                                            | 37.18  | 34.85  | 42.24  | 41.46  | 43.54  | 42.81  |
| 31         | 25.56                    | 34.79  | 32.67                                            | 35.55  | 33.63  | 40.57  | 39.80  | 41.72  | 41.18  |
| 32         | 26.50                    | 36.62  | 33.86                                            | 36.46  | 38.28  | 40.00  | 39.78  | 40.84  | 40.59  |
| 33         | 26.42                    | 37.13  | 34.38                                            | 37.14  | 39.06  | 40.77  | 40.53  | 41.65  | 41.40  |
| 34         | 26.28                    | 37.14  | 34.36                                            | 37.19  | 39.14  | 40.86  | 40.63  | 41.73  | 41.41  |
| 35         | 26.10                    | 37.07  | 34.38                                            | 37.22  | 39.19  | 40.91  | 40.66  | 41.78  | 41.44  |
| 36         | 25.74                    | 35.91  | 33.50                                            | 36.29  | 38.22  | 39.94  | 39.69  | 40.76  | 40.35  |
| 37         | 25.63                    | 35.78  | 33.47                                            | 36.25  | 38.19  | 39.90  | 39.65  | 40.71  | 40.27  |
| 38         | 25.53                    | 35.61  | 33.40                                            | 36.18  | 38.11  | 39.83  | 39.57  | 40.62  | 40.10  |

# Appendix C: Single- and two-phase measured data (continued).

## Channel A: Water and helium (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press.. (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 23.28          | 1,652,116  | 23.29             | 1,454,557  | 310,150                   | 105,385 | 0.00                            | 52.75   | 0.00    | 8.38    |
| 2          | 24.70          | 1,620,400  | 24.71             | 1,420,558  | 387,394                   | 108,421 | 0.00                            | 133.49  | 0.00    | 8.32    |
| 3          | 24.72          | 1,607,990  | 24.70             | 1,395,081  | 461,518                   | 113,255 | 0.00                            | 189.53  | 0.00    | 8.92    |
| 4          | 24.73          | 1,597,998  | 24.70             | 1,365,423  | 582,661                   | 123,294 | 0.00                            | 0.00    | 333.37  | 8.92    |
| 5          | 24.73          | 1,594,200  | 24.68             | 1,346,592  | 694,175                   | 131,439 | 0.00                            | 0.00    | 438.74  | 8.92    |
| 6          | 24.75          | 1,703,770  | 24.78             | 1,311,553  | 460,229                   | 97,476  | 0.00                            | 41.33   | 0.00    | 17.45   |
| 7          | 24.79          | 1,625,916  | 24.96             | 1,294,328  | 545,317                   | 101,606 | 0.00                            | 108.94  | 0.00    | 18.49   |
| 8          | 24.79          | 1,609,369  | 25.11             | 1,290,168  | 594,326                   | 107,122 | 0.00                            | 166.25  | 0.00    | 15.74   |
| 9          | 24.78          | 1,596,958  | 25.24             | 1,289,897  | 712,079                   | 119,071 | 0.00                            | 0.00    | 293.77  | 14.41   |
| 10         | 24.77          | 1,591,442  | 25.27             | 1,288,270  | 805,440                   | 128,210 | 0.00                            | 0.00    | 396.66  | 12.54   |
| 11         | 24.75          | 1,692,467  | 25.51             | 1,257,164  | 610,308                   | 95,837  | 0.00                            | 35.00   | 0.00    | 24.68   |
| 12         | 24.78          | 1,628,335  | 25.76             | 1,249,117  | 653,756                   | 99,666  | 0.00                            | 99.91   | 0.00    | 23.15   |
| 13         | 24.79          | 1,613,505  | 25.90             | 1,253,819  | 691,621                   | 104,762 | 0.00                            | 145.57  | 0.00    | 22.11   |
| 14         | 24.82          | 1,601,095  | 25.97             | 1,266,071  | 783,852                   | 117,581 | 0.00                            | 0.00    | 273.98  | 19.80   |
| 15         | 24.82          | 1,591,691  | 25.96             | 1,279,114  | 866,024                   | 127,806 | 0.00                            | 0.00    | 375.46  | 15.51   |
| 16         | 24.88          | 1,674,224  | 26.44             | 1,228,229  | 754,193                   | 95,183  | 0.00                            | 30.15   | 0.00    | 30.95   |
| 17         | 24.89          | 1,628,357  | 26.58             | 1,224,815  | 823,231                   | 98,204  | 0.00                            | 83.34   | 0.00    | 30.55   |
| 18         | 24.90          | 1,612,353  | 26.68             | 1,223,482  | 901,537                   | 104,138 | 0.00                            | 120.19  | 0.00    | 30.67   |
| 19         | 24.91          | 1,602,270  | 26.68             | 1,246,268  | 971,592                   | 117,100 | 0.00                            | 0.00    | 231.13  | 27.02   |
| 20         | 24.94          | 1,596,664  | 26.66             | 1,247,760  | 1,031,814                 | 125,828 | 0.00                            | 0.00    | 328.02  | 23.68   |
| 21         | 22.92          | 3,589,355  | 25.51             | 3,976,492  | 1,655,924                 | 119,756 | 0.00                            | 0.00    | 162.09  | 62.14   |
| 22         | 22.92          | 3,585,670  | 25.79             | 3,994,554  | 1,716,326                 | 124,121 | 0.00                            | 0.00    | 216.77  | 60.09   |
| 23         | 22.86          | 3,589,536  | 25.97             | 3,981,918  | 1,901,580                 | 139,565 | 0.00                            | 59.00   | 222.21  | 57.84   |
| 24         | 22.86          | 3,544,302  | 26.12             | 3,979,612  | 1,920,410                 | 140,289 | 0.00                            | 62.69   | 238.43  | 57.26   |
| 25         | 22.85          | 3,528,433  | 26.22             | 3,978,979  | 1,956,286                 | 143,395 | 0.00                            | 69.78   | 270.70  | 55.98   |
| 26         | 22.79          | 3,594,374  | 26.57             | 3,953,502  | 2,146,919                 | 119,955 | 0.00                            | 0.00    | 128.74  | 70.68   |
| 27         | 22.80          | 3,584,043  | 26.69             | 3,951,671  | 2,230,086                 | 124,982 | 0.00                            | 0.00    | 179.79  | 69.86   |
| 28         | 22.79          | 3,609,859  | 26.77             | 3,956,057  | 2,346,708                 | 136,995 | 0.00                            | 46.02   | 173.72  | 67.77   |
| 29         | 22.76          | 3,545,252  | 26.78             | 3,995,865  | 2,409,439                 | 140,395 | 0.00                            | 50.32   | 192.41  | 69.69   |
| 30         | 22.75          | 3,519,278  | 26.79             | 4,013,475  | 2,447,191                 | 144,423 | 0.00                            | 54.62   | 211.29  | 66.80   |
| 31         | 22.75          | 3,579,861  | 27.01             | 3,943,104  | 2,842,835                 | 119,421 | 0.00                            | 0.00    | 95.07   | 84.36   |
| 32         | 23.37          | 4,558,732  | 26.55             | 4,653,713  | 458,460                   | 113,458 | 0.00                            | 36.70   | 128.67  | 12.75   |
| 33         | 23.38          | 4,603,175  | 26.33             | 4,708,871  | 521,236                   | 121,861 | 0.00                            | 56.14   | 199.60  | 12.14   |
| 34         | 23.39          | 4,566,011  | 26.17             | 4,726,413  | 617,514                   | 130,417 | 0.00                            | 76.10   | 275.83  | 11.59   |
| 35         | 23.41          | 4,578,512  | 26.06             | 4,735,229  | 682,460                   | 137,770 | 0.00                            | 91.15   | 335.79  | 11.77   |
| 36         | 23.42          | 4,518,426  | 25.95             | 4,754,806  | 817,891                   | 146,462 | 0.00                            | 105.09  | 396.28  | 10.53   |
| 37         | 23.43          | 4,528,599  | 25.87             | 4,742,260  | 870,200                   | 150,470 | 0.00                            | 113.12  | 431.97  | 9.99    |
| 38         | 23.44          | 4,545,576  | 25.79             | 4,769,364  | 953,819                   | 158,023 | 0.00                            | 125.68  | 490.33  | 10.52   |



## Appendix C: Single- and two-phase measured data (continued).

Channel C1: Water and nitrogen tests. Number of channels: 5

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 134.64 Hyd. Diameter ( $\mu\text{m}$ ): 127.92Width ( $\mu\text{m}$ ): 121.83 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 27.01                    | 38.98  | 36.01                                            | 39.03  | 41.41  | 43.23  | 42.82  | 44.10  | 43.61  |
| 2          | 27.19                    | 40.32  | 36.82                                            | 40.10  | 42.59  | 44.40  | 43.98  | 45.29  | 44.68  |
| 3          | 27.40                    | 40.91  | 37.53                                            | 40.97  | 43.49  | 45.30  | 44.86  | 46.16  | 45.39  |
| 4          | 27.46                    | 41.59  | 38.35                                            | 41.92  | 44.49  | 46.29  | 45.84  | 47.14  | 46.23  |
| 5          | 27.37                    | 42.27  | 39.04                                            | 42.79  | 45.41  | 47.22  | 46.76  | 48.06  | 47.06  |
| 6          | 27.56                    | 43.18  | 39.88                                            | 43.77  | 46.46  | 48.27  | 47.79  | 49.11  | 48.06  |
| 7          | 26.37                    | 38.23  | 35.53                                            | 38.92  | 41.50  | 43.36  | 42.84  | 43.99  | 42.78  |
| 8          | 26.79                    | 39.19  | 36.08                                            | 39.74  | 42.47  | 44.32  | 43.78  | 45.05  | 43.81  |
| 9          | 26.94                    | 39.89  | 36.78                                            | 40.62  | 43.41  | 45.26  | 44.71  | 45.97  | 44.62  |
| 10         | 27.33                    | 40.60  | 37.44                                            | 41.45  | 44.28  | 46.12  | 45.56  | 46.79  | 45.35  |
| 11         | 27.41                    | 41.49  | 38.29                                            | 42.47  | 45.35  | 47.19  | 46.62  | 47.85  | 46.37  |
| 12         | 27.41                    | 42.46  | 39.14                                            | 43.48  | 46.44  | 48.29  | 47.69  | 48.95  | 47.45  |
| 13         | 26.80                    | 38.42  | 36.39                                            | 40.27  | 43.03  | 44.92  | 44.26  | 45.23  | 43.24  |
| 14         | 26.93                    | 39.25  | 36.68                                            | 40.83  | 43.72  | 45.62  | 44.94  | 45.95  | 44.01  |
| 15         | 27.18                    | 40.16  | 37.44                                            | 41.77  | 44.74  | 46.63  | 45.94  | 46.96  | 44.98  |
| 16         | 27.36                    | 41.68  | 38.64                                            | 43.25  | 46.38  | 48.25  | 47.54  | 48.67  | 46.71  |
| 17         | 27.51                    | 42.74  | 39.37                                            | 44.18  | 47.42  | 49.28  | 48.56  | 49.74  | 47.86  |
| 18         | 24.25                    | 34.33  | 32.30                                            | 35.03  | 36.92  | 38.66  | 38.41  | 39.53  | 39.25  |
| 19         | 24.26                    | 34.11  | 31.84                                            | 34.52  | 36.39  | 38.13  | 37.89  | 38.99  | 38.73  |
| 20         | 24.34                    | 34.51  | 32.14                                            | 34.90  | 36.79  | 38.54  | 38.30  | 39.41  | 39.11  |
| 21         | 24.45                    | 34.98  | 32.57                                            | 35.40  | 37.33  | 39.07  | 38.81  | 39.92  | 39.56  |
| 22         | 24.57                    | 35.44  | 33.11                                            | 35.99  | 37.95  | 39.68  | 39.42  | 40.51  | 40.03  |
| 23         | 24.83                    | 35.89  | 33.60                                            | 36.52  | 38.49  | 40.22  | 39.96  | 41.04  | 40.52  |
| 24         | 24.78                    | 35.47  | 33.12                                            | 35.98  | 37.92  | 39.65  | 39.38  | 40.48  | 39.95  |
| 25         | 25.29                    | 33.12  | 31.59                                            | 34.52  | 36.79  | 38.37  | 37.85  | 39.21  | 38.81  |
| 26         | 25.60                    | 33.65  | 31.80                                            | 34.76  | 37.06  | 38.64  | 38.13  | 39.46  | 39.00  |
| 27         | 25.76                    | 33.87  | 31.97                                            | 34.91  | 37.23  | 38.82  | 38.31  | 39.62  | 39.14  |
| 28         | 25.93                    | 34.00  | 32.07                                            | 35.02  | 37.36  | 38.95  | 38.43  | 39.71  | 39.22  |
| 29         | 26.02                    | 34.03  | 32.04                                            | 34.97  | 37.31  | 38.90  | 38.38  | 39.62  | 39.11  |
| 30         | 26.11                    | 34.26  | 32.18                                            | 35.15  | 37.51  | 39.11  | 38.58  | 39.82  | 39.28  |
| 31         | 26.13                    | 34.27  | 32.19                                            | 35.16  | 37.53  | 39.13  | 38.60  | 39.84  | 39.29  |
| 32         | 26.12                    | 34.28  | 32.22                                            | 35.21  | 37.59  | 39.19  | 38.66  | 39.90  | 39.31  |

## Appendix C: Single- and two-phase measured data (continued).

Channel C1: Water and nitrogen (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.86          | 1,861,467  | 26.44             | 1,742,418  | 496,240                   | 100,313 | 0.00                            | 26.59   | 0.00    | 17.93   |
| 2          | 24.85          | 1,853,442  | 26.37             | 1,744,452  | 574,998                   | 101,626 | 0.00                            | 77.46   | 0.00    | 15.61   |
| 3          | 24.84          | 1,841,032  | 26.27             | 1,734,144  | 640,871                   | 104,701 | 0.00                            | 114.03  | 0.00    | 13.77   |
| 4          | 24.82          | 1,833,346  | 26.16             | 1,736,495  | 714,068                   | 108,835 | 0.00                            | 0.00    | 148.49  | 14.95   |
| 5          | 24.75          | 1,825,863  | 26.01             | 1,746,283  | 798,274                   | 113,783 | 0.00                            | 0.00    | 183.00  | 12.50   |
| 6          | 24.70          | 1,820,348  | 25.89             | 1,760,751  | 886,550                   | 119,222 | 0.00                            | 0.00    | 214.21  | 12.65   |
| 7          | 24.58          | 1,867,232  | 26.08             | 1,760,819  | 691,169                   | 102,490 | 0.00                            | 22.84   | 0.00    | 25.79   |
| 8          | 24.54          | 1,860,337  | 26.20             | 1,746,962  | 743,365                   | 101,818 | 0.00                            | 58.00   | 0.00    | 24.24   |
| 9          | 24.55          | 1,842,456  | 26.27             | 1,736,631  | 818,281                   | 105,031 | 0.00                            | 92.68   | 0.00    | 21.83   |
| 10         | 24.59          | 1,836,850  | 26.31             | 1,754,308  | 896,700                   | 110,361 | 0.00                            | 0.00    | 123.40  | 19.91   |
| 11         | 24.59          | 1,825,660  | 26.31             | 1,748,476  | 973,582                   | 114,780 | 0.00                            | 0.00    | 158.37  | 19.50   |
| 12         | 24.65          | 1,819,489  | 26.30             | 1,756,908  | 1,050,667                 | 120,016 | 0.00                            | 0.00    | 188.60  | 18.33   |
| 13         | 24.67          | 1,868,611  | 26.64             | 1,741,378  | 883,747                   | 103,109 | 0.00                            | 20.45   | 0.00    | 33.49   |
| 14         | 24.72          | 1,856,200  | 26.84             | 1,743,910  | 946,997                   | 103,541 | 0.00                            | 49.14   | 0.00    | 31.34   |
| 15         | 24.76          | 1,842,411  | 26.96             | 1,744,859  | 1,012,079                 | 106,737 | 0.00                            | 80.18   | 0.00    | 29.20   |
| 16         | 24.78          | 1,835,516  | 26.97             | 1,750,737  | 1,027,338                 | 110,603 | 0.00                            | 0.00    | 111.41  | 26.05   |
| 17         | 24.82          | 1,827,242  | 26.96             | 1,756,501  | 1,103,248                 | 115,608 | 0.00                            | 0.00    | 143.62  | 24.04   |
| 18         | 23.58          | 3,654,527  | 24.36             | 3,445,824  | 560,367                   | 115,398 | 0.00                            | 0.00    | 259.32  | 11.69   |
| 19         | 23.71          | 3,678,422  | 24.30             | 3,481,179  | 654,090                   | 119,525 | 0.00                            | 0.00    | 278.08  | 11.45   |
| 20         | 23.68          | 3,658,303  | 24.27             | 3,485,474  | 703,257                   | 121,917 | 0.00                            | 0.00    | 306.70  | 10.40   |
| 21         | 23.69          | 3,704,441  | 24.25             | 3,480,953  | 763,660                   | 124,627 | 0.00                            | 0.00    | 337.29  | 9.88    |
| 22         | 23.60          | 3,796,717  | 24.23             | 3,498,405  | 893,574                   | 130,810 | 0.00                            | 71.91   | 270.05  | 9.84    |
| 23         | 23.58          | 3,666,915  | 24.24             | 3,442,885  | 947,805                   | 132,010 | 0.00                            | 76.00   | 288.15  | 11.23   |
| 24         | 23.57          | 3,652,583  | 24.22             | 3,428,372  | 1,078,602                 | 135,734 | 0.00                            | 78.27   | 300.88  | 11.62   |
| 25         | 23.43          | 4,073,863  | 26.99             | 3,443,744  | 2,137,497                 | 108,609 | 0.00                            | 8.38    | 0.00    | 64.40   |
| 26         | 23.41          | 3,705,006  | 27.30             | 3,449,305  | 2,400,967                 | 115,000 | 0.00                            | 30.04   | 0.00    | 63.09   |
| 27         | 23.52          | 3,664,745  | 27.48             | 3,445,440  | 2,501,110                 | 117,690 | 0.00                            | 12.24   | 43.44   | 61.80   |
| 28         | 23.52          | 3,678,263  | 27.65             | 3,455,409  | 2,682,656                 | 122,602 | 0.00                            | 16.17   | 58.35   | 62.80   |
| 29         | 23.53          | 3,737,942  | 27.77             | 3,424,687  | 3,000,469                 | 128,954 | 0.00                            | 20.66   | 76.14   | 64.12   |
| 30         | 23.49          | 3,644,807  | 27.87             | 3,434,318  | 3,117,137                 | 133,891 | 0.00                            | 24.74   | 92.77   | 62.87   |
| 31         | 23.49          | 3,695,625  | 27.90             | 3,432,803  | 3,248,861                 | 137,402 | 0.00                            | 27.02   | 102.50  | 62.79   |
| 32         | 23.53          | 3,764,888  | 27.98             | 3,435,606  | 3,399,753                 | 142,206 | 0.00                            | 30.19   | 116.40  | 62.96   |

## Appendix C: Single- and two-phase measured data (continued).

Channel C2: Argon gas tests. Number of channels: 3  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ): 263.73 Hyd. Diameter ( $\mu\text{m}$ ): 207.01  
 Width ( $\mu\text{m}$ ): 170.37 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 33.69                    | 34.74  | 47.02                                            | 47.76  | 48.14  | 49.89  | 49.86  | 21.54  | 49.17  |
| 2          | 33.33                    | 37.62  | 47.34                                            | 48.09  | 48.49  | 50.24  | 50.20  | 21.86  | 49.52  |
| 3          | 32.83                    | 38.33  | 47.44                                            | 48.22  | 48.63  | 50.38  | 50.35  | 21.94  | 49.67  |
| 4          | 32.36                    | 40.86  | 47.43                                            | 48.22  | 48.65  | 50.40  | 50.37  | 31.25  | 49.71  |
| 5          | 31.84                    | 42.14  | 47.23                                            | 48.05  | 48.50  | 50.24  | 50.21  | 31.17  | 49.58  |
| 6          | 31.37                    | 42.77  | 47.05                                            | 47.88  | 48.35  | 50.09  | 50.07  | 30.93  | 49.46  |
| 7          | 31.09                    | 43.07  | 46.91                                            | 47.76  | 48.26  | 50.00  | 49.97  | 31.01  | 49.39  |
| 8          | 30.86                    | 43.56  | 46.74                                            | 47.61  | 48.14  | 49.88  | 49.85  | 31.10  | 49.30  |
| 9          | 30.70                    | 44.55  | 46.51                                            | 47.40  | 47.95  | 49.69  | 49.67  | 31.39  | 49.15  |
| 10         | 30.60                    | 44.98  | 46.26                                            | 47.17  | 47.73  | 49.47  | 49.45  | 30.87  | 48.96  |
| 11         | 30.47                    | 45.06  | 46.01                                            | 46.93  | 47.52  | 49.27  | 49.24  | 31.04  | 48.78  |
| 12         | 30.49                    | 45.06  | 45.78                                            | 46.71  | 47.32  | 49.06  | 49.04  | 31.03  | 48.60  |
| 13         | 30.44                    | 45.00  | 45.54                                            | 46.49  | 47.12  | 48.86  | 48.84  | 31.33  | 48.43  |
| 14         | 30.28                    | 44.82  | 45.09                                            | 46.07  | 46.70  | 48.44  | 48.43  | 30.74  | 48.05  |
| 15         | 30.19                    | 44.79  | 44.90                                            | 45.90  | 46.54  | 48.28  | 48.27  | 30.95  | 47.91  |
| 16         | 30.07                    | 44.76  | 44.63                                            | 45.63  | 46.30  | 48.03  | 48.02  | 30.30  | 47.70  |
| 17         | 29.95                    | 44.73  | 44.34                                            | 45.36  | 46.05  | 47.78  | 47.77  | 30.76  | 47.48  |
| 18         | 29.83                    | 44.67  | 44.05                                            | 45.08  | 45.78  | 47.52  | 47.51  | 30.94  | 47.23  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.03                        | 1,375,129   | 13,583                    | 3,296  | 28.37                    | 0.00    | 0.00    |
| 2          | 24.07                        | 1,343,503   | 49,435                    | 3,307  | 0.00                     | 129.96  | 0.00    |
| 3          | 24.10                        | 1,335,659   | 94,873                    | 3,400  | 0.00                     | 249.33  | 0.04    |
| 4          | 24.06                        | 1,315,947   | 140,242                   | 3,495  | 0.00                     | 345.09  | 0.00    |
| 5          | 24.03                        | 1,331,070   | 191,422                   | 3,721  | 0.00                     | 0.00    | 404.96  |
| 6          | 24.02                        | 1,300,485   | 252,140                   | 3,875  | 0.00                     | 0.00    | 460.46  |
| 7          | 24.02                        | 1,310,160   | 319,709                   | 4,019  | 0.00                     | 0.00    | 484.90  |
| 8          | 24.04                        | 1,300,259   | 392,793                   | 4,291  | 0.00                     | 0.00    | 502.68  |
| 9          | 24.04                        | 1,300,485   | 450,709                   | 4,453  | 0.00                     | 0.00    | 524.04  |
| 10         | 24.08                        | 1,296,890   | 512,761                   | 4,614  | 0.00                     | 0.00    | 545.22  |
| 11         | 24.06                        | 1,296,303   | 571,920                   | 4,835  | 0.00                     | 0.00    | 561.56  |
| 12         | 24.07                        | 1,300,010   | 628,593                   | 5,104  | 0.00                     | 0.00    | 575.87  |
| 13         | 24.09                        | 1,297,116   | 687,888                   | 5,376  | 0.00                     | 0.00    | 587.99  |
| 14         | 24.08                        | 1,312,466   | 754,054                   | 5,694  | 0.00                     | 0.00    | 599.42  |
| 15         | 24.09                        | 1,322,593   | 791,309                   | 5,812  | 0.00                     | 130.50  | 485.49  |
| 16         | 24.10                        | 1,326,436   | 846,851                   | 6,205  | 0.00                     | 132.01  | 494.31  |
| 17         | 24.13                        | 1,330,661   | 905,646                   | 6,481  | 0.00                     | 133.28  | 502.23  |
| 18         | 24.13                        | 1,327,205   | 963,089                   | 6,757  | 0.00                     | 134.11  | 508.35  |

## Appendix C: Single- and two-phase measured data (continued).

Channel C2: Helium gas tests.

Number of channels:

3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.73Hyd. Diameter ( $\mu\text{m}$ ): 207.01Width ( $\mu\text{m}$ ): 170.37

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 30.69                    | 31.75  | 38.29                                            | 39.38  | 39.69  | 41.48  | 41.45  | 35.20  | 40.61  |
| 2          | 31.12                    | 31.97  | 41.59                                            | 42.28  | 42.70  | 44.47  | 44.44  | 22.10  | 43.54  |
| 3          | 31.65                    | 37.10  | 43.43                                            | 44.19  | 44.68  | 46.45  | 46.41  | 22.04  | 45.59  |
| 4          | 31.66                    | 37.68  | 44.27                                            | 45.10  | 45.60  | 47.36  | 47.32  | 21.99  | 46.53  |
| 5          | 31.43                    | 38.50  | 44.89                                            | 45.75  | 46.28  | 48.04  | 48.00  | 22.00  | 47.23  |
| 6          | 31.39                    | 40.43  | 45.12                                            | 46.02  | 46.57  | 48.32  | 48.28  | 22.08  | 47.53  |
| 7          | 31.34                    | 40.56  | 45.22                                            | 46.15  | 46.72  | 48.47  | 48.43  | 22.11  | 47.70  |
| 8          | 31.45                    | 37.41  | 45.27                                            | 46.22  | 46.77  | 48.53  | 48.49  | 22.23  | 47.69  |
| 9          | 31.45                    | 37.59  | 45.11                                            | 46.05  | 46.62  | 48.37  | 48.34  | 22.16  | 47.55  |
| 10         | 31.47                    | 41.31  | 45.10                                            | 46.07  | 46.67  | 48.42  | 48.39  | 22.14  | 47.67  |
| 11         | 31.75                    | 42.48  | 45.11                                            | 46.12  | 46.74  | 48.49  | 48.46  | 22.24  | 47.80  |
| 12         | 28.50                    | 38.83  | 40.98                                            | 42.03  | 42.61  | 44.37  | 44.35  | 21.71  | 43.73  |
| 13         | 28.80                    | 39.57  | 41.28                                            | 42.32  | 42.93  | 44.69  | 44.67  | 21.76  | 44.07  |
| 14         | 28.95                    | 39.44  | 41.41                                            | 42.47  | 43.08  | 44.83  | 44.81  | 21.85  | 44.19  |
| 15         | 28.97                    | 39.87  | 41.46                                            | 42.54  | 43.16  | 44.91  | 44.89  | 21.96  | 44.27  |
| 16         | 28.97                    | 40.32  | 41.48                                            | 42.58  | 43.22  | 44.97  | 44.96  | 21.87  | 44.36  |
| 17         | 28.90                    | 40.62  | 41.37                                            | 42.47  | 43.14  | 44.89  | 44.87  | 21.81  | 44.31  |
| 18         | 28.81                    | 40.87  | 41.24                                            | 42.36  | 43.05  | 44.80  | 44.79  | 21.91  | 44.26  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.54                        | 1,263,592   | 11,904                    | 3,425  | 25.54                    | 0.00    | 0.00    |
| 2          | 24.54                        | 1,143,375   | 40,817                    | 3,208  | 0.00                     | 121.70  | 0.00    |
| 3          | 24.53                        | 1,144,664   | 83,564                    | 3,305  | 0.00                     | 261.59  | 0.00    |
| 4          | 24.51                        | 1,126,737   | 119,937                   | 3,436  | 0.00                     | 368.03  | 0.00    |
| 5          | 24.52                        | 1,125,358   | 144,238                   | 3,450  | 0.00                     | 0.00    | 457.20  |
| 6          | 24.52                        | 1,115,706   | 174,575                   | 3,504  | 0.00                     | 0.00    | 548.08  |
| 7          | 24.57                        | 1,104,674   | 200,775                   | 3,588  | 0.00                     | 0.00    | 621.36  |
| 8          | 24.65                        | 1,115,706   | 228,354                   | 3,723  | 0.00                     | 0.00    | 694.69  |
| 9          | 24.68                        | 1,108,811   | 250,417                   | 3,732  | 0.00                     | 0.00    | 751.34  |
| 10         | 24.65                        | 1,103,476   | 272,480                   | 3,850  | 0.00                     | 0.00    | 809.26  |
| 11         | 24.66                        | 1,104,674   | 297,301                   | 3,886  | 0.00                     | 0.00    | 873.58  |
| 12         | 24.27                        | 662,032     | 308,333                   | 4,372  | 0.00                     | 0.00    | 923.70  |
| 13         | 24.26                        | 660,653     | 330,328                   | 4,489  | 0.00                     | 0.00    | 974.29  |
| 14         | 24.25                        | 660,653     | 349,701                   | 4,578  | 0.00                     | 0.00    | 1019.32 |
| 15         | 24.22                        | 659,320     | 370,385                   | 4,695  | 0.00                     | 222.71  | 835.85  |
| 16         | 24.22                        | 659,274     | 389,690                   | 4,781  | 0.00                     | 229.37  | 866.93  |
| 17         | 24.18                        | 660,495     | 408,996                   | 4,831  | 0.00                     | 237.13  | 903.22  |
| 18         | 24.14                        | 660,653     | 427,216                   | 4,964  | 0.00                     | 243.97  | 935.99  |

## Appendix C: Single- and two-phase measured data (continued).

Channel C2: Nitrogen gas tests.

Channel Dimensions:

Number of channels: 3

Depth ( $\mu\text{m}$ ): 263.73Hyd. Diameter ( $\mu\text{m}$ ): 207.01Width ( $\mu\text{m}$ ): 170.37

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 31.62                    | 32.12  | 43.24                                            | 43.98  | 44.34  | 46.10  | 46.07  | 21.79  | 45.40  |
| 2          | 32.73                    | 35.77  | 46.48                                            | 47.25  | 47.64  | 49.39  | 49.36  | 21.57  | 48.67  |
| 3          | 32.37                    | 36.88  | 46.62                                            | 47.40  | 47.81  | 49.56  | 49.53  | 22.03  | 48.83  |
| 4          | 32.08                    | 38.97  | 46.66                                            | 47.46  | 47.89  | 49.64  | 49.61  | 21.98  | 48.95  |
| 5          | 31.80                    | 39.94  | 46.60                                            | 47.42  | 47.87  | 49.61  | 49.58  | 22.11  | 48.92  |
| 6          | 31.49                    | 40.73  | 46.47                                            | 47.31  | 47.77  | 49.52  | 49.49  | 22.05  | 48.87  |
| 7          | 31.22                    | 41.30  | 46.36                                            | 47.21  | 47.69  | 49.44  | 49.41  | 22.15  | 48.80  |
| 8          | 30.85                    | 41.66  | 46.17                                            | 47.04  | 47.54  | 49.28  | 49.26  | 22.02  | 48.68  |
| 9          | 30.57                    | 42.09  | 45.96                                            | 46.84  | 47.37  | 49.11  | 49.09  | 22.07  | 48.54  |
| 10         | 30.17                    | 42.00  | 45.67                                            | 46.57  | 47.11  | 48.86  | 48.84  | 21.97  | 48.31  |
| 11         | 29.85                    | 42.22  | 45.39                                            | 46.31  | 46.89  | 48.64  | 48.61  | 21.89  | 48.11  |
| 12         | 29.77                    | 43.27  | 45.12                                            | 46.06  | 46.66  | 48.40  | 48.38  | 21.97  | 47.92  |
| 13         | 29.56                    | 43.81  | 44.88                                            | 45.84  | 46.47  | 48.21  | 48.19  | 22.01  | 47.76  |
| 14         | 29.29                    | 44.11  | 44.62                                            | 45.60  | 46.25  | 47.99  | 47.98  | 21.80  | 47.60  |
| 15         | 29.21                    | 44.22  | 44.41                                            | 45.41  | 46.09  | 47.83  | 47.81  | 21.91  | 47.47  |
| 16         | 29.05                    | 44.22  | 44.17                                            | 45.18  | 45.88  | 47.62  | 47.61  | 22.11  | 47.30  |
| 17         | 29.00                    | 44.19  | 43.85                                            | 44.87  | 45.59  | 47.33  | 47.32  | 21.96  | 47.04  |
| 18         | 28.94                    | 44.15  | 43.57                                            | 44.60  | 45.34  | 47.08  | 47.06  | 21.80  | 46.82  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |          | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|----------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet   | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.13                        | 1074337.3   | 10010.93                  | 3300.43  | 26.34                    | 0.00    | 0.00    |
| 2          | 24.07                        | 952990.03   | 30129.98                  | 3345.641 | 0.00                     | 91.38   | 0.00    |
| 3          | 24.09                        | 904726.9    | 63224.7                   | 3397.634 | 0.00                     | 201.83  | 0.00    |
| 4          | 24.08                        | 896362.8    | 93561.53                  | 3449.627 | 0.00                     | 290.53  | 0.00    |
| 5          | 24.09                        | 890937.43   | 122519.4                  | 3524.226 | 0.00                     | 0.00    | 352.28  |
| 6          | 24.07                        | 884042.7    | 151477.3                  | 3589.782 | 0.00                     | 0.00    | 418.09  |
| 7          | 24.06                        | 881443.05   | 177677.3                  | 3691.508 | 0.00                     | 0.00    | 466.12  |
| 8          | 24.07                        | 879792.83   | 214908.8                  | 3757.064 | 0.00                     | 0.00    | 513.70  |
| 9          | 24.09                        | 878526.91   | 246624.6                  | 3863.311 | 0.00                     | 0.00    | 541.09  |
| 10         | 24.05                        | 877147.97   | 289372                    | 3996.685 | 0.00                     | 0.00    | 556.34  |
| 11         | 24.04                        | 877147.97   | 340031.3                  | 4136.84  | 0.00                     | 0.00    | 566.37  |
| 12         | 24.05                        | 877147.97   | 379003.5                  | 4272.474 | 0.00                     | 0.00    | 583.78  |
| 13         | 24.06                        | 875769.02   | 414856.1                  | 4392.284 | 0.00                     | 0.00    | 599.36  |
| 14         | 24.05                        | 876334.16   | 456224.5                  | 4566.348 | 0.00                     | 0.00    | 613.50  |
| 15         | 24.07                        | 877147.97   | 489319.2                  | 4688.419 | 0.00                     | 132.64  | 495.00  |
| 16         | 24.10                        | 877147.97   | 527929.7                  | 4873.785 | 0.00                     | 134.72  | 506.32  |
| 17         | 24.10                        | 877147.97   | 565161.3                  | 5018.462 | 0.00                     | 136.25  | 515.47  |
| 18         | 24.11                        | 878526.91   | 602392.8                  | 5140.532 | 0.00                     | 137.53  | 523.76  |

# Appendix C: Single- and two-phase measured data (continued).

Channel C2: Water tests.

Number of channels:

3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.73Hyd. Diameter ( $\mu\text{m}$ ): 207.01Width ( $\mu\text{m}$ ): 170.37

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 23.46                    | 34.42  | 30.96                                            | 33.88  | 36.82  | 38.16  | 38.41  | 26.26  | 39.69  |
| 2          | 23.40                    | 35.30  | 31.87                                            | 35.50  | 39.06  | 40.22  | 40.58  | 26.93  | 41.56  |
| 3          | 23.59                    | 35.89  | 32.52                                            | 36.67  | 40.72  | 41.73  | 42.19  | 27.61  | 42.89  |
| 4          | 23.86                    | 35.97  | 32.86                                            | 37.40  | 41.85  | 42.74  | 43.28  | 28.18  | 43.91  |
| 5          | 24.10                    | 35.47  | 32.10                                            | 36.40  | 40.50  | 41.41  | 41.95  | 28.11  | 40.90  |
| 6          | 24.27                    | 36.35  | 32.86                                            | 37.54  | 41.93  | 42.68  | 43.31  | 28.02  | 41.96  |
| 7          | 24.39                    | 37.29  | 33.16                                            | 37.74  | 42.01  | 42.40  | 43.21  | 28.79  | 42.51  |
| 8          | 24.71                    | 38.62  | 33.81                                            | 38.44  | 43.01  | 43.24  | 44.17  | 28.86  | 43.39  |
| 9          | 24.92                    | 39.97  | 34.55                                            | 39.22  | 43.97  | 44.06  | 45.10  | 29.14  | 44.12  |
| 10         | 25.22                    | 39.77  | 34.14                                            | 38.51  | 43.32  | 43.39  | 44.44  | 29.09  | 43.49  |
| 11         | 25.40                    | 41.45  | 35.15                                            | 39.80  | 45.03  | 44.93  | 46.10  | 30.32  | 45.28  |
| 12         | 25.65                    | 41.23  | 34.68                                            | 38.84  | 44.48  | 44.54  | 45.68  | 30.22  | 44.90  |
| 13         | 25.73                    | 40.90  | 34.25                                            | 38.24  | 43.90  | 43.98  | 45.14  | 30.58  | 44.46  |
| 14         | 25.80                    | 40.34  | 33.71                                            | 37.59  | 43.15  | 43.24  | 44.43  | 30.52  | 43.77  |
| 15         | 25.91                    | 41.11  | 34.21                                            | 38.26  | 44.14  | 44.07  | 45.39  | 30.39  | 44.67  |
| 16         | 26.02                    | 40.71  | 33.92                                            | 37.84  | 43.67  | 43.59  | 44.94  | 30.47  | 44.19  |
| 17         | 26.13                    | 40.34  | 33.68                                            | 37.49  | 43.25  | 43.18  | 44.53  | 30.24  | 43.74  |
| 18         | 26.19                    | 39.65  | 33.22                                            | 36.85  | 42.50  | 42.43  | 43.79  | 29.64  | 42.92  |
| 19         | 26.30                    | 39.04  | 32.85                                            | 36.33  | 41.87  | 41.80  | 43.17  | 29.76  | 42.19  |
| 20         | 26.42                    | 39.63  | 33.33                                            | 36.96  | 42.93  | 42.65  | 44.17  | 29.72  | 43.00  |
| 21         | 26.11                    | 37.50  | 31.56                                            | 34.43  | 39.45  | 39.51  | 40.60  | 34.09  | 39.95  |
| 22         | 26.15                    | 36.60  | 30.96                                            | 33.61  | 38.48  | 38.55  | 39.64  | 33.30  | 38.85  |
| 23         | 26.25                    | 35.93  | 30.54                                            | 33.02  | 37.74  | 37.82  | 38.91  | 32.75  | 38.01  |
| 24         | 26.31                    | 35.40  | 30.21                                            | 32.54  | 37.18  | 37.25  | 38.35  | 32.27  | 37.36  |
| 25         | 26.40                    | 35.03  | 29.97                                            | 32.20  | 36.75  | 36.84  | 37.93  | 31.93  | 36.89  |
| 26         | 26.42                    | 34.68  | 29.73                                            | 31.87  | 36.36  | 36.44  | 37.54  | 31.73  | 36.45  |
| 27         | 26.43                    | 34.38  | 29.51                                            | 31.58  | 35.99  | 36.09  | 37.18  | 34.57  | 36.08  |
| 28         | 26.42                    | 34.12  | 29.34                                            | 31.34  | 35.69  | 35.78  | 36.88  | 34.43  | 35.76  |

## Appendix C: Single- and two-phase measured data (continued).

## Channel C2: Water tests (continued).

| Data Point | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | liquid Flow Rate   |
|------------|-------------------|------------|---------------------------|---------|--------------------|
|            | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F. M. #1, (cc/min) |
| 1          | 23.94             | 1,647,979  | 263,990                   | 101,796 | 18.29              |
| 2          | 24.04             | 1,627,860  | 338,566                   | 100,975 | 24.95              |
| 3          | 24.32             | 1,588,119  | 407,378                   | 99,056  | 31.30              |
| 4          | 24.70             | 1,571,165  | 479,875                   | 98,423  | 38.83              |
| 5          | 25.14             | 1,545,937  | 542,877                   | 97,340  | 42.26              |
| 6          | 25.56             | 1,511,283  | 611,847                   | 96,104  | 47.34              |
| 7          | 25.91             | 1,500,568  | 688,661                   | 95,412  | 51.65              |
| 8          | 26.23             | 1,493,243  | 757,902                   | 95,294  | 54.77              |
| 9          | 26.48             | 1,485,693  | 824,363                   | 95,025  | 55.72              |
| 10         | 26.71             | 1,480,335  | 903,392                   | 94,935  | 58.41              |
| 11         | 26.86             | 1,460,488  | 962,596                   | 93,868  | 59.38              |
| 12         | 27.00             | 1,465,077  | 1,039,682                 | 94,035  | 62.44              |
| 13         | 27.12             | 1,461,301  | 1,108,878                 | 93,694  | 65.51              |
| 14         | 27.23             | 1,462,160  | 1,214,763                 | 93,610  | 68.80              |
| 15         | 27.35             | 2,176,568  | 1,326,932                 | 93,194  | 70.59              |
| 16         | 27.47             | 2,206,837  | 1,433,111                 | 93,771  | 75.98              |
| 17         | 27.62             | 2,225,713  | 1,523,647                 | 94,623  | 77.88              |
| 18         | 27.79             | 2,252,478  | 1,690,658                 | 95,593  | 84.15              |
| 19         | 27.99             | 2,240,632  | 1,864,495                 | 95,561  | 89.42              |
| 20         | 28.23             | 2,226,617  | 2,075,429                 | 95,697  | 92.52              |
| 21         | 27.32             | 5,094,261  | 1,721,729                 | 103,656 | 81.22              |
| 22         | 27.49             | 5,034,966  | 2,060,385                 | 103,771 | 89.22              |
| 23         | 27.78             | 5,018,600  | 2,407,947                 | 104,011 | 98.75              |
| 24         | 27.93             | 4,969,523  | 2,763,693                 | 103,493 | 108.35             |
| 25         | 28.06             | 4,916,422  | 3,094,663                 | 102,795 | 116.16             |
| 26         | 28.14             | 4,910,686  | 3,477,963                 | 103,469 | 121.51             |
| 27         | 28.23             | 4,894,517  | 3,808,121                 | 102,356 | 128.71             |
| 28         | 28.28             | 4,837,099  | 4,126,929                 | 102,273 | 135.78             |

# Appendix C: Single- and two-phase measured data (continued).

Channel C2: Water and argon tests.      Number of channels:      3

Channel Dimensions:

Depth ( $\mu\text{m}$ ):      263.73      Hyd. Diameter ( $\mu\text{m}$ ):      207.01

Width ( $\mu\text{m}$ ):      170.37      Channel Length (m):      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 28.48                    | 46.27  | 37.73                                            | 41.69  | 45.11  | 46.51  | 46.69  | 28.04  | 48.50  |
| 2          | 28.09                    | 45.18  | 36.88                                            | 40.83  | 44.21  | 45.63  | 45.81  | 27.89  | 47.47  |
| 3          | 27.97                    | 44.17  | 36.29                                            | 40.10  | 43.33  | 44.77  | 44.95  | 28.33  | 46.22  |
| 4          | 29.04                    | 47.61  | 39.68                                            | 43.60  | 46.88  | 48.33  | 48.48  | 28.07  | 49.64  |
| 5          | 26.45                    | 37.77  | 31.28                                            | 34.47  | 37.34  | 38.74  | 38.97  | 28.80  | 40.32  |
| 6          | 26.71                    | 43.02  | 34.74                                            | 39.43  | 43.53  | 44.78  | 45.07  | 28.51  | 46.61  |
| 7          | 26.93                    | 43.77  | 35.18                                            | 39.86  | 43.93  | 45.19  | 45.48  | 28.78  | 46.44  |
| 8          | 27.27                    | 45.64  | 36.36                                            | 41.01  | 45.06  | 46.33  | 46.61  | 28.62  | 47.87  |
| 9          | 26.46                    | 43.07  | 35.00                                            | 40.66  | 45.66  | 46.66  | 47.09  | 28.41  | 48.55  |
| 10         | 26.86                    | 44.57  | 35.68                                            | 41.48  | 46.67  | 47.67  | 48.11  | 29.20  | 49.30  |
| 11         | 27.20                    | 46.23  | 36.35                                            | 41.85  | 46.81  | 47.86  | 48.30  | 29.09  | 49.29  |
| 12         | 26.67                    | 40.76  | 33.82                                            | 39.16  | 43.95  | 44.94  | 45.40  | 29.16  | 46.33  |
| 13         | 27.05                    | 43.03  | 34.45                                            | 39.67  | 44.49  | 45.51  | 45.96  | 28.55  | 46.89  |
| 14         | 27.29                    | 44.57  | 35.30                                            | 40.47  | 45.19  | 46.24  | 46.70  | 28.87  | 47.53  |
| 15         | 26.37                    | 38.49  | 32.64                                            | 36.01  | 41.78  | 41.60  | 42.82  | 37.46  | 43.43  |
| 16         | 26.37                    | 38.62  | 32.70                                            | 36.11  | 41.95  | 41.76  | 42.99  | 36.94  | 43.55  |
| 17         | 26.33                    | 39.30  | 33.03                                            | 36.73  | 42.77  | 42.59  | 43.80  | 37.69  | 44.30  |
| 18         | 26.23                    | 39.02  | 32.76                                            | 36.41  | 42.40  | 42.22  | 43.43  | 37.33  | 43.87  |
| 19         | 26.15                    | 39.04  | 32.71                                            | 36.40  | 42.40  | 42.24  | 43.44  | 37.30  | 43.79  |
| 20         | 26.12                    | 37.12  | 31.72                                            | 34.77  | 40.35  | 40.18  | 41.41  | 35.35  | 41.70  |
| 21         | 26.15                    | 37.30  | 31.77                                            | 34.90  | 40.51  | 40.35  | 41.57  | 35.42  | 41.87  |
| 22         | 26.15                    | 36.78  | 31.51                                            | 34.46  | 39.95  | 39.79  | 41.02  | 35.00  | 41.29  |
| 23         | 26.18                    | 36.99  | 31.56                                            | 34.60  | 40.12  | 39.98  | 41.19  | 35.79  | 41.40  |
| 24         | 26.14                    | 37.58  | 31.87                                            | 35.15  | 40.83  | 40.68  | 41.89  | 36.22  | 42.03  |
| 25         | 26.10                    | 37.70  | 31.92                                            | 35.26  | 40.97  | 40.83  | 42.03  | 36.42  | 42.13  |
| 26         | 26.07                    | 38.02  | 32.11                                            | 35.56  | 41.36  | 41.22  | 42.41  | 36.63  | 42.48  |
| 27         | 24.68                    | 36.02  | 29.47                                            | 32.19  | 34.61  | 36.10  | 36.22  | 36.39  | 37.40  |
| 28         | 24.70                    | 36.06  | 29.50                                            | 32.18  | 34.59  | 36.05  | 36.16  | 36.48  | 37.31  |
| 29         | 24.80                    | 36.02  | 29.51                                            | 32.17  | 34.71  | 36.10  | 36.27  | 36.37  | 37.31  |
| 30         | 24.74                    | 35.99  | 29.28                                            | 31.88  | 34.25  | 35.73  | 35.85  | 36.28  | 36.98  |
| 31         | 24.76                    | 35.98  | 29.49                                            | 32.07  | 34.40  | 35.86  | 35.97  | 36.35  | 36.97  |
| 32         | 24.78                    | 36.19  | 29.38                                            | 31.94  | 34.32  | 35.79  | 35.91  | 36.24  | 37.05  |
| 33         | 24.59                    | 35.28  | 28.65                                            | 31.07  | 33.39  | 34.86  | 34.98  | 35.64  | 36.07  |
| 34         | 24.58                    | 35.13  | 28.78                                            | 31.21  | 33.50  | 34.97  | 35.09  | 35.66  | 36.01  |
| 35         | 24.57                    | 35.12  | 29.05                                            | 31.50  | 33.75  | 35.19  | 35.30  | 35.82  | 36.06  |



## Appendix C: Single- and two-phase measured data (continued).

Channel C2: Water and argon (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.30          | 1,667,171  | 26.79             | 1,524,996  | 297,847                   | 93,526  | 0.00                            | 47.60   | 0.00    | 8.96    |
| 2          | 25.32          | 1,674,654  | 26.71             | 1,517,130  | 555,823                   | 100,347 | 0.00                            | 131.88  | 0.00    | 11.44   |
| 3          | 25.31          | 1,670,992  | 26.65             | 1,526,760  | 858,242                   | 110,013 | 0.00                            | 0.00    | 175.22  | 9.95    |
| 4          | 25.29          | 1,672,868  | 26.55             | 1,538,831  | 1,128,018                 | 121,289 | 0.00                            | 0.00    | 236.31  | 6.49    |
| 5          | 25.26          | 1,689,574  | 26.68             | 1,572,536  | 535,280                   | 98,228  | 0.00                            | 38.96   | 0.00    | 18.89   |
| 6          | 25.26          | 1,679,627  | 26.76             | 1,551,784  | 752,560                   | 102,503 | 0.00                            | 103.53  | 0.00    | 18.73   |
| 7          | 25.29          | 1,672,416  | 26.85             | 1,562,205  | 1,061,761                 | 112,246 | 0.00                            | 0.00    | 146.20  | 17.76   |
| 8          | 25.28          | 1,661,452  | 26.87             | 1,554,293  | 1,247,896                 | 119,204 | 0.00                            | 0.00    | 183.07  | 13.02   |
| 9          | 25.33          | 1,690,772  | 27.21             | 1,585,037  | 764,948                   | 102,117 | 0.00                            | 33.02   | 0.02    | 26.00   |
| 10         | 25.32          | 1,677,819  | 27.35             | 1,563,833  | 1,018,606                 | 104,850 | 0.00                            | 84.62   | 0.00    | 24.99   |
| 11         | 25.32          | 1,670,268  | 27.41             | 1,557,458  | 1,269,462                 | 113,422 | 0.00                            | 0.00    | 127.86  | 21.02   |
| 12         | 25.32          | 1,661,000  | 27.74             | 1,600,025  | 968,354                   | 103,303 | 0.00                            | 25.74   | 0.00    | 32.38   |
| 13         | 25.33          | 1,677,412  | 27.85             | 1,518,983  | 1,176,281                 | 104,029 | 0.00                            | 79.16   | 0.00    | 28.97   |
| 14         | 25.34          | 1,670,947  | 27.82             | 1,576,470  | 1,398,766                 | 114,613 | 0.00                            | 0.00    | 118.80  | 25.04   |
| 15         | 22.63          | 3,078,648  | 27.51             | 4,876,854  | 1,876,666                 | 112,515 | 0.00                            | 0.00    | 144.05  | 79.72   |
| 16         | 22.60          | 2,843,571  | 27.45             | 4,832,615  | 2,024,440                 | 117,025 | 0.00                            | 0.00    | 212.55  | 79.15   |
| 17         | 22.55          | 2,853,179  | 27.37             | 4,708,577  | 2,219,933                 | 126,002 | 0.00                            | 49.68   | 188.08  | 72.12   |
| 18         | 22.54          | 2,820,581  | 27.29             | 4,691,284  | 2,320,529                 | 127,810 | 0.00                            | 51.08   | 194.59  | 74.12   |
| 19         | 22.57          | 2,808,171  | 27.21             | 4,668,701  | 2,408,714                 | 130,627 | 0.00                            | 55.40   | 213.45  | 72.77   |
| 20         | 22.43          | 3,045,101  | 27.34             | 4,882,528  | 2,214,576                 | 112,484 | 0.00                            | 26.21   | 0.00    | 88.53   |
| 21         | 22.54          | 2,833,534  | 27.35             | 4,832,547  | 2,338,772                 | 117,480 | 0.00                            | 45.23   | 0.00    | 87.82   |
| 22         | 22.64          | 3,108,532  | 27.40             | 4,915,758  | 2,312,888                 | 112,165 | 0.00                            | 0.00    | 93.40   | 91.68   |
| 23         | 22.48          | 2,895,225  | 27.43             | 4,782,023  | 2,460,119                 | 117,701 | 0.00                            | 0.00    | 158.10  | 89.94   |
| 24         | 22.55          | 2,843,503  | 27.36             | 4,667,096  | 2,604,434                 | 126,221 | 0.00                            | 40.76   | 153.70  | 84.60   |
| 25         | 22.53          | 2,814,048  | 27.30             | 4,672,657  | 2,647,565                 | 129,189 | 0.00                            | 43.92   | 166.82  | 82.77   |
| 26         | 22.56          | 2,780,094  | 27.25             | 4,609,790  | 2,715,134                 | 132,300 | 0.00                            | 50.75   | 195.87  | 78.52   |
| 27         | 23.31          | 4,371,489  | 24.74             | 4,650,933  | 639,125                   | 124,560 | 0.00                            | 66.77   | 240.07  | 10.87   |
| 28         | 23.28          | 4,268,317  | 24.73             | 4,664,428  | 714,560                   | 128,886 | 0.00                            | 72.44   | 262.64  | 10.18   |
| 29         | 23.29          | 4,190,373  | 24.84             | 4,594,712  | 911,975                   | 132,196 | 0.00                            | 74.86   | 275.43  | 13.26   |
| 30         | 23.29          | 4,232,487  | 24.71             | 4,605,993  | 889,370                   | 134,513 | 0.00                            | 80.85   | 298.06  | 10.30   |
| 31         | 23.35          | 4,343,888  | 24.70             | 4,627,491  | 935,892                   | 138,293 | 0.00                            | 85.76   | 318.51  | 11.51   |
| 32         | 23.28          | 4,269,425  | 24.66             | 4,600,952  | 1,051,633                 | 141,166 | 0.00                            | 87.13   | 326.39  | 9.17    |
| 33         | 23.28          | 4,265,288  | 24.63             | 4,560,533  | 1,182,565                 | 144,509 | 0.00                            | 87.47   | 330.49  | 11.75   |
| 34         | 23.27          | 4,258,596  | 24.63             | 4,516,067  | 1,247,828                 | 147,507 | 0.00                            | 91.26   | 347.73  | 10.19   |
| 35         | 23.26          | 4,259,071  | 24.59             | 4,505,420  | 1,322,902                 | 151,322 | 0.00                            | 93.30   | 357.93  | 9.64    |

# Appendix C: Single- and two-phase measured data (continued).

Channel C2: Water and helium tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.73 Hyd. Diameter ( $\mu\text{m}$ ): 207.01

Width ( $\mu\text{m}$ ): 170.37 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.23                    | 39.08  | 32.71                                            | 36.17  | 39.39  | 40.73  | 40.99  | 28.77  | 42.31  |
| 2          | 26.38                    | 40.88  | 33.28                                            | 37.23  | 40.75  | 42.09  | 42.32  | 29.61  | 43.67  |
| 3          | 26.49                    | 41.72  | 33.81                                            | 37.64  | 41.15  | 42.49  | 42.72  | 29.40  | 43.95  |
| 4          | 26.95                    | 43.83  | 35.74                                            | 39.79  | 43.40  | 44.74  | 44.95  | 29.69  | 46.10  |
| 5          | 27.00                    | 47.01  | 37.80                                            | 44.47  | 50.30  | 51.13  | 51.61  | 32.35  | 53.45  |
| 6          | 27.68                    | 48.03  | 38.19                                            | 44.44  | 49.82  | 50.80  | 51.20  | 32.89  | 52.43  |
| 7          | 28.18                    | 50.54  | 39.98                                            | 46.20  | 51.51  | 52.50  | 52.89  | 34.20  | 54.10  |
| 8          | 28.54                    | 52.22  | 41.17                                            | 47.30  | 52.70  | 53.66  | 54.05  | 34.55  | 55.68  |
| 9          | 26.91                    | 40.89  | 34.09                                            | 39.49  | 44.27  | 45.25  | 45.71  | 32.20  | 46.58  |
| 10         | 27.38                    | 43.26  | 35.03                                            | 40.62  | 45.54  | 46.53  | 46.98  | 32.83  | 47.62  |
| 11         | 27.57                    | 44.76  | 35.84                                            | 41.23  | 45.99  | 47.00  | 47.44  | 32.86  | 48.03  |
| 12         | 25.53                    | 37.10  | 31.54                                            | 34.77  | 40.43  | 40.27  | 41.49  | 38.58  | 42.03  |
| 13         | 25.76                    | 37.27  | 31.65                                            | 34.89  | 40.57  | 40.40  | 41.63  | 39.32  | 42.11  |
| 14         | 25.89                    | 37.31  | 31.76                                            | 34.94  | 40.58  | 40.42  | 41.65  | 39.41  | 42.12  |
| 15         | 25.97                    | 37.41  | 31.83                                            | 35.02  | 40.70  | 40.53  | 41.76  | 39.43  | 42.19  |
| 16         | 26.04                    | 37.16  | 31.67                                            | 34.81  | 40.40  | 40.23  | 41.47  | 38.48  | 41.88  |
| 17         | 26.08                    | 37.36  | 31.73                                            | 35.06  | 40.81  | 40.64  | 41.87  | 38.75  | 42.11  |
| 18         | 26.05                    | 37.21  | 31.53                                            | 34.83  | 40.55  | 40.39  | 41.61  | 38.61  | 41.81  |
| 19         | 26.04                    | 37.31  | 31.58                                            | 34.90  | 40.66  | 40.49  | 41.72  | 38.65  | 41.91  |
| 37         | 25.63                    | 35.78  | 33.47                                            | 36.25  | 38.19  | 39.90  | 39.65  | 40.71  | 40.27  |
| 38         | 25.53                    | 35.61  | 33.40                                            | 36.18  | 38.11  | 39.83  | 39.57  | 40.62  | 40.10  |

## Appendix C: Single- and two-phase measured data (continued).

Channel A: Water and helium (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.23          | 1,458,996  | 26.60             | 1,598,985  | 343,917                   | 101,513 | 0.00                            | 49.26   | 0.00    | 19.20   |
| 2          | 24.24          | 1,431,778  | 26.44             | 1,610,039  | 581,435                   | 122,068 | 0.00                            | 0.00    | 293.54  | 16.69   |
| 3          | 24.26          | 1,423,256  | 26.34             | 1,623,602  | 790,221                   | 138,281 | 0.00                            | 0.00    | 442.70  | 12.33   |
| 4          | 24.28          | 1,413,355  | 26.15             | 1,631,062  | 1,076,070                 | 153,558 | 0.00                            | 111.82  | 430.55  | 10.27   |
| 5          | 25.38          | 1,472,830  | 27.42             | 1,559,334  | 599,881                   | 100,041 | 0.00                            | 34.60   | 0.00    | 23.71   |
| 6          | 25.41          | 1,442,516  | 27.42             | 1,562,205  | 802,157                   | 119,783 | 0.00                            | 0.00    | 238.89  | 17.94   |
| 7          | 25.44          | 1,425,652  | 27.35             | 1,580,697  | 995,684                   | 135,797 | 0.00                            | 0.00    | 385.01  | 16.17   |
| 8          | 25.44          | 1,423,143  | 27.23             | 1,582,550  | 1,189,279                 | 147,018 | 0.00                            | 96.25   | 366.47  | 11.13   |
| 9          | 25.41          | 1,477,012  | 27.76             | 1,515,728  | 886,499                   | 99,343  | 0.00                            | 28.01   | 0.00    | 32.21   |
| 10         | 25.42          | 1,446,653  | 27.83             | 1,528,681  | 1,029,231                 | 119,051 | 0.00                            | 0.00    | 196.84  | 27.25   |
| 11         | 25.42          | 1,431,191  | 27.77             | 1,536,638  | 1,201,328                 | 134,314 | 0.00                            | 0.00    | 328.65  | 21.91   |
| 12         | 22.75          | 3,463,329  | 26.82             | 4,563,358  | 1,730,747                 | 109,724 | 0.00                            | 17.70   | 0.00    | 83.23   |
| 13         | 22.77          | 3,046,480  | 26.97             | 4,665,423  | 1,831,432                 | 118,359 | 0.00                            | 41.11   | 0.00    | 82.53   |
| 14         | 22.80          | 3,236,526  | 27.09             | 4,678,331  | 1,818,004                 | 115,438 | 0.00                            | 0.00    | 92.15   | 85.20   |
| 15         | 22.78          | 3,014,221  | 27.15             | 4,695,285  | 1,891,473                 | 120,362 | 0.00                            | 0.00    | 141.29  | 83.60   |
| 16         | 22.83          | 3,026,202  | 27.21             | 4,717,371  | 2,087,057                 | 126,664 | 0.00                            | 0.00    | 191.47  | 85.75   |
| 17         | 22.79          | 3,049,373  | 27.20             | 4,717,484  | 2,201,058                 | 139,213 | 0.00                            | 48.63   | 183.88  | 82.82   |
| 18         | 22.79          | 2,979,703  | 27.19             | 4,732,449  | 2,340,648                 | 143,049 | 0.00                            | 52.58   | 201.57  | 83.95   |
| 19         | 22.79          | 2,957,232  | 27.18             | 4,749,584  | 2,383,033                 | 146,562 | 0.00                            | 57.44   | 223.02  | 85.20   |

# Appendix C: Single- and two-phase measured data (continued).

Channel C2: Water and nitrogen tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.73 Hyd. Diameter ( $\mu\text{m}$ ): 207.01

Width ( $\mu\text{m}$ ): 170.37 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 25.68                    | 42.92  | 35.40                                            | 39.29  | 42.88  | 44.21  | 44.43  | 29.25  | 46.12  |
| 2          | 25.92                    | 42.99  | 35.69                                            | 39.64  | 43.29  | 44.61  | 44.84  | 29.84  | 46.80  |
| 3          | 26.08                    | 46.16  | 37.38                                            | 41.93  | 45.87  | 47.22  | 47.41  | 30.48  | 49.30  |
| 4          | 26.68                    | 48.08  | 38.77                                            | 43.49  | 47.57  | 48.93  | 49.10  | 31.11  | 50.89  |
| 5          | 26.30                    | 44.83  | 35.82                                            | 39.94  | 43.67  | 45.02  | 45.24  | 30.27  | 46.83  |
| 6          | 25.08                    | 39.77  | 33.81                                            | 38.16  | 42.28  | 43.41  | 43.79  | 29.89  | 45.13  |
| 7          | 25.31                    | 40.91  | 34.24                                            | 38.80  | 43.11  | 44.22  | 44.60  | 30.13  | 46.18  |
| 8          | 25.56                    | 44.45  | 35.70                                            | 40.91  | 45.63  | 46.77  | 47.11  | 30.73  | 48.76  |
| 9          | 25.97                    | 46.65  | 36.93                                            | 42.17  | 46.91  | 48.04  | 48.38  | 31.17  | 49.91  |
| 10         | 26.66                    | 49.49  | 38.58                                            | 43.76  | 48.56  | 49.68  | 50.02  | 31.62  | 52.01  |
| 11         | 25.17                    | 38.35  | 33.83                                            | 38.87  | 43.80  | 44.67  | 45.23  | 29.72  | 46.13  |
| 12         | 25.58                    | 39.81  | 34.37                                            | 39.53  | 44.55  | 45.43  | 45.98  | 30.69  | 46.97  |
| 13         | 25.95                    | 43.02  | 34.71                                            | 39.72  | 44.66  | 45.54  | 46.08  | 30.87  | 47.13  |
| 14         | 26.22                    | 45.13  | 35.59                                            | 40.39  | 45.25  | 46.09  | 46.63  | 31.17  | 48.02  |
| 15         | 26.60                    | 49.08  | 37.96                                            | 43.26  | 48.56  | 49.37  | 49.92  | 31.90  | 51.94  |
| 16         | 25.66                    | 39.80  | 34.03                                            | 38.69  | 43.82  | 44.44  | 45.22  | 30.78  | 45.43  |
| 17         | 26.07                    | 41.13  | 34.53                                            | 39.31  | 44.46  | 45.08  | 45.85  | 30.95  | 46.19  |
| 18         | 26.36                    | 44.56  | 35.56                                            | 40.37  | 45.60  | 46.12  | 46.91  | 31.28  | 48.11  |
| 19         | 26.71                    | 48.39  | 37.43                                            | 42.74  | 48.43  | 48.93  | 49.71  | 32.58  | 51.63  |
| 20         | 26.18                    | 37.76  | 32.14                                            | 35.33  | 40.97  | 40.80  | 42.01  | 39.19  | 42.56  |
| 21         | 26.27                    | 37.89  | 32.25                                            | 35.45  | 41.13  | 40.95  | 42.17  | 39.99  | 42.70  |
| 22         | 26.28                    | 37.84  | 32.19                                            | 35.42  | 41.11  | 40.92  | 42.14  | 39.98  | 42.62  |
| 23         | 26.30                    | 38.26  | 32.40                                            | 35.83  | 41.66  | 41.47  | 42.68  | 37.24  | 43.10  |
| 24         | 26.29                    | 38.07  | 32.24                                            | 35.62  | 41.42  | 41.23  | 42.45  | 37.08  | 42.82  |
| 25         | 26.25                    | 38.16  | 32.25                                            | 35.66  | 41.50  | 41.31  | 42.52  | 36.56  | 42.88  |
| 26         | 26.21                    | 36.66  | 31.47                                            | 34.34  | 39.82  | 39.62  | 40.87  | 35.26  | 41.14  |
| 27         | 26.28                    | 36.88  | 31.62                                            | 34.55  | 40.05  | 39.87  | 41.11  | 35.49  | 41.39  |
| 28         | 26.33                    | 36.84  | 31.58                                            | 34.52  | 40.03  | 39.84  | 41.08  | 35.47  | 41.28  |
| 29         | 26.33                    | 37.26  | 31.76                                            | 34.87  | 40.48  | 40.30  | 41.53  | 35.87  | 41.69  |
| 30         | 26.32                    | 37.33  | 31.78                                            | 34.93  | 40.57  | 40.39  | 41.61  | 35.90  | 41.77  |
| 31         | 26.24                    | 37.19  | 31.66                                            | 34.81  | 40.45  | 40.27  | 41.50  | 35.85  | 41.59  |
| 32         | 24.57                    | 34.62  | 28.57                                            | 31.10  | 33.37  | 34.87  | 34.98  | 35.75  | 36.05  |
| 33         | 24.62                    | 34.92  | 28.67                                            | 31.24  | 33.53  | 35.01  | 35.12  | 35.87  | 36.26  |
| 34         | 24.63                    | 35.10  | 28.69                                            | 31.26  | 33.59  | 35.07  | 35.18  | 35.97  | 36.38  |
| 35         | 24.64                    | 35.38  | 28.85                                            | 31.44  | 33.80  | 35.29  | 35.41  | 36.02  | 36.61  |
| 36         | 24.66                    | 35.51  | 28.95                                            | 31.54  | 33.92  | 35.39  | 35.50  | 36.12  | 36.70  |
| 37         | 24.60                    | 35.36  | 28.75                                            | 31.31  | 33.69  | 35.16  | 35.28  | 32.32  | 36.49  |
| 38         | 24.61                    | 35.30  | 28.76                                            | 31.31  | 33.66  | 35.12  | 35.24  | 32.79  | 36.39  |

## Appendix C: Single- and two-phase measured data (continued).

Channel C2: Water and nitrogen (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.54          | 1,595,579  | 24.50             | 1,684,095  | 253,721                   | 107,298 | 0.00                            | 20.82   | 0.00    | 11.26   |
| 2          | 24.52          | 1,578,399  | 24.51             | 1,660,653  | 272,913                   | 103,557 | 0.00                            | 39.45   | 0.00    | 12.52   |
| 3          | 24.52          | 1,586,605  | 24.57             | 1,627,490  | 427,445                   | 108,274 | 0.00                            | 0.00    | 140.65  | 10.23   |
| 4          | 24.49          | 1,563,863  | 24.54             | 1,598,985  | 639,102                   | 116,218 | 0.00                            | 0.00    | 220.94  | 8.47    |
| 5          | 24.47          | 1,562,756  | 24.57             | 1,590,282  | 890,545                   | 124,942 | 0.00                            | 0.00    | 261.15  | 11.25   |
| 6          | 24.38          | 1,700,583  | 24.86             | 1,611,893  | 405,043                   | 104,337 | 0.00                            | 15.33   | 0.00    | 23.30   |
| 7          | 24.35          | 1,594,607  | 25.12             | 1,586,032  | 419,036                   | 102,775 | 0.00                            | 29.90   | 0.00    | 23.75   |
| 8          | 24.39          | 1,584,050  | 25.31             | 1,546,540  | 577,253                   | 105,338 | 0.00                            | 0.00    | 120.36  | 18.90   |
| 9          | 24.39          | 1,562,484  | 25.39             | 1,564,511  | 786,536                   | 114,554 | 0.00                            | 0.00    | 189.82  | 17.28   |
| 10         | 24.35          | 1,548,152  | 25.37             | 1,569,032  | 1,000,070                 | 123,970 | 0.00                            | 0.00    | 244.72  | 13.31   |
| 11         | 24.25          | 1,690,026  | 26.17             | 1,596,385  | 614,982                   | 103,224 | 0.00                            | 12.15   | 0.00    | 39.62   |
| 12         | 24.21          | 1,591,872  | 26.50             | 1,562,364  | 626,172                   | 103,724 | 0.00                            | 23.43   | 0.00    | 37.13   |
| 13         | 24.21          | 1,580,840  | 26.65             | 1,551,038  | 805,322                   | 107,336 | 0.00                            | 0.00    | 99.67   | 31.67   |
| 14         | 24.22          | 1,561,264  | 26.64             | 1,558,159  | 986,032                   | 115,456 | 0.00                            | 0.00    | 158.15  | 25.99   |
| 15         | 24.22          | 1,560,812  | 26.53             | 1,571,632  | 1,158,242                 | 124,058 | 0.00                            | 0.00    | 213.48  | 20.55   |
| 16         | 24.17          | 1,698,164  | 27.16             | 1,589,264  | 832,923                   | 101,407 | 0.00                            | 8.76    | 0.00    | 47.98   |
| 17         | 24.14          | 1,592,414  | 27.32             | 1,508,517  | 834,641                   | 102,013 | 0.00                            | 18.68   | 0.00    | 45.30   |
| 18         | 24.17          | 1,579,145  | 27.33             | 1,552,779  | 1,005,947                 | 107,492 | 0.00                            | 0.00    | 85.11   | 37.32   |
| 19         | 24.21          | 1,539,381  | 27.14             | 1,572,536  | 1,159,824                 | 117,509 | 0.00                            | 0.00    | 148.11  | 29.96   |
| 20         | 22.69          | 3,391,714  | 27.47             | 4,818,599  | 1,802,474                 | 108,076 | 0.00                            | 0.00    | 55.97   | 82.67   |
| 21         | 22.69          | 3,336,239  | 27.50             | 4,814,440  | 1,833,444                 | 109,988 | 0.00                            | 0.00    | 72.87   | 83.52   |
| 22         | 22.63          | 3,056,811  | 27.51             | 4,831,100  | 1,954,000                 | 114,545 | 0.00                            | 0.00    | 130.66  | 83.74   |
| 23         | 22.64          | 2,823,113  | 27.47             | 4,810,800  | 2,136,745                 | 125,344 | 0.00                            | 37.50   | 142.26  | 78.41   |
| 24         | 22.65          | 2,791,985  | 27.45             | 4,784,465  | 2,245,794                 | 126,418 | 0.00                            | 38.50   | 147.04  | 80.83   |
| 25         | 22.68          | 2,797,071  | 27.41             | 4,767,442  | 2,306,943                 | 128,136 | 0.00                            | 42.39   | 164.01  | 80.33   |
| 26         | 22.71          | 3,445,244  | 27.61             | 4,882,234  | 2,245,862                 | 109,271 | 0.00                            | 0.00    | 47.79   | 95.99   |
| 27         | 22.66          | 3,378,964  | 27.63             | 4,837,904  | 2,222,307                 | 109,981 | 0.00                            | 0.00    | 61.97   | 91.92   |
| 28         | 22.60          | 3,052,945  | 27.67             | 4,845,116  | 2,383,576                 | 115,924 | 0.00                            | 0.00    | 116.63  | 95.84   |
| 29         | 22.67          | 2,837,242  | 27.62             | 4,762,605  | 2,487,856                 | 124,207 | 0.00                            | 31.98   | 121.02  | 90.69   |
| 30         | 22.64          | 2,829,103  | 27.59             | 4,757,767  | 2,514,327                 | 125,297 | 0.00                            | 34.23   | 130.53  | 88.47   |
| 31         | 22.65          | 2,809,097  | 27.51             | 4,773,817  | 2,582,393                 | 127,019 | 0.00                            | 36.42   | 140.18  | 90.77   |
| 32         | 23.62          | 4,169,711  | 25.34             | 4,661,060  | 607,996                   | 129,002 | 0.00                            | 75.53   | 278.82  | 14.62   |
| 33         | 23.49          | 4,063,735  | 25.26             | 4,646,728  | 653,704                   | 130,986 | 0.00                            | 76.28   | 282.84  | 12.18   |
| 34         | 23.50          | 3,996,484  | 25.20             | 4,642,410  | 687,975                   | 132,085 | 0.00                            | 78.80   | 293.75  | 10.93   |
| 35         | 23.49          | 3,990,538  | 25.12             | 4,604,071  | 700,430                   | 132,738 | 0.00                            | 82.14   | 307.60  | 10.36   |
| 36         | 23.47          | 3,985,384  | 25.05             | 4,622,178  | 730,044                   | 134,124 | 0.00                            | 83.72   | 314.86  | 10.06   |
| 37         | 23.44          | 3,972,883  | 25.01             | 4,646,728  | 763,952                   | 135,469 | 0.00                            | 83.84   | 316.36  | 11.68   |
| 38         | 23.48          | 4,036,179  | 24.96             | 4,653,239  | 786,852                   | 137,524 | 0.00                            | 87.16   | 330.86  | 12.10   |

## Appendix C: Single- and two-phase measured data (continued).

Channel C3: Argon gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.3Hyd. Diameter ( $\mu\text{m}$ ): 95.55Width ( $\mu\text{m}$ ): 144.79

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 33.41                    | 33.95  | 44.25                                            | 44.72  | 44.95  | 32.74  | 40.51  | 46.65  | 46.27  |
| 2          | 33.10                    | 36.74  | 48.30                                            | 48.96  | 49.30  | 33.50  | 50.91  | 50.93  | 50.38  |
| 3          | 32.97                    | 38.78  | 49.91                                            | 50.62  | 50.98  | 34.56  | 52.58  | 52.60  | 52.02  |
| 4          | 32.84                    | 40.53  | 50.59                                            | 51.34  | 51.71  | 34.41  | 53.30  | 53.33  | 52.75  |
| 5          | 32.77                    | 41.91  | 50.98                                            | 51.75  | 52.13  | 34.81  | 53.72  | 53.75  | 53.16  |
| 6          | 32.64                    | 42.76  | 51.12                                            | 51.90  | 52.30  | 34.84  | 53.89  | 53.92  | 53.32  |
| 7          | 32.42                    | 43.55  | 51.13                                            | 51.94  | 52.35  | 35.36  | 53.94  | 53.98  | 53.39  |
| 8          | 32.22                    | 44.03  | 51.05                                            | 51.88  | 52.30  | 35.04  | 53.89  | 53.94  | 53.35  |
| 9          | 32.02                    | 44.40  | 50.93                                            | 51.77  | 52.20  | 34.99  | 53.79  | 53.85  | 53.28  |
| 10         | 31.83                    | 44.67  | 50.87                                            | 51.73  | 52.18  | 35.10  | 53.77  | 53.84  | 53.27  |
| 11         | 31.61                    | 43.56  | 50.81                                            | 51.70  | 52.17  | 35.10  | 53.76  | 53.85  | 53.28  |
| 12         | 31.37                    | 43.66  | 50.66                                            | 51.58  | 52.07  | 34.70  | 50.15  | 53.76  | 53.20  |
| 13         | 31.07                    | 43.72  | 50.38                                            | 51.33  | 51.84  | 34.83  | 47.56  | 53.54  | 52.99  |
| 14         | 30.72                    | 43.76  | 50.15                                            | 51.12  | 51.66  | 35.06  | 47.37  | 53.38  | 52.83  |
| 15         | 30.42                    | 43.86  | 49.88                                            | 50.88  | 51.44  | 34.77  | 47.24  | 53.18  | 52.63  |
| 16         | 30.18                    | 44.03  | 49.45                                            | 50.48  | 51.06  | 34.45  | 49.82  | 52.81  | 52.28  |
| 17         | 30.04                    | 44.20  | 49.12                                            | 50.18  | 50.77  | 34.61  | 46.20  | 52.54  | 52.01  |
| 18         | 29.93                    | 44.28  | 48.86                                            | 49.95  | 50.56  | 34.36  | 45.90  | 52.34  | 51.81  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.33                        | 1,848,266   | 18,340                    | 3,269  | 13.73                    | 0.00    | 0.00    |
| 2          | 24.37                        | 1,709,625   | 110,729                   | 3,257  | 0.00                     | 102.49  | 0.00    |
| 3          | 24.36                        | 1,693,371   | 172,782                   | 3,307  | 0.00                     | 159.64  | 0.00    |
| 4          | 24.34                        | 1,685,211   | 223,803                   | 3,312  | 0.00                     | 210.82  | 0.00    |
| 5          | 24.35                        | 1,687,539   | 263,793                   | 3,418  | 0.00                     | 248.20  | 0.00    |
| 6          | 24.35                        | 1,690,320   | 307,919                   | 3,493  | 0.00                     | 285.98  | 0.06    |
| 7          | 24.35                        | 1,698,955   | 361,720                   | 3,619  | 0.00                     | 0.00    | 316.55  |
| 8          | 24.39                        | 1,672,687   | 403,066                   | 3,725  | 0.00                     | 0.00    | 349.20  |
| 9          | 24.40                        | 1,676,417   | 438,919                   | 3,861  | 0.00                     | 0.00    | 372.92  |
| 10         | 24.41                        | 1,683,493   | 476,896                   | 3,999  | 0.00                     | 0.00    | 393.14  |
| 11         | 24.40                        | 1,685,505   | 527,533                   | 4,137  | 0.00                     | 0.00    | 413.40  |
| 12         | 24.39                        | 1,696,627   | 590,987                   | 4,413  | 0.00                     | 0.00    | 429.56  |
| 13         | 24.38                        | 1,706,505   | 669,971                   | 4,551  | 0.00                     | 0.00    | 448.46  |
| 14         | 24.36                        | 1,704,629   | 721,829                   | 4,688  | 0.00                     | 0.00    | 468.98  |
| 15         | 24.35                        | 1,698,345   | 782,819                   | 4,826  | 0.00                     | 0.00    | 485.85  |
| 16         | 24.34                        | 1,697,734   | 837,412                   | 5,382  | 0.00                     | 0.00    | 506.12  |
| 17         | 24.37                        | 1,700,080   | 882,917                   | 5,346  | 0.00                     | 0.00    | 524.52  |
| 18         | 24.38                        | 1,703,137   | 910,519                   | 5,439  | 0.00                     | 116.94  | 435.33  |

## Appendix C: Single- and two-phase measured data (continued).

Channel C3: Helium gas tests.

Number of channels:

7

Channel Dimensions:

Depth ( $\mu\text{m}$ ):

71.3

Hyd. Diameter ( $\mu\text{m}$ ):

95.55

Width ( $\mu\text{m}$ ):

144.79

Channel Length (m):

0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 27.02                    | 27.14  | 36.62                                            | 37.11  | 37.35  | 24.69  | 33.21  | 39.07  | 38.63  |
| 2          | 26.94                    | 29.20  | 37.54                                            | 38.03  | 38.25  | 24.91  | 39.10  | 39.95  | 39.49  |
| 3          | 27.78                    | 30.45  | 42.78                                            | 43.52  | 43.89  | 24.27  | 45.53  | 45.47  | 44.76  |
| 4          | 28.37                    | 33.41  | 45.46                                            | 46.29  | 46.71  | 24.43  | 48.33  | 48.33  | 47.66  |
| 5          | 28.63                    | 35.14  | 46.93                                            | 47.80  | 48.25  | 32.49  | 49.86  | 49.90  | 49.25  |
| 6          | 29.39                    | 36.88  | 47.88                                            | 48.77  | 49.23  | 32.73  | 50.84  | 50.88  | 50.23  |
| 7          | 29.85                    | 38.69  | 48.53                                            | 49.43  | 49.89  | 32.85  | 51.49  | 51.54  | 50.88  |
| 8          | 30.08                    | 39.54  | 48.90                                            | 49.81  | 50.29  | 33.30  | 51.89  | 51.94  | 51.26  |
| 9          | 30.26                    | 40.32  | 49.33                                            | 50.26  | 50.75  | 33.92  | 52.35  | 52.39  | 51.71  |
| 10         | 30.44                    | 40.84  | 49.58                                            | 50.52  | 51.02  | 33.63  | 52.62  | 52.67  | 51.99  |
| 11         | 30.59                    | 41.20  | 49.69                                            | 50.63  | 51.14  | 33.80  | 52.74  | 52.80  | 52.12  |
| 12         | 30.60                    | 41.40  | 49.69                                            | 50.66  | 51.19  | 34.16  | 52.79  | 52.86  | 52.20  |
| 13         | 30.45                    | 41.98  | 49.67                                            | 50.66  | 51.21  | 33.78  | 52.81  | 52.89  | 52.25  |
| 14         | 30.41                    | 41.57  | 48.48                                            | 49.43  | 49.96  | 34.13  | 51.58  | 51.68  | 51.10  |
| 15         | 30.42                    | 41.28  | 47.90                                            | 48.85  | 49.39  | 33.53  | 51.01  | 51.13  | 50.57  |
| 16         | 30.26                    | 41.46  | 47.53                                            | 48.51  | 49.06  | 33.42  | 50.68  | 50.81  | 50.26  |
| 17         | 30.08                    | 41.88  | 47.15                                            | 48.14  | 48.71  | 33.36  | 50.34  | 50.48  | 49.93  |
| 18         | 29.88                    | 42.07  | 46.78                                            | 47.79  | 48.38  | 33.68  | 50.00  | 50.18  | 49.66  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.00                        | 1,945,560   | 14,158                    | 3,786  | 0.00                     | 8.96    | 0.00    |
| 2          | 24.01                        | 1,806,242   | 88,056                    | 3,463  | 0.00                     | 67.94   | 0.00    |
| 3          | 23.99                        | 1,794,125   | 145,203                   | 3,481  | 0.00                     | 114.44  | 0.00    |
| 4          | 23.98                        | 1,785,874   | 194,845                   | 3,549  | 0.00                     | 157.39  | 0.00    |
| 5          | 23.96                        | 1,783,274   | 229,319                   | 3,536  | 0.00                     | 189.04  | 0.00    |
| 6          | 23.95                        | 1,780,245   | 267,929                   | 3,585  | 0.00                     | 223.73  | 0.00    |
| 7          | 23.92                        | 1,780,358   | 298,266                   | 3,610  | 0.00                     | 0.00    | 249.81  |
| 8          | 23.89                        | 1,776,221   | 328,603                   | 3,707  | 0.00                     | 0.00    | 278.50  |
| 9          | 23.90                        | 1,776,221   | 351,457                   | 3,723  | 0.00                     | 0.00    | 305.50  |
| 10         | 23.91                        | 1,774,842   | 367,733                   | 3,843  | 0.00                     | 0.00    | 335.41  |
| 11         | 23.91                        | 1,774,842   | 375,329                   | 3,863  | 0.00                     | 0.00    | 368.29  |
| 12         | 23.89                        | 1,776,244   | 400,308                   | 3,963  | 0.00                     | 0.00    | 404.23  |
| 13         | 23.84                        | 1,774,842   | 428,226                   | 4,058  | 0.00                     | 0.00    | 436.09  |
| 14         | 23.83                        | 1,774,955   | 463,740                   | 4,157  | 0.00                     | 0.00    | 460.04  |
| 15         | 23.82                        | 1,776,040   | 503,661                   | 4,277  | 0.00                     | 0.00    | 479.39  |
| 16         | 23.80                        | 1,774,707   | 542,340                   | 4,404  | 0.00                     | 0.00    | 494.11  |
| 17         | 23.81                        | 1,776,221   | 590,490                   | 4,485  | 0.00                     | 0.00    | 506.82  |
| 18         | 23.79                        | 1,776,018   | 631,971                   | 4,553  | 0.00                     | 109.61  | 408.82  |

### Appendix C: Single- and two-phase measured data (continued).

Channel C3: Nitrogen gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.3Hyd. Diameter ( $\mu\text{m}$ ): 95.55Width ( $\mu\text{m}$ ): 144.79

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 27.02                    | 27.14  | 36.62                                            | 37.11  | 37.35  | 24.69  | 33.21  | 39.07  | 38.63  |
| 2          | 26.94                    | 29.20  | 37.54                                            | 38.03  | 38.25  | 24.91  | 39.10  | 39.95  | 39.49  |
| 3          | 27.78                    | 30.45  | 42.78                                            | 43.52  | 43.89  | 24.27  | 45.53  | 45.47  | 44.76  |
| 4          | 28.37                    | 33.41  | 45.46                                            | 46.29  | 46.71  | 24.43  | 48.33  | 48.33  | 47.66  |
| 5          | 28.63                    | 35.14  | 46.93                                            | 47.80  | 48.25  | 32.49  | 49.86  | 49.90  | 49.25  |
| 6          | 29.39                    | 36.88  | 47.88                                            | 48.77  | 49.23  | 32.73  | 50.84  | 50.88  | 50.23  |
| 7          | 29.85                    | 38.69  | 48.53                                            | 49.43  | 49.89  | 32.85  | 51.49  | 51.54  | 50.88  |
| 8          | 30.08                    | 39.54  | 48.90                                            | 49.81  | 50.29  | 33.30  | 51.89  | 51.94  | 51.26  |
| 9          | 30.26                    | 40.32  | 49.33                                            | 50.26  | 50.75  | 33.92  | 52.35  | 52.39  | 51.71  |
| 10         | 30.44                    | 40.84  | 49.58                                            | 50.52  | 51.02  | 33.63  | 52.62  | 52.67  | 51.99  |
| 11         | 30.59                    | 41.20  | 49.69                                            | 50.63  | 51.14  | 33.80  | 52.74  | 52.80  | 52.12  |
| 12         | 30.60                    | 41.40  | 49.69                                            | 50.66  | 51.19  | 34.16  | 52.79  | 52.86  | 52.20  |
| 13         | 30.45                    | 41.98  | 49.67                                            | 50.66  | 51.21  | 33.78  | 52.81  | 52.89  | 52.25  |
| 14         | 30.41                    | 41.57  | 48.48                                            | 49.43  | 49.96  | 34.13  | 51.58  | 51.68  | 51.10  |
| 15         | 30.42                    | 41.28  | 47.90                                            | 48.85  | 49.39  | 33.53  | 51.01  | 51.13  | 50.57  |
| 16         | 30.26                    | 41.46  | 47.53                                            | 48.51  | 49.06  | 33.42  | 50.68  | 50.81  | 50.26  |
| 17         | 30.08                    | 41.88  | 47.15                                            | 48.14  | 48.71  | 33.36  | 50.34  | 50.48  | 49.93  |
| 18         | 29.88                    | 42.07  | 46.78                                            | 47.79  | 48.38  | 33.68  | 50.00  | 50.18  | 49.66  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.00                        | 1,945,560   | 14,158                    | 3,786  | 0.00                     | 8.96    | 0.00    |
| 2          | 24.01                        | 1,806,242   | 88,056                    | 3,463  | 0.00                     | 67.94   | 0.00    |
| 3          | 23.99                        | 1,794,125   | 145,203                   | 3,481  | 0.00                     | 114.44  | 0.00    |
| 4          | 23.98                        | 1,785,874   | 194,845                   | 3,549  | 0.00                     | 157.39  | 0.00    |
| 5          | 23.96                        | 1,783,274   | 229,319                   | 3,536  | 0.00                     | 189.04  | 0.00    |
| 6          | 23.95                        | 1,780,245   | 267,929                   | 3,585  | 0.00                     | 223.73  | 0.00    |
| 7          | 23.92                        | 1,780,358   | 298,266                   | 3,610  | 0.00                     | 0.00    | 249.81  |
| 8          | 23.89                        | 1,776,221   | 328,603                   | 3,707  | 0.00                     | 0.00    | 278.50  |
| 9          | 23.90                        | 1,776,221   | 351,457                   | 3,723  | 0.00                     | 0.00    | 305.50  |
| 10         | 23.91                        | 1,774,842   | 367,733                   | 3,843  | 0.00                     | 0.00    | 335.41  |
| 11         | 23.91                        | 1,774,842   | 375,329                   | 3,863  | 0.00                     | 0.00    | 368.29  |
| 12         | 23.89                        | 1,776,244   | 400,308                   | 3,963  | 0.00                     | 0.00    | 404.23  |
| 13         | 23.84                        | 1,774,842   | 428,226                   | 4,058  | 0.00                     | 0.00    | 436.09  |
| 14         | 23.83                        | 1,774,955   | 463,740                   | 4,157  | 0.00                     | 0.00    | 460.04  |
| 15         | 23.82                        | 1,776,040   | 503,661                   | 4,277  | 0.00                     | 0.00    | 479.39  |
| 16         | 23.80                        | 1,774,707   | 542,340                   | 4,404  | 0.00                     | 0.00    | 494.11  |
| 17         | 23.81                        | 1,776,221   | 590,490                   | 4,485  | 0.00                     | 0.00    | 506.82  |
| 18         | 23.79                        | 1,776,018   | 631,971                   | 4,553  | 0.00                     | 109.61  | 408.82  |



### Appendix C: Single- and two-phase measured data (continued).

Channel C3: Water tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.3

Hyd. Diameter ( $\mu\text{m}$ ): 95.55

Width ( $\mu\text{m}$ ): 144.79

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 23.77                    | 38.69  | 33.85                                            | 36.85  | 40.30  | 29.11  | 41.68  | 43.63  | 44.26  |
| 2          | 23.84                    | 37.13  | 32.35                                            | 34.86  | 38.08  | 29.33  | 39.45  | 41.16  | 41.72  |
| 3          | 23.84                    | 37.88  | 32.67                                            | 35.38  | 39.04  | 29.79  | 40.25  | 42.16  | 42.72  |
| 4          | 23.80                    | 36.08  | 31.46                                            | 33.83  | 37.29  | 29.57  | 38.58  | 40.18  | 40.65  |
| 5          | 23.83                    | 34.92  | 30.64                                            | 32.76  | 36.07  | 29.25  | 37.37  | 38.80  | 39.21  |
| 6          | 23.99                    | 35.21  | 31.00                                            | 33.29  | 37.02  | 29.55  | 38.22  | 39.83  | 40.52  |
| 7          | 24.39                    | 36.09  | 31.76                                            | 34.34  | 38.42  | 29.95  | 39.46  | 41.21  | 41.86  |
| 8          | 24.70                    | 37.15  | 32.46                                            | 35.25  | 39.76  | 30.15  | 40.66  | 42.54  | 43.21  |
| 9          | 24.80                    | 38.20  | 33.08                                            | 36.08  | 40.98  | 30.25  | 41.75  | 43.72  | 44.43  |
| 10         | 25.08                    | 39.05  | 33.54                                            | 36.79  | 42.03  | 31.10  | 42.66  | 44.72  | 45.44  |
| 11         | 25.30                    | 38.73  | 33.25                                            | 36.36  | 41.33  | 30.84  | 41.96  | 43.67  | 43.60  |
| 12         | 25.30                    | 39.67  | 33.83                                            | 37.33  | 42.70  | 31.17  | 38.44  | 44.97  | 44.77  |
| 13         | 25.51                    | 39.13  | 33.42                                            | 36.83  | 42.07  | 31.05  | 37.85  | 44.25  | 44.16  |
| 14         | 25.66                    | 38.50  | 33.14                                            | 36.47  | 41.50  | 31.06  | 38.09  | 43.58  | 43.45  |
| 15         | 25.79                    | 38.03  | 32.84                                            | 36.18  | 41.10  | 30.54  | 37.87  | 43.11  | 42.92  |
| 16         | 26.01                    | 38.74  | 33.21                                            | 36.91  | 42.08  | 30.63  | 38.00  | 44.03  | 43.78  |
| 17         | 26.11                    | 38.96  | 33.32                                            | 37.32  | 42.72  | 31.94  | 36.56  | 44.51  | 44.06  |
| 18         | 23.75                    | 32.68  | 29.37                                            | 32.26  | 36.97  | 29.00  | 35.53  | 39.57  | 39.36  |
| 19         | 24.26                    | 31.77  | 28.66                                            | 31.03  | 35.48  | 29.01  | 34.67  | 37.59  | 36.79  |
| 20         | 24.85                    | 31.45  | 28.48                                            | 30.52  | 34.45  | 29.15  | 34.00  | 36.21  | 35.83  |

# Appendix C: Single- and two-phase measured data (continued).

## Channel C3: Water tests (continued).

| Data Point | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | liquid Flow Rate   |
|------------|-------------------|------------|---------------------------|---------|--------------------|
|            | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F. M. #1, (cc/min) |
| 1          | 23.39             | 2,305,239  | 330,072                   | 99,092  | 9.37               |
| 2          | 23.75             | 2,263,374  | 412,131                   | 97,421  | 12.76              |
| 3          | 23.85             | 2,236,021  | 466,565                   | 96,185  | 14.30              |
| 4          | 24.06             | 2,194,517  | 548,941                   | 94,682  | 17.69              |
| 5          | 24.37             | 2,200,146  | 624,240                   | 94,903  | 21.05              |
| 6          | 24.75             | 2,170,826  | 693,233                   | 93,913  | 24.49              |
| 7          | 25.17             | 2,158,822  | 762,429                   | 93,673  | 28.66              |
| 8          | 25.62             | 2,168,882  | 826,086                   | 94,107  | 31.62              |
| 9          | 26.05             | 2,135,855  | 894,491                   | 93,000  | 36.60              |
| 10         | 26.43             | 2,137,505  | 962,670                   | 93,224  | 39.76              |
| 11         | 26.73             | 2,136,194  | 1,035,257                 | 93,529  | 42.86              |
| 12         | 27.01             | 2,111,373  | 1,098,055                 | 92,591  | 48.03              |
| 13         | 27.22             | 2,110,944  | 1,176,022                 | 92,661  | 51.80              |
| 14         | 27.42             | 2,136,149  | 1,263,077                 | 94,060  | 54.61              |
| 15         | 27.55             | 2,131,470  | 1,318,167                 | 93,850  | 57.72              |
| 16         | 27.76             | 2,127,378  | 1,379,586                 | 93,951  | 61.09              |
| 17         | 27.89             | 2,108,773  | 1,510,473                 | 93,640  | 69.83              |
| 18         | 25.11             | 3,975,596  | 1,371,384                 | 106,086 | 58.78              |
| 19         | 25.75             | 3,925,389  | 1,718,404                 | 105,187 | 73.03              |
| 20         | 26.46             | 3,851,604  | 2,049,261                 | 103,968 | 84.08              |

## Appendix C: Single- and two-phase measured data (continued).

Channel C3: Water and argon tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.3 Hyd. Diameter ( $\mu\text{m}$ ): 95.55Width ( $\mu\text{m}$ ): 144.79 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 24.84                    | 37.15  | 33.27                                            | 35.85  | 38.29  | 29.63  | 36.68  | 41.21  | 41.61  |
| 2          | 25.90                    | 38.69  | 34.51                                            | 37.05  | 39.43  | 30.97  | 37.34  | 42.23  | 42.47  |
| 3          | 25.91                    | 38.56  | 34.79                                            | 37.29  | 39.64  | 31.17  | 37.46  | 42.40  | 42.54  |
| 4          | 25.93                    | 38.36  | 34.89                                            | 37.36  | 39.65  | 31.16  | 37.44  | 42.39  | 42.40  |
| 5          | 25.12                    | 36.22  | 32.87                                            | 35.23  | 37.89  | 30.70  | 36.14  | 40.69  | 41.05  |
| 6          | 26.46                    | 37.77  | 33.76                                            | 36.34  | 39.07  | 30.54  | 40.58  | 41.92  | 42.14  |
| 7          | 26.49                    | 38.53  | 34.48                                            | 37.20  | 39.98  | 31.57  | 41.50  | 42.85  | 42.99  |
| 8          | 26.49                    | 39.55  | 35.45                                            | 38.34  | 41.12  | 31.49  | 42.61  | 44.00  | 44.04  |
| 9          | 25.89                    | 36.47  | 32.55                                            | 35.14  | 38.11  | 30.65  | 39.55  | 40.90  | 41.16  |
| 10         | 26.18                    | 37.84  | 33.61                                            | 36.34  | 39.41  | 30.87  | 40.85  | 42.26  | 42.46  |
| 11         | 26.35                    | 38.77  | 34.52                                            | 37.34  | 40.44  | 31.70  | 41.90  | 43.34  | 43.47  |
| 12         | 26.35                    | 40.65  | 35.94                                            | 39.15  | 42.37  | 32.22  | 43.76  | 45.33  | 45.36  |

| Data Point | Gas Flow Meter               |             | Liquid Flow Meter            |             | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|------------------------------|-------------|------------------------------|-------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.27                        | 1,166,727   | 24.22                        | 1,619,646   | 449,339                   | 102,580 | 0.00                            | 20.49   | 0.00    | 10.02   |
| 2          | 25.21                        | 1,173,599   | 25.21                        | 1,560,894   | 591,664                   | 102,261 | 0.00                            | 77.25   | 0.00    | 10.97   |
| 3          | 25.17                        | 1,171,090   | 25.20                        | 1,517,130   | 718,256                   | 105,110 | 0.00                            | 124.89  | 0.00    | 11.94   |
| 4          | 25.19                        | 1,168,467   | 25.28                        | 1,519,842   | 889,946                   | 112,463 | 0.00                            | 0.00    | 165.52  | 9.75    |
| 5          | 25.15                        | 1,178,798   | 25.42                        | 1,544,957   | 626,409                   | 99,137  | 0.00                            | 14.73   | 0.00    | 15.91   |
| 6          | 25.17                        | 1,176,379   | 25.56                        | 1,526,511   | 713,486                   | 101,129 | 0.00                            | 71.99   | 0.00    | 15.85   |
| 7          | 25.15                        | 1,170,864   | 25.65                        | 1,515,547   | 818,874                   | 104,999 | 0.00                            | 115.61  | 0.00    | 13.23   |
| 8          | 25.16                        | 1,169,485   | 25.72                        | 1,518,011   | 953,107                   | 112,992 | 0.00                            | 0.00    | 158.88  | 13.10   |
| 9          | 25.11                        | 1,172,017   | 26.02                        | 1,546,585   | 765,705                   | 100,607 | 0.00                            | 14.72   | 0.00    | 22.15   |
| 10         | 25.16                        | 1,175,000   | 26.19                        | 1,520,860   | 837,524                   | 101,789 | 0.00                            | 65.27   | 0.00    | 19.02   |
| 11         | 25.14                        | 1,169,485   | 26.28                        | 1,508,268   | 915,830                   | 105,851 | 0.00                            | 109.63  | 0.00    | 19.11   |

# Appendix C: Single- and two-phase measured data (continued).

Channel C3: Water and helium tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.3 Hyd. Diameter ( $\mu\text{m}$ ): 95.55

Width ( $\mu\text{m}$ ): 144.79 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.21                    | 37.80  | 33.70                                            | 36.29  | 38.97  | 30.77  | 40.48  | 41.82  | 42.09  |
| 2          | 26.30                    | 38.12  | 34.07                                            | 36.70  | 39.37  | 31.15  | 40.87  | 42.20  | 42.36  |
| 3          | 26.54                    | 38.38  | 34.28                                            | 36.92  | 39.63  | 30.75  | 41.12  | 42.51  | 42.63  |
| 4          | 26.58                    | 37.95  | 33.98                                            | 36.55  | 39.21  | 30.86  | 40.70  | 42.07  | 42.15  |
| 5          | 26.66                    | 38.60  | 34.47                                            | 37.11  | 39.83  | 31.34  | 41.30  | 42.74  | 42.79  |
| 6          | 26.74                    | 38.11  | 33.50                                            | 36.21  | 39.31  | 31.07  | 40.73  | 42.23  | 42.54  |
| 7          | 26.80                    | 38.94  | 34.32                                            | 37.17  | 40.27  | 31.01  | 41.69  | 43.21  | 43.42  |
| 8          | 26.75                    | 39.82  | 35.07                                            | 38.04  | 41.20  | 30.83  | 42.60  | 44.20  | 44.35  |
| 9          | 26.77                    | 39.81  | 35.07                                            | 38.05  | 41.20  | 31.09  | 42.60  | 44.20  | 44.32  |
| 10         | 26.47                    | 37.14  | 32.90                                            | 35.55  | 38.79  | 30.74  | 40.15  | 41.59  | 41.87  |
| 11         | 26.61                    | 37.48  | 33.14                                            | 35.89  | 39.15  | 30.98  | 40.51  | 41.97  | 42.18  |
| 12         | 26.90                    | 37.99  | 33.56                                            | 36.39  | 39.69  | 31.08  | 41.04  | 42.54  | 42.69  |

| Data Point | Gas Flow Meter              |            | Liquid Flow Meter           |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|-----------------------------|------------|-----------------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.( $^{\circ}\text{C}$ ) | Press.(Pa) | Temp.( $^{\circ}\text{C}$ ) | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.03                       | 1,186,032  | 26.04                       | 1,559,515  | 667,165                   | 108,173 | 0.00                            | 0.00    | 125.03  | 13.12   |
| 2          | 25.03                       | 1,179,137  | 26.06                       | 1,548,778  | 768,936                   | 118,983 | 0.00                            | 0.00    | 224.46  | 14.24   |
| 3          | 25.00                       | 1,177,758  | 26.06                       | 1,550,902  | 850,248                   | 127,137 | 0.00                            | 0.00    | 301.10  | 14.15   |
| 4          | 24.97                       | 1,176,221  | 26.06                       | 1,540,911  | 941,349                   | 133,658 | 0.00                            | 0.00    | 366.33  | 14.35   |
| 5          | 24.95                       | 1,174,503  | 26.05                       | 1,542,425  | 1,009,596                 | 140,675 | 0.00                            | 0.00    | 440.16  | 12.23   |
| 6          | 24.89                       | 1,197,064  | 26.23                       | 1,503,950  | 756,932                   | 105,103 | 0.00                            | 0.00    | 112.38  | 19.22   |
| 7          | 24.88                       | 1,188,722  | 26.26                       | 1,507,386  | 832,910                   | 116,908 | 0.00                            | 0.00    | 212.04  | 17.37   |
| 8          | 24.84                       | 1,185,286  | 26.26                       | 1,510,936  | 899,438                   | 125,658 | 0.00                            | 0.00    | 302.78  | 15.23   |
| 9          | 24.81                       | 1,181,488  | 26.25                       | 1,509,489  | 979,575                   | 132,639 | 0.00                            | 0.00    | 368.34  | 14.24   |
| 10         | 24.77                       | 1,209,406  | 26.73                       | 1,458,016  | 880,608                   | 99,090  | 0.00                            | 0.00    | 52.73   | 26.27   |
| 11         | 24.75                       | 1,198,307  | 26.81                       | 1,477,547  | 920,710                   | 104,757 | 0.00                            | 0.00    | 97.01   | 25.60   |
| 12         | 24.75                       | 1,191,548  | 26.87                       | 1,478,022  | 988,640                   | 115,404 | 0.00                            | 0.00    | 181.81  | 23.91   |

**Appendix C: Single- and two-phase measured data (continued).**

Channel C3: Water and nitrogen tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.3 Hyd. Diameter ( $\mu\text{m}$ ): 95.55

Width ( $\mu\text{m}$ ): 144.79 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 23.07                    | 34.33  | 30.68                                            | 32.90  | 35.62  | 28.55  | 34.75  | 38.54  | 38.97  |
| 2          | 23.48                    | 35.43  | 31.13                                            | 33.44  | 36.21  | 28.65  | 35.07  | 39.16  | 39.59  |
| 3          | 23.84                    | 38.22  | 33.07                                            | 35.84  | 39.16  | 29.55  | 36.98  | 42.32  | 42.79  |
| 4          | 24.05                    | 38.87  | 33.66                                            | 36.54  | 39.83  | 29.70  | 37.49  | 42.97  | 43.36  |
| 5          | 24.26                    | 39.46  | 34.38                                            | 37.38  | 40.61  | 30.51  | 38.48  | 43.70  | 43.97  |
| 6          | 24.45                    | 40.21  | 35.11                                            | 38.29  | 41.56  | 30.02  | 38.68  | 44.66  | 44.81  |
| 7          | 23.93                    | 37.63  | 32.64                                            | 35.38  | 38.93  | 29.44  | 36.79  | 42.02  | 42.52  |
| 8          | 24.23                    | 38.10  | 32.89                                            | 35.76  | 39.30  | 29.68  | 37.03  | 42.38  | 42.81  |
| 9          | 24.42                    | 38.70  | 33.40                                            | 36.38  | 39.92  | 30.02  | 37.49  | 43.04  | 43.40  |
| 10         | 24.50                    | 39.19  | 33.96                                            | 37.07  | 40.57  | 30.45  | 37.86  | 43.67  | 43.89  |
| 11         | 24.09                    | 36.39  | 32.06                                            | 34.61  | 38.09  | 29.37  | 36.86  | 41.01  | 41.32  |
| 12         | 24.33                    | 37.04  | 32.20                                            | 34.93  | 38.51  | 30.33  | 36.50  | 41.50  | 41.82  |
| 13         | 24.49                    | 36.72  | 32.18                                            | 34.85  | 38.30  | 30.09  | 36.35  | 41.24  | 41.47  |

| Data Point | Gas Flow Meter               |             | Liquid Flow Meter            |             | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|------------------------------|-------------|------------------------------|-------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 23.52                        | 1,232,916   | 23.75                        | 1,451,641   | 606,776                   | 101,701 | 0.00                            | 11.88   | 0.00    | 17.09   |
| 2          | 23.51                        | 1,235,629   | 23.88                        | 1,433,782   | 609,534                   | 100,145 | 0.00                            | 23.23   | 0.00    | 15.12   |
| 3          | 23.51                        | 1,217,748   | 24.00                        | 1,421,417   | 639,848                   | 99,569  | 0.00                            | 47.04   | 0.00    | 16.16   |
| 4          | 23.52                        | 1,209,474   | 24.08                        | 1,413,776   | 714,492                   | 102,148 | 0.00                            | 86.34   | 0.00    | 16.40   |
| 5          | 23.50                        | 1,210,830   | 24.16                        | 1,420,332   | 866,425                   | 109,950 | 0.00                            | 0.00    | 143.22  | 15.11   |
| 6          | 23.47                        | 1,203,958   | 24.20                        | 1,426,752   | 973,282                   | 117,091 | 0.00                            | 0.00    | 191.49  | 14.18   |
| 7          | 23.46                        | 1,228,779   | 24.67                        | 1,451,867   | 727,558                   | 102,813 | 0.00                            | 19.89   | 0.00    | 21.52   |
| 8          | 23.47                        | 1,217,748   | 24.78                        | 1,434,664   | 772,724                   | 101,350 | 0.00                            | 41.75   | 0.00    | 20.01   |
| 9          | 23.50                        | 1,212,752   | 24.88                        | 1,401,999   | 822,728                   | 102,790 | 0.00                            | 73.73   | 0.00    | 20.15   |
| 10         | 23.52                        | 1,208,547   | 24.91                        | 1,422,208   | 958,046                   | 111,026 | 0.00                            | 0.00    | 133.50  | 19.66   |
| 11         | 23.53                        | 1,223,987   | 25.23                        | 1,463,034   | 874,563                   | 104,215 | 0.00                            | 18.31   | 0.00    | 27.27   |
| 12         | 23.53                        | 1,216,052   | 25.35                        | 1,458,106   | 906,663                   | 103,247 | 0.00                            | 37.18   | 0.00    | 26.77   |
| 13         | 23.56                        | 1,210,853   | 25.50                        | 1,457,722   | 995,752                   | 105,923 | 0.00                            | 64.20   | 0.00    | 27.39   |

## Appendix C: Single- and two-phase measured data (continued).

Channel D: Argon gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.33      Hyd. Diameter ( $\mu\text{m}$ ): 111.86Width ( $\mu\text{m}$ ): 112.73      Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 29.88                    | 32.23  | 39.20                                            | 42.37  | 42.89  | 44.45  | 44.42  | 44.06  | 41.85  |
| 2          | 29.73                    | 33.93  | 40.80                                            | 45.23  | 45.74  | 47.28  | 47.20  | 46.70  | 45.68  |
| 3          | 30.05                    | 34.31  | 40.74                                            | 46.83  | 47.40  | 48.93  | 48.89  | 48.43  | 48.87  |
| 4          | 30.32                    | 36.08  | 41.83                                            | 48.01  | 48.63  | 50.15  | 50.16  | 49.77  | 50.08  |
| 5          | 30.22                    | 38.85  | 42.51                                            | 48.72  | 49.35  | 50.86  | 50.87  | 50.44  | 50.79  |
| 6          | 30.53                    | 39.31  | 42.86                                            | 49.08  | 49.71  | 51.23  | 51.23  | 50.78  | 51.16  |
| 7          | 30.63                    | 39.44  | 42.97                                            | 49.22  | 49.86  | 51.37  | 51.36  | 50.89  | 51.30  |
| 8          | 30.68                    | 39.96  | 43.06                                            | 49.33  | 49.97  | 51.48  | 51.46  | 50.98  | 51.42  |
| 9          | 30.84                    | 40.25  | 42.95                                            | 49.30  | 49.96  | 51.46  | 51.45  | 50.96  | 51.40  |
| 10         | 30.87                    | 40.47  | 42.75                                            | 49.19  | 49.87  | 51.37  | 51.36  | 50.88  | 51.30  |
| 11         | 30.75                    | 40.75  | 42.55                                            | 49.08  | 49.78  | 51.28  | 51.28  | 50.79  | 51.21  |
| 12         | 30.78                    | 41.06  | 42.45                                            | 48.98  | 49.69  | 50.88  | 51.14  | 50.72  | 51.12  |
| 13         | 30.33                    | 41.45  | 42.10                                            | 48.80  | 49.54  | 51.04  | 51.07  | 50.58  | 50.97  |
| 14         | 30.25                    | 42.90  | 41.74                                            | 48.52  | 49.29  | 50.80  | 50.85  | 50.39  | 50.72  |
| 15         | 30.65                    | 43.17  | 41.55                                            | 48.39  | 49.17  | 50.67  | 50.74  | 50.30  | 50.60  |
| 16         | 29.47                    | 40.98  | 38.15                                            | 45.01  | 45.82  | 47.30  | 47.43  | 47.15  | 47.19  |
| 17         | 29.53                    | 41.51  | 38.52                                            | 45.46  | 46.30  | 47.77  | 47.91  | 47.63  | 47.66  |
| 18         | 29.51                    | 41.74  | 38.56                                            | 45.56  | 46.42  | 47.89  | 48.04  | 47.77  | 47.77  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |          | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|----------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet   | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 25.35                        | 1,724,997   | 67,913                    | 3,460.93 | 29.43                    | 0.00    | 0.00    |
| 2          | 25.37                        | 1,611,697   | 152,865                   | 3,307.21 | 0.00                     | 84.70   | 0.00    |
| 3          | 25.40                        | 1,602,406   | 254,071                   | 3,431.54 | 0.00                     | 163.12  | 0.00    |
| 4          | 25.39                        | 1,595,579   | 346,460                   | 3,585.26 | 0.00                     | 221.58  | 0.05    |
| 5          | 25.41                        | 1,595,285   | 441,608                   | 3,723.16 | 0.00                     | 0.00    | 255.09  |
| 6          | 25.41                        | 1,568,543   | 518,829                   | 3,879.14 | 0.00                     | 0.00    | 287.79  |
| 7          | 25.40                        | 1,584,548   | 613,592                   | 4,141.36 | 0.00                     | 0.00    | 308.80  |
| 8          | 25.41                        | 1,570,374   | 737,629                   | 4,319.95 | 0.00                     | 0.00    | 316.82  |
| 9          | 25.40                        | 1,566,124   | 848,555                   | 4,568.61 | 0.00                     | 0.00    | 326.53  |
| 10         | 25.41                        | 1,571,391   | 953,649                   | 4,794.67 | 0.00                     | 0.00    | 339.50  |
| 11         | 25.40                        | 1,568,995   | 1,037,313                 | 4,977.77 | 0.00                     | 0.00    | 351.89  |
| 12         | 25.38                        | 1,573,426   | 1,112,816                 | 5,212.87 | 0.00                     | 0.00    | 361.79  |
| 13         | 25.42                        | 1,783,116   | 1,206,923                 | 5,407.28 | 0.00                     | 0.00    | 369.46  |
| 14         | 25.42                        | 1,783,252   | 1,306,094                 | 5,961.12 | 0.00                     | 0.00    | 377.42  |
| 15         | 25.42                        | 1,785,580   | 1,378,591                 | 6,182.65 | 0.00                     | 82.24   | 306.13  |
| 16         | 25.40                        | 1,790,237   | 1,441,186                 | 7,080.10 | 0.00                     | 83.80   | 314.09  |
| 17         | 25.41                        | 1,793,424   | 1,551,479                 | 7,301.64 | 0.00                     | 84.06   | 317.10  |
| 18         | 25.40                        | 1,796,159   | 1,647,011                 | 7,532.21 | 0.00                     | 84.27   | 319.65  |

## Appendix C: Single- and two-phase measured data (continued).

Channel D: Helium gas tests.

Number of channels:

7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.33Hyd. Diameter ( $\mu\text{m}$ ): 111.86Width ( $\mu\text{m}$ ): 112.73

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 33.13                    | 32.92  | 37.02                                            | 43.71  | 44.31  | 45.79  | 45.82  | 45.54  | 45.68  |
| 2          | 33.28                    | 34.38  | 37.68                                            | 44.41  | 45.03  | 46.50  | 46.54  | 46.27  | 46.39  |
| 3          | 32.87                    | 38.71  | 37.92                                            | 44.68  | 45.31  | 46.78  | 46.83  | 46.55  | 46.67  |
| 4          | 32.77                    | 40.33  | 37.96                                            | 44.76  | 45.39  | 46.86  | 46.89  | 46.59  | 46.75  |
| 5          | 32.79                    | 40.64  | 38.00                                            | 44.81  | 45.45  | 46.91  | 46.93  | 46.60  | 46.80  |
| 6          | 32.76                    | 40.89  | 37.99                                            | 44.83  | 45.49  | 46.95  | 46.98  | 46.62  | 46.84  |
| 7          | 32.70                    | 40.72  | 37.98                                            | 44.84  | 45.52  | 46.97  | 47.00  | 46.65  | 46.86  |
| 8          | 32.61                    | 42.32  | 37.90                                            | 44.79  | 45.48  | 46.94  | 46.98  | 46.61  | 46.83  |
| 9          | 32.52                    | 43.08  | 37.81                                            | 44.72  | 45.43  | 46.88  | 46.94  | 46.57  | 46.78  |
| 10         | 32.33                    | 43.71  | 37.67                                            | 44.62  | 45.37  | 46.82  | 46.88  | 46.52  | 46.71  |
| 11         | 32.17                    | 43.89  | 37.49                                            | 44.47  | 45.23  | 46.68  | 46.76  | 46.39  | 46.57  |
| 12         | 31.94                    | 43.97  | 37.22                                            | 44.21  | 44.99  | 46.44  | 46.53  | 46.16  | 46.33  |
| 13         | 31.70                    | 44.02  | 36.94                                            | 43.95  | 44.76  | 46.21  | 46.31  | 45.95  | 46.10  |
| 14         | 31.41                    | 44.13  | 36.61                                            | 43.66  | 44.51  | 45.96  | 46.08  | 45.73  | 45.84  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |          | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|----------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet   | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.44                        | 1,271,753   | 33,853                    | 3,431.54 | 30.48                    | 0.00    | 0.00    |
| 2          | 24.44                        | 1,157,572   | 98,664                    | 3,417.98 | 0.00                     | 97.25   | 0.00    |
| 3          | 24.43                        | 1,135,011   | 218,632                   | 3,562.66 | 0.00                     | 214.61  | 0.00    |
| 4          | 24.44                        | 1,126,263   | 304,127                   | 3,664.38 | 0.00                     | 288.85  | 0.00    |
| 5          | 24.47                        | 1,119,436   | 363,421                   | 3,757.06 | 0.00                     | 0.00    | 369.98  |
| 6          | 24.48                        | 1,111,569   | 424,095                   | 3,890.44 | 0.00                     | 0.00    | 431.96  |
| 7          | 24.48                        | 1,108,811   | 476,495                   | 4,010.25 | 0.00                     | 0.00    | 486.80  |
| 8          | 24.45                        | 1,108,879   | 526,137                   | 4,179.79 | 0.00                     | 0.00    | 537.31  |
| 9          | 24.46                        | 1,104,674   | 568,884                   | 4,272.47 | 0.00                     | 0.00    | 581.15  |
| 10         | 24.46                        | 1,106,053   | 617,148                   | 4,410.37 | 0.00                     | 0.00    | 629.13  |
| 11         | 24.46                        | 1,107,432   | 654,379                   | 4,548.26 | 0.00                     | 0.00    | 665.47  |
| 12         | 24.46                        | 1,101,916   | 698,505                   | 4,636.43 | 0.00                     | 146.59  | 551.60  |
| 13         | 24.48                        | 1,102,504   | 739,874                   | 4,796.93 | 0.00                     | 153.13  | 582.01  |
| 14         | 24.46                        | 1,104,674   | 781,242                   | 4,961.95 | 0.00                     | 159.06  | 610.66  |

Appendix C: Single- and two-phase measured data (continued).

Channel D: Nitrogen gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.33

Hyd. Diameter ( $\mu\text{m}$ ): 111.86

Width ( $\mu\text{m}$ ): 112.73

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 31.97                    | 32.43  | 33.94                                            | 40.51  | 40.93  | 42.50  | 42.54  | 42.36  | 42.42  |
| 2          | 32.03                    | 35.67  | 37.15                                            | 43.91  | 44.47  | 45.95  | 45.99  | 45.76  | 45.85  |
| 3          | 31.80                    | 37.95  | 38.31                                            | 45.12  | 45.71  | 47.18  | 47.22  | 46.95  | 47.08  |
| 4          | 31.39                    | 39.75  | 38.50                                            | 45.37  | 45.98  | 47.45  | 47.50  | 47.21  | 47.35  |
| 5          | 31.09                    | 42.00  | 38.56                                            | 45.45  | 46.10  | 47.56  | 47.61  | 47.33  | 47.46  |
| 6          | 30.88                    | 42.93  | 38.55                                            | 45.48  | 46.15  | 47.61  | 47.68  | 47.39  | 47.51  |
| 7          | 30.71                    | 43.38  | 38.44                                            | 45.39  | 46.08  | 47.54  | 47.62  | 47.33  | 47.43  |
| 8          | 30.48                    | 42.91  | 38.18                                            | 45.13  | 45.84  | 47.30  | 47.38  | 47.09  | 47.19  |
| 9          | 30.32                    | 42.95  | 37.98                                            | 44.97  | 45.70  | 47.16  | 47.25  | 46.97  | 47.05  |
| 10         | 30.12                    | 43.13  | 37.87                                            | 44.82  | 45.59  | 47.04  | 47.15  | 46.86  | 46.93  |
| 11         | 29.93                    | 43.12  | 37.63                                            | 44.61  | 45.40  | 46.85  | 46.97  | 46.69  | 46.74  |
| 12         | 29.72                    | 43.12  | 37.33                                            | 44.31  | 45.13  | 46.59  | 46.72  | 46.46  | 46.47  |
| 13         | 29.53                    | 43.17  | 37.02                                            | 44.07  | 44.92  | 46.37  | 46.53  | 46.28  | 46.26  |
| 14         | 29.26                    | 43.11  | 36.68                                            | 43.74  | 44.62  | 46.07  | 46.26  | 46.02  | 45.96  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 24.44                        | 1,068,641   | 19,788                    | 3,174  | 21.60                    | 0.00    | 0.00    |
| 2          | 24.40                        | 907,485     | 61,608                    | 3,221  | 0.00                     | 71.84   | 0.00    |
| 3          | 24.41                        | 1,209,158   | 145,272                   | 3,287  | 0.00                     | 167.06  | 0.00    |
| 4          | 24.40                        | 1,188,790   | 233,525                   | 3,325  | 0.00                     | 245.89  | 0.18    |
| 5          | 24.38                        | 1,177,758   | 301,093                   | 3,454  | 0.00                     | 0.00    | 295.22  |
| 6          | 24.39                        | 1,168,852   | 364,525                   | 3,583  | 0.00                     | 0.00    | 337.83  |
| 7          | 24.39                        | 1,161,211   | 427,956                   | 3,725  | 0.00                     | 0.00    | 370.64  |
| 8          | 24.39                        | 1,156,780   | 505,177                   | 3,859  | 0.00                     | 0.00    | 394.68  |
| 9          | 24.41                        | 1,154,316   | 577,086                   | 4,001  | 0.00                     | 0.00    | 406.39  |
| 10         | 24.42                        | 1,154,610   | 672,346                   | 4,171  | 0.00                     | 0.00    | 410.52  |
| 11         | 24.44                        | 1,150,586   | 765,798                   | 4,401  | 0.00                     | 0.00    | 415.55  |
| 12         | 24.48                        | 1,147,422   | 862,483                   | 4,553  | 0.00                     | 89.89   | 336.89  |
| 13         | 24.49                        | 1,150,179   | 928,356                   | 4,684  | 0.00                     | 90.31   | 340.76  |
| 14         | 24.50                        | 1,150,903   | 1,018,145                 | 4,829  | 0.00                     | 91.45   | 348.58  |



## Appendix C: Single- and two-phase measured data (continued).

Channel D: Water tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.33      Hyd. Diameter ( $\mu\text{m}$ ): 111.86Width ( $\mu\text{m}$ ): 112.73      Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 23.84                    | 43.12  | 31.14                                            | 38.44  | 43.43  | 43.56  | 45.90  | 48.04  | 43.19  |
| 2          | 23.71                    | 41.33  | 29.90                                            | 36.52  | 41.25  | 41.33  | 43.46  | 45.53  | 41.01  |
| 3          | 23.63                    | 39.94  | 28.99                                            | 35.03  | 39.53  | 39.58  | 41.52  | 43.48  | 39.30  |
| 4          | 23.58                    | 40.30  | 29.43                                            | 35.93  | 41.03  | 40.71  | 42.72  | 44.77  | 40.42  |
| 5          | 23.99                    | 39.82  | 29.26                                            | 35.32  | 40.25  | 39.88  | 41.69  | 43.56  | 39.61  |
| 6          | 24.03                    | 40.86  | 29.80                                            | 36.71  | 42.39  | 41.53  | 43.41  | 45.35  | 41.25  |
| 7          | 24.14                    | 40.50  | 29.66                                            | 36.36  | 41.99  | 41.08  | 42.84  | 44.64  | 40.83  |
| 8          | 24.29                    | 40.49  | 29.38                                            | 35.96  | 41.52  | 40.58  | 42.22  | 43.88  | 40.34  |
| 9          | 24.43                    | 41.36  | 30.35                                            | 37.22  | 43.46  | 42.07  | 43.74  | 45.39  | 41.82  |
| 10         | 24.64                    | 40.59  | 30.42                                            | 37.18  | 43.57  | 42.12  | 43.99  | 46.28  | 41.87  |
| 11         | 24.84                    | 40.32  | 30.02                                            | 37.01  | 43.36  | 41.89  | 43.72  | 45.95  | 41.65  |
| 12         | 25.05                    | 39.85  | 29.72                                            | 36.68  | 42.99  | 41.49  | 43.22  | 45.32  | 41.27  |
| 13         | 25.26                    | 40.88  | 30.46                                            | 38.04  | 45.22  | 43.15  | 44.91  | 46.91  | 42.92  |
| 14         | 25.43                    | 40.67  | 30.38                                            | 37.99  | 45.22  | 43.07  | 44.76  | 46.63  | 42.85  |
| 15         | 25.58                    | 40.14  | 30.26                                            | 37.62  | 44.80  | 42.62  | 44.18  | 45.74  | 42.41  |
| 16         | 26.11                    | 41.72  | 31.84                                            | 39.79  | 48.05  | 45.13  | 46.73  | 48.22  | 44.92  |
| 17         | 26.21                    | 41.16  | 31.77                                            | 39.42  | 47.62  | 44.67  | 46.17  | 47.38  | 44.46  |
| 18         | 26.34                    | 40.26  | 31.38                                            | 38.80  | 46.98  | 44.03  | 45.46  | 46.47  | 43.83  |
| 19         | 26.48                    | 40.04  | 31.77                                            | 38.29  | 46.34  | 43.40  | 44.65  | 45.12  | 43.21  |
| 20         | 26.57                    | 38.64  | 31.47                                            | 36.97  | 44.92  | 41.99  | 42.94  | 42.65  | 41.82  |
| 21         | 27.58                    | 32.32  | 29.68                                            | 30.84  | 33.82  | 34.10  | 34.86  | 35.44  | 31.85  |
| 22         | 27.63                    | 32.22  | 29.25                                            | 30.15  | 32.94  | 33.21  | 33.73  | 33.92  | 31.24  |
| 23         | 27.65                    | 32.12  | 29.01                                            | 29.66  | 32.35  | 32.61  | 33.10  | 33.50  | 30.88  |
| 24         | 27.67                    | 32.04  | 28.55                                            | 29.39  | 32.04  | 32.28  | 32.75  | 33.27  | 30.45  |
| 25         | 27.70                    | 31.98  | 28.38                                            | 29.23  | 31.85  | 32.09  | 32.55  | 33.13  | 30.27  |
| 26         | 27.68                    | 31.93  | 28.29                                            | 29.08  | 31.72  | 31.95  | 32.42  | 33.04  | 30.17  |

Appendix C: Single- and two-phase measured data (continued).

Channel D: Water tests (continued).

| Data Point | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | liquid Flow Rate   |
|------------|-------------------|------------|---------------------------|---------|--------------------|
|            | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F. M. #1. (cc/min) |
| 1          | 23.96             | 2,225,645  | 406,862                   | 104,174 | 9.24               |
| 2          | 23.95             | 2,179,687  | 478,522                   | 102,173 | 11.71              |
| 3          | 23.99             | 2,158,619  | 545,254                   | 101,326 | 14.58              |
| 4          | 24.08             | 2,132,555  | 609,657                   | 100,041 | 13.98              |
| 5          | 24.68             | 2,300,967  | 686,856                   | 99,173  | 17.98              |
| 6          | 24.89             | 2,295,564  | 764,167                   | 98,814  | 18.59              |
| 7          | 25.14             | 2,274,337  | 826,740                   | 97,905  | 21.73              |
| 8          | 25.45             | 2,273,162  | 893,200                   | 97,844  | 22.80              |
| 9          | 25.68             | 2,221,531  | 962,238                   | 95,853  | 24.67              |
| 10         | 25.98             | 2,240,271  | 1,048,185                 | 96,388  | 26.69              |
| 11         | 26.24             | 2,210,499  | 1,096,245                 | 95,561  | 27.72              |
| 12         | 26.49             | 2,203,288  | 1,178,303                 | 95,425  | 29.63              |
| 13         | 26.72             | 2,243,255  | 1,267,641                 | 96,809  | 31.46              |
| 14         | 26.92             | 2,231,681  | 1,320,629                 | 96,416  | 33.17              |
| 15         | 27.13             | 2,241,288  | 1,464,084                 | 96,992  | 36.92              |
| 16         | 27.72             | 2,234,303  | 1,521,819                 | 96,935  | 37.67              |
| 17         | 27.86             | 2,196,190  | 1,642,307                 | 95,753  | 38.85              |
| 18         | 28.00             | 2,200,892  | 1,785,040                 | 96,004  | 43.58              |
| 19         | 28.17             | 2,206,746  | 1,922,347                 | 96,345  | 44.61              |
| 20         | 28.35             | 2,209,482  | 2,218,436                 | 96,718  | 50.85              |
| 21         | 29.27             | 4,271,595  | 2,114,910                 | 102,015 | 60.45              |
| 22         | 29.34             | 4,259,591  | 2,435,639                 | 102,212 | 65.24              |
| 23         | 29.43             | 4,261,196  | 2,778,545                 | 102,567 | 69.86              |
| 24         | 29.50             | 4,243,790  | 3,111,775                 | 102,230 | 72.52              |
| 25         | 29.58             | 4,234,182  | 3,467,815                 | 102,234 | 76.93              |
| 26         | 29.65             | 4,229,661  | 3,820,418                 | 102,347 | 79.44              |

**Appendix C: Single- and two-phase measured data (continued).**

Channel D: Water and argon tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.33 Hyd. Diameter ( $\mu\text{m}$ ): 111.86

Width ( $\mu\text{m}$ ): 112.73 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 27.03                    | 40.71  | 30.19                                            | 35.66  | 39.53  | 39.88  | 41.52  | 43.00  | 39.64  |
| 2          | 27.01                    | 40.20  | 29.91                                            | 35.20  | 39.02  | 39.36  | 40.91  | 42.26  | 39.13  |
| 3          | 27.25                    | 41.44  | 31.17                                            | 36.59  | 40.47  | 40.84  | 42.37  | 43.57  | 40.59  |
| 4          | 27.69                    | 43.15  | 32.27                                            | 38.67  | 42.61  | 42.97  | 44.47  | 45.46  | 42.70  |
| 5          | 27.66                    | 42.82  | 31.53                                            | 38.49  | 42.39  | 42.79  | 44.19  | 45.02  | 42.55  |
| 6          | 26.64                    | 41.64  | 30.40                                            | 36.73  | 41.30  | 41.26  | 43.03  | 44.65  | 41.00  |
| 7          | 27.14                    | 42.90  | 30.97                                            | 37.73  | 42.42  | 42.37  | 44.18  | 45.73  | 42.09  |
| 8          | 27.43                    | 43.78  | 31.55                                            | 38.80  | 43.53  | 43.50  | 45.27  | 46.65  | 43.21  |
| 9          | 27.90                    | 45.61  | 32.52                                            | 40.78  | 45.60  | 45.57  | 47.31  | 48.48  | 45.26  |
| 10         | 27.88                    | 45.28  | 32.97                                            | 40.63  | 45.36  | 45.35  | 46.96  | 47.92  | 45.06  |
| 11         | 26.49                    | 40.75  | 30.12                                            | 35.77  | 40.23  | 40.15  | 41.79  | 43.30  | 39.92  |
| 12         | 26.58                    | 40.30  | 29.83                                            | 35.33  | 39.70  | 39.62  | 41.15  | 42.47  | 39.39  |
| 13         | 26.88                    | 40.77  | 30.23                                            | 36.11  | 40.51  | 40.44  | 41.92  | 43.12  | 40.20  |
| 14         | 27.10                    | 42.12  | 30.78                                            | 37.35  | 41.86  | 41.80  | 43.29  | 44.33  | 41.54  |
| 15         | 26.53                    | 33.88  | 27.65                                            | 31.17  | 35.08  | 35.00  | 36.03  | 36.63  | 31.36  |
| 16         | 26.54                    | 33.33  | 27.30                                            | 30.46  | 34.23  | 34.12  | 35.06  | 35.73  | 30.63  |
| 17         | 26.57                    | 33.51  | 27.35                                            | 30.46  | 34.22  | 34.10  | 35.04  | 35.78  | 30.63  |
| 18         | 26.55                    | 33.64  | 27.32                                            | 30.46  | 34.20  | 34.07  | 34.96  | 35.69  | 30.61  |
| 19         | 26.47                    | 33.21  | 26.48                                            | 29.80  | 33.44  | 33.29  | 34.13  | 35.01  | 29.89  |
| 20         | 26.38                    | 33.11  | 26.43                                            | 29.76  | 33.41  | 33.26  | 34.12  | 34.98  | 29.86  |
| 21         | 27.61                    | 33.90  | 27.39                                            | 30.44  | 34.38  | 33.88  | 34.71  | 35.94  | 30.60  |
| 22         | 27.70                    | 34.09  | 27.47                                            | 30.50  | 34.44  | 33.94  | 34.76  | 36.00  | 30.65  |
| 23         | 27.71                    | 34.30  | 27.52                                            | 30.65  | 34.65  | 34.14  | 34.98  | 36.18  | 30.82  |
| 24         | 27.73                    | 34.03  | 27.81                                            | 30.40  | 34.33  | 33.81  | 34.62  | 35.85  | 30.64  |
| 25         | 27.75                    | 34.10  | 27.85                                            | 30.47  | 34.42  | 33.92  | 34.72  | 35.92  | 30.72  |
| 26         | 25.11                    | 36.19  | 28.76                                            | 32.59  | 35.41  | 36.38  | 37.29  | 37.37  | 36.28  |
| 27         | 25.13                    | 36.41  | 29.46                                            | 32.85  | 35.69  | 36.64  | 37.56  | 37.57  | 36.50  |
| 28         | 25.22                    | 36.95  | 29.73                                            | 33.29  | 36.18  | 37.12  | 38.07  | 38.10  | 36.97  |
| 29         | 25.38                    | 37.36  | 30.02                                            | 33.93  | 36.80  | 37.78  | 38.68  | 38.63  | 37.67  |

# Appendix C: Single- and two-phase measured data (continued).

## Channel D: Water and argon (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.42          | 1,470,977  | 26.48             | 1,555,717  | 688,682                   | 96,960  | 0.00                            | 15.05   | 0.00    | 11.07   |
| 2          | 25.47          | 1,479,092  | 26.47             | 1,554,881  | 804,062                   | 95,954  | 0.00                            | 27.96   | 0.00    | 12.99   |
| 3          | 25.49          | 1,490,282  | 26.46             | 1,544,822  | 883,588                   | 97,894  | 0.00                            | 54.96   | 0.00    | 12.06   |
| 4          | 25.46          | 1,467,563  | 26.34             | 1,561,640  | 978,442                   | 101,920 | 0.00                            | 85.11   | 0.00    | 9.45    |
| 5          | 25.43          | 1,470,095  | 26.29             | 1,558,701  | 1,173,597                 | 105,914 | 0.00                            | 0.00    | 96.44   | 9.60    |
| 6          | 25.28          | 1,488,270  | 26.36             | 1,620,144  | 811,747                   | 101,027 | 0.00                            | 13.85   | 0.00    | 15.23   |
| 7          | 25.32          | 1,497,697  | 26.35             | 1,606,196  | 862,000                   | 98,525  | 0.00                            | 29.22   | 0.00    | 11.95   |
| 8          | 25.30          | 1,484,540  | 26.32             | 1,596,634  | 955,294                   | 99,856  | 0.00                            | 49.83   | 0.00    | 12.96   |
| 9          | 25.29          | 1,482,053  | 26.36             | 1,577,713  | 1,056,816                 | 102,191 | 0.00                            | 74.52   | 0.00    | 12.15   |
| 10         | 25.34          | 1,456,758  | 26.33             | 1,571,067  | 1,231,173                 | 105,833 | 0.00                            | 90.72   | 0.00    | 12.23   |
| 11         | 25.32          | 1,472,356  | 26.51             | 1,608,750  | 904,273                   | 100,093 | 0.00                            | 11.00   | 0.00    | 16.74   |
| 12         | 25.34          | 1,500,432  | 26.57             | 1,603,348  | 1,041,964                 | 100,304 | 0.00                            | 23.81   | 0.00    | 16.80   |
| 13         | 25.35          | 1,483,342  | 26.60             | 1,604,161  | 1,112,855                 | 101,387 | 0.00                            | 43.91   | 0.00    | 15.10   |
| 14         | 25.37          | 1,468,716  | 26.60             | 1,594,780  | 1,244,872                 | 104,484 | 0.00                            | 69.13   | 0.00    | 15.29   |
| 15         | 24.51          | 3,533,225  | 28.10             | 3,984,314  | 1,994,489                 | 117,100 | 0.00                            | 0.00    | 197.97  | 46.32   |
| 16         | 24.50          | 3,514,508  | 28.13             | 4,040,127  | 2,258,094                 | 120,791 | 0.00                            | 0.00    | 194.64  | 50.99   |
| 17         | 24.50          | 3,545,591  | 28.14             | 4,069,198  | 2,310,743                 | 122,717 | 0.00                            | 0.00    | 208.81  | 49.67   |
| 18         | 24.39          | 3,562,635  | 28.10             | 3,958,159  | 2,506,666                 | 129,203 | 0.00                            | 44.70   | 168.81  | 45.25   |
| 19         | 24.42          | 3,531,372  | 28.08             | 3,967,518  | 2,764,574                 | 131,495 | 0.00                            | 44.56   | 169.65  | 49.85   |
| 20         | 24.59          | 3,592,407  | 28.05             | 3,914,372  | 2,594,806                 | 127,024 | 0.00                            | 21.03   | 78.36   | 54.56   |
| 21         | 25.35          | 3,988,323  | 29.33             | 4,101,728  | 2,779,675                 | 109,423 | 0.00                            | 10.54   | 0.00    | 68.22   |
| 22         | 25.37          | 3,605,586  | 29.39             | 4,157,812  | 2,910,155                 | 114,050 | 0.00                            | 24.72   | 0.00    | 67.02   |
| 23         | 25.47          | 3,521,131  | 29.39             | 4,068,294  | 3,039,166                 | 119,507 | 0.00                            | 45.42   | 0.00    | 62.79   |
| 24         | 25.56          | 3,790,184  | 29.43             | 4,172,009  | 3,048,502                 | 115,058 | 0.00                            | 0.00    | 62.22   | 66.69   |
| 25         | 25.43          | 3,602,738  | 29.43             | 4,045,982  | 3,125,678                 | 117,206 | 0.00                            | 0.00    | 89.14   | 64.03   |
| 26         | 23.95          | 2,578,248  | 24.82             | 1,996,867  | 1,648,274                 | 122,645 | 0.00                            | 46.76   | 171.88  | 10.14   |
| 27         | 23.94          | 2,550,601  | 24.82             | 2,030,233  | 1,721,675                 | 125,706 | 0.00                            | 47.89   | 176.74  | 11.31   |
| 28         | 23.93          | 2,538,033  | 24.78             | 2,049,086  | 1,757,663                 | 128,355 | 0.00                            | 49.80   | 184.51  | 9.41    |
| 29         | 23.93          | 2,526,933  | 24.75             | 2,047,436  | 1,807,870                 | 130,582 | 0.00                            | 52.46   | 195.50  | 8.86    |

Appendix C: Single- and two-phase measured data (continued).

Channel D: Water and helium tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.33 Hyd. Diameter ( $\mu\text{m}$ ): 111.86

Width ( $\mu\text{m}$ ): 112.73 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 27.25                    | 41.86  | 30.52                                            | 36.16  | 40.12  | 40.47  | 42.16  | 43.69  | 40.22  |
| 2          | 27.65                    | 42.24  | 30.67                                            | 36.47  | 40.44  | 40.79  | 42.46  | 43.89  | 40.54  |
| 3          | 28.04                    | 43.21  | 31.70                                            | 38.50  | 42.49  | 42.86  | 44.43  | 45.56  | 42.60  |
| 4          | 27.67                    | 41.56  | 31.09                                            | 37.57  | 41.42  | 41.77  | 43.12  | 43.89  | 41.51  |
| 5          | 26.98                    | 41.34  | 30.82                                            | 36.13  | 40.53  | 40.54  | 42.27  | 43.92  | 40.30  |
| 6          | 27.11                    | 41.89  | 30.96                                            | 36.48  | 41.02  | 41.00  | 42.78  | 44.43  | 40.74  |
| 7          | 27.39                    | 42.24  | 31.24                                            | 36.97  | 41.50  | 41.48  | 43.21  | 44.73  | 41.22  |
| 8          | 27.28                    | 41.72  | 30.67                                            | 36.85  | 41.35  | 41.31  | 42.93  | 44.24  | 41.05  |
| 9          | 27.09                    | 40.78  | 30.26                                            | 36.27  | 40.68  | 40.63  | 42.13  | 43.26  | 40.38  |
| 10         | 27.25                    | 41.36  | 30.78                                            | 37.21  | 41.64  | 41.63  | 43.10  | 44.06  | 41.37  |
| 11         | 26.52                    | 39.15  | 29.53                                            | 34.31  | 38.50  | 38.47  | 39.94  | 41.37  | 38.26  |
| 12         | 26.57                    | 39.32  | 29.52                                            | 34.40  | 38.63  | 38.59  | 40.09  | 41.47  | 38.38  |
| 13         | 26.63                    | 38.90  | 29.27                                            | 34.17  | 38.37  | 38.33  | 39.76  | 41.04  | 38.11  |
| 14         | 26.68                    | 38.63  | 29.92                                            | 34.28  | 38.44  | 38.41  | 39.77  | 40.88  | 38.20  |
| 15         | 26.68                    | 38.68  | 29.89                                            | 34.52  | 38.71  | 38.68  | 40.01  | 41.01  | 38.45  |
| 16         | 27.80                    | 33.92  | 28.49                                            | 30.61  | 34.66  | 34.11  | 34.92  | 36.10  | 31.11  |
| 17         | 27.77                    | 33.71  | 28.40                                            | 30.39  | 34.42  | 33.86  | 34.65  | 35.82  | 30.96  |
| 18         | 27.73                    | 33.68  | 28.45                                            | 30.41  | 34.46  | 33.90  | 34.68  | 35.85  | 31.01  |
| 19         | 27.71                    | 33.66  | 28.38                                            | 30.39  | 34.45  | 33.88  | 34.67  | 35.83  | 30.97  |
| 20         | 27.64                    | 33.62  | 28.40                                            | 30.41  | 34.50  | 33.93  | 34.72  | 35.86  | 31.00  |

Appendix C: Single- and two-phase measured data (continued).

Channel A: Water and helium (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.48          | 1,958,852  | 26.44             | 1,620,279  | 662,934                   | 98,647  | 0.00                            | 16.04   | 0.00    | 11.94   |
| 2          | 25.52          | 1,901,999  | 26.40             | 1,608,863  | 692,322                   | 99,947  | 0.00                            | 35.37   | 0.00    | 12.04   |
| 3          | 25.53          | 1,896,438  | 26.37             | 1,594,848  | 830,488                   | 109,658 | 0.00                            | 0.00    | 131.46  | 9.00    |
| 4          | 25.56          | 1,889,317  | 26.30             | 1,603,009  | 1,086,271                 | 123,949 | 0.00                            | 0.00    | 219.04  | 11.54   |
| 5          | 25.53          | 1,975,739  | 26.38             | 1,595,255  | 754,872                   | 100,704 | 0.00                            | 13.84   | 0.00    | 14.13   |
| 6          | 25.55          | 1,900,028  | 26.39             | 1,575,493  | 813,510                   | 98,199  | 0.00                            | 30.60   | 0.00    | 13.17   |
| 7          | 25.56          | 1,897,320  | 26.41             | 1,560,487  | 860,485                   | 100,726 | 0.00                            | 58.93   | 0.00    | 13.00   |
| 8          | 25.57          | 1,904,463  | 26.44             | 1,548,438  | 976,905                   | 105,243 | 0.00                            | 92.91   | 0.00    | 13.59   |
| 9          | 25.59          | 1,894,426  | 26.48             | 1,543,940  | 1,088,938                 | 110,144 | 0.00                            | 0.00    | 125.96  | 14.44   |
| 10         | 25.62          | 1,872,702  | 26.49             | 1,553,095  | 1,146,560                 | 116,860 | 0.00                            | 0.00    | 172.77  | 13.31   |
| 11         | 25.60          | 1,965,182  | 26.64             | 1,548,551  | 938,769                   | 97,677  | 0.00                            | 12.13   | 0.00    | 19.06   |
| 12         | 25.58          | 1,899,558  | 26.67             | 1,533,428  | 980,476                   | 97,507  | 0.00                            | 27.91   | 0.00    | 16.93   |
| 13         | 25.54          | 1,895,963  | 26.72             | 1,524,612  | 1,053,854                 | 98,904  | 0.00                            | 46.66   | 0.00    | 19.38   |
| 14         | 25.49          | 1,898,947  | 26.75             | 1,529,427  | 1,143,079                 | 104,809 | 0.00                            | 81.89   | 0.00    | 18.74   |
| 15         | 25.45          | 1,886,650  | 26.76             | 1,533,383  | 1,215,439                 | 110,178 | 0.00                            | 0.00    | 118.61  | 18.64   |
| 16         | 25.37          | 3,764,436  | 29.52             | 4,026,360  | 3,041,028                 | 129,036 | 0.00                            | 30.75   | 114.59  | 64.33   |
| 17         | 25.35          | 3,716,241  | 29.47             | 4,201,984  | 3,304,045                 | 137,874 | 0.00                            | 32.79   | 123.70  | 67.08   |
| 18         | 25.37          | 3,707,719  | 29.41             | 4,193,823  | 3,324,006                 | 141,952 | 0.00                            | 37.66   | 144.16  | 66.87   |
| 19         | 25.40          | 3,710,725  | 29.37             | 4,192,490  | 3,369,647                 | 143,815 | 0.00                            | 40.47   | 156.41  | 65.88   |
| 20         | 25.42          | 3,704,938  | 29.32             | 4,183,696  | 3,379,006                 | 148,228 | 0.00                            | 45.58   | 178.94  | 64.94   |

# Appendix C: Single- and two-phase measured data (continued).

Channel D: Water and nitrogen tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.33 Hyd. Diameter ( $\mu\text{m}$ ): 111.86

Width ( $\mu\text{m}$ ): 112.73 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature. ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.36                    | 41.91  | 28.36                                            | 35.89  | 39.93  | 40.30  | 42.07  | 43.66  | 40.04  |
| 2          | 26.73                    | 41.71  | 28.42                                            | 36.02  | 40.05  | 40.41  | 42.14  | 43.66  | 40.15  |
| 3          | 26.51                    | 40.46  | 28.00                                            | 35.40  | 39.31  | 39.66  | 41.25  | 42.66  | 39.42  |
| 4          | 26.63                    | 40.72  | 27.98                                            | 36.14  | 40.07  | 40.42  | 41.94  | 43.15  | 40.17  |
| 5          | 27.03                    | 42.30  | 29.45                                            | 38.07  | 42.06  | 42.42  | 43.90  | 44.87  | 42.14  |
| 6          | 25.94                    | 41.09  | 28.13                                            | 36.01  | 40.69  | 40.58  | 42.42  | 44.26  | 40.32  |
| 7          | 26.38                    | 41.29  | 28.72                                            | 36.16  | 40.82  | 40.72  | 42.52  | 44.28  | 40.46  |
| 8          | 26.76                    | 41.93  | 29.10                                            | 36.79  | 41.50  | 41.40  | 43.19  | 44.83  | 41.13  |
| 9          | 26.87                    | 42.09  | 29.30                                            | 37.18  | 41.88  | 41.79  | 43.51  | 44.98  | 41.51  |
| 10         | 27.19                    | 43.45  | 29.90                                            | 38.71  | 43.49  | 43.42  | 45.14  | 46.46  | 43.13  |
| 11         | 26.01                    | 40.91  | 28.30                                            | 36.23  | 41.34  | 40.85  | 42.63  | 44.45  | 40.60  |
| 12         | 26.17                    | 41.18  | 28.22                                            | 36.29  | 41.47  | 40.96  | 42.73  | 44.49  | 40.71  |
| 13         | 26.70                    | 42.22  | 31.16                                            | 37.33  | 42.59  | 42.09  | 43.86  | 45.45  | 41.81  |
| 14         | 25.86                    | 30.71  | 24.19                                            | 27.84  | 30.74  | 31.00  | 31.72  | 32.40  | 27.74  |
| 15         | 26.01                    | 30.80  | 23.91                                            | 27.81  | 30.69  | 30.95  | 31.64  | 32.35  | 27.72  |
| 16         | 26.12                    | 30.90  | 23.95                                            | 27.81  | 30.67  | 30.92  | 31.60  | 32.35  | 27.71  |
| 17         | 26.17                    | 31.07  | 24.01                                            | 27.86  | 30.74  | 30.98  | 31.66  | 32.44  | 27.76  |
| 18         | 26.21                    | 31.16  | 24.08                                            | 27.96  | 30.85  | 31.08  | 31.76  | 32.51  | 27.86  |
| 19         | 26.21                    | 31.31  | 24.15                                            | 28.07  | 30.97  | 31.20  | 31.91  | 32.67  | 27.97  |
| 20         | 25.02                    | 36.41  | 28.24                                            | 32.56  | 35.46  | 36.41  | 37.41  | 37.60  | 36.29  |
| 21         | 24.98                    | 36.24  | 27.56                                            | 32.57  | 35.44  | 36.38  | 37.36  | 37.51  | 36.25  |
| 22         | 25.05                    | 36.41  | 25.86                                            | 32.79  | 35.67  | 36.63  | 37.60  | 37.75  | 36.51  |
| 23         | 25.09                    | 36.42  | 25.96                                            | 32.79  | 35.67  | 36.62  | 37.58  | 37.68  | 36.49  |
| 24         | 25.12                    | 36.65  | 26.24                                            | 33.00  | 35.91  | 36.86  | 37.83  | 37.90  | 36.72  |
| 25         | 25.09                    | 36.46  | 26.11                                            | 32.88  | 35.77  | 36.71  | 37.65  | 37.69  | 36.57  |
| 26         | 25.14                    | 36.56  | 26.84                                            | 33.04  | 35.92  | 36.89  | 37.82  | 37.85  | 36.77  |
| 27         | 25.16                    | 36.60  | 26.72                                            | 33.07  | 35.95  | 36.89  | 37.82  | 37.82  | 36.75  |
| 28         | 25.13                    | 36.54  | 26.68                                            | 33.02  | 35.91  | 36.85  | 37.78  | 37.80  | 36.72  |
| 29         | 25.13                    | 36.45  | 26.67                                            | 32.90  | 35.81  | 36.72  | 37.66  | 37.64  | 36.57  |
| 30         | 25.12                    | 36.52  | 26.22                                            | 33.13  | 36.01  | 36.97  | 37.88  | 37.85  | 36.85  |

## Appendix C: Single- and two-phase measured data (continued).

## Channel D: Water and nitrogen (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.21          | 1,259,591  | 25.48             | 1,727,182  | 624,007                   | 106,068 | 0.00                            | 11.41   | 0.00    | 11.81   |
| 2          | 25.27          | 1,194,283  | 25.47             | 1,693,092  | 671,434                   | 104,886 | 0.00                            | 21.49   | 0.00    | 10.14   |
| 3          | 25.29          | 1,194,306  | 25.51             | 1,664,745  | 865,911                   | 106,041 | 0.00                            | 52.86   | 0.00    | 10.55   |
| 4          | 25.32          | 1,177,216  | 25.57             | 1,650,390  | 996,911                   | 109,280 | 0.00                            | 82.48   | 0.00    | 10.97   |
| 5          | 25.36          | 1,171,474  | 25.66             | 1,634,430  | 1,091,448                 | 112,735 | 0.00                            | 0.00    | 111.40  | 9.17    |
| 6          | 25.36          | 1,728,048  | 25.93             | 1,611,327  | 827,730                   | 102,286 | 0.00                            | 9.93    | 0.00    | 15.93   |
| 7          | 25.36          | 1,667,895  | 26.02             | 1,604,501  | 873,619                   | 101,398 | 0.00                            | 19.00   | 0.00    | 13.83   |
| 8          | 25.35          | 1,663,464  | 26.06             | 1,598,555  | 938,837                   | 101,307 | 0.00                            | 36.69   | 0.00    | 14.48   |
| 9          | 25.35          | 1,656,818  | 26.12             | 1,597,199  | 1,033,894                 | 103,369 | 0.00                            | 57.10   | 0.00    | 15.02   |
| 10         | 25.37          | 1,647,979  | 26.15             | 1,597,696  | 1,089,504                 | 105,792 | 0.00                            | 79.11   | 0.00    | 11.56   |
| 11         | 25.36          | 1,776,899  | 26.29             | 1,619,985  | 977,651                   | 100,629 | 0.00                            | 7.92    | 0.00    | 18.06   |
| 12         | 25.35          | 1,670,653  | 26.40             | 1,596,430  | 1,047,276                 | 101,450 | 0.00                            | 14.88   | 0.00    | 19.52   |
| 13         | 25.36          | 1,663,148  | 26.47             | 1,580,787  | 1,107,655                 | 101,163 | 0.00                            | 36.65   | 0.00    | 16.72   |
| 14         | 24.49          | 2,743,631  | 27.59             | 3,988,383  | 2,405,809                 | 118,915 | 0.00                            | 0.00    | 117.66  | 58.94   |
| 15         | 24.46          | 2,707,010  | 27.75             | 3,997,674  | 2,513,344                 | 121,092 | 0.00                            | 0.00    | 123.62  | 59.30   |
| 16         | 24.48          | 2,685,173  | 27.86             | 4,014,108  | 2,611,701                 | 123,549 | 0.00                            | 0.00    | 134.16  | 59.06   |
| 17         | 24.41          | 3,008,909  | 27.91             | 4,012,729  | 2,710,420                 | 129,097 | 0.00                            | 29.27   | 110.29  | 56.89   |
| 18         | 24.44          | 2,943,059  | 27.94             | 4,034,498  | 2,745,323                 | 131,298 | 0.00                            | 32.05   | 122.00  | 55.39   |
| 19         | 24.44          | 2,924,726  | 27.93             | 3,982,211  | 2,777,311                 | 133,552 | 0.00                            | 36.04   | 139.16  | 52.37   |
| 20         | 24.15          | 2,224,379  | 24.91             | 2,117,401  | 1,517,500                 | 129,099 | 0.00                            | 47.40   | 178.03  | 10.05   |
| 21         | 24.16          | 2,210,589  | 24.88             | 2,097,350  | 1,521,773                 | 129,011 | 0.00                            | 48.29   | 181.82  | 11.49   |
| 22         | 24.14          | 2,204,870  | 24.86             | 2,081,955  | 1,547,905                 | 129,671 | 0.00                            | 48.62   | 183.26  | 9.39    |
| 23         | 24.14          | 2,210,296  | 24.83             | 2,078,610  | 1,573,472                 | 130,923 | 0.00                            | 50.08   | 189.55  | 11.32   |
| 24         | 24.15          | 2,205,707  | 24.79             | 2,075,603  | 1,593,659                 | 130,738 | 0.00                            | 50.01   | 189.43  | 10.95   |
| 25         | 24.14          | 2,192,934  | 24.78             | 2,070,381  | 1,626,166                 | 132,065 | 0.00                            | 50.72   | 192.70  | 11.02   |
| 26         | 24.15          | 2,197,501  | 24.77             | 2,066,583  | 1,649,811                 | 132,433 | 0.00                            | 51.42   | 195.87  | 11.28   |
| 27         | 24.13          | 2,195,582  | 24.74             | 2,047,989  | 1,658,459                 | 132,225 | 0.00                            | 51.90   | 198.00  | 10.10   |
| 28         | 24.11          | 2,190,855  | 24.72             | 2,060,774  | 1,676,916                 | 133,498 | 0.00                            | 52.23   | 199.58  | 10.77   |
| 29         | 24.10          | 2,196,823  | 24.71             | 2,062,288  | 1,726,196                 | 134,470 | 0.00                            | 52.42   | 200.91  | 10.45   |
| 30         | 24.08          | 2,188,368  | 24.71             | 2,058,287  | 1,747,016                 | 135,399 | 0.00                            | 53.55   | 205.96  | 9.84    |



## Appendix C: Single- and two-phase measured data (continued).

Channel E: Argon gas tests.

Number of channels: 9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.91 Hyd. Diameter ( $\mu\text{m}$ ): 79.99Width ( $\mu\text{m}$ ): 58.02 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 31.63                    | 32.45  | 40.43                                            | 43.81  | 40.69  | 45.87  | 45.80  | 45.88  | 44.75  |
| 2          | 31.84                    | 34.47  | 41.94                                            | 45.40  | 42.31  | 47.46  | 47.38  | 47.45  | 46.28  |
| 3          | 31.80                    | 34.90  | 42.63                                            | 46.15  | 43.12  | 48.22  | 48.14  | 48.22  | 47.03  |
| 4          | 31.46                    | 38.75  | 42.81                                            | 46.39  | 43.40  | 48.47  | 48.40  | 48.46  | 47.27  |
| 5          | 31.29                    | 39.70  | 42.83                                            | 46.48  | 43.50  | 48.56  | 48.49  | 48.56  | 47.40  |
| 6          | 30.98                    | 40.80  | 42.37                                            | 46.39  | 43.10  | 48.49  | 48.42  | 48.49  | 47.88  |
| 7          | 30.85                    | 41.34  | 42.22                                            | 46.25  | 42.97  | 48.36  | 48.29  | 48.37  | 47.76  |
| 8          | 30.66                    | 41.54  | 41.95                                            | 45.99  | 42.73  | 48.11  | 48.05  | 48.13  | 47.51  |
| 9          | 30.52                    | 41.50  | 41.78                                            | 45.83  | 42.58  | 47.97  | 47.91  | 47.99  | 47.38  |
| 10         | 30.35                    | 41.65  | 41.59                                            | 45.66  | 42.42  | 47.82  | 47.76  | 47.86  | 47.26  |
| 11         | 30.22                    | 41.59  | 41.38                                            | 45.47  | 42.25  | 47.66  | 47.60  | 47.71  | 47.13  |
| 12         | 30.04                    | 41.64  | 41.11                                            | 45.22  | 42.00  | 47.41  | 47.36  | 47.48  | 46.91  |
| 13         | 29.81                    | 41.66  | 40.84                                            | 44.96  | 41.75  | 47.17  | 47.11  | 47.24  | 46.67  |
| 14         | 29.64                    | 41.50  | 40.41                                            | 44.56  | 41.34  | 46.78  | 46.73  | 46.87  | 46.30  |
| 15         | 29.42                    | 41.36  | 40.06                                            | 44.20  | 41.01  | 46.45  | 46.40  | 46.55  | 45.99  |
| 16         | 29.27                    | 41.18  | 39.73                                            | 43.88  | 40.69  | 46.13  | 46.08  | 46.23  | 45.68  |
| 17         | 29.04                    | 41.03  | 39.29                                            | 43.45  | 40.27  | 45.72  | 45.67  | 45.82  | 45.27  |
| 18         | 28.83                    | 40.78  | 38.88                                            | 43.06  | 39.88  | 45.33  | 45.29  | 45.45  | 44.90  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.58                        | 3,010,695   | 45,781                    | 3,138  | 25.60                    | 0.00    | 0.00    |
| 2          | 23.51                        | 2,990,779   | 100,939                   | 3,122  | 0.00                     | 46.31   | 0.00    |
| 3          | 23.43                        | 2,796,190   | 171,921                   | 3,126  | 0.00                     | 74.14   | 0.00    |
| 4          | 23.45                        | 2,275,897   | 331,246                   | 3,190  | 0.00                     | 149.53  | 0.00    |
| 5          | 23.54                        | 2,305,669   | 433,265                   | 3,312  | 0.00                     | 188.69  | 0.00    |
| 6          | 23.59                        | 2,262,696   | 582,191                   | 3,456  | 0.00                     | 0.00    | 214.67  |
| 7          | 23.61                        | 2,247,776   | 682,854                   | 3,603  | 0.00                     | 0.00    | 234.80  |
| 8          | 23.62                        | 2,258,853   | 812,521                   | 3,757  | 0.00                     | 0.00    | 247.93  |
| 9          | 23.63                        | 2,226,775   | 972,682                   | 3,906  | 0.00                     | 0.00    | 251.99  |
| 10         | 23.64                        | 2,244,656   | 1,129,633                 | 4,137  | 0.00                     | 0.00    | 257.33  |
| 11         | 23.64                        | 2,230,437   | 1,265,448                 | 4,275  | 0.00                     | 0.00    | 264.43  |
| 12         | 23.65                        | 2,236,902   | 1,393,509                 | 4,449  | 0.00                     | 0.00    | 272.15  |
| 13         | 23.66                        | 2,225,758   | 1,510,222                 | 4,679  | 0.00                     | 0.00    | 277.69  |
| 14         | 23.74                        | 2,223,000   | 1,640,635                 | 4,826  | 0.00                     | 0.00    | 282.50  |
| 15         | 23.80                        | 2,236,269   | 1,787,391                 | 5,102  | 0.00                     | 0.00    | 286.56  |
| 16         | 23.82                        | 2,235,885   | 1,870,127                 | 5,240  | 0.00                     | 62.22   | 231.62  |
| 17         | 23.85                        | 2,234,461   | 1,995,046                 | 5,516  | 0.00                     | 62.67   | 234.77  |
| 18         | 23.92                        | 2,235,410   | 2,115,625                 | 5,823  | 0.00                     | 63.04   | 237.59  |

# Appendix C: Single- and two-phase measured data (continued).

Channel E: Helium gas tests.

Number of channels:

9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.91Hyd. Diameter ( $\mu\text{m}$ ): 79.99Width ( $\mu\text{m}$ ): 58.02

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 33.65                    | 33.66  | 42.13                                            | 45.56  | 42.42  | 47.65  | 47.58  | 47.63  | 46.43  |
| 2          | 33.98                    | 34.48  | 42.75                                            | 46.18  | 43.03  | 48.26  | 48.19  | 48.24  | 47.04  |
| 3          | 34.13                    | 35.29  | 42.83                                            | 46.26  | 43.12  | 48.34  | 48.27  | 48.33  | 47.14  |
| 4          | 33.66                    | 39.15  | 42.85                                            | 46.30  | 43.16  | 48.39  | 48.32  | 48.37  | 47.17  |
| 5          | 33.48                    | 38.57  | 42.76                                            | 46.22  | 43.08  | 48.31  | 48.24  | 48.29  | 47.08  |
| 6          | 33.34                    | 37.55  | 42.73                                            | 46.19  | 43.07  | 48.30  | 48.23  | 48.28  | 47.06  |
| 7          | 33.19                    | 38.82  | 42.61                                            | 46.09  | 42.97  | 48.20  | 48.14  | 48.20  | 46.97  |
| 8          | 33.06                    | 40.47  | 42.54                                            | 46.03  | 42.92  | 48.16  | 48.10  | 48.17  | 46.94  |
| 9          | 32.90                    | 40.50  | 42.47                                            | 45.97  | 42.88  | 48.13  | 48.07  | 48.16  | 46.95  |
| 10         | 32.72                    | 40.85  | 42.28                                            | 45.80  | 42.71  | 47.96  | 47.90  | 47.99  | 46.76  |
| 11         | 32.54                    | 40.96  | 42.10                                            | 45.63  | 42.55  | 47.81  | 47.75  | 47.85  | 46.62  |
| 12         | 32.40                    | 41.30  | 41.95                                            | 45.49  | 42.42  | 47.69  | 47.63  | 47.74  | 46.51  |
| 13         | 32.23                    | 41.17  | 41.55                                            | 45.08  | 42.02  | 47.28  | 47.23  | 47.33  | 46.11  |
| 14         | 32.02                    | 41.11  | 41.48                                            | 45.04  | 42.00  | 47.27  | 47.22  | 47.34  | 46.11  |
| 15         | 31.86                    | 41.43  | 41.28                                            | 44.85  | 41.81  | 47.09  | 47.04  | 47.16  | 45.92  |
| 16         | 31.67                    | 41.71  | 41.03                                            | 44.62  | 41.58  | 46.87  | 46.82  | 46.95  | 45.71  |
| 17         | 31.48                    | 41.59  | 40.79                                            | 44.39  | 41.36  | 46.66  | 46.61  | 46.75  | 45.51  |
| 18         | 31.26                    | 42.23  | 40.48                                            | 44.08  | 41.06  | 46.36  | 46.31  | 46.45  | 45.21  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.65                        | 2,317,695   | 43,340                    | 3,149  | 32.21                    | 0.00    | 0.00    |
| 2          | 23.65                        | 2,438,048   | 105,550                   | 3,135  | 0.00                     | 55.97   | 0.00    |
| 3          | 23.64                        | 2,400,115   | 162,991                   | 3,135  | 0.00                     | 80.20   | 0.00    |
| 4          | 23.55                        | 1,855,318   | 308,210                   | 3,248  | 0.00                     | 140.02  | 0.00    |
| 5          | 23.57                        | 1,320,965   | 399,922                   | 3,346  | 0.00                     | 199.79  | 0.00    |
| 6          | 23.55                        | 1,251,882   | 473,254                   | 3,450  | 0.00                     | 0.00    | 247.10  |
| 7          | 23.55                        | 1,260,495   | 543,581                   | 3,554  | 0.00                     | 0.00    | 286.02  |
| 8          | 23.53                        | 1,230,158   | 598,739                   | 3,603  | 0.00                     | 0.00    | 318.82  |
| 9          | 23.53                        | 1,231,537   | 658,033                   | 3,707  | 0.00                     | 0.00    | 351.59  |
| 10         | 23.51                        | 1,221,726   | 711,812                   | 3,795  | 0.00                     | 0.00    | 380.85  |
| 11         | 23.50                        | 1,212,232   | 762,833                   | 3,881  | 0.00                     | 0.00    | 408.77  |
| 12         | 23.56                        | 1,212,232   | 806,643                   | 3,994  | 0.00                     | 0.00    | 432.10  |
| 13         | 23.62                        | 1,210,853   | 852,261                   | 4,107  | 0.00                     | 0.00    | 456.75  |
| 14         | 23.65                        | 1,209,474   | 897,970                   | 4,178  | 0.00                     | 0.00    | 478.37  |
| 15         | 23.67                        | 1,208,479   | 939,338                   | 4,282  | 0.00                     | 0.00    | 498.70  |
| 16         | 23.66                        | 1,208,095   | 987,602                   | 4,406  | 0.00                     | 108.56  | 407.62  |
| 17         | 23.63                        | 1,205,880   | 1,030,349                 | 4,535  | 0.00                     | 111.98  | 423.70  |
| 18         | 23.59                        | 1,208,095   | 1,075,854                 | 4,598  | 0.00                     | 115.18  | 439.12  |

# Appendix C: Single- and two-phase measured data (continued).

Channel E: Nitrogen gas tests. Number of channels: 9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.91 Hyd. Diameter ( $\mu\text{m}$ ): 79.99

Width ( $\mu\text{m}$ ): 58.02 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.26                    | 26.66  | 38.48                                            | 41.17  | 38.66  | 43.30  | 43.21  | 43.26  | 40.82  |
| 2          | 27.29                    | 29.25  | 40.73                                            | 43.50  | 41.06  | 45.63  | 45.54  | 45.59  | 43.11  |
| 3          | 27.59                    | 30.49  | 41.59                                            | 44.41  | 41.98  | 46.53  | 46.44  | 46.49  | 44.01  |
| 4          | 28.25                    | 32.99  | 42.62                                            | 45.44  | 43.03  | 47.58  | 47.49  | 47.55  | 45.06  |
| 5          | 28.68                    | 35.99  | 42.90                                            | 45.75  | 43.32  | 47.88  | 47.80  | 47.83  | 45.34  |
| 6          | 28.54                    | 37.57  | 43.22                                            | 46.11  | 43.66  | 48.25  | 48.17  | 48.22  | 45.75  |
| 7          | 28.64                    | 38.51  | 43.27                                            | 46.20  | 43.73  | 48.35  | 48.28  | 48.32  | 45.88  |
| 8          | 28.63                    | 38.61  | 42.49                                            | 45.41  | 42.92  | 47.56  | 47.49  | 47.53  | 45.16  |
| 9          | 28.60                    | 38.86  | 42.15                                            | 45.09  | 42.59  | 47.25  | 47.18  | 47.24  | 44.89  |
| 10         | 28.61                    | 38.97  | 41.93                                            | 44.88  | 42.38  | 47.05  | 46.99  | 47.05  | 44.71  |
| 11         | 28.58                    | 38.98  | 41.76                                            | 44.74  | 42.23  | 46.92  | 46.86  | 46.91  | 44.58  |
| 12         | 28.55                    | 39.16  | 41.66                                            | 44.66  | 42.15  | 46.85  | 46.79  | 46.85  | 44.54  |
| 13         | 28.52                    | 39.20  | 41.46                                            | 44.46  | 41.98  | 46.68  | 46.63  | 46.70  | 44.40  |
| 14         | 28.48                    | 39.25  | 41.26                                            | 44.29  | 41.80  | 46.52  | 46.46  | 46.55  | 44.27  |
| 15         | 28.40                    | 39.31  | 41.07                                            | 44.11  | 41.64  | 46.37  | 46.31  | 46.41  | 44.14  |
| 16         | 28.30                    | 39.58  | 40.93                                            | 43.98  | 41.52  | 46.27  | 46.21  | 46.34  | 44.10  |
| 17         | 28.26                    | 40.21  | 40.89                                            | 43.96  | 41.52  | 46.28  | 46.23  | 46.38  | 44.17  |
| 18         | 28.15                    | 40.50  | 40.72                                            | 43.82  | 41.38  | 46.16  | 46.11  | 46.28  | 44.10  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.60                        | 3,902,060   | 43,023                    | 3,364  | 21.30                    | 0.93    | 0.00    |
| 2          | 23.57                        | 3,913,588   | 84,392                    | 3,219  | 0.00                     | 37.95   | 0.00    |
| 3          | 23.50                        | 3,808,043   | 142,307                   | 3,158  | 0.00                     | 61.36   | 0.00    |
| 4          | 23.40                        | 3,166,968   | 256,330                   | 3,212  | 0.00                     | 105.22  | 0.00    |
| 5          | 23.55                        | 2,883,335   | 338,276                   | 3,269  | 0.00                     | 155.90  | 0.00    |
| 6          | 23.53                        | 2,723,671   | 422,233                   | 3,348  | 0.00                     | 0.00    | 182.97  |
| 7          | 23.54                        | 2,700,816   | 507,140                   | 3,445  | 0.00                     | 0.00    | 214.53  |
| 8          | 23.55                        | 2,711,735   | 557,257                   | 3,547  | 0.00                     | 0.00    | 232.72  |
| 9          | 23.54                        | 2,689,378   | 638,660                   | 3,678  | 0.00                     | 0.00    | 256.08  |
| 10         | 23.56                        | 2,685,422   | 703,267                   | 3,753  | 0.00                     | 0.00    | 270.81  |
| 11         | 23.55                        | 2,682,099   | 788,084                   | 3,866  | 0.00                     | 0.00    | 279.74  |
| 12         | 23.54                        | 2,668,264   | 854,002                   | 3,981  | 0.00                     | 0.00    | 285.96  |
| 13         | 23.52                        | 2,682,189   | 966,104                   | 4,135  | 0.00                     | 0.00    | 292.00  |
| 14         | 23.52                        | 2,659,538   | 1,037,334                 | 4,173  | 0.00                     | 0.00    | 300.51  |
| 15         | 23.49                        | 2,686,326   | 1,107,909                 | 4,284  | 0.00                     | 0.00    | 306.24  |
| 16         | 23.48                        | 2,672,537   | 1,184,407                 | 4,422  | 0.00                     | 66.24   | 247.38  |
| 17         | 23.50                        | 2,661,550   | 1,258,305                 | 4,557  | 0.00                     | 67.01   | 251.90  |
| 18         | 23.54                        | 2,674,865   | 1,322,957                 | 4,673  | 0.00                     | 68.06   | 257.49  |

Appendix C: Single- and two-phase measured data (continued).

Channel E: Water tests.                      Number of channels:                      9  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):                      74.91                      Hyd. Diameter ( $\mu\text{m}$ ):                      79.99  
Width ( $\mu\text{m}$ ):                      58.02                      Channel Length (m):                      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 22.90                    | 39.26  | 32.78                                            | 36.97  | 34.95  | 41.87  | 42.23  | 44.15  | 45.28  |
| 2          | 22.88                    | 38.09  | 31.19                                            | 34.90  | 34.05  | 39.44  | 39.85  | 41.44  | 42.45  |
| 3          | 22.84                    | 36.76  | 30.12                                            | 33.51  | 32.98  | 37.79  | 38.24  | 39.57  | 40.46  |
| 4          | 22.84                    | 35.75  | 29.34                                            | 32.48  | 32.16  | 36.55  | 37.02  | 38.14  | 38.92  |
| 5          | 22.91                    | 35.06  | 28.86                                            | 31.85  | 30.89  | 35.76  | 36.25  | 37.22  | 37.89  |
| 6          | 23.15                    | 36.99  | 29.99                                            | 33.46  | 32.14  | 37.64  | 38.25  | 39.31  | 40.26  |
| 7          | 23.35                    | 40.77  | 31.86                                            | 36.20  | 34.32  | 40.95  | 41.76  | 42.93  | 43.99  |
| 8          | 23.74                    | 39.87  | 31.60                                            | 35.72  | 33.76  | 40.20  | 41.04  | 41.85  | 42.40  |
| 9          | 24.18                    | 39.75  | 31.72                                            | 35.78  | 33.74  | 40.18  | 41.03  | 41.74  | 42.25  |
| 10         | 24.48                    | 39.17  | 31.56                                            | 35.48  | 34.18  | 39.75  | 40.61  | 41.20  | 41.64  |
| 11         | 26.34                    | 39.95  | 32.87                                            | 36.61  | 35.24  | 40.70  | 41.57  | 42.01  | 42.35  |
| 12         | 26.64                    | 39.61  | 32.81                                            | 36.46  | 35.07  | 40.45  | 41.32  | 41.67  | 41.97  |
| 13         | 26.98                    | 39.49  | 32.90                                            | 36.51  | 34.37  | 40.41  | 41.29  | 41.58  | 41.81  |
| 14         | 27.30                    | 39.26  | 32.92                                            | 36.47  | 34.32  | 40.29  | 41.18  | 41.37  | 41.56  |
| 15         | 27.59                    | 39.13  | 32.95                                            | 36.43  | 34.20  | 40.17  | 41.06  | 41.19  | 41.36  |
| 16         | 27.86                    | 39.05  | 33.00                                            | 36.47  | 34.30  | 40.17  | 41.07  | 41.12  | 41.24  |
| 17         | 28.10                    | 40.38  | 33.83                                            | 37.75  | 35.44  | 41.52  | 42.54  | 42.58  | 42.77  |
| 18         | 28.32                    | 40.24  | 33.82                                            | 37.74  | 35.40  | 41.57  | 42.61  | 42.45  | 42.57  |
| 19         | 28.50                    | 40.13  | 33.78                                            | 37.62  | 35.93  | 41.27  | 42.30  | 42.17  | 42.37  |
| 20         | 28.71                    | 39.89  | 33.64                                            | 37.47  | 35.87  | 41.05  | 42.09  | 41.91  | 42.08  |

Appendix C: Single- and two-phase measured data (continued).

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Channel E: Water tests (continued).

| Data Point | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | liquid Flow Rate   |
|------------|-------------------|------------|---------------------------|---------|--------------------|
|            | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F. M. #1, (cc/min) |
| 1          | 23.38             | 5,335,644  | 834,679                   | 104,016 | 10.13              |
| 2          | 23.40             | 5,309,670  | 1,026,194                 | 102,892 | 12.74              |
| 3          | 23.51             | 5,397,968  | 1,213,889                 | 103,353 | 16.86              |
| 4          | 23.73             | 5,396,024  | 1,391,886                 | 103,111 | 17.02              |
| 5          | 24.05             | 5,396,725  | 1,543,751                 | 102,578 | 19.62              |
| 6          | 24.53             | 5,421,342  | 1,752,741                 | 102,381 | 22.09              |
| 7          | 24.85             | 5,466,848  | 1,862,084                 | 102,808 | 24.59              |
| 8          | 25.36             | 5,492,211  | 2,092,775                 | 102,980 | 27.55              |
| 9          | 25.88             | 5,414,877  | 2,212,337                 | 101,355 | 28.78              |
| 10         | 26.28             | 5,427,966  | 2,394,765                 | 101,362 | 31.45              |
| 11         | 28.20             | 5,467,141  | 2,612,570                 | 101,656 | 34.30              |
| 12         | 28.59             | 5,521,486  | 2,772,732                 | 102,397 | 35.67              |
| 13         | 28.98             | 5,564,346  | 2,944,286                 | 102,786 | 36.94              |
| 14         | 29.32             | 5,604,697  | 3,111,749                 | 103,333 | 38.43              |
| 15         | 29.65             | 5,608,246  | 3,267,570                 | 103,062 | 40.11              |
| 16         | 29.94             | 5,631,801  | 3,455,378                 | 103,297 | 41.67              |
| 17         | 30.19             | 5,698,285  | 3,640,112                 | 104,072 | 44.40              |
| 18         | 30.42             | 5,683,704  | 3,802,308                 | 103,961 | 46.55              |
| 19         | 30.63             | 5,632,728  | 3,943,503                 | 102,849 | 48.55              |
| 20         | 30.88             | 5,709,158  | 4,203,061                 | 103,903 | 51.11              |

# Appendix C: Single- and two-phase measured data (continued).

Channel E: Water and argon tests. Number of channels: 9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.91 Hyd. Diameter ( $\mu\text{m}$ ): 79.99

Width ( $\mu\text{m}$ ): 58.02 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.56                    | 38.84  | 31.84                                            | 34.86  | 33.30  | 38.80  | 39.18  | 40.38  | 41.37  |
| 2          | 27.03                    | 38.88  | 32.09                                            | 35.15  | 34.32  | 39.10  | 39.44  | 40.64  | 41.51  |
| 3          | 27.05                    | 39.11  | 32.40                                            | 35.48  | 34.66  | 39.41  | 39.75  | 40.93  | 41.70  |
| 4          | 27.23                    | 39.77  | 33.25                                            | 36.49  | 35.21  | 40.48  | 40.81  | 41.99  | 42.63  |
| 5          | 27.18                    | 39.95  | 33.42                                            | 36.78  | 34.52  | 40.77  | 41.09  | 42.19  | 42.52  |
| 6          | 26.97                    | 39.76  | 33.82                                            | 37.19  | 34.69  | 41.12  | 41.42  | 42.40  | 42.47  |
| 7          | 26.93                    | 39.24  | 33.39                                            | 36.84  | 34.60  | 40.76  | 41.04  | 41.99  | 41.96  |
| 8          | 27.15                    | 40.50  | 34.65                                            | 38.43  | 35.68  | 42.51  | 42.77  | 43.77  | 43.52  |
| 9          | 26.14                    | 39.35  | 31.83                                            | 35.47  | 35.07  | 39.59  | 40.17  | 41.18  | 42.09  |
| 10         | 26.32                    | 39.49  | 32.00                                            | 35.67  | 35.21  | 39.79  | 40.38  | 41.36  | 42.23  |
| 11         | 26.57                    | 39.74  | 32.29                                            | 36.01  | 35.33  | 40.14  | 40.74  | 41.71  | 42.54  |
| 12         | 26.87                    | 40.28  | 33.07                                            | 36.81  | 34.93  | 40.97  | 41.54  | 42.51  | 43.14  |
| 13         | 27.09                    | 41.11  | 33.74                                            | 37.84  | 35.66  | 42.16  | 42.70  | 43.71  | 44.13  |
| 14         | 26.99                    | 40.73  | 33.65                                            | 37.83  | 35.51  | 42.10  | 42.64  | 43.53  | 43.78  |
| 15         | 27.05                    | 40.86  | 33.99                                            | 38.28  | 35.84  | 42.57  | 43.10  | 43.96  | 44.10  |
| 16         | 26.67                    | 36.57  | 30.84                                            | 33.98  | 32.93  | 37.60  | 38.25  | 38.76  | 39.44  |
| 17         | 26.82                    | 36.79  | 31.04                                            | 34.22  | 33.82  | 37.88  | 38.51  | 39.04  | 39.63  |
| 18         | 27.03                    | 36.94  | 31.04                                            | 34.27  | 33.73  | 37.94  | 38.58  | 39.10  | 39.69  |
| 19         | 27.27                    | 37.61  | 31.64                                            | 35.03  | 34.11  | 38.79  | 39.39  | 39.96  | 40.43  |
| 20         | 27.34                    | 38.15  | 32.01                                            | 35.63  | 33.66  | 39.45  | 40.04  | 40.57  | 40.91  |
| 21         | 27.33                    | 38.76  | 32.66                                            | 36.39  | 34.16  | 40.30  | 40.87  | 41.42  | 41.67  |
| 22         | 25.88                    | 38.52  | 32.82                                            | 35.78  | 37.50  | 39.59  | 39.77  | 40.81  | 38.07  |
| 23         | 25.86                    | 38.72  | 32.85                                            | 35.82  | 36.49  | 39.63  | 39.83  | 40.88  | 37.48  |
| 24         | 25.87                    | 38.77  | 32.95                                            | 36.00  | 36.69  | 39.84  | 40.03  | 41.08  | 37.65  |
| 25         | 25.98                    | 39.00  | 33.28                                            | 36.37  | 37.09  | 40.23  | 40.41  | 41.48  | 37.96  |
| 26         | 25.90                    | 38.81  | 32.95                                            | 36.01  | 36.78  | 39.86  | 40.05  | 41.12  | 37.69  |
| 27         | 26.04                    | 39.05  | 33.69                                            | 36.79  | 37.56  | 40.64  | 40.80  | 41.83  | 38.14  |
| 28         | 26.22                    | 39.74  | 34.11                                            | 37.30  | 39.23  | 41.21  | 41.38  | 42.45  | 39.65  |
| 29         | 25.75                    | 38.05  | 32.43                                            | 35.41  | 35.47  | 39.19  | 39.38  | 40.38  | 37.31  |
| 30         | 25.92                    | 38.60  | 33.35                                            | 36.44  | 36.41  | 40.25  | 40.43  | 41.40  | 37.95  |
| 31         | 26.13                    | 39.33  | 34.31                                            | 37.53  | 37.59  | 41.36  | 41.54  | 42.49  | 38.84  |

Appendix C: Single- and two-phase measured data (continued).

Channel E: Water and argon (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press.. (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.10          | 4,826.429  | 28.57             | 4,759,485  | 1,462,078                 | 111,726 | 0.00                            | 8.44    | 0.00    | 16.99   |
| 2          | 24.02          | 4,707.884  | 28.41             | 4,648,537  | 1,542,464                 | 109,800 | 0.00                            | 15.71   | 0.00    | 16.43   |
| 3          | 24.03          | 4,436.526  | 28.22             | 4,611,305  | 1,661,890                 | 111,356 | 0.00                            | 28.98   | 0.00    | 14.16   |
| 4          | 24.15          | 4,450.926  | 28.04             | 4,487,901  | 1,773,290                 | 112,696 | 0.00                            | 55.26   | 0.00    | 12.78   |
| 5          | 24.14          | 4,398.978  | 27.87             | 4,352,764  | 2,200,312                 | 119,010 | 0.00                            | 0.00    | 78.84   | 12.54   |
| 6          | 24.12          | 4,357.587  | 27.70             | 4,307,304  | 2,534,062                 | 126,963 | 0.00                            | 0.00    | 100.75  | 14.11   |
| 7          | 24.11          | 4,341.062  | 27.54             | 4,266,048  | 2,843,330                 | 132,596 | 0.00                            | 0.00    | 115.31  | 12.17   |
| 8          | 24.12          | 4,374.473  | 27.32             | 4,273,802  | 3,148,778                 | 141,478 | 0.00                            | 0.00    | 139.18  | 9.77    |
| 9          | 24.07          | 5,042.448  | 27.83             | 4,731,838  | 2,176,259                 | 109,861 | 0.00                            | 6.31    | 0.00    | 23.41   |
| 10         | 24.02          | 4,872.974  | 27.97             | 4,694,042  | 2,283,772                 | 112,262 | 0.00                            | 11.34   | 0.00    | 24.53   |
| 11         | 24.01          | 4,521.433  | 28.10             | 4,639,359  | 2,376,975                 | 112,504 | 0.00                            | 19.72   | 0.00    | 24.15   |
| 12         | 24.12          | 4,362.786  | 28.16             | 4,541,363  | 2,581,285                 | 116,193 | 0.00                            | 42.01   | 0.00    | 23.26   |
| 13         | 24.12          | 4,383.402  | 28.16             | 4,412,714  | 2,846,292                 | 122,412 | 0.00                            | 0.00    | 63.14   | 21.37   |
| 14         | 24.13          | 4,371.399  | 28.12             | 4,374,737  | 3,176,809                 | 127,869 | 0.00                            | 0.00    | 80.86   | 20.72   |
| 15         | 24.17          | 4,337.264  | 28.07             | 4,340,376  | 3,514,470                 | 135,137 | 0.00                            | 0.00    | 98.06   | 20.28   |
| 16         | 24.17          | 4,981.074  | 28.68             | 4,670,532  | 3,084,646                 | 109,733 | 0.00                            | 4.22    | 0.00    | 34.12   |
| 17         | 24.08          | 4,892.663  | 28.89             | 4,613,927  | 3,109,264                 | 112,622 | 0.00                            | 8.62    | 0.00    | 34.49   |
| 18         | 24.03          | 4,544.400  | 29.06             | 4,641,710  | 3,241,642                 | 113,071 | 0.00                            | 14.96   | 0.00    | 33.97   |
| 19         | 24.17          | 4,368.437  | 29.15             | 4,498,819  | 3,347,482                 | 117,428 | 0.00                            | 34.33   | 0.00    | 31.39   |
| 20         | 24.15          | 4,394.479  | 29.15             | 4,393,929  | 3,563,299                 | 123,890 | 0.00                            | 0.00    | 53.07   | 28.89   |
| 21         | 24.18          | 4,319.157  | 29.05             | 4,337,980  | 3,738,696                 | 130,353 | 0.00                            | 0.00    | 76.24   | 26.00   |
| 22         | 23.98          | 3,664.949  | 24.81             | 3,374,955  | 2,869,813                 | 123,994 | 0.00                            | 28.95   | 106.60  | 10.13   |
| 23         | 23.98          | 3,645.869  | 24.78             | 3,423,489  | 2,956,777                 | 125,353 | 0.00                            | 29.34   | 108.38  | 9.49    |
| 24         | 23.99          | 3,643.179  | 24.77             | 3,419,692  | 3,067,002                 | 126,938 | 0.00                            | 30.54   | 113.39  | 8.33    |
| 25         | 23.97          | 3,628.147  | 24.74             | 3,419,601  | 3,133,621                 | 128,624 | 0.00                            | 31.91   | 119.05  | 8.22    |
| 26         | 24.01          | 3,657.963  | 24.74             | 3,412,887  | 3,253,590                 | 129,126 | 0.00                            | 31.43   | 117.44  | 9.19    |
| 27         | 23.99          | 3,622.066  | 24.74             | 3,388,925  | 3,299,841                 | 131,755 | 0.00                            | 34.41   | 129.67  | 9.31    |
| 28         | 24.02          | 3,724.944  | 24.71             | 3,390,236  | 3,347,539                 | 131,656 | 0.00                            | 34.22   | 129.08  | 7.65    |
| 29         | 23.98          | 3,663.524  | 24.75             | 3,766,214  | 3,581,937                 | 132,591 | 0.00                            | 32.76   | 123.76  | 8.59    |
| 30         | 23.99          | 3,892.090  | 24.72             | 3,769,741  | 3,637,163                 | 134,588 | 0.00                            | 35.09   | 133.60  | 8.51    |
| 31         | 24.01          | 3,858.883  | 24.69             | 3,794,969  | 3,718,430                 | 137,429 | 0.00                            | 36.41   | 139.45  | 10.55   |

Appendix C: Single- and two-phase measured data (continued).

Channel E: Water and helium tests.      Number of channels:      9  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      74.91      Hyd. Diameter ( $\mu\text{m}$ ):      79.99  
 Width ( $\mu\text{m}$ ):      58.02      Channel Length (m):      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.58                    | 37.68  | 31.34                                            | 34.06  | 33.53  | 37.75  | 38.11  | 39.13  | 39.92  |
| 2          | 26.80                    | 37.93  | 31.53                                            | 34.33  | 33.77  | 38.06  | 38.42  | 39.46  | 40.23  |
| 3          | 26.91                    | 38.09  | 31.68                                            | 34.61  | 33.17  | 38.40  | 38.75  | 39.81  | 40.53  |
| 4          | 26.79                    | 37.16  | 31.22                                            | 34.10  | 32.76  | 37.78  | 38.13  | 39.05  | 39.58  |
| 5          | 26.73                    | 36.64  | 31.03                                            | 33.90  | 32.62  | 37.54  | 37.88  | 38.72  | 39.10  |
| 6          | 26.61                    | 36.25  | 31.22                                            | 34.18  | 32.84  | 37.79  | 38.13  | 38.90  | 38.97  |
| 7          | 26.47                    | 35.83  | 31.19                                            | 34.20  | 32.83  | 37.79  | 38.12  | 38.81  | 38.64  |
| 8          | 26.40                    | 39.77  | 32.61                                            | 36.20  | 35.47  | 40.23  | 40.80  | 41.81  | 42.66  |
| 9          | 26.61                    | 39.90  | 32.65                                            | 36.30  | 35.61  | 40.40  | 40.96  | 42.00  | 42.85  |
| 10         | 26.91                    | 40.06  | 32.81                                            | 36.55  | 35.78  | 40.67  | 41.23  | 42.27  | 43.06  |
| 11         | 27.13                    | 40.27  | 33.06                                            | 36.92  | 34.80  | 41.09  | 41.65  | 42.70  | 43.41  |
| 12         | 27.20                    | 40.26  | 33.26                                            | 37.20  | 34.64  | 41.40  | 41.95  | 42.99  | 43.50  |
| 13         | 27.25                    | 40.48  | 33.82                                            | 37.99  | 35.27  | 42.27  | 42.79  | 43.79  | 43.94  |
| 14         | 26.55                    | 37.54  | 31.45                                            | 34.75  | 32.85  | 38.51  | 39.13  | 39.84  | 40.47  |
| 15         | 26.90                    | 37.90  | 31.84                                            | 35.16  | 33.12  | 38.93  | 39.54  | 40.25  | 40.86  |
| 16         | 27.17                    | 37.81  | 31.96                                            | 35.22  | 33.91  | 38.99  | 39.59  | 40.30  | 40.86  |
| 17         | 27.34                    | 37.80  | 32.03                                            | 35.41  | 33.87  | 39.20  | 39.79  | 40.50  | 40.96  |
| 18         | 27.44                    | 37.97  | 32.19                                            | 35.68  | 34.04  | 39.52  | 40.10  | 40.82  | 41.18  |
| 19         | 27.40                    | 38.17  | 32.38                                            | 36.17  | 33.83  | 40.11  | 40.67  | 41.43  | 41.52  |
| 20         | 28.80                    | 38.16  | 34.34                                            | 38.20  | 45.24  | 45.67  | 44.24  | 44.07  | 45.45  |
| 21         | 28.80                    | 37.63  | 34.38                                            | 38.28  | 45.34  | 45.77  | 44.34  | 44.23  | 45.54  |
| 22         | 28.74                    | 37.93  | 34.31                                            | 38.31  | 45.45  | 45.87  | 44.42  | 44.40  | 45.64  |
| 23         | 28.86                    | 37.96  | 34.22                                            | 38.26  | 45.41  | 45.83  | 44.39  | 44.45  | 45.60  |
| 24         | 28.78                    | 37.55  | 34.14                                            | 38.26  | 45.48  | 45.88  | 44.43  | 44.55  | 45.63  |
| 25         | 29.08                    | 37.17  | 34.60                                            | 38.62  | 47.36  | 47.32  | 45.34  | 44.46  | 46.32  |
| 26         | 29.08                    | 37.41  | 34.54                                            | 38.68  | 47.54  | 47.47  | 45.47  | 44.69  | 46.40  |
| 27         | 29.02                    | 37.45  | 34.48                                            | 38.71  | 47.70  | 47.62  | 45.59  | 44.90  | 46.54  |
| 28         | 29.92                    | 38.22  | 35.13                                            | 39.42  | 48.47  | 48.38  | 46.35  | 45.76  | 47.32  |
| 29         | 29.90                    | 38.12  | 35.00                                            | 39.31  | 48.43  | 48.33  | 46.29  | 45.82  | 47.37  |
| 30         | 29.64                    | 38.36  | 34.98                                            | 39.38  | 48.65  | 48.53  | 46.46  | 46.12  | 47.64  |
| 31         | 29.71                    | 36.20  | 33.76                                            | 37.13  | 45.76  | 45.70  | 43.75  | 42.76  | 44.62  |
| 32         | 29.68                    | 36.31  | 33.68                                            | 37.07  | 45.75  | 45.69  | 43.73  | 42.88  | 44.64  |
| 33         | 29.63                    | 36.35  | 33.56                                            | 36.93  | 45.69  | 45.62  | 43.62  | 42.92  | 44.64  |



## Appendix C: Single- and two-phase measured data (continued).

## Channel A: Water and helium (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.25          | 5,725,321  | 28.26             | 4,785,211  | 1,777,947                 | 113,275 | 0.00                            | 7.49    | 0.00    | 16.83   |
| 2          | 24.19          | 5,755,680  | 28.16             | 4,770,992  | 1,812,692                 | 113,334 | 0.00                            | 15.46   | 0.00    | 18.10   |
| 3          | 24.13          | 5,377,600  | 28.05             | 4,762,356  | 1,842,147                 | 115,115 | 0.00                            | 27.85   | 0.00    | 15.79   |
| 4          | 24.13          | 4,440,798  | 28.01             | 4,717,891  | 2,097,298                 | 122,297 | 0.00                            | 55.23   | 0.00    | 18.95   |
| 5          | 24.15          | 4,505,089  | 27.99             | 4,704,870  | 2,280,155                 | 131,543 | 0.00                            | 0.00    | 89.35   | 18.14   |
| 6          | 24.19          | 4,486,145  | 27.92             | 4,695,895  | 2,599,279                 | 150,072 | 0.00                            | 0.00    | 164.21  | 17.41   |
| 7          | 24.21          | 4,463,268  | 27.88             | 4,630,294  | 2,952,222                 | 161,708 | 0.00                            | 44.20   | 168.74  | 16.39   |
| 8          | 24.24          | 5,552,636  | 28.22             | 4,610,016  | 2,272,921                 | 113,187 | 0.00                            | 6.65    | 0.00    | 23.77   |
| 9          | 24.22          | 5,626,828  | 28.30             | 4,674,804  | 2,334,590                 | 112,511 | 0.00                            | 11.41   | 0.00    | 23.66   |
| 10         | 24.14          | 5,284,488  | 28.34             | 4,712,872  | 2,379,801                 | 115,067 | 0.00                            | 21.50   | 0.00    | 23.40   |
| 11         | 24.13          | 4,451,061  | 28.36             | 4,705,910  | 2,453,066                 | 121,304 | 0.00                            | 45.48   | 0.00    | 23.07   |
| 12         | 24.18          | 4,521,342  | 28.35             | 4,695,760  | 2,571,520                 | 132,558 | 0.00                            | 0.00    | 80.13   | 22.59   |
| 13         | 24.24          | 4,492,475  | 28.30             | 4,668,769  | 2,811,728                 | 149,166 | 0.00                            | 0.00    | 152.10  | 19.31   |
| 14         | 24.25          | 5,351,739  | 28.76             | 4,729,578  | 2,934,273                 | 108,704 | 0.00                            | 5.39    | 0.10    | 31.18   |
| 15         | 24.23          | 5,429,639  | 28.91             | 4,647,361  | 2,890,056                 | 111,564 | 0.00                            | 9.98    | 0.00    | 31.36   |
| 16         | 24.17          | 5,125,253  | 29.03             | 4,671,753  | 2,969,108                 | 115,043 | 0.00                            | 16.85   | 0.00    | 31.55   |
| 17         | 24.19          | 4,500,522  | 29.10             | 4,684,593  | 3,085,189                 | 124,083 | 0.00                            | 40.58   | 0.00    | 30.26   |
| 18         | 24.22          | 4,473,441  | 29.15             | 4,677,947  | 3,160,443                 | 133,597 | 0.00                            | 0.00    | 70.06   | 28.83   |
| 19         | 24.25          | 4,511,803  | 29.07             | 4,645,078  | 3,397,712                 | 148,574 | 0.00                            | 0.00    | 125.06  | 26.61   |
| 20         | 24.87          | 2,491,917  | 29.97             | 3,161,512  | 799,947                   | 125,353 | 0.00                            | 0.00    | 213.34  | 103.27  |
| 21         | 24.88          | 2,469,831  | 29.94             | 3,166,305  | 873,393                   | 133,713 | 0.00                            | 0.00    | 304.66  | 102.02  |
| 22         | 24.86          | 2,460,179  | 29.87             | 3,168,656  | 943,968                   | 141,367 | 0.00                            | 0.00    | 380.87  | 98.69   |
| 23         | 24.88          | 2,456,042  | 29.79             | 3,149,983  | 1,010,949                 | 148,045 | 0.00                            | 95.94   | 358.78  | 96.43   |
| 24         | 24.90          | 2,453,284  | 29.68             | 3,144,603  | 1,080,846                 | 154,311 | 0.00                            | 107.73  | 410.15  | 94.03   |
| 25         | 24.86          | 2,564,866  | 30.02             | 3,110,943  | 1,089,843                 | 117,138 | 0.00                            | 0.00    | 78.69   | 146.74  |
| 26         | 24.85          | 2,490,516  | 29.98             | 3,091,299  | 1,166,114                 | 126,963 | 0.00                            | 0.00    | 161.98  | 145.04  |
| 27         | 24.87          | 2,475,777  | 29.94             | 3,093,243  | 1,239,040                 | 135,896 | 0.00                            | 0.00    | 233.21  | 140.56  |
| 28         | 25.66          | 2,466,938  | 30.62             | 3,067,699  | 1,294,153                 | 142,260 | 0.00                            | 0.00    | 301.34  | 138.65  |
| 29         | 25.67          | 2,460,111  | 30.54             | 3,077,555  | 1,355,957                 | 149,193 | 0.00                            | 76.38   | 285.53  | 133.95  |
| 30         | 25.72          | 2,457,421  | 30.46             | 3,023,414  | 1,395,358                 | 154,058 | 0.00                            | 88.64   | 337.44  | 130.48  |
| 31         | 25.72          | 2,520,852  | 30.66             | 3,026,895  | 1,477,214                 | 117,916 | 0.00                            | 0.00    | 63.35   | 183.08  |
| 32         | 25.74          | 2,485,000  | 30.64             | 3,023,979  | 1,545,211                 | 128,502 | 0.00                            | 0.00    | 129.44  | 177.50  |
| 33         | 25.76          | 2,476,432  | 30.59             | 3,016,316  | 1,603,444                 | 136,898 | 0.00                            | 0.00    | 190.66  | 175.66  |

# Appendix C: Single- and two-phase measured data (continued).

Channel E: Water and nitrogen tests. Number of channels: 9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.91 Hyd. Diameter ( $\mu\text{m}$ ): 79.99

Width ( $\mu\text{m}$ ): 58.02 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.51                    | 40.40  | 33.28                                            | 36.39  | 36.96  | 40.42  | 40.76  | 42.13  | 43.06  |
| 2          | 27.03                    | 40.41  | 33.34                                            | 36.57  | 37.85  | 40.63  | 40.96  | 42.34  | 43.26  |
| 3          | 27.21                    | 40.50  | 33.31                                            | 36.64  | 37.89  | 40.72  | 41.04  | 42.40  | 43.22  |
| 4          | 27.16                    | 39.67  | 32.91                                            | 36.14  | 36.96  | 40.09  | 40.42  | 41.61  | 42.23  |
| 5          | 26.97                    | 39.97  | 33.45                                            | 36.78  | 37.08  | 40.73  | 41.04  | 42.18  | 42.57  |
| 6          | 27.05                    | 40.07  | 33.88                                            | 37.37  | 37.43  | 41.37  | 41.67  | 42.77  | 42.96  |
| 7          | 26.08                    | 41.27  | 33.26                                            | 37.27  | 37.92  | 41.64  | 42.19  | 43.51  | 44.51  |
| 8          | 26.39                    | 40.57  | 32.83                                            | 36.69  | 37.46  | 40.96  | 41.53  | 42.74  | 43.68  |
| 9          | 26.65                    | 40.89  | 33.13                                            | 37.08  | 37.77  | 41.36  | 41.91  | 43.12  | 43.94  |
| 10         | 26.84                    | 41.03  | 33.59                                            | 37.55  | 38.81  | 41.81  | 42.35  | 43.53  | 44.25  |
| 11         | 27.01                    | 41.30  | 33.73                                            | 37.91  | 35.61  | 42.24  | 42.76  | 43.95  | 44.46  |
| 12         | 27.07                    | 41.63  | 34.43                                            | 38.81  | 35.58  | 43.17  | 43.66  | 44.79  | 45.00  |
| 13         | 26.43                    | 40.00  | 32.71                                            | 36.68  | 37.32  | 40.87  | 41.60  | 42.56  | 43.49  |
| 14         | 26.88                    | 40.23  | 32.76                                            | 36.90  | 37.62  | 41.13  | 41.84  | 42.83  | 43.71  |
| 15         | 27.03                    | 40.36  | 33.06                                            | 37.23  | 37.79  | 41.46  | 42.15  | 43.13  | 43.88  |
| 16         | 27.31                    | 40.72  | 33.50                                            | 37.76  | 38.13  | 42.00  | 42.69  | 43.63  | 44.23  |
| 17         | 27.46                    | 40.82  | 33.75                                            | 38.19  | 38.44  | 42.48  | 43.15  | 44.07  | 44.40  |
| 18         | 27.48                    | 41.20  | 34.05                                            | 38.63  | 39.57  | 43.01  | 43.65  | 44.60  | 44.77  |
| 19         | 26.65                    | 39.86  | 33.70                                            | 36.73  | 39.10  | 40.59  | 40.80  | 41.92  | 37.19  |
| 20         | 26.59                    | 39.51  | 33.25                                            | 36.27  | 38.60  | 40.13  | 40.34  | 41.46  | 37.08  |
| 21         | 26.36                    | 38.86  | 32.82                                            | 35.76  | 38.04  | 39.56  | 39.77  | 40.84  | 36.58  |
| 22         | 26.13                    | 38.51  | 32.57                                            | 35.48  | 37.73  | 39.26  | 39.46  | 40.51  | 36.21  |
| 23         | 26.12                    | 38.71  | 32.67                                            | 35.64  | 37.93  | 39.45  | 39.64  | 40.72  | 36.38  |
| 24         | 26.01                    | 38.64  | 32.59                                            | 35.57  | 37.86  | 39.38  | 39.59  | 40.66  | 36.07  |
| 25         | 25.96                    | 38.38  | 32.48                                            | 35.43  | 37.70  | 39.22  | 39.42  | 40.48  | 38.25  |
| 26         | 25.92                    | 38.39  | 32.50                                            | 35.47  | 37.73  | 39.26  | 39.45  | 40.50  | 38.21  |
| 27         | 25.80                    | 38.08  | 32.36                                            | 35.28  | 37.53  | 39.05  | 39.25  | 40.29  | 38.12  |
| 28         | 25.75                    | 38.17  | 32.28                                            | 35.27  | 37.53  | 39.05  | 39.25  | 40.30  | 38.17  |
| 29         | 25.77                    | 38.43  | 32.43                                            | 35.46  | 37.76  | 39.30  | 39.49  | 40.58  | 38.37  |

## Appendix C: Single- and two-phase measured data (continued).

## Channel E: Water and nitrogen (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press.. (Pa) |         | Flow Meter/Flow rates. (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 24.30          | 5,263.600  | 28.19             | 4,810.099  | 1,502.135                 | 110.191 | 0.00                            | 4.87    | 0.00    | 14.63   |
| 2          | 24.26          | 5,274.609  | 27.99             | 4,763.826  | 1,571.896                 | 110.571 | 0.00                            | 11.19   | 0.00    | 14.46   |
| 3          | 24.18          | 5,028.230  | 27.81             | 4,770.178  | 1,684.812                 | 111.338 | 0.00                            | 19.44   | 0.00    | 13.14   |
| 4          | 24.10          | 4,299.332  | 27.69             | 4,779.763  | 1,992.588                 | 115.960 | 0.00                            | 38.96   | 0.00    | 15.10   |
| 5          | 24.22          | 4,291.375  | 27.60             | 4,747.436  | 2,242.064                 | 123.059 | 0.00                            | 0.00    | 65.29   | 12.97   |
| 6          | 24.22          | 4,239.856  | 27.43             | 4,723.113  | 2,509.218                 | 130.704 | 0.00                            | 0.00    | 91.02   | 11.71   |
| 7          | 24.21          | 5,103.190  | 27.66             | 4,826.217  | 2,128.516                 | 112.368 | 0.00                            | 4.39    | 0.00    | 19.98   |
| 8          | 24.15          | 5,075.001  | 27.77             | 4,775.897  | 2,337.008                 | 112.038 | 0.00                            | 8.89    | 0.00    | 19.76   |
| 9          | 24.10          | 4,811.486  | 27.90             | 4,776.824  | 2,397.976                 | 112.373 | 0.00                            | 14.42   | 0.00    | 21.69   |
| 10         | 24.08          | 4,280.388  | 27.96             | 4,758.965  | 2,558.024                 | 116.415 | 0.00                            | 29.04   | 0.00    | 19.82   |
| 11         | 24.18          | 4,259.704  | 28.02             | 4,771.263  | 2,925.999                 | 124.453 | 0.00                            | 0.00    | 55.09   | 19.88   |
| 12         | 24.20          | 4,235.493  | 28.00             | 4,726.323  | 3,118.555                 | 133.245 | 0.00                            | 0.00    | 79.27   | 18.78   |
| 13         | 24.24          | 5,045.796  | 28.50             | 4,832.565  | 2,881.263                 | 111.230 | 0.00                            | 2.92    | 0.00    | 28.72   |
| 14         | 24.18          | 5,051.988  | 28.69             | 4,784.397  | 2,943.293                 | 113.472 | 0.00                            | 6.55    | 0.00    | 29.05   |
| 15         | 24.11          | 4,822.088  | 28.82             | 4,749.200  | 3,028.584                 | 113.044 | 0.00                            | 12.00   | 0.00    | 28.41   |
| 16         | 24.13          | 4,254.460  | 28.92             | 4,729.194  | 3,144.777                 | 117.593 | 0.00                            | 25.60   | 0.00    | 28.41   |
| 17         | 24.20          | 4,270.871  | 28.96             | 4,691.442  | 3,428.750                 | 125.403 | 0.00                            | 0.00    | 47.90   | 27.10   |
| 18         | 24.17          | 4,222.970  | 28.92             | 4,692.618  | 3,602.813                 | 131.823 | 0.00                            | 0.00    | 65.35   | 24.98   |
| 19         | 23.81          | 3,476.462  | 24.90             | 3,302.459  | 2,742.204                 | 123.425 | 0.00                            | 29.23   | 108.66  | 8.63    |
| 20         | 24.12          | 3,461.136  | 25.10             | 3,352.033  | 2,807.670                 | 125.091 | 0.00                            | 29.05   | 108.92  | 10.92   |
| 21         | 24.09          | 3,457.044  | 25.06             | 3,354.429  | 2,845.489                 | 126.013 | 0.00                            | 29.40   | 111.13  | 9.11    |
| 22         | 24.08          | 3,452.975  | 25.03             | 3,362.748  | 2,866.987                 | 126.836 | 0.00                            | 29.51   | 111.80  | 10.53   |
| 23         | 24.10          | 3,451.664  | 25.03             | 3,376.786  | 2,895.538                 | 127.923 | 0.00                            | 30.34   | 115.37  | 9.66    |
| 24         | 24.11          | 3,440.904  | 24.97             | 3,395.164  | 2,915.657                 | 128.385 | 0.00                            | 30.41   | 115.73  | 10.38   |
| 25         | 24.13          | 3,437.038  | 24.94             | 3,389.988  | 2,917.556                 | 128.690 | 0.00                            | 30.97   | 118.08  | 10.35   |
| 26         | 24.11          | 3,436.383  | 24.90             | 3,400.138  | 2,924.451                 | 129.234 | 0.00                            | 31.76   | 121.44  | 8.75    |
| 27         | 24.10          | 3,440.339  | 24.87             | 3,422.472  | 2,969.481                 | 130.616 | 0.00                            | 31.66   | 121.20  | 9.38    |
| 28         | 24.06          | 3,435.094  | 24.84             | 3,426.677  | 2,984.401                 | 130.485 | 0.00                            | 31.94   | 122.45  | 8.85    |
| 29         | 24.07          | 3,448.296  | 24.81             | 3,452.379  | 3,068.155                 | 132.164 | 0.00                            | 32.68   | 125.97  | 10.48   |

# Appendix C: Single- and two-phase measured data (continued).

Channel F: Argon gas tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.09Hyd. Diameter ( $\mu\text{m}$ ): 55.99Width ( $\mu\text{m}$ ): 58.02

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 32.72                    | 33.60  | 46.57                                            | 47.24  | 47.64  | 49.50  | 49.39  | 49.38  | 43.14  |
| 2          | 32.62                    | 35.40  | 46.96                                            | 47.64  | 48.04  | 49.90  | 49.79  | 49.77  | 43.52  |
| 3          | 32.40                    | 38.30  | 47.07                                            | 47.76  | 48.16  | 50.02  | 49.91  | 49.88  | 43.61  |
| 4          | 32.12                    | 39.82  | 46.93                                            | 47.63  | 48.04  | 49.90  | 49.79  | 49.75  | 43.47  |
| 5          | 31.74                    | 40.21  | 46.74                                            | 47.46  | 47.89  | 49.75  | 49.65  | 49.62  | 43.34  |
| 6          | 31.77                    | 40.65  | 46.57                                            | 47.31  | 47.76  | 49.62  | 49.51  | 49.49  | 42.31  |
| 7          | 31.79                    | 40.85  | 46.37                                            | 47.13  | 47.58  | 49.45  | 49.34  | 49.31  | 41.55  |
| 8          | 31.70                    | 40.89  | 46.20                                            | 46.97  | 47.42  | 49.29  | 49.19  | 49.16  | 41.41  |
| 9          | 31.43                    | 40.73  | 46.04                                            | 46.84  | 47.32  | 49.19  | 49.08  | 49.07  | 41.72  |
| 10         | 30.91                    | 41.01  | 45.78                                            | 46.60  | 47.09  | 48.96  | 48.86  | 48.85  | 42.58  |
| 11         | 30.87                    | 41.00  | 45.50                                            | 46.34  | 46.84  | 48.71  | 48.60  | 48.59  | 41.78  |
| 12         | 30.93                    | 40.95  | 45.21                                            | 46.06  | 46.57  | 48.44  | 48.34  | 48.34  | 40.62  |
| 13         | 30.33                    | 40.79  | 44.90                                            | 45.77  | 46.30  | 48.18  | 48.07  | 48.07  | 41.77  |
| 14         | 30.13                    | 40.69  | 44.56                                            | 45.45  | 45.99  | 47.87  | 47.77  | 47.77  | 41.49  |
| 15         | 29.90                    | 40.40  | 44.14                                            | 45.05  | 45.61  | 47.49  | 47.39  | 47.40  | 41.11  |
| 16         | 29.66                    | 40.28  | 43.72                                            | 44.64  | 45.19  | 47.08  | 46.98  | 46.97  | 40.62  |
| 17         | 29.66                    | 39.96  | 43.25                                            | 44.18  | 44.74  | 46.63  | 46.54  | 46.52  | 39.46  |
| 18         | 29.23                    | 39.58  | 42.70                                            | 43.63  | 44.19  | 46.09  | 45.99  | 45.98  | 39.69  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.69                        | 5,307,478   | 107,216                   | 3,402  | 41.80                    | 0.00    | 0.00    |
| 2          | 23.60                        | 5,603,363   | 283,405                   | 3,400  | 0.00                     | 65.82   | 0.00    |
| 3          | 23.45                        | 5,495,195   | 498,385                   | 3,479  | 0.00                     | 97.12   | 0.00    |
| 4          | 23.26                        | 4,878,829   | 698,807                   | 3,585  | 0.00                     | 122.90  | 0.00    |
| 5          | 23.02                        | 3,586,213   | 938,699                   | 3,784  | 0.00                     | 0.00    | 136.82  |
| 6          | 23.30                        | 3,320,076   | 1,128,767                 | 3,990  | 0.00                     | 0.00    | 169.80  |
| 7          | 23.32                        | 3,193,937   | 1,329,528                 | 4,132  | 0.00                     | 0.00    | 174.38  |
| 8          | 23.35                        | 3,254,475   | 1,482,501                 | 4,202  | 0.00                     | 0.00    | 175.53  |
| 9          | 23.33                        | 3,230,626   | 1,694,113                 | 4,410  | 0.00                     | 0.00    | 180.31  |
| 10         | 23.32                        | 3,236,006   | 1,875,614                 | 4,564  | 0.00                     | 0.00    | 186.50  |
| 11         | 23.31                        | 3,220,430   | 2,067,446                 | 4,826  | 0.00                     | 0.00    | 192.72  |
| 12         | 23.31                        | 3,209,670   | 2,220,418                 | 4,966  | 0.00                     | 0.00    | 196.89  |
| 13         | 23.31                        | 3,203,974   | 2,394,799                 | 5,240  | 0.00                     | 0.00    | 199.79  |
| 14         | 23.31                        | 3,210,258   | 2,572,728                 | 5,378  | 0.00                     | 0.00    | 202.14  |
| 15         | 23.31                        | 3,214,259   | 2,758,253                 | 5,724  | 0.00                     | 44.24   | 164.96  |
| 16         | 23.30                        | 3,218,260   | 2,897,029                 | 5,929  | 0.00                     | 44.64   | 167.39  |
| 17         | 23.32                        | 3,221,109   | 3,060,762                 | 6,198  | 0.00                     | 45.14   | 170.37  |
| 18         | 23.32                        | 3,222,035   | 3,224,518                 | 6,395  | 0.00                     | 45.75   | 173.84  |

# Appendix C: Single- and two-phase measured data (continued).

Channel F: Helium gas tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.09      Hyd. Diameter ( $\mu\text{m}$ ): 55.99Width ( $\mu\text{m}$ ): 58.02      Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 30.72                    | 29.73  | 46.82                                            | 48.01  | 48.72  | 50.64  | 50.45  | 50.35  | 43.76  |
| 2          | 31.93                    | 31.65  | 49.23                                            | 50.47  | 51.21  | 53.12  | 52.92  | 52.85  | 46.24  |
| 3          | 32.95                    | 33.28  | 49.53                                            | 50.60  | 51.26  | 53.12  | 52.97  | 52.96  | 46.50  |
| 4          | 32.42                    | 36.18  | 47.19                                            | 48.13  | 48.70  | 50.58  | 50.44  | 50.39  | 43.97  |
| 5          | 32.26                    | 36.03  | 46.71                                            | 47.63  | 48.18  | 50.06  | 49.93  | 49.86  | 43.38  |
| 6          | 32.34                    | 37.12  | 46.74                                            | 47.66  | 48.21  | 50.09  | 49.95  | 49.88  | 43.39  |
| 7          | 32.29                    | 38.79  | 46.78                                            | 47.72  | 48.27  | 50.16  | 50.02  | 49.95  | 43.44  |
| 8          | 32.24                    | 37.62  | 46.79                                            | 47.74  | 48.31  | 50.19  | 50.06  | 49.99  | 43.47  |
| 9          | 32.17                    | 39.71  | 46.79                                            | 47.74  | 48.32  | 50.21  | 50.07  | 50.01  | 43.53  |
| 10         | 31.83                    | 41.06  | 46.71                                            | 47.71  | 48.31  | 50.20  | 50.06  | 50.02  | 43.55  |
| 11         | 32.00                    | 41.86  | 46.74                                            | 47.75  | 48.38  | 50.26  | 50.13  | 50.11  | 43.66  |
| 12         | 32.07                    | 42.28  | 46.78                                            | 47.82  | 48.45  | 50.35  | 50.20  | 50.20  | 43.78  |
| 13         | 31.78                    | 42.59  | 46.83                                            | 47.90  | 48.56  | 50.45  | 50.31  | 50.33  | 43.91  |
| 14         | 31.95                    | 42.78  | 46.80                                            | 47.89  | 48.57  | 50.46  | 50.32  | 50.34  | 43.91  |
| 15         | 31.99                    | 42.81  | 46.80                                            | 47.91  | 48.60  | 50.50  | 50.35  | 50.39  | 43.96  |
| 16         | 31.96                    | 42.98  | 46.75                                            | 47.88  | 48.59  | 50.49  | 50.34  | 50.39  | 43.94  |
| 17         | 31.87                    | 43.46  | 46.66                                            | 47.82  | 48.55  | 50.45  | 50.31  | 50.36  | 43.91  |
| 18         | 31.74                    | 43.38  | 46.46                                            | 47.63  | 48.37  | 50.27  | 50.13  | 50.20  | 43.77  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.75                        | 2,360,216   | 140,515                   | 3,429  | 19.17                    | 0.00    | 0.00    |
| 2          | 23.72                        | 2,242,554   | 267,378                   | 3,434  | 0.00                     | 39.52   | 0.00    |
| 3          | 23.72                        | 2,202,044   | 340,462                   | 3,522  | 0.00                     | 56.50   | 0.00    |
| 4          | 23.72                        | 2,170,736   | 554,199                   | 3,610  | 0.00                     | 99.78   | 0.00    |
| 5          | 23.71                        | 2,152,674   | 707,262                   | 3,698  | 0.00                     | 132.83  | 0.00    |
| 6          | 23.70                        | 2,145,779   | 789,366                   | 3,766  | 0.00                     | 0.00    | 160.56  |
| 7          | 23.68                        | 2,139,562   | 903,072                   | 3,859  | 0.00                     | 0.00    | 191.87  |
| 8          | 23.67                        | 2,136,126   | 976,541                   | 3,970  | 0.00                     | 0.00    | 217.26  |
| 9          | 23.66                        | 2,134,318   | 1,046,370                 | 4,049  | 0.00                     | 0.00    | 240.05  |
| 10         | 23.64                        | 2,131,989   | 1,118,188                 | 4,150  | 0.00                     | 0.00    | 263.25  |
| 11         | 23.62                        | 2,129,232   | 1,187,135                 | 4,311  | 0.00                     | 0.00    | 285.15  |
| 12         | 23.60                        | 2,126,361   | 1,239,173                 | 4,318  | 0.00                     | 0.00    | 303.42  |
| 13         | 23.57                        | 2,129,232   | 1,301,588                 | 4,415  | 0.00                     | 0.00    | 322.24  |
| 14         | 23.57                        | 2,123,716   | 1,356,746                 | 4,560  | 0.00                     | 0.00    | 340.31  |
| 15         | 23.57                        | 2,125,569   | 1,407,993                 | 4,650  | 0.00                     | 0.00    | 357.01  |
| 16         | 23.58                        | 2,138,884   | 1,461,161                 | 4,808  | 0.00                     | 77.79   | 291.83  |
| 17         | 23.61                        | 2,133,346   | 1,519,054                 | 4,917  | 0.00                     | 80.84   | 305.76  |
| 18         | 23.61                        | 2,129,232   | 1,571,680                 | 5,030  | 0.00                     | 83.64   | 318.84  |

# Appendix C: Single- and two-phase measured data (continued).

Channel F: Nitrogen gas tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.09Hyd. Diameter ( $\mu\text{m}$ ): 55.99Width ( $\mu\text{m}$ ): 58.02

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 33.59                    | 33.96  | 46.47                                            | 47.14  | 47.55  | 49.41  | 49.29  | 49.30  | 43.10  |
| 2          | 33.31                    | 35.50  | 46.51                                            | 47.18  | 47.59  | 49.44  | 49.33  | 49.33  | 43.12  |
| 3          | 32.91                    | 38.22  | 46.41                                            | 47.10  | 47.50  | 49.36  | 49.25  | 49.24  | 43.00  |
| 4          | 32.58                    | 38.98  | 46.27                                            | 46.96  | 47.37  | 49.23  | 49.12  | 49.10  | 42.86  |
| 5          | 32.27                    | 39.94  | 46.06                                            | 46.77  | 47.19  | 49.05  | 48.94  | 48.92  | 42.66  |
| 6          | 31.94                    | 40.10  | 45.84                                            | 46.57  | 47.01  | 48.87  | 48.76  | 48.75  | 42.49  |
| 7          | 31.65                    | 40.06  | 45.65                                            | 46.39  | 46.85  | 48.71  | 48.60  | 48.59  | 42.34  |
| 8          | 31.37                    | 40.05  | 45.45                                            | 46.20  | 46.67  | 48.54  | 48.43  | 48.43  | 42.19  |
| 9          | 31.20                    | 40.06  | 45.21                                            | 45.99  | 46.47  | 48.34  | 48.23  | 48.24  | 42.01  |
| 10         | 30.90                    | 39.99  | 44.94                                            | 45.74  | 46.24  | 48.11  | 48.01  | 48.02  | 41.80  |
| 11         | 30.69                    | 40.06  | 44.72                                            | 45.54  | 46.06  | 47.93  | 47.82  | 47.85  | 41.63  |
| 12         | 30.47                    | 40.22  | 44.46                                            | 45.31  | 45.84  | 47.72  | 47.61  | 47.65  | 41.44  |
| 13         | 30.29                    | 40.23  | 44.14                                            | 45.01  | 45.55  | 47.43  | 47.33  | 47.36  | 41.16  |
| 14         | 30.06                    | 40.04  | 43.84                                            | 44.73  | 45.29  | 47.17  | 47.07  | 47.12  | 40.93  |
| 15         | 29.90                    | 40.07  | 43.64                                            | 44.55  | 45.12  | 47.01  | 46.90  | 46.95  | 40.77  |
| 16         | 29.70                    | 39.94  | 43.30                                            | 44.22  | 44.81  | 46.69  | 46.59  | 46.65  | 40.45  |
| 17         | 29.51                    | 39.87  | 42.95                                            | 43.88  | 44.49  | 46.38  | 46.28  | 46.35  | 40.19  |
| 18         | 29.26                    | 39.62  | 42.54                                            | 43.50  | 44.12  | 46.01  | 45.91  | 45.98  | 39.80  |

| Data Point | Gas Flow Meter               |             | Test Fixture Press., (Pa) |        | Gas Flow Rates, (cc/min) |         |         |
|------------|------------------------------|-------------|---------------------------|--------|--------------------------|---------|---------|
|            | Temp. ( $^{\circ}\text{C}$ ) | Press. (Pa) | Inlet                     | Outlet | F.M. #4                  | F.M. #5 | F.M. #6 |
| 1          | 23.32                        | 2,094,509   | 85,153                    | 3,429  | 19.02                    | 0.00    | 0.00    |
| 2          | 23.30                        | 1,938,462   | 211,564                   | 3,411  | 0.00                     | 47.95   | 0.00    |
| 3          | 23.33                        | 1,915,789   | 381,717                   | 3,429  | 0.00                     | 91.31   | 0.00    |
| 4          | 23.33                        | 1,881,021   | 518,414                   | 3,493  | 0.00                     | 119.24  | 0.00    |
| 5          | 23.31                        | 1,881,021   | 634,291                   | 3,585  | 0.00                     | 0.00    | 136.61  |
| 6          | 23.28                        | 1,869,673   | 750,009                   | 3,651  | 0.00                     | 0.00    | 155.95  |
| 7          | 23.26                        | 1,875,505   | 856,188                   | 3,737  | 0.00                     | 0.00    | 172.11  |
| 8          | 23.25                        | 1,872,928   | 953,980                   | 3,827  | 0.00                     | 0.00    | 184.92  |
| 9          | 23.25                        | 1,874,126   | 1,053,377                 | 3,899  | 0.00                     | 0.00    | 192.71  |
| 10         | 23.25                        | 1,870,080   | 1,206,440                 | 4,010  | 0.00                     | 0.00    | 196.43  |
| 11         | 23.28                        | 1,872,250   | 1,345,511                 | 4,123  | 0.00                     | 0.00    | 198.55  |
| 12         | 23.30                        | 1,875,031   | 1,482,456                 | 4,254  | 0.00                     | 0.00    | 201.09  |
| 13         | 23.33                        | 1,867,887   | 1,601,949                 | 4,338  | 0.00                     | 0.00    | 205.66  |
| 14         | 23.38                        | 1,872,431   | 1,750,311                 | 4,551  | 0.00                     | 0.00    | 210.32  |
| 15         | 23.45                        | 2,582,882   | 1,806,508                 | 4,589  | 0.00                     | 45.56   | 170.02  |
| 16         | 23.44                        | 2,564,007   | 1,934,524                 | 4,743  | 0.00                     | 46.26   | 174.01  |
| 17         | 23.46                        | 2,552,093   | 2,051,576                 | 4,887  | 0.00                     | 46.74   | 177.06  |
| 18         | 23.46                        | 2,557,044   | 2,215,264                 | 5,068  | 0.00                     | 47.34   | 181.10  |

## Appendix C: Single- and two-phase measured data (continued).

Channel F: Water tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.09Hyd. Diameter ( $\mu\text{m}$ ): 55.99Width ( $\mu\text{m}$ ): 58.02

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 24.89                    | 42.37  | 35.74                                            | 38.70  | 42.36  | 44.75  | 44.40  | 46.41  | 40.29  |
| 2          | 25.04                    | 42.65  | 35.73                                            | 38.62  | 42.26  | 44.64  | 44.31  | 46.31  | 40.22  |
| 3          | 25.04                    | 42.58  | 35.62                                            | 38.44  | 42.04  | 44.42  | 44.10  | 46.05  | 40.00  |
| 4          | 25.02                    | 42.46  | 35.49                                            | 38.25  | 41.82  | 44.20  | 43.88  | 45.81  | 39.80  |
| 5          | 24.49                    | 42.33  | 35.16                                            | 37.85  | 41.36  | 43.74  | 43.44  | 45.34  | 40.81  |
| 6          | 24.80                    | 42.24  | 34.93                                            | 37.56  | 41.02  | 43.41  | 43.11  | 44.97  | 39.23  |
| 7          | 24.75                    | 41.87  | 34.58                                            | 37.12  | 40.52  | 42.90  | 42.61  | 44.44  | 38.83  |
| 8          | 24.51                    | 41.36  | 34.25                                            | 36.71  | 40.05  | 42.43  | 42.15  | 43.93  | 39.03  |
| 9          | 24.62                    | 40.93  | 33.94                                            | 36.33  | 39.61  | 41.99  | 41.72  | 43.45  | 38.25  |
| 10         | 24.61                    | 40.53  | 33.69                                            | 36.02  | 39.24  | 41.62  | 41.36  | 43.05  | 37.91  |
| 11         | 24.66                    | 40.00  | 33.36                                            | 35.62  | 38.78  | 41.15  | 40.89  | 42.54  | 37.51  |
| 12         | 24.67                    | 39.22  | 32.95                                            | 35.09  | 38.15  | 40.52  | 40.27  | 41.84  | 36.91  |
| 13         | 24.71                    | 38.87  | 32.71                                            | 34.80  | 37.81  | 40.17  | 39.93  | 41.46  | 36.40  |
| 14         | 24.68                    | 37.90  | 32.43                                            | 34.45  | 37.38  | 39.74  | 39.51  | 40.98  | 35.87  |
| 15         | 24.71                    | 37.67  | 32.10                                            | 34.04  | 36.89  | 39.25  | 39.02  | 40.43  | 35.32  |
| 16         | 24.72                    | 37.35  | 31.88                                            | 33.76  | 36.54  | 38.90  | 38.67  | 40.05  | 34.94  |

| Data Point | Liquid Flow Meter           |            | Test Fixture Press.. (Pa) |        | liquid Flow Rate   |
|------------|-----------------------------|------------|---------------------------|--------|--------------------|
|            | Temp.( $^{\circ}\text{C}$ ) | Press.(Pa) | Inlet                     | Outlet | F. M. #1, (cc/min) |
| 1          | 24.79                       | 2.991.684  | 1.748.442                 | 97.939 | 8.55               |
| 2          | 24.78                       | 3.028.056  | 1.851.908                 | 98.416 | 9.31               |
| 3          | 24.78                       | 3.043.225  | 1.941.110                 | 98.016 | 10.07              |
| 4          | 24.80                       | 3.035.177  | 2.012.431                 | 97.293 | 9.72               |
| 5          | 24.84                       | 3.037.257  | 2.143.363                 | 97.019 | 10.59              |
| 6          | 24.89                       | 3.036.805  | 2.235.007                 | 96.574 | 11.01              |
| 7          | 24.95                       | 3.068.498  | 2.341.706                 | 96.960 | 10.40              |
| 8          | 25.03                       | 3.057.489  | 2.446.099                 | 96.454 | 10.87              |
| 9          | 25.10                       | 3.071.595  | 2.563.920                 | 97.085 | 13.68              |
| 10         | 25.21                       | 3.060.224  | 2.661.056                 | 96.662 | 13.20              |
| 11         | 25.31                       | 3.084.028  | 2.768.117                 | 97.134 | 12.29              |
| 12         | 25.42                       | 3.097.546  | 2.929.883                 | 97.444 | 12.87              |
| 13         | 25.58                       | 3.105.435  | 3.039.747                 | 97.270 | 15.76              |
| 14         | 25.72                       | 4.058.152  | 3.187.226                 | 97.876 | 14.06              |
| 15         | 25.83                       | 4.148.281  | 3.347.478                 | 99.243 | 16.04              |
| 16         | 25.96                       | 4.194.690  | 3.499.772                 | 99.551 | 16.64              |

# Appendix C: Single- and two-phase measured data (continued).

Channel F: Water and argon tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.09Hyd. Diameter ( $\mu\text{m}$ ): 55.99Width ( $\mu\text{m}$ ): 58.02

Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.29                    | 43.18  | 36.22                                            | 38.95  | 42.44  | 44.76  | 44.49  | 46.39  | 43.72  |
| 2          | 26.86                    | 43.00  | 36.33                                            | 39.02  | 42.44  | 44.76  | 44.48  | 46.34  | 43.62  |
| 3          | 26.97                    | 43.36  | 36.81                                            | 39.64  | 43.10  | 45.43  | 45.15  | 47.01  | 43.58  |
| 4          | 27.42                    | 43.28  | 37.13                                            | 39.98  | 43.39  | 45.70  | 45.41  | 47.24  | 43.68  |
| 5          | 27.39                    | 43.30  | 37.39                                            | 40.18  | 43.58  | 45.90  | 45.62  | 47.42  | 43.83  |
| 6          | 27.62                    | 43.26  | 37.28                                            | 40.05  | 43.41  | 45.71  | 45.44  | 47.20  | 43.55  |
| 7          | 27.65                    | 43.46  | 37.53                                            | 40.38  | 43.74  | 46.05  | 45.78  | 47.52  | 43.73  |
| 8          | 27.83                    | 43.45  | 37.85                                            | 40.70  | 44.05  | 46.36  | 46.07  | 47.82  | 44.44  |
| 9          | 27.83                    | 43.69  | 38.13                                            | 41.06  | 44.41  | 46.70  | 46.41  | 48.15  | 44.11  |
| 10         | 27.90                    | 43.37  | 38.13                                            | 40.98  | 44.27  | 46.55  | 46.27  | 47.94  | 43.84  |
| 11         | 27.95                    | 43.95  | 38.64                                            | 41.59  | 44.95  | 47.24  | 46.95  | 48.65  | 44.44  |
| 12         | 27.82                    | 43.07  | 38.03                                            | 40.85  | 44.08  | 46.37  | 46.10  | 47.68  | 43.66  |
| 13         | 27.63                    | 39.37  | 36.36                                            | 40.53  | 45.97  | 46.96  | 46.06  | 46.55  | 46.96  |
| 14         | 27.70                    | 40.32  | 36.18                                            | 40.35  | 45.90  | 46.89  | 45.98  | 46.68  | 47.47  |
| 15         | 27.76                    | 40.81  | 36.22                                            | 40.37  | 45.96  | 46.95  | 46.03  | 46.86  | 47.76  |
| 16         | 27.76                    | 40.95  | 36.15                                            | 40.26  | 45.90  | 46.87  | 45.93  | 46.89  | 47.81  |
| 17         | 27.72                    | 40.71  | 36.12                                            | 40.23  | 45.90  | 46.86  | 45.91  | 46.93  | 47.80  |
| 18         | 27.63                    | 39.45  | 36.14                                            | 40.27  | 45.97  | 46.94  | 46.00  | 47.06  | 47.87  |
| 19         | 28.53                    | 37.41  | 36.16                                            | 39.95  | 46.95  | 47.39  | 45.95  | 45.68  | 47.14  |
| 20         | 28.80                    | 38.16  | 36.13                                            | 39.99  | 47.03  | 47.46  | 46.03  | 45.86  | 47.24  |
| 21         | 28.80                    | 37.63  | 36.17                                            | 40.07  | 47.13  | 47.56  | 46.13  | 46.02  | 47.33  |
| 22         | 28.74                    | 37.93  | 36.10                                            | 40.10  | 47.25  | 47.66  | 46.21  | 46.19  | 47.43  |
| 23         | 28.86                    | 37.96  | 36.01                                            | 40.05  | 47.21  | 47.62  | 46.18  | 46.24  | 47.39  |
| 24         | 28.78                    | 37.55  | 35.93                                            | 40.05  | 47.27  | 47.67  | 46.22  | 46.35  | 47.42  |
| 25         | 29.08                    | 37.17  | 36.39                                            | 40.41  | 49.15  | 49.11  | 47.13  | 46.25  | 48.11  |
| 26         | 29.08                    | 37.41  | 36.33                                            | 40.47  | 49.33  | 49.26  | 47.26  | 46.48  | 48.19  |
| 27         | 29.02                    | 37.45  | 36.27                                            | 40.51  | 49.49  | 49.41  | 47.38  | 46.69  | 48.33  |
| 28         | 29.92                    | 38.22  | 36.93                                            | 41.21  | 50.26  | 50.17  | 48.14  | 47.55  | 49.12  |
| 29         | 29.90                    | 38.12  | 36.79                                            | 41.11  | 50.22  | 50.12  | 48.08  | 47.61  | 49.16  |
| 30         | 29.64                    | 38.36  | 36.78                                            | 41.17  | 50.44  | 50.32  | 48.25  | 47.91  | 49.44  |
| 31         | 29.71                    | 36.20  | 35.55                                            | 38.92  | 47.55  | 47.49  | 45.55  | 44.56  | 46.41  |
| 32         | 29.68                    | 36.31  | 35.47                                            | 38.87  | 47.54  | 47.48  | 45.53  | 44.67  | 46.44  |
| 33         | 29.63                    | 36.35  | 35.36                                            | 38.73  | 47.49  | 47.41  | 45.41  | 44.71  | 46.44  |



## Appendix C: Single- and two-phase measured data (continued).

## Channel F: Water and Argon tests (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press.. (Pa) |         | Flow Meter/Flow rates. (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.24          | 4.706.031  | 25.78             | 4.589.671  | 3,036.913                 | 106.622 | 0.00                            | 4.18    | 0.00    | 10.26   |
| 2          | 25.15          | 4.552.629  | 25.84             | 4.572.559  | 3,178.560                 | 107.800 | 0.00                            | 7.46    | 0.00    | 9.98    |
| 3          | 25.11          | 4.151.174  | 25.95             | 4.579.386  | 3,207.043                 | 108.815 | 0.00                            | 11.13   | 0.00    | 11.69   |
| 4          | 25.31          | 3.863.698  | 26.16             | 4.617.680  | 3,288.379                 | 110.117 | 0.00                            | 16.01   | 0.00    | 9.95    |
| 5          | 25.23          | 3.837.837  | 26.13             | 4.568.671  | 3,323.530                 | 111.279 | 0.00                            | 19.32   | 0.00    | 9.53    |
| 6          | 25.30          | 4.121.074  | 26.22             | 4.561.510  | 3,461.869                 | 111.640 | 0.00                            | 23.18   | 0.00    | 9.77    |
| 7          | 25.30          | 4.493.786  | 26.22             | 4.589.581  | 3,523.726                 | 112.490 | 0.00                            | 26.23   | 0.00    | 11.44   |
| 8          | 25.22          | 4.380.102  | 26.18             | 4.514.824  | 3,588.175                 | 112.956 | 0.00                            | 29.72   | 0.00    | 9.55    |
| 9          | 25.24          | 4.329.804  | 26.20             | 4.499.023  | 3,642.519                 | 113.829 | 0.00                            | 33.02   | 0.00    | 10.16   |
| 10         | 25.20          | 4.320.762  | 26.21             | 4.510.438  | 3,811.112                 | 116.663 | 0.00                            | 0.00    | 35.73   | 10.16   |
| 11         | 25.20          | 4.313.212  | 26.23             | 4.533.881  | 3,913.584                 | 117.493 | 0.00                            | 0.00    | 37.47   | 11.02   |
| 12         | 25.19          | 4.341.135  | 26.22             | 4.516.383  | 4,105.736                 | 119.606 | 0.00                            | 0.00    | 41.02   | 10.13   |
| 13         | 24.99          | 2.530.505  | 28.71             | 3.307.093  | 340.216                   | 115.884 | 0.00                            | 0.00    | 171.26  | 52.87   |
| 14         | 24.94          | 2.485.000  | 28.79             | 3.292.173  | 418.951                   | 123.712 | 0.00                            | 0.00    | 317.62  | 51.94   |
| 15         | 24.94          | 2.465.695  | 28.88             | 3.283.877  | 488.351                   | 131.066 | 0.00                            | 0.00    | 436.49  | 50.12   |
| 16         | 24.92          | 2.458.800  | 28.88             | 3.281.051  | 562.429                   | 138.494 | 0.00                            | 0.00    | 535.35  | 48.79   |
| 17         | 24.94          | 2.447.881  | 28.87             | 3.268.505  | 626.381                   | 145.459 | 0.00                            | 130.73  | 488.76  | 47.27   |
| 18         | 24.94          | 2.450.164  | 28.81             | 3.221.756  | 685.450                   | 151.214 | 0.00                            | 145.43  | 553.55  | 44.55   |
| 19         | 24.87          | 2.524.989  | 29.95             | 3.180.976  | 717.640                   | 116.544 | 0.00                            | 0.00    | 111.94  | 107.89  |
| 20         | 24.87          | 2.491.917  | 29.97             | 3.161.512  | 799.947                   | 125.353 | 0.00                            | 0.00    | 208.89  | 103.27  |
| 21         | 24.88          | 2.469.831  | 29.94             | 3.166.305  | 873.393                   | 133.713 | 0.00                            | 0.00    | 298.47  | 102.02  |
| 22         | 24.86          | 2.460.179  | 29.87             | 3.168.656  | 943.968                   | 141.367 | 0.00                            | 0.00    | 372.79  | 98.69   |
| 23         | 24.88          | 2.456.042  | 29.79             | 3.149.983  | 1,010.949                 | 148.045 | 0.00                            | 93.89   | 351.12  | 96.43   |
| 24         | 24.90          | 2.453.284  | 29.68             | 3,144.603  | 1,080.846                 | 154.311 | 0.00                            | 105.46  | 401.49  | 94.03   |
| 25         | 24.86          | 2.564.866  | 30.02             | 3,110.943  | 1,089.843                 | 117.138 | 0.00                            | 0.00    | 77.12   | 146.74  |
| 26         | 24.85          | 2.490.516  | 29.98             | 3,091.299  | 1,166.114                 | 126.963 | 0.00                            | 0.00    | 158.63  | 145.04  |
| 27         | 24.87          | 2.475.777  | 29.94             | 3,093.243  | 1,239.040                 | 135.896 | 0.00                            | 0.00    | 228.29  | 140.56  |
| 28         | 25.66          | 2.466.938  | 30.62             | 3,067.699  | 1,294.153                 | 142.260 | 0.00                            | 0.00    | 294.98  | 138.65  |
| 29         | 25.67          | 2.460.111  | 30.54             | 3,077.555  | 1,355.957                 | 149.193 | 0.00                            | 74.75   | 279.47  | 133.95  |
| 30         | 25.72          | 2.457.421  | 30.46             | 3,023.414  | 1,395.358                 | 154.058 | 0.00                            | 86.66   | 329.94  | 130.48  |
| 31         | 25.72          | 2.520.852  | 30.66             | 3,026.895  | 1,477.214                 | 117.916 | 0.00                            | 0.00    | 62.15   | 183.08  |
| 32         | 25.74          | 2.485.000  | 30.64             | 3,023.979  | 1,545.211                 | 128.502 | 0.00                            | 0.00    | 126.92  | 177.50  |
| 33         | 25.76          | 2.476.432  | 30.59             | 3,016.316  | 1,603.444                 | 136.898 | 0.00                            | 0.00    | 186.88  | 175.66  |

# Appendix C: Single- and two-phase measured data (continued).

Channel F: Water and helium tests.      Number of channels:      11

Channel Dimensions:

Depth ( $\mu\text{m}$ ):      54.09      Hyd. Diameter ( $\mu\text{m}$ ):      55.99

Width ( $\mu\text{m}$ ):      58.02      Channel Length (m):      0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.72                    | 44.20  | 36.71                                            | 39.48  | 42.99  | 45.30  | 45.04  | 47.01  | 43.40  |
| 2          | 27.19                    | 43.66  | 36.87                                            | 39.67  | 43.09  | 45.40  | 45.12  | 47.02  | 43.18  |
| 3          | 27.45                    | 42.93  | 36.45                                            | 39.16  | 42.50  | 44.81  | 44.55  | 46.37  | 42.20  |
| 4          | 27.24                    | 42.83  | 36.22                                            | 38.92  | 42.25  | 44.56  | 44.30  | 46.11  | 42.00  |
| 5          | 27.50                    | 42.59  | 36.45                                            | 39.17  | 42.48  | 44.78  | 44.52  | 46.32  | 42.13  |
| 6          | 27.30                    | 42.11  | 36.05                                            | 38.68  | 41.94  | 44.24  | 43.99  | 45.75  | 41.74  |
| 7          | 27.32                    | 41.29  | 35.70                                            | 38.25  | 41.41  | 43.70  | 43.47  | 45.13  | 41.40  |
| 8          | 27.37                    | 41.36  | 35.92                                            | 38.50  | 41.64  | 43.94  | 43.70  | 45.32  | 42.17  |
| 9          | 27.39                    | 41.17  | 35.89                                            | 38.48  | 41.61  | 43.90  | 43.65  | 45.25  | 42.02  |
| 10         | 27.37                    | 40.99  | 35.86                                            | 38.41  | 41.50  | 43.79  | 43.55  | 45.13  | 42.47  |
| 11         | 27.34                    | 40.62  | 35.74                                            | 38.28  | 41.32  | 43.60  | 43.37  | 44.89  | 42.26  |
| 12         | 27.22                    | 40.30  | 35.51                                            | 38.05  | 41.07  | 43.35  | 43.12  | 44.60  | 41.43  |
| 13         | 27.31                    | 40.35  | 35.89                                            | 38.45  | 41.47  | 43.75  | 43.51  | 44.97  | 41.63  |
| 14         | 27.70                    | 40.32  | 36.18                                            | 40.35  | 45.90  | 46.89  | 45.98  | 46.68  | 47.47  |
| 15         | 27.76                    | 40.81  | 36.22                                            | 40.37  | 45.96  | 46.95  | 46.03  | 46.86  | 47.76  |
| 16         | 27.76                    | 40.95  | 36.15                                            | 40.26  | 45.90  | 46.87  | 45.93  | 46.89  | 47.81  |
| 17         | 27.72                    | 40.71  | 36.12                                            | 40.23  | 45.90  | 46.86  | 45.91  | 46.93  | 47.80  |
| 18         | 27.63                    | 39.45  | 36.14                                            | 40.27  | 45.97  | 46.94  | 46.00  | 47.06  | 47.87  |
| 19         | 28.53                    | 37.41  | 36.16                                            | 39.95  | 46.95  | 47.39  | 45.95  | 45.68  | 47.14  |
| 20         | 28.80                    | 38.16  | 36.13                                            | 39.99  | 47.03  | 47.46  | 46.03  | 45.86  | 47.24  |
| 21         | 28.80                    | 37.63  | 36.17                                            | 40.07  | 47.13  | 47.56  | 46.13  | 46.02  | 47.33  |
| 22         | 28.74                    | 37.93  | 36.10                                            | 40.10  | 47.25  | 47.66  | 46.21  | 46.19  | 47.43  |
| 23         | 28.86                    | 37.96  | 36.01                                            | 40.05  | 47.21  | 47.62  | 46.18  | 46.24  | 47.39  |
| 24         | 28.78                    | 37.55  | 35.93                                            | 40.05  | 47.27  | 47.67  | 46.22  | 46.35  | 47.42  |
| 25         | 29.08                    | 37.17  | 36.39                                            | 40.41  | 49.15  | 49.11  | 47.13  | 46.25  | 48.11  |
| 26         | 29.08                    | 37.41  | 36.33                                            | 40.47  | 49.33  | 49.26  | 47.26  | 46.48  | 48.19  |
| 27         | 29.02                    | 37.45  | 36.27                                            | 40.51  | 49.49  | 49.41  | 47.38  | 46.69  | 48.33  |
| 28         | 29.92                    | 38.22  | 36.93                                            | 41.21  | 50.26  | 50.17  | 48.14  | 47.55  | 49.12  |
| 29         | 29.90                    | 38.12  | 36.79                                            | 41.11  | 50.22  | 50.12  | 48.08  | 47.61  | 49.16  |
| 30         | 29.64                    | 38.36  | 36.78                                            | 41.17  | 50.44  | 50.32  | 48.25  | 47.91  | 49.44  |
| 31         | 29.71                    | 36.20  | 35.55                                            | 38.92  | 47.55  | 47.49  | 45.55  | 44.56  | 46.41  |
| 32         | 29.68                    | 36.31  | 35.47                                            | 38.87  | 47.54  | 47.48  | 45.53  | 44.67  | 46.44  |
| 33         | 29.63                    | 36.35  | 35.36                                            | 38.73  | 47.49  | 47.41  | 45.41  | 44.71  | 46.44  |

## Appendix C: Single- and two-phase measured data (continued).

## Channel F: Water and Helium tests (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates. (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.29          | 7,210.017  | 26.43             | 4,842.267  | 3,023,191                 | 106,165 | 0.00                            | 5.75    | 0.00    | 11.09   |
| 2          | 25.30          | 7,072.461  | 26.46             | 4,863,381  | 3,061,146                 | 111,369 | 0.00                            | 9.79    | 0.00    | 12.09   |
| 3          | 25.27          | 6,819,097  | 26.49             | 4,835,508  | 3,201,143                 | 112,441 | 0.00                            | 14.21   | 0.00    | 10.37   |
| 4          | 25.27          | 6,545.410  | 26.52             | 4,855,379  | 3,285,214                 | 112,452 | 0.00                            | 15.94   | 0.00    | 11.87   |
| 5          | 25.22          | 6,174.338  | 26.54             | 4,878,843  | 3,290,504                 | 115,689 | 0.00                            | 21.31   | 0.00    | 10.26   |
| 6          | 25.19          | 5,483.485  | 26.56             | 4,874,051  | 3,405,408                 | 116,028 | 0.00                            | 22.60   | 0.00    | 11.59   |
| 7          | 25.19          | 4,794.577  | 26.66             | 4,858,453  | 3,554,945                 | 119,315 | 0.00                            | 30.82   | 0.00    | 12.86   |
| 8          | 25.21          | 4,632.178  | 26.70             | 4,880,335  | 3,584,174                 | 123,615 | 0.00                            | 0.00    | 41.41   | 12.08   |
| 9          | 25.23          | 4,637.716  | 26.72             | 4,887,931  | 3,631,985                 | 126,183 | 0.00                            | 0.00    | 47.94   | 11.09   |
| 10         | 25.22          | 4,609,120  | 26.69             | 4,853,841  | 3,680,067                 | 127,659 | 0.00                            | 0.00    | 52.64   | 11.35   |
| 11         | 25.23          | 4,643.187  | 26.73             | 4,872,039  | 3,774,107                 | 130,787 | 0.00                            | 0.00    | 59.56   | 11.33   |
| 12         | 25.23          | 4,565.107  | 26.72             | 4,888,134  | 3,888,718                 | 133,582 | 0.00                            | 0.00    | 64.43   | 12.02   |
| 13         | 25.22          | 4,627,657  | 26.70             | 4,864,037  | 3,905,604                 | 136,925 | 0.00                            | 0.00    | 77.06   | 11.10   |
| 14         | 24.94          | 2,485,000  | 28.79             | 3,292,173  | 418,951                   | 123,712 | 0.00                            | 0.00    | 325.60  | 51.94   |
| 15         | 24.94          | 2,465,695  | 28.88             | 3,283,877  | 488,351                   | 131,066 | 0.00                            | 0.00    | 447.92  | 50.12   |
| 16         | 24.92          | 2,458,800  | 28.88             | 3,281,051  | 562,429                   | 138,494 | 0.00                            | 0.00    | 549.69  | 48.79   |
| 17         | 24.94          | 2,447,881  | 28.87             | 3,268,505  | 626,381                   | 145,459 | 0.00                            | 134.22  | 501.83  | 47.27   |
| 18         | 24.94          | 2,450,164  | 28.81             | 3,221,756  | 685,450                   | 151,214 | 0.00                            | 149.07  | 567.42  | 44.55   |
| 19         | 24.87          | 2,524,989  | 29.95             | 3,180,976  | 717,640                   | 116,544 | 0.00                            | 0.00    | 114.19  | 107.89  |
| 20         | 24.87          | 2,491,917  | 29.97             | 3,161,512  | 799,947                   | 125,353 | 0.00                            | 0.00    | 213.34  | 103.27  |
| 21         | 24.88          | 2,469,831  | 29.94             | 3,166,305  | 873,393                   | 133,713 | 0.00                            | 0.00    | 304.66  | 102.02  |
| 22         | 24.86          | 2,460,179  | 29.87             | 3,168,656  | 943,968                   | 141,367 | 0.00                            | 0.00    | 380.87  | 98.69   |
| 23         | 24.88          | 2,456,042  | 29.79             | 3,149,983  | 1,010,949                 | 148,045 | 0.00                            | 95.94   | 358.78  | 96.43   |
| 24         | 24.90          | 2,453,284  | 29.68             | 3,144,603  | 1,080,846                 | 154,311 | 0.00                            | 107.73  | 410.15  | 94.03   |
| 25         | 24.86          | 2,564,866  | 30.02             | 3,110,943  | 1,089,843                 | 117,138 | 0.00                            | 0.00    | 78.69   | 146.74  |
| 26         | 24.85          | 2,490,516  | 29.98             | 3,091,299  | 1,166,114                 | 126,963 | 0.00                            | 0.00    | 161.98  | 145.04  |
| 27         | 24.87          | 2,475,777  | 29.94             | 3,093,243  | 1,239,040                 | 135,896 | 0.00                            | 0.00    | 233.21  | 140.56  |
| 28         | 25.66          | 2,466,938  | 30.62             | 3,067,699  | 1,294,153                 | 142,260 | 0.00                            | 0.00    | 301.34  | 138.65  |
| 29         | 25.67          | 2,460,111  | 30.54             | 3,077,555  | 1,355,957                 | 149,193 | 0.00                            | 76.38   | 285.53  | 133.95  |
| 30         | 25.72          | 2,457,421  | 30.46             | 3,023,414  | 1,395,358                 | 154,058 | 0.00                            | 88.64   | 337.44  | 130.48  |
| 31         | 25.72          | 2,520,852  | 30.66             | 3,026,895  | 1,477,214                 | 117,916 | 0.00                            | 0.00    | 63.35   | 183.08  |
| 32         | 25.74          | 2,485,000  | 30.64             | 3,023,979  | 1,545,211                 | 128,502 | 0.00                            | 0.00    | 129.44  | 177.50  |
| 33         | 25.76          | 2,476,432  | 30.59             | 3,016,316  | 1,603,444                 | 136,898 | 0.00                            | 0.00    | 190.66  | 175.66  |

# Appendix C: Single- and two-phase measured data (continued).

Channel F: Water and nitrogen tests. Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.09 Hyd. Diameter ( $\mu\text{m}$ ): 55.99

Width ( $\mu\text{m}$ ): 58.02 Channel Length (m): 0.0635

| Data Point | Test Fixture Temperature |        | Test Section Temperature, ( $^{\circ}\text{C}$ ) |        |        |        |        |        |        |
|------------|--------------------------|--------|--------------------------------------------------|--------|--------|--------|--------|--------|--------|
|            | Inlet                    | Outlet | Pos #1                                           | Pos #2 | Pos #3 | Pos #4 | Pos #5 | Pos #6 | Pos #7 |
| 1          | 26.85                    | 44.87  | 37.17                                            | 39.96  | 43.46  | 45.78  | 45.51  | 47.47  | 44.04  |
| 2          | 27.17                    | 43.98  | 36.83                                            | 39.58  | 42.97  | 45.29  | 45.02  | 46.91  | 43.61  |
| 3          | 27.39                    | 44.07  | 37.02                                            | 39.83  | 43.27  | 45.57  | 45.32  | 47.20  | 43.78  |
| 4          | 27.35                    | 44.06  | 37.10                                            | 39.89  | 43.32  | 45.62  | 45.36  | 47.24  | 44.38  |
| 5          | 27.66                    | 43.85  | 36.97                                            | 39.79  | 43.17  | 45.48  | 45.21  | 47.06  | 44.05  |
| 6          | 27.76                    | 44.04  | 37.38                                            | 40.25  | 43.65  | 45.95  | 45.67  | 47.51  | 43.78  |
| 7          | 27.78                    | 43.44  | 37.06                                            | 39.75  | 43.00  | 45.29  | 45.04  | 46.74  | 43.17  |
| 8          | 27.89                    | 43.88  | 37.76                                            | 40.59  | 43.90  | 46.19  | 45.92  | 47.65  | 43.77  |
| 9          | 27.63                    | 42.97  | 36.94                                            | 39.66  | 42.86  | 45.15  | 44.89  | 46.55  | 42.86  |
| 10         | 27.51                    | 42.88  | 36.83                                            | 39.53  | 42.75  | 45.05  | 44.78  | 46.46  | 42.79  |
| 11         | 27.26                    | 42.38  | 36.06                                            | 38.66  | 41.85  | 44.14  | 43.88  | 45.56  | 42.25  |
| 12         | 26.86                    | 40.06  | 34.96                                            | 38.72  | 43.56  | 44.73  | 43.99  | 45.28  | 45.99  |
| 13         | 27.63                    | 39.37  | 36.36                                            | 40.53  | 45.97  | 46.96  | 46.06  | 46.55  | 46.96  |
| 14         | 27.70                    | 40.32  | 36.18                                            | 40.35  | 45.90  | 46.89  | 45.98  | 46.68  | 47.47  |
| 15         | 27.76                    | 40.81  | 36.22                                            | 40.37  | 45.96  | 46.95  | 46.03  | 46.86  | 47.76  |
| 16         | 27.76                    | 40.95  | 36.15                                            | 40.26  | 45.90  | 46.87  | 45.93  | 46.89  | 47.81  |
| 17         | 27.72                    | 40.71  | 36.12                                            | 40.23  | 45.90  | 46.86  | 45.91  | 46.93  | 47.80  |
| 18         | 27.63                    | 39.45  | 36.14                                            | 40.27  | 45.97  | 46.94  | 46.00  | 47.06  | 47.87  |
| 19         | 28.53                    | 37.41  | 36.16                                            | 39.95  | 46.95  | 47.39  | 45.95  | 45.68  | 47.14  |
| 20         | 28.80                    | 38.16  | 36.13                                            | 39.99  | 47.03  | 47.46  | 46.03  | 45.86  | 47.24  |
| 21         | 28.80                    | 37.63  | 36.17                                            | 40.07  | 47.13  | 47.56  | 46.13  | 46.02  | 47.33  |
| 22         | 28.74                    | 37.93  | 36.10                                            | 40.10  | 47.25  | 47.66  | 46.21  | 46.19  | 47.43  |
| 23         | 28.86                    | 37.96  | 36.01                                            | 40.05  | 47.21  | 47.62  | 46.18  | 46.24  | 47.39  |
| 24         | 28.78                    | 37.55  | 35.93                                            | 40.05  | 47.27  | 47.67  | 46.22  | 46.35  | 47.42  |
| 25         | 29.08                    | 37.17  | 36.39                                            | 40.41  | 49.15  | 49.11  | 47.13  | 46.25  | 48.11  |
| 26         | 29.08                    | 37.41  | 36.33                                            | 40.47  | 49.33  | 49.26  | 47.26  | 46.48  | 48.19  |
| 27         | 29.02                    | 37.45  | 36.27                                            | 40.51  | 49.49  | 49.41  | 47.38  | 46.69  | 48.33  |
| 28         | 29.92                    | 38.22  | 36.93                                            | 41.21  | 50.26  | 50.17  | 48.14  | 47.55  | 49.12  |
| 29         | 29.90                    | 38.12  | 36.79                                            | 41.11  | 50.22  | 50.12  | 48.08  | 47.61  | 49.16  |
| 30         | 29.64                    | 38.36  | 36.78                                            | 41.17  | 50.44  | 50.32  | 48.25  | 47.91  | 49.44  |
| 31         | 29.71                    | 36.20  | 35.55                                            | 38.92  | 47.55  | 47.49  | 45.55  | 44.56  | 46.41  |
| 32         | 29.68                    | 36.31  | 35.47                                            | 38.87  | 47.54  | 47.48  | 45.53  | 44.67  | 46.44  |
| 33         | 29.63                    | 36.35  | 35.36                                            | 38.73  | 47.49  | 47.41  | 45.41  | 44.71  | 46.44  |

## Appendix C: Single- and two-phase measured data (continued).

## Channel F: Water and Nitrogen tests (continued).

| Data Point | Gas Flow Meter |            | Liquid Flow Meter |            | Test Fixture Press., (Pa) |         | Flow Meter/Flow rates, (cc/min) |         |         |         |
|------------|----------------|------------|-------------------|------------|---------------------------|---------|---------------------------------|---------|---------|---------|
|            | Temp.(°C)      | Press.(Pa) | Temp.(°C)         | Press.(Pa) | Inlet                     | Outlet  | F.M. #4                         | F.M. #5 | F.M. #6 | F.M. #1 |
| 1          | 25.02          | 4,918,841  | 26.60             | 4,944,807  | 3,267,039                 | 108,724 | 0.00                            | 3.74    | 0.00    | 9.79    |
| 2          | 24.98          | 4,811,238  | 26.59             | 4,908,185  | 3,405,227                 | 107,305 | 0.00                            | 5.51    | 0.00    | 9.91    |
| 3          | 24.94          | 4,639,480  | 26.61             | 4,895,458  | 3,411,738                 | 108,553 | 0.00                            | 8.04    | 0.00    | 10.29   |
| 4          | 24.90          | 4,433,881  | 26.57             | 4,931,288  | 3,513,486                 | 110,002 | 0.00                            | 10.46   | 0.00    | 10.64   |
| 5          | 24.91          | 4,331,907  | 26.59             | 4,937,008  | 3,628,933                 | 111,044 | 0.00                            | 13.37   | 0.00    | 10.22   |
| 6          | 24.91          | 4,290,041  | 26.57             | 4,917,748  | 3,679,073                 | 111,317 | 0.00                            | 15.70   | 0.00    | 18.93   |
| 7          | 24.95          | 4,250,752  | 26.61             | 4,936,646  | 3,895,771                 | 114,930 | 0.00                            | 21.21   | 0.00    | 9.54    |
| 8          | 24.97          | 4,198,895  | 26.57             | 4,894,939  | 4,096,215                 | 117,299 | 0.00                            | 0.00    | 29.32   | 10.10   |
| 9          | 25.01          | 4,391,721  | 26.59             | 4,898,895  | 4,094,226                 | 117,005 | 0.00                            | 0.00    | 26.78   | 12.05   |
| 10         | 24.99          | 4,447,264  | 26.56             | 4,903,551  | 4,082,155                 | 115,563 | 0.00                            | 0.00    | 23.56   | 11.96   |
| 11         | 24.98          | 4,571,346  | 26.61             | 4,953,894  | 4,063,008                 | 113,793 | 0.00                            | 0.00    | 17.14   | 10.10   |
| 12         | 25.08          | 2,448,582  | 28.03             | 3,254,557  | 611,325                   | 150,513 | 0.00                            | 114.32  | 435.15  | 32.54   |
| 13         | 24.99          | 2,530,505  | 28.71             | 3,307,093  | 340,216                   | 115,884 | 0.00                            | 0.00    | 124.69  | 52.87   |
| 14         | 24.94          | 2,485,000  | 28.79             | 3,292,173  | 418,951                   | 123,712 | 0.00                            | 0.00    | 231.62  | 51.94   |
| 15         | 24.94          | 2,465,695  | 28.88             | 3,283,877  | 488,351                   | 131,066 | 0.00                            | 0.00    | 318.58  | 50.12   |
| 16         | 24.92          | 2,458,800  | 28.88             | 3,281,051  | 562,429                   | 138,494 | 0.00                            | 0.00    | 390.90  | 48.79   |
| 17         | 24.94          | 2,447,881  | 28.87             | 3,268,505  | 626,381                   | 145,459 | 0.00                            | 95.44   | 356.81  | 47.27   |
| 18         | 24.94          | 2,450,164  | 28.81             | 3,221,756  | 685,450                   | 151,214 | 0.00                            | 105.98  | 403.39  | 44.55   |
| 19         | 24.87          | 2,524,989  | 29.95             | 3,180,976  | 717,640                   | 116,544 | 0.00                            | 0.00    | 81.17   | 107.89  |
| 20         | 24.87          | 2,491,917  | 29.97             | 3,161,512  | 799,947                   | 125,353 | 0.00                            | 0.00    | 151.63  | 103.27  |
| 21         | 24.88          | 2,469,831  | 29.94             | 3,166,305  | 873,393                   | 133,713 | 0.00                            | 0.00    | 216.49  | 102.02  |
| 22         | 24.86          | 2,460,179  | 29.87             | 3,168,656  | 943,968                   | 141,367 | 0.00                            | 0.00    | 270.61  | 98.69   |
| 23         | 24.88          | 2,456,042  | 29.79             | 3,149,983  | 1,010,949                 | 148,045 | 0.00                            | 68.16   | 254.88  | 96.43   |
| 24         | 24.90          | 2,453,284  | 29.68             | 3,144,603  | 1,080,846                 | 154,311 | 0.00                            | 76.52   | 291.33  | 94.03   |
| 25         | 24.86          | 2,564,866  | 30.02             | 3,110,943  | 1,089,843                 | 117,138 | 0.00                            | 0.00    | 55.89   | 146.74  |
| 26         | 24.85          | 2,490,516  | 29.98             | 3,091,299  | 1,166,114                 | 126,963 | 0.00                            | 0.00    | 115.03  | 145.04  |
| 27         | 24.87          | 2,475,777  | 29.94             | 3,093,243  | 1,239,040                 | 135,896 | 0.00                            | 0.00    | 165.60  | 140.56  |
| 28         | 25.66          | 2,466,938  | 30.62             | 3,067,699  | 1,294,153                 | 142,260 | 0.00                            | 0.00    | 213.95  | 138.65  |
| 29         | 25.67          | 2,460,111  | 30.54             | 3,077,555  | 1,355,957                 | 149,193 | 0.00                            | 54.22   | 202.70  | 133.95  |
| 30         | 25.72          | 2,457,421  | 30.46             | 3,023,414  | 1,395,358                 | 154,058 | 0.00                            | 62.92   | 239.53  | 130.48  |
| 31         | 25.72          | 2,520,852  | 30.66             | 3,026,895  | 1,477,214                 | 117,916 | 0.00                            | 0.00    | 44.96   | 183.08  |
| 32         | 25.74          | 2,485,000  | 30.64             | 3,023,979  | 1,545,211                 | 128,502 | 0.00                            | 0.00    | 91.85   | 177.50  |
| 33         | 25.76          | 2,476,432  | 30.59             | 3,016,316  | 1,603,444                 | 136,898 | 0.00                            | 0.00    | 135.28  | 175.66  |

## APPENDIX D

# Appendix D: Single- and two-phase calculated data.

Channel A: Argon gas tests.

Number of channels:

3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80Hyd. Diameter ( $\mu\text{m}$ ): 256.91Width ( $\mu\text{m}$ ): 258.03

Channel Length (m): 0.0635

| Data Point | Heat Trans. |        |                   |              |                               |                                  |          |  | Uncertainty |       |
|------------|-------------|--------|-------------------|--------------|-------------------------------|----------------------------------|----------|--|-------------|-------|
|            | Re          | f      | Velocity<br>(m/s) | Q<br>(Watts) | coeff.<br>W/m <sup>2</sup> -K | Heat Flux<br>(W/m <sup>2</sup> ) | Nu       |  | U-f         | U-Nu  |
| 1          |             |        |                   |              |                               |                                  |          |  |             |       |
| 2          |             |        |                   |              |                               |                                  |          |  |             |       |
| 3          | 413.0       | 0.1543 | 20.94             | 0.0178       | 7.765                         | 121.63                           | 0.110417 |  | 0.031       | 0.225 |
| 4          | 633.0       | 0.1095 | 30.94             | 0.0320       | 14.344                        | 217.93                           | 0.203729 |  | 0.031       | 0.196 |
| 5          | 867.0       | 0.0868 | 40.68             | 0.0495       | 22.360                        | 337.39                           | 0.317345 |  | 0.031       | 0.177 |
| 6          | 1,079.5     | 0.0768 | 48.93             | 0.0968       | 34.265                        | 660.17                           | 0.483840 |  | 0.031       | 0.118 |
| 7          | 1,255.9     | 0.0758 | 54.47             | 0.1246       | 41.641                        | 849.67                           | 0.586697 |  | 0.031       | 0.108 |
| 8          | 1,483.3     | 0.0720 | 61.15             | 0.1621       | 53.869                        | 1105.34                          | 0.757696 |  | 0.031       | 0.101 |
| 9          | 1,699.8     | 0.0692 | 66.73             | 0.2025       | 66.870                        | 1381.43                          | 0.939469 |  | 0.031       | 0.095 |
| 10         | 1,923.7     | 0.0681 | 71.48             | 0.2352       | 76.532                        | 1604.32                          | 1.075018 |  | 0.031       | 0.093 |
| 11         | 2,101.3     | 0.0683 | 74.68             | 0.2766       | 90.836                        | 1886.32                          | 1.274359 |  | 0.031       | 0.089 |
| 12         | 2,308.3     | 0.0669 | 78.48             | 0.3224       | 108.074                       | 2199.18                          | 1.513778 |  | 0.031       | 0.086 |
| 13         | 3,030.7     | 0.0624 | 89.49             | 0.5053       | 179.677                       | 3446.59                          | 2.511865 |  | 0.031       | 0.080 |
| 14         | 3,726.9     | 0.0597 | 97.55             | 0.7314       | 285.312                       | 4988.49                          | 3.977011 |  | 0.031       | 0.078 |
| 15         | 4,407.0     | 0.0569 | 104.20            | 0.9077       | 370.116                       | 6190.79                          | 5.155816 |  | 0.031       | 0.079 |
| 16         | 5,082.5     | 0.0557 | 108.95            | 1.0864       | 459.665                       | 7409.76                          | 6.401325 |  | 0.031       | 0.080 |

Appendix D: Single- and two-phase calculated data (continued).

Channel A: Helium gas tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | Re    | f      | Velocity | Q       | Heat Trans. coeff.  | Heat Flux           | Nu        | Uncertainty |          |
|------------|-------|--------|----------|---------|---------------------|---------------------|-----------|-------------|----------|
|            |       |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |           | U-f (%)     | U-Nu (%) |
| 1          |       |        |          |         |                     |                     |           |             |          |
| 2          |       |        |          |         |                     |                     |           |             |          |
| 3          | 72.7  | 0.8569 | 32.28    | 0.0200  | 10.730              | 136.71              | 0.0176525 | 0.031       | 0.305    |
| 4          | 95.7  | 0.6968 | 41.33    | 0.0387  | 20.598              | 264.30              | 0.0337881 | 0.031       | 0.216    |
| 5          | 121.7 | 0.5860 | 50.71    | 0.0563  | 30.520              | 383.98              | 0.0500165 | 0.031       | 0.193    |
| 6          | 149.8 | 0.4724 | 60.89    | 0.0803  | 33.172              | 547.83              | 0.0542253 | 0.031       | 0.164    |
| 7          | 171.1 | 0.4269 | 67.95    | 0.0960  | 37.040              | 654.64              | 0.0604353 | 0.031       | 0.156    |
| 8          | 197.5 | 0.3787 | 76.35    | 0.1211  | 46.402              | 825.68              | 0.0755812 | 0.031       | 0.145    |
| 9          | 223.8 | 0.3403 | 84.49    | 0.1640  | 64.542              | 1118.72             | 0.1048675 | 0.031       | 0.126    |
| 10         | 247.8 | 0.3114 | 91.64    | 0.2068  | 83.395              | 1410.24             | 0.1352209 | 0.031       | 0.115    |
| 11         | 274.6 | 0.2856 | 99.12    | 0.2405  | 97.834              | 1640.55             | 0.1584963 | 0.031       | 0.112    |
| 12         | 360.8 | 0.2238 | 121.49   | 0.3970  | 172.375             | 2707.56             | 0.2786209 | 0.031       | 0.099    |
| 13         | 456.1 | 0.1835 | 143.18   | 0.5820  | 266.539             | 3969.59             | 0.4302420 | 0.031       | 0.094    |
| 14         | 547.6 | 0.1609 | 160.40   | 0.7424  | 349.572             | 5063.88             | 0.5643628 | 0.031       | 0.093    |
| 15         | 643.8 | 0.1426 | 176.93   | 0.8884  | 425.075             | 6059.35             | 0.6869200 | 0.031       | 0.093    |



Appendix D: Single- and two-phase calculated data (continued).

Channel A: Nitrogen gas tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80

Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03

Channel Length (m): 0.0635

| Data Point |         |        |                   |              | Heat Trans.                   |                                  |       | Uncertainty |             |
|------------|---------|--------|-------------------|--------------|-------------------------------|----------------------------------|-------|-------------|-------------|
|            | Re      | f      | Velocity<br>(m/s) | Q<br>(Watts) | coeff.<br>W/m <sup>2</sup> -K | Heat Flux<br>(W/m <sup>2</sup> ) | Nu    | U-f<br>(%)  | U-Nu<br>(%) |
| 1          |         |        |                   |              |                               |                                  |       |             |             |
| 2          |         |        |                   |              |                               |                                  |       |             |             |
| 3          |         |        |                   |              |                               |                                  |       |             |             |
| 4          |         |        |                   |              |                               |                                  |       |             |             |
| 5          | 537.7   | 0.1307 | 31.16             | 0.0637       | 30.923                        | 434.34                           | 0.295 | 0.031       | 0.145       |
| 6          | 673.4   | 0.1103 | 38.04             | 0.0848       | 40.794                        | 578.63                           | 0.389 | 0.031       | 0.138       |
| 7          | 819.0   | 0.0971 | 44.94             | 0.1104       | 52.846                        | 752.87                           | 0.504 | 0.031       | 0.132       |
| 8          | 959.8   | 0.0859 | 51.38             | 0.1373       | 66.127                        | 936.45                           | 0.631 | 0.031       | 0.127       |
| 9          | 1,084.2 | 0.0784 | 56.78             | 0.1612       | 78.161                        | 1099.80                          | 0.746 | 0.031       | 0.124       |
| 10         | 1,221.1 | 0.0722 | 62.43             | 0.1907       | 93.531                        | 1300.81                          | 0.893 | 0.031       | 0.121       |
| 11         | 1,351.9 | 0.0690 | 67.61             | 0.2610       | 102.434                       | 1780.29                          | 0.976 | 0.031       | 0.098       |
| 12         | 1,480.9 | 0.0665 | 72.38             | 0.3182       | 118.987                       | 2170.12                          | 1.131 | 0.031       | 0.091       |
| 13         | 1,963.9 | 0.0638 | 86.03             | 0.4600       | 177.026                       | 3137.45                          | 1.681 | 0.031       | 0.087       |
| 14         | 2,417.5 | 0.0632 | 95.72             | 0.6278       | 254.355                       | 4281.83                          | 2.411 | 0.031       | 0.085       |
| 15         | 2,856.4 | 0.0619 | 103.48            | 0.7976       | 335.670                       | 5439.91                          | 3.179 | 0.031       | 0.084       |
| 16         | 3,332.6 | 0.0609 | 110.18            | 0.9777       | 423.995                       | 6668.32                          | 4.016 | 0.031       | 0.084       |

## Appendix D: Single- and two-phase calculated data (continued).

Channel A: Water tests.                      Number of channels:                      3  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):                      255.80                      Hyd. Diameter ( $\mu\text{m}$ ):                      256.91  
Width ( $\mu\text{m}$ ):                      258.03                      Channel Length (m):                      0.0635

| Data Point | Re       | f      | Velocity | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|----------|--------|----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |          |        |          |         |                     |                     |        | U-f         | U_Nu  |
|            |          |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 292.67   | 2.1342 | 0.90     | 11.550  | 8493.92472          | 78779               | 3.481  | 0.031       | 0.127 |
| 2          | 452.76   | 0.8574 | 1.45     | 14.937  | 11248.3605          | 101878              | 4.629  | 0.031       | 0.137 |
| 3          | 813.40   | 0.2748 | 2.65     | 22.172  | 15561.9094          | 151230              | 6.419  | 0.031       | 0.143 |
| 4          | 1,102.66 | 0.1611 | 3.58     | 27.525  | 19263.5396          | 187738              | 7.941  | 0.031       | 0.149 |
| 5          | 1,400.19 | 0.1123 | 4.45     | 37.885  | 26172.7978          | 258395              | 10.765 | 0.031       | 0.141 |
| 6          | 1,574.26 | 0.0980 | 4.91     | 46.113  | 30587.2304          | 314519              | 12.554 | 0.031       | 0.132 |
| 7          | 1,747.58 | 0.0847 | 5.44     | 47.464  | 35593.8189          | 323735              | 14.607 | 0.031       | 0.146 |
| 8          | 1,928.25 | 0.0759 | 5.92     | 56.149  | 39977.6314          | 382968              | 16.379 | 0.031       | 0.137 |
| 9          | 2,023.96 | 0.0722 | 6.24     | 56.697  | 42232.7974          | 386707              | 17.313 | 0.031       | 0.143 |
| 10         | 2,321.62 | 0.0590 | 7.22     | 59.001  | 47542.2493          | 402422              | 19.507 | 0.031       | 0.156 |
| 11         | 2,576.36 | 0.0531 | 7.94     | 68.972  | 51061.7059          | 470433              | 20.929 | 0.031       | 0.145 |
| 12         | 2,935.60 | 0.0467 | 8.99     | 78.895  | 55422.8406          | 538115              | 22.701 | 0.031       | 0.140 |
| 13         | 3,289.14 | 0.0411 | 10.15    | 80.828  | 60242.4717          | 551297              | 24.696 | 0.031       | 0.151 |
| 14         | 3,581.78 | 0.0383 | 11.02    | 85.446  | 63062.8762          | 582797              | 25.843 | 0.031       | 0.152 |
| 15         | 3,866.52 | 0.0356 | 11.96    | 86.012  | 66318.4592          | 586652              | 27.195 | 0.031       | 0.161 |
| 16         | 4,111.17 | 0.0338 | 12.81    | 88.658  | 69882.3194          | 604702              | 28.679 | 0.031       | 0.166 |
| 17         | 4,332.16 | 0.0328 | 13.57    | 88.002  | 71787.1406          | 600227              | 29.477 | 0.031       | 0.175 |
| 18         | 4,778.31 | 0.0294 | 15.06    | 90.839  | 76777.31            | 619579              | 31.547 | 0.031       | 0.185 |
| 19         | 5,011.42 | 0.0285 | 15.89    | 90.786  | 79303.327           | 619218              | 32.607 | 0.031       | 0.193 |
| 20         | 5,309.29 | 0.0274 | 16.91    | 91.119  | 82474.3963          | 621488              | 33.926 | 0.031       | 0.202 |
| 21         | 5,426.25 | 0.0278 | 17.33    | 87.572  | 82283.6312          | 597293              | 33.858 | 0.031       | 0.213 |

Appendix D: Single- and two-phase calculated data (continued).

Channel A: Water-argon tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |                     |          |        |           |         |                     |                     |        | U f         | U Nu  |
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 1.255               | 0.05901  | 0.3038 | 527       | 15.666  | 13.367              | 106853              | 5.483  | 0.031       | 0.143 |
| 2          | 1.387               | 0.116672 | 0.1675 | 591       | 18.483  | 18.799              | 126062              | 7.704  | 0.031       | 0.163 |
| 3          | 1.345               | 0.180881 | 0.1269 | 574       | 18.724  | 19.060              | 127708              | 7.816  | 0.031       | 0.162 |
| 4          | 1.378               | 0.235876 | 0.1071 | 590       | 19.241  | 19.507              | 131232              | 8.001  | 0.031       | 0.161 |
| 5          | 1.398               | 0.292012 | 0.1208 | 600       | 19.566  | 19.617              | 133451              | 8.048  | 0.031       | 0.160 |
| 6          | 1.301               | 0.377753 | 0.1100 | 561       | 18.347  | 17.718              | 125136              | 7.272  | 0.031       | 0.155 |
| 7          | 3.980               | 0.017952 | 0.3905 | 1,624     | 41.428  | 34.528              | 282563              | 14.201 | 0.031       | 0.147 |
| 8          | 3.662               | 0.043857 | 0.2087 | 1,510     | 39.578  | 35.723              | 269943              | 14.680 | 0.031       | 0.154 |
| 9          | 3.196               | 0.075929 | 0.1318 | 1,367     | 34.441  | 33.171              | 234910              | 13.583 | 0.031       | 0.162 |
| 10         | 3.446               | 0.093957 | 0.1324 | 1,424     | 36.756  | 31.774              | 250700              | 13.061 | 0.031       | 0.150 |
| 11         | 3.340               | 0.12225  | 0.1466 | 1,371     | 33.637  | 26.997              | 229424              | 11.108 | 0.031       | 0.145 |
| 12         | 3.176               | 0.154612 | 0.1329 | 1,324     | 36.018  | 30.648              | 245666              | 12.594 | 0.031       | 0.146 |
| 13         | 8.483               | 0.009105 | 0.5808 | 3,406     | 61.586  | 45.628              | 420051              | 18.796 | 0.031       | 0.159 |
| 14         | 8.380               | 0.015089 | 0.3790 | 3,402     | 66.534  | 50.514              | 453800              | 20.786 | 0.031       | 0.154 |
| 15         | 8.076               | 0.021849 | 0.2887 | 3,288     | 65.494  | 49.066              | 446706              | 20.184 | 0.031       | 0.151 |
| 16         | 7.656               | 0.034562 | 0.2094 | 3,134     | 65.603  | 48.705              | 447450              | 20.027 | 0.031       | 0.147 |
| 17         | 7.159               | 0.051604 | 0.1637 | 2,938     | 63.138  | 45.039              | 430636              | 18.518 | 0.031       | 0.142 |
| 18         | 6.659               | 0.073816 | 0.1691 | 2,736     | 60.102  | 40.977              | 409935              | 16.850 | 0.031       | 0.137 |
| 19         | 11.739              | 0.006417 | 0.7974 | 4,737     | 83.240  | 58.195              | 567748              | 23.959 | 0.031       | 0.157 |
| 20         | 11.525              | 0.010913 | 0.4955 | 4,662     | 83.791  | 57.781              | 571508              | 23.783 | 0.031       | 0.154 |
| 21         | 11.028              | 0.015786 | 0.3683 | 4,475     | 84.298  | 57.187              | 574967              | 23.532 | 0.031       | 0.149 |
| 22         | 10.477              | 0.025034 | 0.2591 | 4,281     | 85.792  | 58.482              | 585156              | 24.049 | 0.031       | 0.144 |
| 23         | 9.642               | 0.038722 | 0.1923 | 3,961     | 83.784  | 55.420              | 571461              | 22.780 | 0.031       | 0.138 |
| 24         | 9.048               | 0.052643 | 0.1994 | 3,733     | 82.676  | 54.281              | 563904              | 22.305 | 0.031       | 0.134 |

Appendix D: Single- and two-phase calculated data (continued).

Channel A: Water-helium tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | G                   | x       | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|---------------------|---------|--------|-----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |                     |         |        |           |         |                     |                     |        | U f         | U Nu  |
|            | kg/s-m <sup>2</sup> | Quality |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 2.372               | 0.0033  | 0.0858 | 952.56    | 17.966  | 18687.6             | 122538              | 7.698  | 0.031       | 0.206 |
| 2          | 2.277               | 0.0070  | 0.0890 | 922.15    | 17.477  | 20749.5             | 119205              | 8.540  | 0.031       | 0.227 |
| 3          | 2.244               | 0.0107  | 0.0905 | 910.06    | 16.928  | 22811.4             | 115458              | 9.387  | 0.031       | 0.233 |
| 4          | 2.197               | 0.0149  | 0.0933 | 886.69    | 16.138  | 22317.5             | 110072              | 9.189  | 0.031       | 0.238 |
| 5          | 2.158               | 0.0189  | 0.0959 | 865.97    | 16.144  | 23092.7             | 110113              | 9.514  | 0.031       | 0.240 |
| 6          | 2.125               | 0.0230  | 0.0982 | 849.85    | 15.579  | 22331.9             | 106257              | 9.205  | 0.031       | 0.157 |
| 7          | 4.046               | 0.0019  | 0.0489 | 1,670.00  | 36.260  | 30870.6             | 247318              | 12.679 | 0.031       | 0.167 |
| 8          | 3.868               | 0.0041  | 0.0512 | 1,599.67  | 35.096  | 33158.3             | 239379              | 13.616 | 0.031       | 0.174 |
| 9          | 3.881               | 0.0062  | 0.0509 | 1,610.98  | 34.681  | 34616.3             | 236545              | 14.209 | 0.031       | 0.176 |
| 10         | 3.800               | 0.0086  | 0.0521 | 1,577.11  | 34.542  | 35022.3             | 235599              | 14.376 | 0.031       | 0.175 |
| 11         | 3.728               | 0.0109  | 0.0534 | 1,544.07  | 34.867  | 35620.1             | 237814              | 14.625 | 0.031       | 0.173 |
| 12         | 3.549               | 0.0138  | 0.0563 | 1,469.08  | 33.124  | 33276.7             | 225924              | 13.664 | 0.031       | 0.181 |
| 13         | 8.178               | 0.0009  | 0.0443 | 3,310.06  | 55.722  | 50198.0             | 380059              | 20.659 | 0.031       | 0.180 |
| 14         | 8.051               | 0.0020  | 0.0444 | 3,264.47  | 55.635  | 50501.2             | 379463              | 20.780 | 0.031       | 0.164 |
| 15         | 7.827               | 0.0031  | 0.0446 | 3,224.33  | 60.275  | 49963.8             | 411115              | 20.525 | 0.031       | 0.163 |
| 16         | 7.594               | 0.0043  | 0.0449 | 3,132.15  | 59.695  | 49717.4             | 407160              | 20.421 | 0.031       | 0.159 |
| 17         | 7.422               | 0.0055  | 0.0452 | 3,060.64  | 61.565  | 51284.1             | 419910              | 21.065 | 0.031       | 0.158 |
| 18         | 7.272               | 0.0067  | 0.0454 | 3,008.38  | 63.134  | 53609.4             | 430611              | 22.013 | 0.031       | 0.174 |
| 19         | 11.287              | 0.0007  | 0.0408 | 4,576.26  | 76.296  | 62966.5             | 520382              | 25.908 | 0.031       | 0.171 |
| 20         | 10.972              | 0.0015  | 0.0411 | 4,463.80  | 77.157  | 64218.6             | 526259              | 26.414 | 0.031       | 0.173 |
| 21         | 10.640              | 0.0023  | 0.0414 | 4,344.92  | 73.849  | 62382.2             | 503692              | 25.649 | 0.031       | 0.173 |

Appendix D: Single- and two-phase calculated data (continued).

Channel A: Water-Nitrogen tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 255.80 Hyd. Diameter ( $\mu\text{m}$ ): 256.91

Width ( $\mu\text{m}$ ): 258.03 Channel Length (m): 0.0635

| Data Point | G                   | x       | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty    |                 |
|------------|---------------------|---------|--------|-----------|---------|---------------------|---------------------|--------|----------------|-----------------|
|            | kg/s-m <sup>2</sup> | Quality |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | U <sub>f</sub> | U <sub>Nu</sub> |
|            |                     |         |        |           |         |                     |                     |        | (%)            | (%)             |
| 1          | 1.865               | 0.0210  | 0.1050 | 809.20    | 21.601  | 16.521              | 147333              | 6.903  | 0.031          | 0.134           |
| 2          | 1.795               | 0.0448  | 0.1113 | 801.24    | 20.783  | 17.799              | 141756              | 7.611  | 0.031          | 0.145           |
| 3          | 1.868               | 0.0650  | 0.1090 | 853.55    | 21.586  | 21.426              | 147229              | 9.348  | 0.031          | 0.162           |
| 4          | 1.852               | 0.0876  | 0.1123 | 869.52    | 21.329  | 21.879              | 145475              | 9.767  | 0.031          | 0.166           |
| 5          | 1.771               | 0.1155  | 0.1210 | 857.54    | 20.019  | 21.565              | 136539              | 9.916  | 0.031          | 0.173           |
| 6          | 1.810               | 0.1354  | 0.1213 | 895.18    | 19.953  | 21.762              | 136094              | 10.226 | 0.031          | 0.175           |
| 7          | 3.222               | 0.0118  | 0.0608 | 1,373.08  | 32.516  | 24.046              | 221778              | 9.967  | 0.031          | 0.137           |
| 8          | 3.165               | 0.0253  | 0.0622 | 1,378.77  | 32.552  | 29.747              | 222025              | 12.481 | 0.031          | 0.157           |
| 9          | 3.074               | 0.0395  | 0.0645 | 1,366.89  | 32.173  | 30.986              | 219437              | 13.177 | 0.031          | 0.162           |
| 10         | 3.043               | 0.0533  | 0.0658 | 1,379.89  | 32.483  | 32.754              | 221555              | 14.115 | 0.031          | 0.167           |
| 11         | 2.986               | 0.0683  | 0.0681 | 1,375.87  | 31.488  | 32.150              | 214764              | 14.066 | 0.031          | 0.169           |
| 12         | 2.935               | 0.0836  | 0.0706 | 1,371.68  | 30.131  | 30.416              | 205513              | 13.522 | 0.031          | 0.168           |
| 13         | 4.407               | 0.0086  | 0.0434 | 1,910.47  | 42.640  | 34.934              | 290833              | 14.405 | 0.031          | 0.149           |
| 14         | 4.370               | 0.0183  | 0.0437 | 1,932.08  | 45.138  | 39.317              | 307867              | 16.347 | 0.031          | 0.152           |
| 15         | 4.260               | 0.0284  | 0.0451 | 1,913.20  | 45.153  | 40.239              | 307974              | 16.886 | 0.031          | 0.153           |
| 16         | 4.193               | 0.0389  | 0.0463 | 1,905.03  | 44.565  | 40.342              | 303961              | 17.105 | 0.031          | 0.154           |
| 17         | 4.108               | 0.0496  | 0.0479 | 1,881.39  | 42.638  | 37.985              | 290816              | 16.283 | 0.031          | 0.153           |
| 18         | 3.927               | 0.0624  | 0.0515 | 1,797.50  | 36.696  | 29.853              | 250291              | 12.983 | 0.031          | 0.148           |
| 19         | 8.959               | 0.0044  | 0.0428 | 3,824.74  | 65.731  | 50.904              | 448323              | 20.928 | 0.031          | 0.161           |
| 20         | 8.614               | 0.0092  | 0.0431 | 3,733.10  | 66.425  | 54.313              | 453060              | 22.409 | 0.031          | 0.162           |
| 21         | 8.554               | 0.0142  | 0.0433 | 3,705.02  | 61.945  | 48.632              | 422506              | 20.174 | 0.031          | 0.163           |
| 22         | 8.319               | 0.0194  | 0.0437 | 3,630.20  | 62.464  | 49.522              | 426043              | 20.643 | 0.031          | 0.161           |
| 23         | 8.174               | 0.0249  | 0.0439 | 3,591.24  | 60.536  | 48.689              | 412894              | 20.402 | 0.031          | 0.163           |
| 24         | 8.018               | 0.0306  | 0.0442 | 3,525.12  | 57.016  | 44.591              | 388883              | 18.799 | 0.031          | 0.163           |

Appendix D: Single- and two-phase calculated data (continued).

Channel B: Argon gas tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.140 Hyd. Diameter ( $\mu\text{m}$ ): 210.051

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | Heat Trans. |        |          |         |                     |                     |          |             |       |
|------------|-------------|--------|----------|---------|---------------------|---------------------|----------|-------------|-------|
|            | Re          | f      | Velocity | Q       | coeff.              | Heat Flux           | Nu       | Uncertainty |       |
|            |             |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |          | U-f         | U-Nu  |
| 1          | 260.3       | 0.2402 | 16.09    | 0.0086  | 2.935               | 71.92               | 0.034098 | 0.031       | 0.232 |
| 2          | 706.1       | 0.0923 | 39.59    | 0.0407  | 14.391              | 338.48              | 0.166318 | 0.031       | 0.140 |
| 3          | 1.026.7     | 0.0671 | 53.88    | 0.0798  | 28.189              | 663.86              | 0.324900 | 0.031       | 0.109 |
| 4          | 1.422.6     | 0.0576 | 67.98    | 0.1450  | 54.637              | 1205.39             | 0.625138 | 0.031       | 0.091 |
| 5          | 1.790.1     | 0.0510 | 78.83    | 0.1977  | 75.734              | 1644.17             | 0.864497 | 0.031       | 0.087 |
| 6          | 2.250.5     | 0.0510 | 86.91    | 0.2810  | 105.909             | 2337.13             | 1.209111 | 0.031       | 0.080 |
| 7          | 2.524.3     | 0.0506 | 90.97    | 0.3163  | 120.034             | 2630.08             | 1.369598 | 0.031       | 0.080 |
| 8          | 2.953.7     | 0.0487 | 97.08    | 0.3971  | 151.371             | 3302.39             | 1.726652 | 0.031       | 0.077 |
| 9          | 3.310.3     | 0.0469 | 101.84   | 0.4615  | 179.546             | 3837.38             | 2.046069 | 0.031       | 0.077 |
| 10         | 3.631.2     | 0.0456 | 105.63   | 0.5272  | 209.444             | 4384.24             | 2.385056 | 0.031       | 0.076 |
| 11         | 3.979.8     | 0.0445 | 109.47   | 0.6449  | 270.952             | 5362.90             | 3.078541 | 0.031       | 0.074 |
| 12         | 4.354.6     | 0.0392 | 117.29   | 0.7213  | 306.381             | 5997.93             | 3.480945 | 0.031       | 0.074 |
| 13         | 4.664.1     | 0.0393 | 119.18   | 0.7957  | 342.464             | 6616.97             | 3.890101 | 0.031       | 0.073 |
| 14         | 5.007.0     | 0.0378 | 122.91   | 0.8770  | 383.340             | 7293.29             | 4.352510 | 0.031       | 0.073 |
| 15         | 5.380.8     | 0.0377 | 124.94   | 0.9647  | 427.681             | 8022.28             | 4.856246 | 0.031       | 0.073 |
| 16         | 5.692.9     | 0.0375 | 126.65   | 1.0388  | 465.965             | 8638.64             | 5.291541 | 0.031       | 0.074 |
| 17         | 5.930.5     | 0.0373 | 127.98   | 1.0935  | 496.640             | 9093.22             | 5.640217 | 0.031       | 0.074 |

Appendix D: Single- and two-phase calculated data (continued).

Channel B: Helium gas tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.140

Hyd. Diameter ( $\mu\text{m}$ ): 210.051

Width ( $\mu\text{m}$ ): 208.97

Channel Length (m): 0.0635

| Data Point | Re    | f      | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   | Heat Flux<br>(W/m <sup>2</sup> ) | Nu        | Uncertainty |             |
|------------|-------|--------|-------------------|--------------|-------------------------------|----------------------------------|-----------|-------------|-------------|
|            |       |        |                   |              | coeff.<br>W/m <sup>2</sup> -K |                                  |           | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 31.2  | 1.9987 | 16.85             | 0.0033       | 1.149                         | 27.33                            | 0.0015622 | 0.031       | 0.625       |
| 2          | 79.3  | 0.7799 | 39.75             | 0.0360       | 13.232                        | 299.74                           | 0.0178406 | 0.031       | 0.153       |
| 3          | 121.7 | 0.5066 | 57.64             | 0.0936       | 36.918                        | 778.19                           | 0.0495003 | 0.031       | 0.100       |
| 4          | 172.6 | 0.3585 | 76.66             | 0.1342       | 54.630                        | 1115.96                          | 0.0730729 | 0.031       | 0.099       |
| 5          | 218.5 | 0.2838 | 92.39             | 0.1934       | 82.515                        | 1607.99                          | 0.1100241 | 0.031       | 0.092       |
| 6          | 258.8 | 0.2408 | 105.37            | 0.2537       | 111.804                       | 2109.54                          | 0.1487222 | 0.031       | 0.087       |
| 7          | 312.5 | 0.2016 | 121.16            | 0.3360       | 152.173                       | 2793.88                          | 0.2020723 | 0.031       | 0.084       |
| 8          | 362.5 | 0.1767 | 134.15            | 0.3827       | 170.479                       | 3182.52                          | 0.2264976 | 0.031       | 0.084       |
| 9          | 409.6 | 0.1593 | 145.18            | 0.3984       | 170.227                       | 3313.23                          | 0.2265631 | 0.031       | 0.086       |
| 10         | 458.5 | 0.1446 | 156.36            | 0.4639       | 201.180                       | 3857.48                          | 0.2676377 | 0.031       | 0.084       |
| 11         | 510.4 | 0.1319 | 167.44            | 0.5484       | 244.260                       | 4560.55                          | 0.3247277 | 0.031       | 0.082       |
| 12         | 556.9 | 0.1227 | 176.82            | 0.6306       | 286.242                       | 5244.07                          | 0.3802599 | 0.031       | 0.081       |
| 13         | 604.5 | 0.1148 | 186.19            | 0.7055       | 325.961                       | 5866.39                          | 0.4328321 | 0.031       | 0.080       |
| 14         | 649.7 | 0.1099 | 193.52            | 0.7705       | 361.113                       | 6407.34                          | 0.4794401 | 0.031       | 0.080       |
| 15         | 709.0 | 0.1026 | 203.38            | 0.8665       | 413.591                       | 7205.32                          | 0.5489410 | 0.031       | 0.080       |
| 16         | 755.4 | 0.0977 | 211.26            | 0.9368       | 455.488                       | 7790.53                          | 0.6044350 | 0.031       | 0.080       |
| 17         | 815.8 | 0.0920 | 220.54            | 1.0180       | 509.119                       | 8465.36                          | 0.6753118 | 0.031       | 0.081       |

Appendix D: Single- and two-phase calculated data (continued).

Channel B: Nitrogen gas tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.140 Hyd. Diameter ( $\mu\text{m}$ ): 210.051

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point |         |        |          |         | Heat Trans.         |                     |         |       |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|---------|-------|-------|
|            | Re      | f      | Velocity | Q       | coeff.              | Heat Flux           | Nu      | U-f   | U-Nu  |
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |         | (%)   | (%)   |
| 1          | 160.5   | 0.3662 | 11.96    | 0.01258 | 4.504               | 104.62              | 0.03503 | 0.031 | 0.161 |
| 2          | 404.9   | 0.1488 | 28.65    | 0.0493  | 17.652              | 410.29              | 0.137   | 0.031 | 0.110 |
| 3          | 676.0   | 0.0935 | 45.15    | 0.1042  | 37.722              | 866.67              | 0.292   | 0.031 | 0.092 |
| 4          | 910.7   | 0.0752 | 57.68    | 0.1694  | 63.308              | 1408.56             | 0.488   | 0.031 | 0.082 |
| 5          | 1,173.1 | 0.0615 | 70.35    | 0.2330  | 87.502              | 1937.33             | 0.675   | 0.031 | 0.079 |
| 6          | 1,414.6 | 0.0535 | 81.11    | 0.3278  | 129.840             | 2725.75             | 0.999   | 0.031 | 0.074 |
| 7          | 1,647.6 | 0.0489 | 90.06    | 0.3989  | 159.972             | 3317.35             | 1.230   | 0.031 | 0.073 |
| 8          | 1,874.4 | 0.0484 | 96.24    | 0.4444  | 178.696             | 3695.42             | 1.374   | 0.031 | 0.074 |
| 9          | 2,139.9 | 0.0483 | 102.27   | 0.5113  | 207.960             | 4252.22             | 1.600   | 0.031 | 0.074 |
| 10         | 2,359.9 | 0.0489 | 106.15   | 0.5830  | 241.269             | 4848.20             | 1.855   | 0.031 | 0.074 |
| 11         | 2,592.0 | 0.0488 | 110.06   | 0.6614  | 275.103             | 5499.96             | 2.116   | 0.031 | 0.073 |
| 12         | 2,846.2 | 0.0402 | 120.99   | 0.7268  | 305.258             | 6044.32             | 2.349   | 0.031 | 0.073 |
| 13         | 3,049.6 | 0.0401 | 123.96   | 0.7875  | 334.974             | 6548.45             | 2.578   | 0.031 | 0.073 |
| 14         | 3,323.8 | 0.0395 | 128.32   | 0.8694  | 375.705             | 7230.10             | 2.892   | 0.031 | 0.074 |
| 15         | 3,533.1 | 0.0394 | 130.94   | 0.9363  | 408.970             | 7785.83             | 3.149   | 0.031 | 0.074 |
| 16         | 3,761.7 | 0.0394 | 133.37   | 1.0115  | 446.545             | 8411.75             | 3.439   | 0.031 | 0.074 |
| 17         | 4,055.6 | 0.0394 | 136.10   | 1.1063  | 496.146             | 9199.65             | 3.823   | 0.031 | 0.074 |



# Appendix D: Single- and two-phase calculated data (continued).

Channel B: Water tests.

Number of channels:

3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.140Hyd. Diameter ( $\mu\text{m}$ ): 210.051Width ( $\mu\text{m}$ ): 208.97

Channel Length (m): 0.0635

| Data Point | Re       | f      | Velocity<br>(m/s) | Q<br>(Watts) | h - overall<br>W/m <sup>2</sup> -K | Heat Flux<br>(W/m <sup>2</sup> ) | Nu     | Uncertainty |             |
|------------|----------|--------|-------------------|--------------|------------------------------------|----------------------------------|--------|-------------|-------------|
|            |          |        |                   |              |                                    |                                  |        | U-f<br>(%)  | U Nu<br>(%) |
| 1          | 345.07   | 0.8484 | 1.28              | 12.186       | 6360.797                           | 101335                           | 2.129  | 0.031       | 0.148       |
| 2          | 485.95   | 0.4370 | 1.84              | 14.394       | 9096.572                           | 119696                           | 3.050  | 0.031       | 0.178       |
| 3          | 637.37   | 0.2506 | 2.52              | 14.942       | 11030.43                           | 124255                           | 3.716  | 0.031       | 0.225       |
| 4          | 882.72   | 0.1395 | 3.48              | 19.060       | 13276.27                           | 158497                           | 4.472  | 0.031       | 0.234       |
| 5          | 1.131.56 | 0.0914 | 4.44              | 23.331       | 14994.44                           | 194012                           | 5.048  | 0.031       | 0.237       |
| 6          | 1.388.62 | 0.0656 | 5.41              | 29.418       | 18079.26                           | 244632                           | 6.081  | 0.031       | 0.228       |
| 7          | 1.597.12 | 0.0549 | 6.11              | 34.530       | 20832.44                           | 287144                           | 6.993  | 0.031       | 0.221       |
| 8          | 1.676.50 | 0.0537 | 6.34              | 38.646       | 23754.35                           | 321370                           | 7.964  | 0.031       | 0.209       |
| 9          | 1.861.79 | 0.0479 | 6.89              | 42.566       | 27317.14                           | 353971                           | 9.137  | 0.031       | 0.210       |
| 10         | 1.991.82 | 0.0450 | 7.30              | 48.239       | 30081.47                           | 401146                           | 10.050 | 0.031       | 0.198       |
| 11         | 2.068.42 | 0.0437 | 7.59              | 46.785       | 30860.81                           | 389055                           | 10.312 | 0.031       | 0.212       |
| 12         | 2.239.66 | 0.0400 | 8.17              | 54.618       | 34068.53                           | 454192                           | 11.376 | 0.031       | 0.197       |
| 13         | 2.308.60 | 0.0387 | 8.45              | 54.417       | 34749.22                           | 452520                           | 11.608 | 0.031       | 0.203       |
| 14         | 2.433.41 | 0.0360 | 8.94              | 53.436       | 35709.09                           | 444365                           | 11.933 | 0.031       | 0.217       |
| 15         | 2.532.57 | 0.0343 | 9.35              | 54.109       | 36802.77                           | 449957                           | 12.306 | 0.031       | 0.223       |
| 16         | 2.583.10 | 0.0345 | 9.47              | 59.227       | 37403.22                           | 492521                           | 12.496 | 0.031       | 0.207       |
| 17         | 2.750.13 | 0.0316 | 10.13             | 60.312       | 39082.49                           | 501544                           | 13.065 | 0.031       | 0.216       |
| 18         | 2.778.45 | 0.0314 | 10.26             | 59.793       | 39104.31                           | 497230                           | 13.075 | 0.031       | 0.220       |
| 19         | 3.134.97 | 0.0281 | 11.30             | 64.865       | 39626.15                           | 539402                           | 13.214 | 0.031       | 0.218       |
| 20         | 3.348.11 | 0.0261 | 12.14             | 67.385       | 43498.36                           | 560358                           | 14.515 | 0.031       | 0.227       |
| 21         | 3.472.80 | 0.0254 | 12.66             | 66.481       | 44264.47                           | 552842                           | 14.779 | 0.031       | 0.239       |
| 22         | 3.633.99 | 0.0242 | 13.29             | 66.742       | 45600.65                           | 555015                           | 15.231 | 0.031       | 0.248       |
| 23         | 3.784.38 | 0.0233 | 13.86             | 64.607       | 45832.62                           | 537259                           | 15.311 | 0.031       | 0.265       |
| 24         | 4.014.68 | 0.0222 | 14.80             | 64.345       | 48072.2                            | 535079                           | 16.070 | 0.031       | 0.283       |
| 25         | 4.220.39 | 0.0213 | 15.62             | 64.294       | 50157.4                            | 534659                           | 16.774 | 0.031       | 0.298       |
| 26         | 4.413.17 | 0.0204 | 16.38             | 66.000       | 53329.03                           | 548845                           | 17.840 | 0.031       | 0.306       |
| 27         | 4.761.85 | 0.0187 | 17.75             | 66.366       | 56722.1                            | 551888                           | 18.985 | 0.031       | 0.328       |
| 28         | 5.000.88 | 0.0176 | 18.71             | 66.567       | 59219.85                           | 553558                           | 19.828 | 0.031       | 0.344       |
| 29         | 5.201.20 | 0.0171 | 19.50             | 62.378       | 58978.7                            | 518719                           | 19.752 | 0.031       | 0.379       |
| 30         | 5.517.87 | 0.0161 | 20.79             | 62.372       | 61343.81                           | 518676                           | 20.555 | 0.031       | 0.403       |
| 31         | 5.930.67 | 0.0144 | 22.44             | 63.536       | 64313.03                           | 528350                           | 21.560 | 0.031       | 0.425       |
| 32         | 6.066.64 | 0.0140 | 23.32             | 79.414       | 76942.38                           | 660391                           | 25.838 | 0.031       | 0.363       |
| 33         | 6.693.65 | 0.0124 | 25.91             | 80.591       | 82255.85                           | 670179                           | 27.643 | 0.031       | 0.394       |
| 34         | 6.555.81 | 0.0124 | 25.41             | 61.541       | 53642.82                           | 511763                           | 18.030 | 0.031       | 0.337       |
| 35         | 7.181.26 | 0.0118 | 27.90             | 62.617       | 56712.47                           | 520710                           | 19.066 | 0.031       | 0.361       |
| 36         | 7.852.99 | 0.0111 | 30.56             | 64.856       | 60340.83                           | 539326                           | 20.290 | 0.031       | 0.380       |
| 37         | 8.336.22 | 0.0108 | 32.49             | 66.378       | 62592.93                           | 551986                           | 21.050 | 0.031       | 0.393       |
| 38         | 8.770.81 | 0.0107 | 34.26             | 67.700       | 65125.45                           | 562983                           | 21.906 | 0.031       | 0.406       |
| 39         | 9.305.06 | 0.0104 | 36.42             | 69.715       | 68204.63                           | 579733                           | 22.946 | 0.031       | 0.418       |

Appendix D: Single- and two-phase calculated data (continued).

Channel B: Water-argon tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.140 Hyd. Diameter ( $\mu\text{m}$ ): 210.051

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | U f (%)     | U Nu (%) |
| 1          | 1119.036            | 0.026055 | 0.1881 | 444.94    | 13.767  | 7067.0              | 114487              | 2.333  | 0.031       | 0.079    |
| 2          | 1159.937            | 0.147082 | 0.2004 | 477.44    | 16.084  | 9045.4              | 133751              | 2.979  | 0.031       | 0.081    |
| 3          | 1296.409            | 0.236895 | 0.2002 | 534.66    | 17.783  | 11009.2             | 147883              | 3.628  | 0.031       | 0.087    |
| 4          | 1439.653            | 0.312862 | 0.1999 | 595.12    | 19.534  | 12318.3             | 162442              | 4.062  | 0.031       | 0.088    |
| 5          | 1576.583            | 0.372584 | 0.1995 | 653.25    | 20.824  | 13279.3             | 173165              | 4.380  | 0.031       | 0.090    |
| 6          | 1774.711            | 0.410118 | 0.1977 | 701.46    | 20.249  | 15479.9             | 168389              | 5.134  | 0.031       | 0.106    |
| 7          | 4306.38             | 0.006831 | 0.0543 | 1,509.76  | 28.333  | 18166.2             | 235613              | 6.076  | 0.031       | 0.116    |
| 8          | 4301.51             | 0.039199 | 0.0547 | 1,551.60  | 31.989  | 28079.1             | 266011              | 9.366  | 0.031       | 0.131    |
| 9          | 4585.722            | 0.066148 | 0.0534 | 1,635.35  | 29.874  | 30491.0             | 248422              | 10.186 | 0.031       | 0.151    |
| 10         | 4492.317            | 0.100768 | 0.0565 | 1,604.12  | 29.375  | 30782.6             | 244276              | 10.285 | 0.031       | 0.153    |
| 11         | 4386.938            | 0.135326 | 0.0602 | 1,567.96  | 30.202  | 30909.8             | 251151              | 10.330 | 0.031       | 0.148    |
| 12         | 4630.725            | 0.156665 | 0.0590 | 1,639.45  | 29.702  | 32582.1             | 246992              | 10.903 | 0.031       | 0.159    |
| 13         | 7914.442            | 0.003503 | 0.0293 | 2,793.20  | 45.398  | 36273.5             | 377523              | 12.123 | 0.031       | 0.138    |
| 14         | 7661.691            | 0.021702 | 0.0302 | 2,755.53  | 48.453  | 41668.9             | 402922              | 13.901 | 0.031       | 0.137    |
| 15         | 7525.456            | 0.040567 | 0.0316 | 2,691.56  | 47.614  | 42258.7             | 395948              | 14.108 | 0.031       | 0.140    |
| 16         | 7797.694            | 0.057872 | 0.0311 | 2,778.87  | 48.232  | 44944.5             | 401086              | 15.013 | 0.031       | 0.145    |
| 17         | 7706.493            | 0.076753 | 0.0322 | 2,744.62  | 47.999  | 46703.4             | 399152              | 15.604 | 0.031       | 0.148    |
| 18         | 7363.327            | 0.100529 | 0.0345 | 2,625.19  | 47.389  | 46683.7             | 394075              | 15.600 | 0.031       | 0.148    |
| 19         | 13066.54            | 0.002237 | 0.0408 | 4,596.96  | 65.751  | 51015.5             | 546769              | 17.054 | 0.031       | 0.146    |
| 20         | 12170.27            | 0.013526 | 0.0415 | 4,340.07  | 69.465  | 55057.2             | 577659              | 18.381 | 0.031       | 0.138    |
| 21         | 11566.02            | 0.026938 | 0.0421 | 4,142.69  | 71.391  | 57025.3             | 593674              | 19.032 | 0.031       | 0.133    |
| 22         | 11327.35            | 0.040092 | 0.0425 | 4,053.72  | 69.548  | 57980.8             | 578343              | 19.355 | 0.031       | 0.136    |
| 23         | 11294.71            | 0.05425  | 0.0437 | 3,698.98  | 52.517  | 63892.5             | 436722              | 21.533 | 0.031       | 0.190    |
| 24         | 16176.9             | 0.002208 | 0.0396 | 5,181.88  | 48.575  | 65459.5             | 403939              | 22.101 | 0.031       | 0.246    |
| 25         | 16195.23            | 0.010464 | 0.0396 | 5,202.39  | 48.184  | 68089.7             | 400689              | 22.984 | 0.031       | 0.253    |
| 26         | 10698.79            | 0.002722 | 0.0436 | 3,522.45  | 58.637  | 52174.7             | 487614              | 17.565 | 0.031       | 0.149    |
| 27         | 10050.67            | 0.011714 | 0.0442 | 3,356.62  | 58.863  | 52340.6             | 489493              | 17.596 | 0.031       | 0.144    |
| 28         | 9951.487            | 0.020386 | 0.0442 | 3,395.53  | 59.327  | 52509.5             | 493354              | 17.614 | 0.031       | 0.143    |
| 29         | 14219.87            | 0.027385 | 0.0402 | 5,007.53  | 102.978 | 56964.4             | 856347              | 19.046 | 0.031       | 0.103    |
| 30         | 12661.34            | 0.013561 | 0.0416 | 4,311.50  | 59.073  | 46350.4             | 491239              | 15.550 | 0.031       | 0.153    |
| 31         | 12793.79            | 0.017224 | 0.0415 | 4,357.86  | 60.138  | 47474.2             | 500094              | 15.927 | 0.031       | 0.153    |
| 32         | 12521.8             | 0.023576 | 0.0418 | 4,277.61  | 61.288  | 48056.7             | 509661              | 16.118 | 0.031       | 0.149    |
| 33         | 12329.61            | 0.029245 | 0.0420 | 4,217.64  | 62.200  | 48732.5             | 517240              | 16.343 | 0.031       | 0.146    |
| 34         | 12052.65            | 0.040635 | 0.0423 | 4,135.38  | 63.522  | 49290.3             | 528234              | 16.527 | 0.031       | 0.142    |
| 35         | 12092.46            | 0.041628 | 0.0422 | 4,177.76  | 63.362  | 49796.7             | 526902              | 16.684 | 0.031       | 0.143    |

Appendix D: Single- and two-phase calculated data (continued).

Channel B: Water-helium tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.140 Hyd. Diameter ( $\mu\text{m}$ ): 210.051

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |                     |          |        |           |         |                     |                     |        | U f         | U Nu  |
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 1925.433            | 0.001616 | 0.1220 | 668.94    | 17.025  | 10872.1             | 141573              | 3.640  | 0.031       | 0.101 |
| 2          | 1445.991            | 0.014185 | 0.1610 | 513.64    | 14.243  | 9578.9              | 118441              | 3.199  | 0.031       | 0.101 |
| 3          | 1584.227            | 0.027938 | 0.1479 | 566.83    | 16.344  | 11518.6             | 135914              | 3.845  | 0.031       | 0.102 |
| 4          | 1424.962            | 0.052327 | 0.1688 | 509.63    | 14.500  | 10424.6             | 120580              | 3.480  | 0.031       | 0.104 |
| 5          | 4089.663            | 0.000726 | 0.0619 | 1,317.19  | 23.857  | 15700.3             | 198389              | 5.298  | 0.031       | 0.125 |
| 6          | 3495.863            | 0.005978 | 0.0706 | 1,161.60  | 24.695  | 17342.5             | 205358              | 5.833  | 0.031       | 0.117 |
| 7          | 2871.775            | 0.015743 | 0.0845 | 979.60    | 23.592  | 17619.1             | 196190              | 5.910  | 0.031       | 0.114 |
| 8          | 1966.268            | 0.036654 | 0.1217 | 695.25    | 18.836  | 13683.2             | 156639              | 4.573  | 0.031       | 0.107 |
| 9          | 6228.61             | 0.000453 | 0.0405 | 2,011.02  | 33.443  | 23056.3             | 278107              | 7.779  | 0.031       | 0.134 |
| 10         | 5193.128            | 0.003972 | 0.0472 | 1,732.72  | 34.658  | 25632.8             | 288212              | 8.618  | 0.031       | 0.123 |
| 11         | 4114.761            | 0.010955 | 0.0579 | 1,423.19  | 34.208  | 24484.5             | 284463              | 8.201  | 0.031       | 0.111 |
| 12         | 2720.373            | 0.026821 | 0.0849 | 986.17    | 28.797  | 18530.4             | 239474              | 6.176  | 0.031       | 0.096 |
| 13         | 7637.554            | 0.000383 | 0.0329 | 2,479.00  | 38.434  | 31333.5             | 319605              | 10.565 | 0.031       | 0.149 |
| 14         | 6864.585            | 0.00294  | 0.0360 | 2,269.63  | 39.248  | 32010.0             | 326379              | 10.772 | 0.031       | 0.139 |
| 15         | 5938.165            | 0.007488 | 0.0411 | 1,999.71  | 38.721  | 30864.4             | 321993              | 10.366 | 0.031       | 0.130 |
| 16         | 13161.86            | 0.000907 | 0.0420 | 4,100.71  | 60.056  | 44617.5             | 499416              | 15.109 | 0.031       | 0.152 |
| 17         | 12820.03            | 0.002373 | 0.0421 | 4,042.58  | 60.649  | 45038.1             | 504345              | 15.231 | 0.031       | 0.149 |
| 18         | 12636.8             | 0.003469 | 0.0422 | 4,018.78  | 61.229  | 45405.7             | 509165              | 15.342 | 0.031       | 0.146 |
| 19         | 12506.09            | 0.004765 | 0.0423 | 3,998.08  | 61.647  | 45980.2             | 512641              | 15.527 | 0.031       | 0.145 |
| 20         | 12252.61            | 0.006004 | 0.0425 | 3,930.02  | 60.746  | 45295.5             | 505150              | 15.291 | 0.031       | 0.145 |
| 21         | 15970.44            | 0.000913 | 0.0398 | 5,075.27  | 67.673  | 50760.3             | 562755              | 17.151 | 0.031       | 0.160 |
| 22         | 16488.13            | 0.001836 | 0.0394 | 5,253.31  | 69.225  | 52962.4             | 575657              | 17.890 | 0.031       | 0.162 |
| 23         | 16458.79            | 0.002765 | 0.0395 | 5,256.12  | 70.612  | 53698.9             | 587198              | 18.135 | 0.031       | 0.160 |
| 24         | 15869.9             | 0.003733 | 0.0398 | 5,083.90  | 69.787  | 52782.1             | 580332              | 17.819 | 0.031       | 0.157 |
| 25         | 15566.99            | 0.004725 | 0.0400 | 4,989.15  | 70.168  | 52830.2             | 583503              | 17.834 | 0.031       | 0.154 |
| 26         | 19028.62            | 0.000708 | 0.0381 | 6,025.35  | 71.399  | 56929.5             | 593739              | 19.242 | 0.031       | 0.177 |
| 27         | 19177.27            | 0.001689 | 0.0380 | 6,086.84  | 73.309  | 58465.7             | 609624              | 19.756 | 0.031       | 0.175 |
| 28         | 18750.7             | 0.002425 | 0.0382 | 5,958.07  | 72.386  | 57796.7             | 601950              | 19.528 | 0.031       | 0.174 |
| 29         | 18449.6             | 0.003327 | 0.0384 | 5,864.52  | 72.496  | 57464.1             | 602862              | 19.415 | 0.031       | 0.171 |
| 30         | 18670.39            | 0.003893 | 0.0383 | 5,927.24  | 73.133  | 58151.4             | 608159              | 19.649 | 0.031       | 0.172 |

# Appendix D: Single- and two-phase calculated data (continued).

Channel B: Water-Nitrogen tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 211.140 Hyd. Diameter ( $\mu\text{m}$ ): 210.051

Width ( $\mu\text{m}$ ): 208.97 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty    |                 |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|----------------|-----------------|
|            |                     |          |        |           |         |                     |                     |        | U <sub>f</sub> | U <sub>Nu</sub> |
|            | kg/s-m <sup>2</sup> | Quality, |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)            | (%)             |
| 1          | 2853.194            | 0.005711 | 0.0856 | 962.78    | 20.123  | 14211.4             | 168139              | 4.763  | 0.031          | 0.116           |
| 2          | 2431.893            | 0.051424 | 0.1023 | 883.91    | 19.797  | 15456.8             | 165415              | 5.402  | 0.031          | 0.115           |
| 3          | 2367.315            | 0.099361 | 0.1087 | 921.14    | 20.071  | 16505.3             | 167707              | 6.050  | 0.031          | 0.117           |
| 4          | 1954.428            | 0.151837 | 0.1389 | 811.14    | 16.446  | 13456.6             | 137414              | 5.219  | 0.031          | 0.115           |
| 5          | 2241.605            | 0.164679 | 0.1232 | 942.30    | 18.410  | 15268.4             | 153829              | 6.009  | 0.031          | 0.117           |
| 6          | 5861.516            | 0.002646 | 0.0443 | 1,849.45  | 25.585  | 21191.6             | 213773              | 7.130  | 0.031          | 0.161           |
| 7          | 4753.687            | 0.026787 | 0.0532 | 1,617.12  | 30.229  | 27128.6             | 252579              | 9.292  | 0.031          | 0.138           |
| 8          | 4191.489            | 0.056571 | 0.0609 | 1,501.35  | 29.924  | 25817.7             | 250026              | 9.089  | 0.031          | 0.128           |
| 9          | 3799.817            | 0.078729 | 0.0679 | 1,411.02  | 29.187  | 23323.2             | 243875              | 8.388  | 0.031          | 0.118           |
| 10         | 3413.208            | 0.109726 | 0.0771 | 1,328.33  | 27.847  | 21338.6             | 232675              | 7.917  | 0.031          | 0.112           |
| 11         | 8015.253            | 0.001973 | 0.0319 | 2,562.27  | 37.293  | 31555.3             | 311599              | 10.594 | 0.031          | 0.156           |
| 12         | 7168.526            | 0.018019 | 0.0352 | 2,402.90  | 41.909  | 35957.5             | 350170              | 12.219 | 0.031          | 0.139           |
| 13         | 5623.413            | 0.043522 | 0.0451 | 1,972.15  | 37.863  | 30660.1             | 316365              | 10.662 | 0.031          | 0.126           |
| 14         | 4992.725            | 0.060721 | 0.0511 | 1,802.81  | 35.569  | 27870.1             | 297195              | 9.849  | 0.031          | 0.121           |
| 15         | 9327.963            | 0.00165  | 0.0454 | 2,990.44  | 41.194  | 35142.9             | 344197              | 11.790 | 0.031          | 0.162           |
| 16         | 7827.603            | 0.016263 | 0.0323 | 2,609.36  | 43.425  | 36078.4             | 362835              | 12.244 | 0.031          | 0.141           |
| 17         | 6393.225            | 0.038788 | 0.0396 | 2,225.19  | 41.744  | 32191.6             | 348793              | 11.145 | 0.031          | 0.125           |
| 18         | 17102.02            | 0.004605 | 0.0387 | 5,721.42  | 72.231  | 56127.3             | 603525              | 18.801 | 0.031          | 0.160           |
| 19         | 16840.63            | 0.009309 | 0.0389 | 5,673.28  | 73.178  | 56967.9             | 611436              | 19.164 | 0.031          | 0.157           |
| 20         | 17107.14            | 0.013422 | 0.0388 | 5,778.79  | 74.268  | 57946.1             | 620543              | 19.573 | 0.031          | 0.157           |
| 21         | 16888.56            | 0.018246 | 0.0389 | 5,726.90  | 73.273  | 57639.6             | 612236              | 19.562 | 0.031          | 0.157           |
| 22         | 12775.58            | 0.004641 | 0.0415 | 4,324.66  | 54.833  | 44127.6             | 458156              | 14.765 | 0.031          | 0.161           |
| 23         | 12819.26            | 0.013709 | 0.0415 | 4,403.96  | 57.676  | 46124.8             | 481914              | 15.559 | 0.031          | 0.155           |
| 24         | 12753.15            | 0.01774  | 0.0416 | 4,406.07  | 58.810  | 47056.3             | 491384              | 15.932 | 0.031          | 0.153           |
| 25         | 12678.43            | 0.02364  | 0.0417 | 4,411.94  | 60.561  | 48635.7             | 506018              | 16.559 | 0.031          | 0.149           |
| 26         | 12103.35            | 0.031425 | 0.0422 | 4,250.12  | 59.909  | 47466.9             | 500567              | 16.283 | 0.031          | 0.145           |

Appendix D: Single- and two-phase calculated data (continued).

Channel C1: Argon gas tests.                      Number of channels:                      5  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):                      134.640                      Hyd. Diameter ( $\mu\text{m}$ ):                      127.92  
 Width ( $\mu\text{m}$ ):                      121.83                      Channel Length (m):                      0.0635

| Data Point | Re      | f      | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   | Heat Flux<br>(W/m <sup>2</sup> ) | Nu       | Uncertainty |       |
|------------|---------|--------|-------------------|--------------|-------------------------------|----------------------------------|----------|-------------|-------|
|            |         |        |                   |              | coeff.<br>W/m <sup>2</sup> -K |                                  |          | U-f         | U-Nu  |
| 1          | 53.4    | 1.1009 | 5.48              | 0.0002       | 0.273                         | 1.93                             | 0.001927 | 0.031       | 1.722 |
| 2          | 246.6   | 0.2478 | 21.26             | 0.0044       | 3.566                         | 35.23                            | 0.025198 | 0.031       | 0.449 |
| 3          | 631.6   | 0.1006 | 44.00             | 0.0286       | 14.928                        | 230.43                           | 0.105073 | 0.031       | 0.186 |
| 4          | 1.000.2 | 0.0680 | 59.98             | 0.0681       | 32.504                        | 548.58                           | 0.227941 | 0.031       | 0.132 |
| 5          | 1.390.3 | 0.0576 | 71.06             | 0.1354       | 67.096                        | 1090.06                          | 0.468532 | 0.031       | 0.105 |
| 6          | 1.740.3 | 0.0505 | 79.44             | 0.1901       | 95.079                        | 1530.48                          | 0.662900 | 0.031       | 0.099 |
| 7          | 2.076.5 | 0.0507 | 82.76             | 0.2297       | 112.734                       | 1849.67                          | 0.785977 | 0.031       | 0.099 |
| 8          | 2.378.2 | 0.0509 | 84.97             | 0.2531       | 120.080                       | 2038.42                          | 0.837660 | 0.031       | 0.101 |
| 9          | 2.687.0 | 0.0495 | 87.94             | 0.2961       | 138.557                       | 2384.62                          | 0.966646 | 0.031       | 0.100 |
| 10         | 2.989.2 | 0.0480 | 90.78             | 0.3536       | 166.361                       | 2847.23                          | 1.159983 | 0.031       | 0.097 |
| 11         | 3.235.7 | 0.0466 | 93.15             | 0.4053       | 192.530                       | 3263.68                          | 1.341784 | 0.031       | 0.095 |
| 12         | 3.515.7 | 0.0452 | 95.75             | 0.5273       | 269.391                       | 4246.39                          | 1.872281 | 0.031       | 0.091 |
| 13         | 3.738.8 | 0.0443 | 97.57             | 0.6060       | 321.515                       | 4880.32                          | 2.231997 | 0.031       | 0.090 |
| 14         | 3.959.6 | 0.0438 | 98.97             | 0.6706       | 365.836                       | 5400.14                          | 2.538045 | 0.031       | 0.091 |
| 15         | 4.172.5 | 0.0421 | 101.42            | 0.7322       | 403.897                       | 5896.45                          | 2.801572 | 0.031       | 0.091 |
| 16         | 4.365.0 | 0.0418 | 102.52            | 0.8007       | 449.148                       | 6447.90                          | 3.114988 | 0.031       | 0.091 |
| 17         | 4.531.2 | 0.0416 | 103.19            | 0.8621       | 490.450                       | 6942.47                          | 3.401878 | 0.031       | 0.092 |
| 18         | 4.698.6 | 0.0415 | 103.85            | 0.9281       | 538.762                       | 7473.93                          | 3.737730 | 0.031       | 0.093 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C1: Helium gas tests. Number of channels: 5

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 134.640 Hyd. Diameter ( $\mu\text{m}$ ): 127.92

Width ( $\mu\text{m}$ ): 121.83 Channel Length (m): 0.0635

| Data Point | Re    | f      | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   |                                  | Nu        | Uncertainty |             |
|------------|-------|--------|-------------------|--------------|-------------------------------|----------------------------------|-----------|-------------|-------------|
|            |       |        |                   |              | coeff.<br>W/m <sup>2</sup> -K | Heat Flux<br>(W/m <sup>2</sup> ) |           | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 7.7   | 8.5782 | 6.65              |              |                               |                                  |           |             |             |
| 2          | 31.3  | 2.2071 | 22.68             | 0.0015       | 0.719                         | 12.08                            | 0.0005979 | 0.031       | 1.370       |
| 3          | 79.6  | 0.9175 | 45.34             | 0.0110       | 9.647                         | 88.84                            | 0.0080457 | 0.031       | 0.474       |
| 4          | 127.1 | 0.5950 | 62.59             | 0.0496       | 28.055                        | 399.36                           | 0.0232386 | 0.031       | 0.178       |
| 5          | 180.9 | 0.4048 | 80.23             | 0.0836       | 41.360                        | 673.30                           | 0.0341347 | 0.031       | 0.150       |
| 6          | 227.7 | 0.3236 | 93.11             | 0.1111       | 53.807                        | 894.59                           | 0.0442757 | 0.031       | 0.142       |
| 7          | 280.9 | 0.2655 | 105.93            | 0.1498       | 70.227                        | 1205.99                          | 0.0576794 | 0.031       | 0.131       |
| 8          | 332.0 | 0.2243 | 117.73            | 0.1904       | 90.235                        | 1532.99                          | 0.0739434 | 0.031       | 0.123       |
| 9          | 385.8 | 0.1953 | 128.59            | 0.2337       | 111.429                       | 1882.19                          | 0.0911686 | 0.031       | 0.118       |
| 10         | 437.1 | 0.1733 | 138.47            | 0.2860       | 137.413                       | 2303.03                          | 0.1122417 | 0.031       | 0.111       |
| 11         | 487.9 | 0.1565 | 147.48            | 0.3446       | 167.269                       | 2774.95                          | 0.1364453 | 0.031       | 0.106       |
| 12         | 543.4 | 0.1426 | 156.11            | 0.3867       | 208.373                       | 3114.43                          | 0.1700141 | 0.031       | 0.109       |
| 13         | 599.3 | 0.1310 | 164.39            | 0.4380       | 244.412                       | 3527.45                          | 0.1994393 | 0.031       | 0.108       |
| 14         | 658.8 | 0.1204 | 172.90            | 0.5010       | 283.835                       | 4034.43                          | 0.2316009 | 0.031       | 0.106       |
| 15         | 707.5 | 0.1148 | 178.48            | 0.5624       | 326.201                       | 4528.91                          | 0.2661107 | 0.031       | 0.105       |
| 16         | 770.9 | 0.1072 | 186.02            | 0.6251       | 365.869                       | 5034.05                          | 0.2985233 | 0.031       | 0.104       |
| 17         | 825.2 | 0.1011 | 192.61            | 0.6771       | 396.265                       | 5452.42                          | 0.3233312 | 0.031       | 0.103       |
| 18         | 883.5 | 0.0957 | 199.11            | 0.7385       | 434.934                       | 5947.37                          | 0.3549218 | 0.031       | 0.102       |

Appendix D: Single- and two-phase calculated data (continued).

Channel C1: Nitrogen gas tests.      Number of channels:      5  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      134.640      Hyd. Diameter ( $\mu\text{m}$ ):      127.92  
 Width ( $\mu\text{m}$ ):      121.83      Channel Length (m):      0.0635

| Data Point |         |        |          |         | Heat Trans.         |                     |         |       |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|---------|-------|-------|
|            | Re      | f      | Velocity | Q       | coeff.              | Heat Flux           | Nu      | U-f   | U-Nu  |
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |         | (%)   | (%)   |
| 1          | 37.5    | 1.7984 | 4.37     | 0.00018 | 0.169               | 1.45                | 0.00082 | 0.031 | 2.523 |
| 2          | 172.8   | 0.3747 | 17.80    | 0.0048  | 3.819               | 38.27               | 0.018   | 0.031 | 0.453 |
| 3          | 407.4   | 0.1602 | 36.05    | 0.0180  | 14.119              | 145.16              | 0.068   | 0.031 | 0.293 |
| 4          | 647.1   | 0.1069 | 50.69    | 0.0502  | 25.879              | 404.23              | 0.125   | 0.031 | 0.172 |
| 5          | 897.6   | 0.0845 | 62.70    | 0.1052  | 50.181              | 847.46              | 0.241   | 0.031 | 0.123 |
| 6          | 1,140.9 | 0.0691 | 73.21    | 0.1641  | 78.100              | 1321.21             | 0.374   | 0.031 | 0.107 |
| 7          | 1,357.5 | 0.0603 | 81.39    | 0.2289  | 111.389             | 1843.49             | 0.531   | 0.031 | 0.098 |
| 8          | 1,597.4 | 0.0541 | 88.91    | 0.2941  | 144.717             | 2368.55             | 0.690   | 0.031 | 0.094 |
| 9          | 1,807.1 | 0.0519 | 93.50    | 0.3479  | 170.778             | 2801.52             | 0.813   | 0.031 | 0.093 |
| 10         | 2,013.0 | 0.0526 | 95.35    | 0.3414  | 156.800             | 2749.15             | 0.748   | 0.031 | 0.098 |
| 11         | 2,215.4 | 0.0528 | 97.47    | 0.4157  | 196.209             | 3347.37             | 0.935   | 0.031 | 0.094 |
| 12         | 2,420.9 | 0.0523 | 99.94    | 0.5321  | 266.603             | 4285.28             | 1.267   | 0.031 | 0.089 |
| 13         | 2,604.2 | 0.0514 | 102.04   | 0.5687  | 278.781             | 4579.42             | 1.326   | 0.031 | 0.089 |
| 14         | 2,793.0 | 0.0503 | 104.44   | 0.6706  | 342.857             | 5400.21             | 1.628   | 0.031 | 0.088 |
| 15         | 2,978.1 | 0.0487 | 107.12   | 0.7418  | 388.335             | 5973.90             | 1.843   | 0.031 | 0.088 |
| 16         | 3,150.3 | 0.0481 | 108.83   | 0.8140  | 428.703             | 6554.81             | 2.034   | 0.031 | 0.088 |
| 17         | 3,319.6 | 0.0477 | 110.14   | 0.8776  | 469.790             | 7067.07             | 2.229   | 0.031 | 0.088 |
| 18         | 3,484.3 | 0.0472 | 111.48   | 0.9520  | 515.596             | 7666.50             | 2.446   | 0.031 | 0.088 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C1: Water tests.                      Number of channels:                      5  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):                      134.640                      Hyd. Diameter ( $\mu\text{m}$ ):                      127.92  
 Width ( $\mu\text{m}$ ):                      121.83                      Channel Length (m):                      0.0635

| Data Point | Re       | f      | Velocity | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|----------|--------|----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |          |        |          |         |                     |                     |        | U-f         | U_Nu  |
|            |          |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 302.26   | 0.3442 | 1.77     | 10.153  | 7567.223            | 81765               | 1.535  | 0.031       | 0.111 |
| 2          | 353.68   | 0.2586 | 2.12     | 10.929  | 9472.409            | 88013               | 1.926  | 0.031       | 0.128 |
| 3          | 523.85   | 0.1273 | 3.23     | 13.720  | 14597.34            | 110489              | 2.978  | 0.031       | 0.156 |
| 4          | 613.52   | 0.1064 | 3.72     | 17.487  | 15206.55            | 140822              | 3.097  | 0.031       | 0.131 |
| 5          | 804.55   | 0.0699 | 4.79     | 25.492  | 17949.92            | 205283              | 3.647  | 0.031       | 0.110 |
| 6          | 896.27   | 0.0598 | 5.38     | 27.287  | 19510.71            | 219742              | 3.969  | 0.031       | 0.113 |
| 7          | 978.30   | 0.0533 | 5.93     | 27.664  | 20658.77            | 222775              | 4.206  | 0.031       | 0.119 |
| 8          | 1,074.41 | 0.0468 | 6.55     | 28.382  | 22089.32            | 228559              | 4.501  | 0.031       | 0.126 |
| 9          | 1,259.71 | 0.0380 | 7.51     | 37.443  | 24537.53            | 301525              | 4.987  | 0.031       | 0.108 |
| 10         | 1,290.56 | 0.0390 | 7.72     | 36.699  | 24727.53            | 295535              | 5.028  | 0.031       | 0.112 |
| 11         | 1,364.59 | 0.0364 | 8.20     | 36.357  | 25025.44            | 292782              | 5.091  | 0.031       | 0.116 |
| 12         | 1,522.45 | 0.0323 | 8.92     | 46.580  | 28809               | 375111              | 5.844  | 0.031       | 0.102 |
| 13         | 1,605.43 | 0.0306 | 9.43     | 48.788  | 30544.46            | 392886              | 6.197  | 0.031       | 0.103 |
| 14         | 1,656.56 | 0.0304 | 9.75     | 48.762  | 31332.94            | 392677              | 6.359  | 0.031       | 0.106 |
| 15         | 1,711.65 | 0.0294 | 10.10    | 49.201  | 32227.02            | 396214              | 6.542  | 0.031       | 0.109 |
| 16         | 1,708.89 | 0.0295 | 10.09    | 49.130  | 32177.99            | 395644              | 6.532  | 0.031       | 0.109 |
| 17         | 1,754.68 | 0.0307 | 10.40    | 48.460  | 34008.4             | 390244              | 6.907  | 0.031       | 0.115 |
| 18         | 1,844.43 | 0.0286 | 10.95    | 49.490  | 35839.51            | 398546              | 7.280  | 0.031       | 0.119 |
| 19         | 1,387.56 | 0.0358 | 8.83     | 35.112  | 21738.79            | 282753              | 4.450  | 0.031       | 0.116 |
| 20         | 1,660.17 | 0.0310 | 10.61    | 38.372  | 29312.42            | 309008              | 6.003  | 0.031       | 0.135 |
| 21         | 1,794.17 | 0.0316 | 11.46    | 39.526  | 35230.72            | 318302              | 7.214  | 0.031       | 0.149 |
| 22         | 1,948.20 | 0.0316 | 12.45    | 40.551  | 40157.43            | 326555              | 8.224  | 0.031       | 0.162 |
| 23         | 2,079.52 | 0.0318 | 13.27    | 42.144  | 46524.47            | 339383              | 9.525  | 0.031       | 0.175 |
| 24         | 2,268.77 | 0.0300 | 14.51    | 43.278  | 49932.66            | 348521              | 10.225 | 0.031       | 0.184 |
| 25         | 2,435.56 | 0.0289 | 15.60    | 44.228  | 52647.56            | 356165              | 10.783 | 0.031       | 0.191 |
| 26         | 2,751.78 | 0.0269 | 17.70    | 46.258  | 57814.36            | 372513              | 11.846 | 0.031       | 0.203 |



Appendix D: Single- and two-phase calculated data (continued).

Channel C1: Water-argon tests.

Number of channels: 5

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 134.640

Hyd. Diameter ( $\mu\text{m}$ ): 127.92

Width ( $\mu\text{m}$ ): 121.83

Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|-------------|-------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U f         | U Nu  |
|            |                     |          |        |           |         |                     |                     |       | (%)         | (%)   |
| 1          | 3.300               | 0.015222 | 0.1173 | 707.57    | 14.754  | 13943.4             | 118817              | 2.840 | 0.031       | 0.142 |
| 2          | 3.224               | 0.047053 | 0.1218 | 704.34    | 15.994  | 13690.1             | 128797              | 2.783 | 0.031       | 0.128 |
| 3          | 2.813               | 0.085278 | 0.1427 | 626.47    | 15.261  | 11803.5             | 122901              | 2.396 | 0.031       | 0.117 |
| 4          | 2.537               | 0.130342 | 0.1664 | 565.12    | 13.598  | 10501.0             | 109507              | 2.132 | 0.031       | 0.117 |
| 5          | 2.067               | 0.252469 | 0.2282 | 480.08    | 12.828  | 8537.8              | 103305              | 1.728 | 0.031       | 0.101 |
| 6          | 5.164               | 0.01009  | 0.0760 | 1,085.91  | 20.036  | 18806.5             | 161347              | 3.838 | 0.031       | 0.148 |
| 7          | 4.775               | 0.028589 | 0.0827 | 1,016.78  | 20.094  | 17964.9             | 161821              | 3.662 | 0.031       | 0.139 |
| 8          | 4.659               | 0.050585 | 0.0856 | 1,005.22  | 21.705  | 17867.7             | 174789              | 3.638 | 0.031       | 0.128 |
| 9          | 4.144               | 0.080309 | 0.0979 | 907.90    | 21.000  | 16328.6             | 169113              | 3.320 | 0.031       | 0.120 |
| 10         | 5.771               | 0.008604 | 0.0661 | 1,247.42  | 27.698  | 21093.6             | 223055              | 4.292 | 0.031       | 0.120 |
| 11         | 5.360               | 0.021277 | 0.0710 | 1,175.15  | 27.597  | 20426.7             | 222235              | 4.150 | 0.031       | 0.115 |
| 12         | 5.065               | 0.03847  | 0.0753 | 1,129.03  | 27.362  | 19490.2             | 220344              | 3.954 | 0.031       | 0.111 |
| 13         | 4.758               | 0.055227 | 0.0803 | 1,076.92  | 27.861  | 18847.4             | 224368              | 3.818 | 0.031       | 0.104 |
| 14         | 4.410               | 0.075967 | 0.0873 | 1,013.46  | 27.794  | 17838.6             | 223822              | 3.608 | 0.031       | 0.099 |
| 15         | 2.765               | 0.172805 | 0.1721 | 574.63    | 10.403  | 11121.9             | 83775               | 2.276 | 0.031       | 0.162 |
| 16         | 2.523               | 0.239492 | 0.2052 | 524.59    | 9.528   | 9984.3              | 76726               | 2.045 | 0.031       | 0.160 |
| 17         | 2.994               | 0.243694 | 0.1748 | 619.35    | 11.080  | 11685.4             | 89230               | 2.395 | 0.031       | 0.162 |
| 18         | 3.233               | 0.260412 | 0.1682 | 658.13    | 11.110  | 12714.6             | 89466               | 2.610 | 0.031       | 0.175 |
| 19         | 3.506               | 0.272107 | 0.1594 | 706.10    | 11.392  | 13502.7             | 91740               | 2.776 | 0.031       | 0.182 |
| 20         | 3.578               | 0.299363 | 0.1626 | 719.21    | 11.548  | 13662.3             | 92994               | 2.810 | 0.031       | 0.182 |
| 21         | 3.275               | 0.37127  | 0.1979 | 658.86    | 10.670  | 12428.2             | 85928               | 2.558 | 0.031       | 0.180 |
| 22         | 13.427              | 0.003895 | 0.0311 | 2,638.05  | 34.156  | 40705.8             | 275054              | 8.365 | 0.031       | 0.201 |
| 23         | 12.944              | 0.015069 | 0.0323 | 2,569.79  | 34.826  | 40997.9             | 280451              | 8.416 | 0.031       | 0.195 |
| 24         | 13.241              | 0.025609 | 0.0318 | 2,638.45  | 35.483  | 41868.2             | 285741              | 8.592 | 0.031       | 0.196 |
| 25         | 13.252              | 0.036678 | 0.0319 | 2,655.55  | 37.049  | 43208.9             | 298354              | 8.863 | 0.031       | 0.191 |
| 26         | 13.183              | 0.05564  | 0.0327 | 2,650.39  | 37.203  | 42801.7             | 299599              | 8.778 | 0.031       | 0.189 |
| 27         | 12.746              | 0.070491 | 0.0341 | 2,577.73  | 37.958  | 42439.2             | 305678              | 8.699 | 0.031       | 0.182 |
| 28         | 12.055              | 0.085515 | 0.0365 | 2,451.28  | 37.725  | 41036.9             | 303799              | 8.408 | 0.031       | 0.175 |
| 29         | 10.730              | 0.116418 | 0.0420 | 2,201.32  | 36.475  | 37688.4             | 293736              | 7.717 | 0.031       | 0.165 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C1: Water-helium tests. Number of channels: 5

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 134.640 Hyd. Diameter ( $\mu\text{m}$ ): 127.92

Width ( $\mu\text{m}$ ): 121.83 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | U f (%)     | U Nu (%) |
| 1          | 1.676               | 0.003086 | 0.2204 | 371.86    | 10.251  | 8001.3              | 82553               | 1.623  | 0.031       | 0.114    |
| 2          | 1.670               | 0.008804 | 0.2148 | 383.78    | 10.553  | 7865.5              | 84982               | 1.590  | 0.031       | 0.109    |
| 3          | 1.798               | 0.012926 | 0.2005 | 412.76    | 11.387  | 8418.6              | 91702               | 1.702  | 0.031       | 0.109    |
| 4          | 1.822               | 0.026202 | 0.2001 | 419.29    | 11.515  | 8016.7              | 92727               | 1.621  | 0.031       | 0.104    |
| 5          | 1.846               | 0.038525 | 0.2001 | 424.69    | 11.546  | 7715.7              | 92981               | 1.560  | 0.031       | 0.102    |
| 6          | 3.483               | 0.001433 | 0.1070 | 764.86    | 18.733  | 15710.4             | 150853              | 3.191  | 0.031       | 0.124    |
| 7          | 3.701               | 0.003978 | 0.1018 | 805.93    | 18.977  | 15881.1             | 152825              | 3.229  | 0.031       | 0.125    |
| 8          | 3.161               | 0.007552 | 0.1186 | 693.82    | 16.437  | 13321.2             | 132363              | 2.706  | 0.031       | 0.122    |
| 9          | 2.920               | 0.016516 | 0.1294 | 641.84    | 15.556  | 11911.1             | 125273              | 2.419  | 0.031       | 0.117    |
| 10         | 2.569               | 0.027806 | 0.1473 | 570.64    | 14.305  | 10274.2             | 115197              | 2.085  | 0.031       | 0.110    |
| 11         | 4.931               | 0.00103  | 0.0780 | 1048.55   | 22.680  | 18757.3             | 182639              | 3.823  | 0.031       | 0.129    |
| 12         | 4.634               | 0.003284 | 0.0821 | 997.96    | 22.321  | 18050.4             | 179754              | 3.674  | 0.031       | 0.125    |
| 13         | 4.433               | 0.005219 | 0.0853 | 962.58    | 22.118  | 17337.8             | 178119              | 3.526  | 0.031       | 0.121    |
| 14         | 3.994               | 0.012023 | 0.0941 | 878.93    | 21.243  | 15505.8             | 171068              | 3.149  | 0.031       | 0.113    |
| 15         | 3.161               | 0.022493 | 0.1182 | 707.45    | 17.807  | 12276.8             | 143400              | 2.489  | 0.031       | 0.107    |
| 16         | 6.182               | 0.000819 | 0.0623 | 1312.26   | 27.067  | 21307.6             | 217974              | 4.343  | 0.031       | 0.127    |
| 17         | 6.112               | 0.002445 | 0.0629 | 1302.90   | 26.844  | 21111.1             | 216177              | 4.301  | 0.031       | 0.127    |
| 18         | 6.145               | 0.003772 | 0.0628 | 1306.14   | 26.289  | 20749.9             | 211709              | 4.229  | 0.031       | 0.128    |
| 19         | 5.438               | 0.008741 | 0.0704 | 1170.82   | 25.178  | 19105.5             | 202761              | 3.889  | 0.031       | 0.122    |
| 20         | 4.793               | 0.014789 | 0.0792 | 1047.66   | 24.334  | 17313.3             | 195959              | 3.518  | 0.031       | 0.113    |
| 21         | 12.493              | 0.004144 | 0.0334 | 2454.66   | 43.945  | 42845.4             | 353889              | 8.805  | 0.031       | 0.157    |
| 22         | 12.099              | 0.005901 | 0.0343 | 2397.88   | 43.061  | 42963.8             | 346766              | 8.821  | 0.031       | 0.158    |
| 23         | 11.675              | 0.008698 | 0.0353 | 2334.40   | 42.941  | 44205.5             | 345803              | 9.068  | 0.031       | 0.160    |
| 24         | 11.565              | 0.009477 | 0.0355 | 2322.78   | 42.700  | 43654.4             | 343864              | 8.950  | 0.031       | 0.159    |
| 25         | 11.323              | 0.011125 | 0.0362 | 2283.84   | 42.474  | 43291.7             | 342045              | 8.872  | 0.031       | 0.158    |
| 26         | 14.189              | 0.0036   | 0.0287 | 2859.77   | 51.479  | 51609.6             | 414561              | 10.577 | 0.031       | 0.158    |
| 27         | 14.047              | 0.005257 | 0.0289 | 2841.06   | 51.044  | 51809.5             | 411054              | 10.614 | 0.031       | 0.159    |
| 28         | 13.647              | 0.00694  | 0.0297 | 2772.27   | 50.016  | 50518.0             | 402782              | 10.345 | 0.031       | 0.158    |
| 29         | 14.045              | 0.007632 | 0.0289 | 2853.02   | 51.331  | 52243.3             | 413369              | 10.698 | 0.031       | 0.159    |
| 30         | 13.477              | 0.008842 | 0.0301 | 2741.20   | 49.365  | 50117.9             | 397533              | 10.261 | 0.031       | 0.158    |
| 31         | 16.930              | 0.002857 | 0.0441 | 3384.05   | 53.640  | 59592.3             | 431960              | 12.223 | 0.031       | 0.177    |
| 32         | 2.569               | 0.008001 | 0.1555 | 529.78    | 8.930   | 10671.2             | 71916               | 2.182  | 0.031       | 0.179    |
| 33         | 2.461               | 0.014094 | 0.1626 | 509.66    | 9.047   | 10048.2             | 72859               | 2.054  | 0.031       | 0.168    |
| 34         | 2.370               | 0.022635 | 0.1705 | 490.24    | 8.842   | 9667.7              | 71208               | 1.976  | 0.031       | 0.165    |
| 35         | 2.421               | 0.028933 | 0.1685 | 499.50    | 9.122   | 9756.6              | 73457               | 1.995  | 0.031       | 0.162    |
| 36         | 2.199               | 0.042781 | 0.1912 | 446.57    | 7.684   | 8465.8              | 61877               | 1.734  | 0.031       | 0.170    |
| 37         | 2.105               | 0.050947 | 0.2019 | 426.46    | 7.338   | 8005.4              | 59096               | 1.641  | 0.031       | 0.169    |
| 38         | 2.234               | 0.058314 | 0.1923 | 451.30    | 7.737   | 8388.9              | 62303               | 1.720  | 0.031       | 0.168    |

Appendix D: Single- and two-phase calculated data (continued).

Channel C1: Water-Nitrogen tests. Number of channels: 5  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ): 134.640 Hyd. Diameter ( $\mu\text{m}$ ): 127.92  
 Width ( $\mu\text{m}$ ): 121.83 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty    |                 |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|----------------|-----------------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U <sub>f</sub> | U <sub>Nu</sub> |
|            |                     |          |        |           |         |                     |                     |       | (%)            | (%)             |
| 1          | 3.602               | 0.006603 | 0.1075 | 769.92    | 14.741  | 14536.5             | 118706              | 2.982 | 0.031          | 0.150           |
| 2          | 3.191               | 0.023836 | 0.1216 | 704.30    | 14.136  | 13412.6             | 113840              | 2.793 | 0.031          | 0.142           |
| 3          | 2.868               | 0.042052 | 0.1368 | 649.80    | 12.889  | 11646.1             | 103793              | 2.467 | 0.031          | 0.136           |
| 4          | 3.150               | 0.05385  | 0.1252 | 727.75    | 14.690  | 12489.8             | 118295              | 2.676 | 0.031          | 0.129           |
| 5          | 2.719               | 0.083488 | 0.1488 | 651.62    | 13.048  | 10474.3             | 105075              | 2.312 | 0.031          | 0.122           |
| 6          | 2.808               | 0.102413 | 0.1456 | 693.99    | 13.914  | 10698.4             | 112052              | 2.406 | 0.031          | 0.117           |
| 7          | 5.176               | 0.004933 | 0.0758 | 1,088.49  | 21.021  | 19619.7             | 169282              | 4.024 | 0.031          | 0.145           |
| 8          | 4.907               | 0.013869 | 0.0795 | 1,055.71  | 20.696  | 18867.3             | 166662              | 3.898 | 0.031          | 0.140           |
| 9          | 4.472               | 0.026091 | 0.0876 | 982.37    | 19.512  | 16957.1             | 157134              | 3.542 | 0.031          | 0.134           |
| 10         | 4.137               | 0.040276 | 0.0951 | 931.86    | 18.294  | 15484.8             | 147319              | 3.276 | 0.031          | 0.131           |
| 11         | 4.115               | 0.055374 | 0.0961 | 950.35    | 19.083  | 15307.4             | 153674              | 3.285 | 0.031          | 0.124           |
| 12         | 3.942               | 0.073116 | 0.1013 | 936.00    | 19.279  | 14655.8             | 155256              | 3.199 | 0.031          | 0.117           |
| 13         | 6.714               | 0.004061 | 0.0580 | 1,419.59  | 26.734  | 22757.2             | 215290              | 4.661 | 0.031          | 0.138           |
| 14         | 6.325               | 0.0109   | 0.0614 | 1,359.48  | 26.557  | 22289.0             | 213862              | 4.590 | 0.031          | 0.134           |
| 15         | 5.943               | 0.01992  | 0.0652 | 1,303.96  | 26.115  | 21107.4             | 210307              | 4.380 | 0.031          | 0.128           |
| 16         | 5.360               | 0.031051 | 0.0719 | 1,209.33  | 25.760  | 19431.7             | 207448              | 4.069 | 0.031          | 0.119           |
| 17         | 5.018               | 0.045245 | 0.0770 | 1,162.34  | 25.387  | 18484.4             | 204445              | 3.921 | 0.031          | 0.114           |
| 18         | 2.598               | 0.09936  | 0.1776 | 565.58    | 8.322   | 8793.7              | 67014               | 1.997 | 0.031          | 0.166           |
| 19         | 2.600               | 0.118395 | 0.1817 | 576.43    | 8.018   | 8959.1              | 64570               | 2.077 | 0.031          | 0.173           |
| 20         | 2.439               | 0.146448 | 0.1991 | 560.69    | 7.580   | 8305.2              | 61040               | 1.985 | 0.031          | 0.169           |
| 21         | 2.394               | 0.173978 | 0.2083 | 571.54    | 7.523   | 8022.7              | 60585               | 1.977 | 0.031          | 0.164           |
| 22         | 2.443               | 0.19429  | 0.2080 | 600.70    | 7.787   | 8010.1              | 62709               | 2.019 | 0.031          | 0.159           |
| 23         | 2.774               | 0.19018  | 0.1809 | 683.83    | 9.030   | 9097.6              | 72717               | 2.281 | 0.031          | 0.156           |
| 24         | 2.932               | 0.207194 | 0.1757 | 733.65    | 9.088   | 9531.0              | 73185               | 2.439 | 0.031          | 0.162           |
| 25         | 12.920              | 0.001803 | 0.0323 | 2,536.11  | 34.670  | 38480.2             | 279196              | 7.923 | 0.031          | 0.189           |
| 26         | 12.721              | 0.00728  | 0.0327 | 2,531.71  | 34.987  | 39786.0             | 281750              | 8.228 | 0.031          | 0.189           |
| 27         | 12.548              | 0.014192 | 0.0333 | 2,523.42  | 34.577  | 39480.1             | 278446              | 8.216 | 0.031          | 0.189           |
| 28         | 12.822              | 0.019808 | 0.0327 | 2,600.11  | 34.997  | 40223.7             | 281833              | 8.413 | 0.031          | 0.190           |
| 29         | 13.199              | 0.027693 | 0.0320 | 2,698.72  | 35.529  | 41597.0             | 286112              | 8.767 | 0.031          | 0.193           |
| 230        | 13.041              | 0.035252 | 0.0325 | 2,694.11  | 35.523  | 41443.6             | 286063              | 8.797 | 0.031          | 0.191           |
| 31         | 13.091              | 0.040224 | 0.0325 | 2,717.32  | 35.523  | 41455.0             | 286064              | 8.843 | 0.031          | 0.191           |
| 32         | 13.222              | 0.04704  | 0.0324 | 2,761.49  | 35.746  | 41440.7             | 287859              | 8.900 | 0.031          | 0.190           |

Appendix D: Single- and two-phase calculated data (continued).

Channel C2: Argon gas tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.730 Hyd. Diameter ( $\mu\text{m}$ ): 207.01

Width ( $\mu\text{m}$ ): 190.37 Channel Length (m): 0.0635

| Data Point |         |        |          |         | Heat Trans.         |                     | Nu       | Uncertainty |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|----------|-------------|-------|
|            | Re      | f      | Velocity | Q       | coeff.              | Heat Flux           |          | U-f         | U-Nu  |
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |          |             |       |
| 1          | 53.8    | 1.4968 | 3.51     | 0.0004  | 0.235               | 3.33                | 0.002683 | 0.031       | 0.957 |
| 2          | 284.0   | 0.3274 | 16.07    | 0.0096  | 5.459               | 72.37               | 0.062066 | 0.031       | 0.246 |
| 3          | 638.8   | 0.1505 | 30.83    | 0.0279  | 15.802              | 209.83              | 0.179611 | 0.031       | 0.198 |
| 4          | 1.006.4 | 0.1012 | 42.67    | 0.0684  | 41.949              | 514.47              | 0.475537 | 0.031       | 0.145 |
| 5          | 1.344.4 | 0.0866 | 50.07    | 0.1116  | 71.580              | 839.39              | 0.810644 | 0.031       | 0.131 |
| 6          | 1.745.8 | 0.0754 | 56.93    | 0.1619  | 105.988             | 1217.75             | 1.200066 | 0.031       | 0.125 |
| 7          | 2.085.6 | 0.0739 | 59.96    | 0.2059  | 136.091             | 1548.50             | 1.540876 | 0.031       | 0.123 |
| 8          | 2.427.3 | 0.0728 | 62.15    | 0.2575  | 174.170             | 1936.70             | 1.971372 | 0.031       | 0.121 |
| 9          | 2.735.8 | 0.0688 | 64.79    | 0.3208  | 229.653             | 2413.21             | 2.596582 | 0.031       | 0.121 |
| 10         | 3.069.2 | 0.0648 | 67.41    | 0.3790  | 281.691             | 2851.02             | 3.183585 | 0.031       | 0.123 |
| 11         | 3.373.1 | 0.0616 | 69.43    | 0.4291  | 324.999             | 3227.91             | 3.673283 | 0.031       | 0.123 |
| 12         | 3.657.3 | 0.0586 | 71.20    | 0.4715  | 365.051             | 3546.85             | 4.125885 | 0.031       | 0.125 |
| 13         | 3.936.6 | 0.0561 | 72.70    | 0.5152  | 405.323             | 3875.88             | 4.581664 | 0.031       | 0.127 |
| 14         | 4.232.5 | 0.0538 | 74.12    | 0.5639  | 455.135             | 4241.80             | 5.147022 | 0.031       | 0.129 |
| 15         | 4.469.1 | 0.0501 | 76.16    | 0.6049  | 493.993             | 4549.96             | 5.587245 | 0.031       | 0.130 |
| 16         | 4.717.4 | 0.0478 | 77.44    | 0.6537  | 544.094             | 4917.17             | 6.155084 | 0.031       | 0.131 |
| 17         | 4.961.1 | 0.0458 | 78.58    | 0.7050  | 598.279             | 5303.08             | 6.769494 | 0.031       | 0.133 |
| 18         | 5.176.8 | 0.0441 | 79.44    | 0.7527  | 652.223             | 5662.27             | 7.381554 | 0.031       | 0.135 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C2: Helium gas tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.730

Hyd. Diameter ( $\mu\text{m}$ ): 207.01

Width ( $\mu\text{m}$ ): 190.37

Channel Length (m): 0.0635

| Data Point | Re    | f       | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   |                                  | Nu        | Uncertainty |             |
|------------|-------|---------|-------------------|--------------|-------------------------------|----------------------------------|-----------|-------------|-------------|
|            |       |         |                   |              | coeff.<br>W/m <sup>2</sup> -K | Heat Flux<br>(W/m <sup>2</sup> ) |           | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 5.6   | 14.0952 | 3.16              | 0.0004       | 0.352                         | 3.05                             | 0.0004753 | 0.031       | 0.948       |
| 2          | 30.7  | 3.0777  | 15.05             | 0.0017       | 1.147                         | 13.03                            | 0.0015476 | 0.031       | 1.189       |
| 3          | 77.3  | 1.2372  | 32.34             | 0.0279       | 20.048                        | 210.19                           | 0.0268562 | 0.031       | 0.208       |
| 4          | 123.9 | 0.7973  | 45.51             | 0.0489       | 33.162                        | 367.81                           | 0.0443897 | 0.031       | 0.190       |
| 5          | 166.5 | 0.5720  | 56.53             | 0.0766       | 50.230                        | 576.04                           | 0.0671842 | 0.031       | 0.167       |
| 6          | 218.1 | 0.4379  | 67.77             | 0.1272       | 88.634                        | 957.11                           | 0.1182625 | 0.031       | 0.146       |
| 7          | 266.6 | 0.3604  | 76.83             | 0.1571       | 108.513                       | 1181.78                          | 0.1447691 | 0.031       | 0.144       |
| 8          | 324.1 | 0.2999  | 85.89             | 0.1219       | 73.595                        | 916.98                           | 0.0985731 | 0.031       | 0.187       |
| 9          | 370.8 | 0.2626  | 92.90             | 0.1428       | 87.967                        | 1074.40                          | 0.1177945 | 0.031       | 0.183       |
| 10         | 417.3 | 0.2315  | 100.06            | 0.2567       | 185.835                       | 1931.25                          | 0.2476487 | 0.031       | 0.141       |
| 11         | 475.6 | 0.2023  | 108.01            | 0.3171       | 245.024                       | 2385.48                          | 0.3259174 | 0.031       | 0.140       |
| 12         | 526.7 | 0.1768  | 114.21            | 0.3341       | 277.058                       | 2513.34                          | 0.3718284 | 0.031       | 0.148       |
| 13         | 581.7 | 0.1599  | 120.47            | 0.3824       | 324.296                       | 2876.20                          | 0.4346357 | 0.031       | 0.147       |
| 14         | 634.3 | 0.1458  | 126.03            | 0.4035       | 337.260                       | 3034.93                          | 0.4520013 | 0.031       | 0.148       |
| 15         | 686.7 | 0.1345  | 130.89            | 0.4514       | 383.936                       | 3395.24                          | 0.5142531 | 0.031       | 0.147       |
| 16         | 738.3 | 0.1246  | 135.55            | 0.5027       | 436.072                       | 3781.83                          | 0.5837435 | 0.031       | 0.147       |
| 17         | 796.9 | 0.1142  | 141.00            | 0.5575       | 494.975                       | 4193.43                          | 0.6623978 | 0.031       | 0.147       |
| 18         | 853.2 | 0.1054  | 145.90            | 0.6114       | 554.161                       | 4599.01                          | 0.7414481 | 0.031       | 0.148       |

Appendix D: Single- and two-phase calculated data (continued).

Channel C2: Nitrogen gas tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.730 Hyd. Diameter ( $\mu\text{m}$ ): 207.01

Width ( $\mu\text{m}$ ): 190.37 Channel Length (m): 0.0635

| Data Point |         |        |          |         | Heat Trans.         |                     | Nu      | Uncertainty |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|---------|-------------|-------|
|            | Re      | f      | Velocity | Q       | coeff.              | Heat Flux           |         | U-f         | U-Nu  |
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |         | (%)         | (%)   |
| 1          | 44.5    | 1.3940 | 3.26     | 0.00028 | 0.164               | 2.09                | 0.00129 | 0.031       | 1.968 |
| 2          | 166.5   | 0.5681 | 11.30    | 0.0062  | 3.447               | 46.99               | 0.027   | 0.031       | 0.338 |
| 3          | 417.2   | 0.2353 | 24.95    | 0.0233  | 13.091              | 175.55              | 0.102   | 0.031       | 0.235 |
| 4          | 662.8   | 0.1532 | 35.92    | 0.0569  | 34.004              | 428.10              | 0.264   | 0.031       | 0.167 |
| 5          | 876.7   | 0.1238 | 43.56    | 0.0893  | 55.025              | 671.70              | 0.427   | 0.031       | 0.149 |
| 6          | 1,126.4 | 0.0986 | 51.69    | 0.1309  | 82.896              | 984.34              | 0.643   | 0.031       | 0.139 |
| 7          | 1,341.8 | 0.0854 | 57.63    | 0.1708  | 110.460             | 1284.94             | 0.857   | 0.031       | 0.133 |
| 8          | 1,612.8 | 0.0763 | 63.52    | 0.2213  | 144.945             | 1664.59             | 1.125   | 0.031       | 0.129 |
| 9          | 1,816.3 | 0.0721 | 66.90    | 0.2672  | 178.974             | 2010.31             | 1.388   | 0.031       | 0.126 |
| 10         | 2,030.3 | 0.0717 | 68.79    | 0.3090  | 207.284             | 2324.78             | 1.609   | 0.031       | 0.125 |
| 11         | 2,255.6 | 0.0723 | 70.03    | 0.3627  | 247.416             | 2728.51             | 1.921   | 0.031       | 0.123 |
| 12         | 2,464.1 | 0.0694 | 72.18    | 0.4365  | 318.576             | 3283.34             | 2.470   | 0.031       | 0.124 |
| 13         | 2,660.9 | 0.0664 | 74.11    | 0.5022  | 379.942             | 3777.58             | 2.945   | 0.031       | 0.124 |
| 14         | 2,876.1 | 0.0639 | 75.86    | 0.5701  | 441.647             | 4288.83             | 3.423   | 0.031       | 0.125 |
| 15         | 3,063.4 | 0.0607 | 77.61    | 0.6203  | 490.152             | 4665.83             | 3.799   | 0.031       | 0.126 |
| 16         | 3,270.3 | 0.0580 | 79.26    | 0.6761  | 541.519             | 5086.12             | 4.198   | 0.031       | 0.127 |
| 17         | 3,458.3 | 0.0557 | 80.58    | 0.7235  | 595.438             | 5442.12             | 4.616   | 0.031       | 0.129 |
| 18         | 3,640.2 | 0.0536 | 81.77    | 0.7706  | 648.743             | 5796.80             | 5.030   | 0.031       | 0.131 |

# Appendix D: Single- and two-phase calculated data (continued).

Channel C2: Water tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.730Hyd. Diameter ( $\mu\text{m}$ ): 207.01Width ( $\mu\text{m}$ ): 190.37

Channel Length (m): 0.0635

| Data Point | Re       | f      | Velocity | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|----------|--------|----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |          |        |          |         |                     |                     |        | U-f         | U_Nu  |
|            |          |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 551.40   | 0.1402 | 2.26     | 13.773  | 14772.61            | 103606              | 4.917  | 0.031       | 0.171 |
| 2          | 758.47   | 0.1163 | 3.08     | 20.396  | 18342.2             | 153428              | 6.099  | 0.031       | 0.148 |
| 3          | 959.11   | 0.0981 | 3.87     | 26.457  | 21498.35            | 199023              | 7.143  | 0.031       | 0.137 |
| 4          | 1,194.11 | 0.0798 | 4.80     | 32.307  | 24431.23            | 243026              | 8.114  | 0.031       | 0.132 |
| 5          | 1,296.19 | 0.0791 | 5.23     | 32.999  | 28918.3             | 248227              | 9.607  | 0.031       | 0.147 |
| 6          | 1,467.33 | 0.0732 | 5.85     | 39.304  | 32107.47            | 295659              | 10.654 | 0.031       | 0.138 |
| 7          | 1,618.07 | 0.0709 | 6.39     | 45.759  | 38739.26            | 344216              | 12.839 | 0.031       | 0.138 |
| 8          | 1,743.94 | 0.0704 | 6.77     | 52.297  | 44186.04            | 393399              | 14.618 | 0.031       | 0.135 |
| 9          | 1,801.99 | 0.0747 | 6.89     | 57.547  | 48399.02            | 432893              | 15.984 | 0.031       | 0.132 |
| 10         | 1,890.38 | 0.0753 | 7.22     | 58.305  | 52929.43            | 438594              | 17.479 | 0.031       | 0.140 |
| 11         | 1,956.88 | 0.0781 | 7.34     | 65.342  | 55551.08            | 491525              | 18.308 | 0.031       | 0.131 |
| 12         | 2,058.55 | 0.0766 | 7.72     | 66.700  | 60625.72            | 501745              | 19.979 | 0.031       | 0.138 |
| 13         | 2,154.26 | 0.0745 | 8.10     | 68.135  | 65015.79            | 512537              | 21.432 | 0.031       | 0.144 |
| 14         | 2,251.24 | 0.0743 | 8.51     | 68.621  | 69165.71            | 516195              | 22.812 | 0.031       | 0.152 |
| 15         | 2,329.78 | 0.0775 | 8.73     | 73.560  | 70735.6             | 553348              | 23.308 | 0.031       | 0.145 |
| 16         | 2,500.38 | 0.0723 | 9.39     | 76.571  | 76327.6             | 575999              | 25.158 | 0.031       | 0.150 |
| 17         | 2,556.20 | 0.0731 | 9.63     | 75.912  | 78204.2             | 571041              | 25.784 | 0.031       | 0.155 |
| 18         | 2,744.80 | 0.0696 | 10.41    | 77.704  | 84287.04            | 584516              | 27.808 | 0.031       | 0.163 |
| 19         | 2,901.66 | 0.0681 | 11.06    | 78.152  | 88873.67            | 587887              | 29.338 | 0.031       | 0.172 |
| 20         | 3,022.74 | 0.0709 | 11.44    | 83.882  | 89456.6             | 630990              | 29.507 | 0.031       | 0.162 |
| 21         | 2,591.73 | 0.0742 | 10.04    | 63.528  | 88701.25            | 477884              | 29.336 | 0.031       | 0.206 |
| 22         | 2,821.63 | 0.0743 | 11.03    | 64.062  | 97672.05            | 481896              | 32.333 | 0.031       | 0.225 |
| 23         | 3,104.54 | 0.0712 | 12.21    | 65.603  | 108344.8            | 493489              | 35.889 | 0.031       | 0.244 |
| 24         | 3,389.45 | 0.0680 | 13.40    | 67.633  | 119119.8            | 508761              | 39.478 | 0.031       | 0.260 |
| 25         | 3,622.32 | 0.0663 | 14.36    | 68.873  | 128312.2            | 518093              | 42.539 | 0.031       | 0.274 |
| 26         | 3,775.56 | 0.0680 | 15.02    | 68.974  | 135026.4            | 518848              | 44.781 | 0.031       | 0.288 |
| 27         | 3,987.14 | 0.0662 | 15.91    | 70.327  | 144549              | 529025              | 47.954 | 0.031       | 0.302 |
| 28         | 4,193.15 | 0.0643 | 16.79    | 71.845  | 152991.8            | 540445              | 50.771 | 0.031       | 0.312 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C2: Water-argon tests.      Number of channels:      3  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      263.730      Hyd. Diameter ( $\mu\text{m}$ ):      207.01  
 Width ( $\mu\text{m}$ ):      190.37      Channel Length (m):      0.0635

| Data Point | G                 | x        | f      | Two-phase | Q       | h - overall             | Heat Flux        | Nu     | Uncertainty |       |
|------------|-------------------|----------|--------|-----------|---------|-------------------------|------------------|--------|-------------|-------|
|            | $\text{kg/s-m}^2$ | Quality  |        | Re-avg    | (Watts) | $\text{W/m}^2\text{-K}$ | $(\text{W/m}^2)$ |        | U f         | U Nu  |
|            |                   |          |        |           |         |                         |                  |        | (%)         | (%)   |
| 1          | 1.112             | 0.02509  | 0.2009 | 436.25    | 11.181  | 12809.2                 | 84111            | 4.188  | 0.031       | 0.164 |
| 2          | 1.497             | 0.074837 | 0.1597 | 578.81    | 14.452  | 16963.2                 | 108711           | 5.557  | 0.031       | 0.168 |
| 3          | 1.408             | 0.144303 | 0.1856 | 538.74    | 12.873  | 15859.8                 | 96839            | 5.205  | 0.031       | 0.176 |
| 4          | 1.124             | 0.301427 | 0.2726 | 449.90    | 11.767  | 12077.8                 | 88517            | 3.951  | 0.031       | 0.148 |
| 5          | 2.328             | 0.013916 | 0.1055 | 821.71    | 14.882  | 25632.6                 | 111945           | 8.473  | 0.031       | 0.246 |
| 6          | 2.380             | 0.045749 | 0.1008 | 888.38    | 21.920  | 23530.3                 | 164890           | 7.734  | 0.031       | 0.157 |
| 7          | 2.353             | 0.085078 | 0.1054 | 886.69    | 22.374  | 24644.7                 | 168304           | 8.096  | 0.031       | 0.159 |
| 8          | 1.862             | 0.153367 | 0.1408 | 717.68    | 19.306  | 20966.1                 | 145225           | 6.876  | 0.031       | 0.156 |
| 9          | 3.188             | 0.011032 | 0.0728 | 1,187.20  | 29.903  | 26079.2                 | 224942           | 8.571  | 0.031       | 0.132 |
| 10         | 3.140             | 0.035546 | 0.0744 | 1,191.36  | 31.413  | 27686.5                 | 236304           | 9.083  | 0.031       | 0.132 |
| 11         | 2.747             | 0.073375 | 0.0868 | 1,063.12  | 29.527  | 28460.7                 | 222117           | 9.321  | 0.031       | 0.140 |
| 12         | 3.963             | 0.008236 | 0.0596 | 1,444.89  | 31.531  | 29579.6                 | 237188           | 9.743  | 0.031       | 0.145 |
| 13         | 3.630             | 0.03216  | 0.0650 | 1,358.91  | 32.759  | 33996.3                 | 246425           | 11.169 | 0.031       | 0.153 |
| 14         | 3.237             | 0.062607 | 0.0739 | 1,233.58  | 31.577  | 33415.0                 | 237531           | 10.961 | 0.031       | 0.153 |
| 15         | 10.004            | 0.031524 | 0.0444 | 3,550.31  | 68.421  | 74508.3                 | 514685           | 24.616 | 0.031       | 0.168 |
| 16         | 10.116            | 0.049216 | 0.0444 | 3,595.46  | 69.960  | 75581.6                 | 526268           | 24.971 | 0.031       | 0.166 |
| 17         | 9.368             | 0.064688 | 0.0454 | 3,350.98  | 68.564  | 70545.3                 | 515766           | 23.294 | 0.031       | 0.158 |
| 18         | 9.658             | 0.067482 | 0.0451 | 3,441.00  | 69.716  | 73334.7                 | 524430           | 24.226 | 0.031       | 0.162 |
| 19         | 9.580             | 0.077047 | 0.0454 | 3,411.22  | 69.671  | 73254.3                 | 524093           | 24.203 | 0.031       | 0.161 |
| 20         | 10.833            | 0.006126 | 0.0434 | 3,779.19  | 67.247  | 79413.9                 | 505860           | 26.276 | 0.031       | 0.183 |
| 21         | 10.799            | 0.011149 | 0.0435 | 3,775.25  | 68.014  | 79940.0                 | 511629           | 26.446 | 0.031       | 0.181 |
| 22         | 11.396            | 0.021555 | 0.0430 | 3,963.46  | 68.398  | 83264.9                 | 514516           | 27.564 | 0.031       | 0.188 |
| 23         | 11.378            | 0.038684 | 0.0432 | 3,966.72  | 69.390  | 84335.3                 | 521980           | 27.916 | 0.031       | 0.187 |
| 24         | 10.858            | 0.052633 | 0.0438 | 3,806.93  | 70.139  | 81253.3                 | 527615           | 26.883 | 0.031       | 0.178 |
| 25         | 10.692            | 0.058851 | 0.0441 | 3,752.14  | 69.977  | 80263.9                 | 526391           | 26.555 | 0.031       | 0.176 |
| 26         | 10.300            | 0.073213 | 0.0446 | 3,625.48  | 69.420  | 77528.1                 | 522206           | 25.645 | 0.031       | 0.172 |
| 27         | 1.620             | 0.183173 | 0.1898 | 552.19    | 10.352  | 21446.2                 | 77870            | 7.128  | 0.031       | 0.290 |
| 28         | 1.590             | 0.220733 | 0.2026 | 542.29    | 10.174  | 21423.8                 | 76533            | 7.123  | 0.031       | 0.294 |
| 29         | 2.051             | 0.213258 | 0.1555 | 699.88    | 12.963  | 27237.6                 | 97509            | 9.054  | 0.031       | 0.294 |
| 30         | 1.719             | 0.270832 | 0.2004 | 586.28    | 10.881  | 24915.3                 | 81853            | 8.288  | 0.031       | 0.318 |
| 31         | 1.918             | 0.269597 | 0.1793 | 654.24    | 12.109  | 26706.6                 | 91087            | 8.884  | 0.031       | 0.307 |
| 32         | 1.694             | 0.341368 | 0.2246 | 579.54    | 10.872  | 25304.6                 | 81781            | 8.421  | 0.031       | 0.322 |
| 33         | 2.072             | 0.309509 | 0.1771 | 700.56    | 12.468  | 32416.4                 | 93790            | 10.797 | 0.031       | 0.359 |
| 34         | 1.944             | 0.361954 | 0.2047 | 656.56    | 11.546  | 28347.8                 | 86853            | 9.449  | 0.031       | 0.341 |
| 35         | 1.934             | 0.392685 | 0.2163 | 652.94    | 11.465  | 26225.7                 | 86246            | 8.744  | 0.031       | 0.319 |



# Appendix D: Single- and two-phase calculated data (continued).

Channel C2: Water-helium tests.

Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.730Hyd. Diameter ( $\mu\text{m}$ ): 207.01Width ( $\mu\text{m}$ ): 190.37

Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | U f (%)     | U Nu (%) |
| 1          | 2335.125            | 0.00133  | 0.1026 | 833.65    | 16.948  | 22544.4             | 127488              | 7.442  | 0.031       | 0.194    |
| 2          | 2051.618            | 0.012572 | 0.1159 | 746.93    | 16.797  | 21708.7             | 126354              | 7.152  | 0.031       | 0.186    |
| 3          | 1544.808            | 0.031375 | 0.1554 | 567.77    | 13.289  | 17377.2             | 99963               | 5.720  | 0.031       | 0.187    |
| 4          | 1320.407            | 0.056688 | 0.1820 | 497.88    | 12.595  | 14337.9             | 94745               | 4.708  | 0.031       | 0.164    |
| 5          | 2873.113            | 0.001043 | 0.0765 | 1,118.19  | 32.491  | 23220.3             | 244410              | 7.595  | 0.031       | 0.109    |
| 6          | 2195.576            | 0.011701 | 0.0995 | 868.63    | 25.268  | 20301.3             | 190079              | 6.629  | 0.031       | 0.119    |
| 7          | 2002.183            | 0.024408 | 0.1075 | 815.23    | 25.316  | 19897.0             | 190440              | 6.478  | 0.031       | 0.115    |
| 8          | 1411.218            | 0.047842 | 0.1533 | 585.77    | 18.908  | 14518.7             | 142233              | 4.718  | 0.031       | 0.112    |
| 9          | 3911.848            | 0.000824 | 0.0597 | 1,431.35  | 30.892  | 28579.1             | 232380              | 9.409  | 0.031       | 0.144    |
| 10         | 3329.527            | 0.007698 | 0.0687 | 1,253.31  | 29.869  | 28678.0             | 224683              | 9.414  | 0.031       | 0.144    |
| 11         | 2703.382            | 0.017972 | 0.0841 | 1,034.58  | 26.253  | 26188.8             | 197486              | 8.582  | 0.031       | 0.146    |
| 12         | 10126.57            | 0.000349 | 0.0441 | 3,511.98  | 66.113  | 73790.4             | 497324              | 24.431 | 0.031       | 0.173    |
| 13         | 10045.39            | 0.000859 | 0.0442 | 3,497.89  | 65.291  | 73812.5             | 491144              | 24.428 | 0.031       | 0.175    |
| 14         | 10379.44            | 0.001848 | 0.0438 | 3,620.98  | 66.911  | 76191.3             | 503328              | 25.210 | 0.031       | 0.176    |
| 15         | 10195.35            | 0.00299  | 0.0440 | 3,563.23  | 65.860  | 74998.7             | 495426              | 24.811 | 0.031       | 0.176    |
| 16         | 10473.39            | 0.004304 | 0.0437 | 3,652.46  | 65.782  | 76752.6             | 494840              | 25.397 | 0.031       | 0.180    |
| 17         | 10127.64            | 0.005685 | 0.0441 | 3,540.22  | 64.494  | 73509.4             | 485151              | 24.317 | 0.031       | 0.177    |
| 18         | 10275.68            | 0.006471 | 0.0440 | 3,585.01  | 64.762  | 75661.9             | 487164              | 25.034 | 0.031       | 0.180    |
| 19         | 10435.3             | 0.007151 | 0.0438 | 3,643.87  | 66.372  | 77039.8             | 499273              | 25.488 | 0.031       | 0.171    |

Appendix D: Single- and two-phase calculated data (continued).

Channel C2: Water-Nitrogen tests. Number of channels: 3

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 263.730 Hyd. Diameter ( $\mu\text{m}$ ): 207.01

Width ( $\mu\text{m}$ ): 190.37 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |                     |          |        |           |         |                     |                     |        | U f         | U Nu  |
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 1.374               | 0.005791 | 0.1695 | 509.95    | 13.321  | 13678.6             | 100208              | 4.525  | 0.031       | 0.299 |
| 2          | 1.534               | 0.010093 | 0.1520 | 573.51    | 14.681  | 14531.9             | 110433              | 4.825  | 0.031       | 0.290 |
| 3          | 1.309               | 0.053491 | 0.1803 | 528.20    | 14.256  | 12986.3             | 107237              | 4.485  | 0.031       | 0.264 |
| 4          | 1.167               | 0.121811 | 0.2127 | 518.62    | 12.819  | 11228.9             | 96433               | 4.155  | 0.031       | 0.253 |
| 5          | 1.578               | 0.136169 | 0.1657 | 687.61    | 14.834  | 16555.9             | 111584              | 6.246  | 0.031       | 0.318 |
| 6          | 2.839               | 0.002623 | 0.0849 | 1.011.03  | 23.501  | 21520.0             | 176785              | 7.126  | 0.031       | 0.281 |
| 7          | 2.899               | 0.005088 | 0.0822 | 1.049.59  | 25.427  | 23118.5             | 191268              | 7.662  | 0.031       | 0.276 |
| 8          | 2.363               | 0.030507 | 0.0997 | 911.36    | 24.641  | 21501.7             | 185359              | 7.275  | 0.031       | 0.257 |
| 9          | 2.234               | 0.063207 | 0.1064 | 913.45    | 24.867  | 21884.0             | 187056              | 7.630  | 0.031       | 0.255 |
| 10         | 1.828               | 0.119015 | 0.1336 | 820.23    | 21.482  | 18984.4             | 161596              | 6.993  | 0.031       | 0.253 |
| 11         | 4.824               | 0.001586 | 0.0506 | 1.692.98  | 35.883  | 27516.1             | 269924              | 9.115  | 0.031       | 0.256 |
| 12         | 4.526               | 0.003291 | 0.0530 | 1.621.64  | 36.269  | 28456.9             | 272830              | 9.423  | 0.031       | 0.254 |
| 13         | 3.917               | 0.019242 | 0.0601 | 1.477.79  | 37.214  | 35107.5             | 279941              | 11.761 | 0.031       | 0.279 |
| 14         | 3.290               | 0.042344 | 0.0715 | 1.300.21  | 34.038  | 34143.5             | 256044              | 11.672 | 0.031       | 0.289 |
| 15         | 2.699               | 0.078777 | 0.0869 | 1.154.62  | 32.268  | 28608.5             | 242732              | 10.104 | 0.031       | 0.254 |
| 16         | 5.835               | 0.001164 | 0.0410 | 2.087.63  | 46.531  | 40197.0             | 350022              | 13.282 | 0.031       | 0.272 |
| 17         | 5.513               | 0.002625 | 0.0427 | 2.010.40  | 46.797  | 41561.7             | 352024              | 13.727 | 0.031       | 0.273 |
| 18         | 4.600               | 0.016459 | 0.0500 | 1.764.32  | 46.706  | 44780.4             | 351340              | 14.930 | 0.031       | 0.280 |
| 19         | 3.773               | 0.039003 | 0.0599 | 1.541.19  | 44.884  | 40015.7             | 337631              | 13.581 | 0.031       | 0.256 |
| 20         | 10.131              | 0.007988 | 0.0441 | 3.588.65  | 65.840  | 74675.9             | 495276              | 24.879 | 0.031       | 0.350 |
| 21         | 10.260              | 0.010426 | 0.0439 | 3.650.58  | 66.806  | 75398.7             | 502538              | 25.173 | 0.031       | 0.348 |
| 22         | 10.382              | 0.019554 | 0.0439 | 3.725.20  | 66.771  | 75733.6             | 502281              | 25.511 | 0.031       | 0.350 |
| 23         | 9.833               | 0.030806 | 0.0446 | 3.582.04  | 64.913  | 71238.1             | 488298              | 24.252 | 0.031       | 0.339 |
| 24         | 10.152              | 0.032189 | 0.0443 | 3.694.54  | 65.906  | 73628.5             | 495772              | 25.105 | 0.031       | 0.344 |
| 25         | 10.137              | 0.036736 | 0.0443 | 3.707.07  | 66.278  | 73762.3             | 498571              | 25.263 | 0.031       | 0.343 |
| 26         | 11.759              | 0.007129 | 0.0426 | 4.113.91  | 69.011  | 85172.5             | 519130              | 28.386 | 0.031       | 0.382 |
| 27         | 11.286              | 0.00954  | 0.0430 | 3.969.55  | 67.045  | 81785.6             | 504342              | 27.312 | 0.031       | 0.378 |
| 28         | 11.871              | 0.018198 | 0.0425 | 4.209.62  | 69.473  | 85497.2             | 522603              | 28.792 | 0.031       | 0.381 |
| 29         | 11.322              | 0.026056 | 0.0431 | 4.062.48  | 68.460  | 82148.4             | 514985              | 27.865 | 0.031       | 0.370 |
| 30         | 11.077              | 0.028958 | 0.0434 | 3.988.10  | 67.374  | 80375.3             | 506812              | 27.339 | 0.031       | 0.368 |
| 31         | 11.390              | 0.030941 | 0.0431 | 4.098.51  | 68.730  | 82218.7             | 517015              | 28.028 | 0.031       | 0.369 |
| 32         | 2.010               | 0.114131 | 0.1433 | 757.26    | 10.420  | 24326.6             | 78380               | 9.077  | 0.031       | 0.655 |
| 33         | 1.727               | 0.141331 | 0.1714 | 673.27    | 8.978   | 21118.9             | 67535               | 8.115  | 0.031       | 0.658 |
| 34         | 1.593               | 0.164619 | 0.1906 | 638.94    | 8.255   | 19682.1             | 62097               | 7.761  | 0.031       | 0.666 |
| 35         | 1.539               | 0.180481 | 0.2005 | 630.66    | 8.067   | 18907.0             | 60685               | 7.590  | 0.031       | 0.654 |
| 36         | 1.518               | 0.192729 | 0.2061 | 631.92    | 7.954   | 18477.0             | 59830               | 7.523  | 0.031       | 0.648 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C3: Argon gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.30

Hyd. Diameter ( $\mu\text{m}$ ): 55.55

Width ( $\mu\text{m}$ ): 144.79

Channel Length (m): 0.0635

| Data Point | Re      | f      | Velocity | Q       | Heat Trans. coeff.  | Heat Flux           | Nu       | Uncertainty |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|----------|-------------|-------|
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |          | U-f         | U-Nu  |
| 1          | 23.0    | 2.5728 | 3.17     | 0.0001  | 0.081               | 0.88                | 0.000427 | 0.031       | 1.862 |
| 2          | 238.3   | 0.2341 | 23.64    | 0.0080  | 4.207               | 62.57               | 0.022108 | 0.031       | 0.284 |
| 3          | 438.2   | 0.1276 | 36.82    | 0.0237  | 11.905              | 185.47              | 0.062408 | 0.031       | 0.185 |
| 4          | 649.1   | 0.0841 | 48.62    | 0.0469  | 23.720              | 367.31              | 0.124087 | 0.031       | 0.147 |
| 5          | 827.2   | 0.0657 | 57.24    | 0.0716  | 36.799              | 560.73              | 0.192182 | 0.031       | 0.129 |
| 6          | 1.033.3 | 0.0529 | 65.97    | 0.1000  | 52.029              | 782.54              | 0.271469 | 0.031       | 0.121 |
| 7          | 1.249.1 | 0.0460 | 73.01    | 0.1343  | 70.996              | 1051.22             | 0.370164 | 0.031       | 0.114 |
| 8          | 1.465.3 | 0.0393 | 80.54    | 0.1685  | 90.292              | 1319.09             | 0.470596 | 0.031       | 0.111 |
| 9          | 1.644.1 | 0.0355 | 86.01    | 0.1997  | 108.360             | 1563.44             | 0.564650 | 0.031       | 0.108 |
| 10         | 1.819.9 | 0.0328 | 90.67    | 0.2314  | 126.120             | 1811.16             | 0.657126 | 0.031       | 0.106 |
| 11         | 2.038.5 | 0.0304 | 95.34    | 0.2438  | 127.098             | 1908.37             | 0.663358 | 0.031       | 0.109 |
| 12         | 2.266.6 | 0.0291 | 99.07    | 0.2833  | 154.147             | 2217.70             | 0.804670 | 0.031       | 0.109 |
| 13         | 2.548.0 | 0.0275 | 103.43   | 0.3347  | 188.855             | 2619.92             | 0.986149 | 0.031       | 0.109 |
| 14         | 2.783.4 | 0.0256 | 108.16   | 0.3824  | 216.240             | 2993.70             | 1.129602 | 0.031       | 0.107 |
| 15         | 3.019.5 | 0.0242 | 112.05   | 0.4353  | 248.078             | 3407.82             | 1.296257 | 0.031       | 0.106 |
| 16         | 3.265.1 | 0.0226 | 116.73   | 0.4938  | 278.566             | 3865.75             | 1.455689 | 0.031       | 0.104 |
| 17         | 3.480.0 | 0.0213 | 120.97   | 0.5460  | 328.302             | 4274.01             | 1.715531 | 0.031       | 0.106 |
| 18         | 3.723.6 | 0.0193 | 127.37   | 0.5974  | 365.422             | 4676.64             | 1.909577 | 0.031       | 0.107 |
| 19         | 3.970.8 | 0.0179 | 132.67   | 0.6559  | 408.406             | 5134.69             | 2.134301 | 0.031       | 0.107 |
| 20         | 4.173.4 | 0.0169 | 137.04   | 0.6978  | 442.499             | 5462.45             | 2.313306 | 0.031       | 0.108 |
| 21         | 4.388.8 | 0.0158 | 142.02   | 0.7528  | 485.628             | 5893.06             | 2.539338 | 0.031       | 0.108 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C3: Helium gas tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.30 Hyd. Diameter ( $\mu\text{m}$ ): 55.55

Width ( $\mu\text{m}$ ): 144.79 Channel Length (m): 0.0635

| Data Point |       |         |          |         | Heat Trans.         |                     |         |       |       |
|------------|-------|---------|----------|---------|---------------------|---------------------|---------|-------|-------|
|            | Re    | f       | Velocity | Q       | coeff.              | Heat Flux           | Nu      | U-f   | U-Nu  |
|            |       |         | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |         | (%)   | (%)   |
| 1          | 2.2   | 31.5231 | 3.27E-08 | 2.59    |                     |                     |         |       |       |
| 2          | 28.9  | 2.1990  | 4.26E-07 | 24.01   | 0.0030              | 1.858               | 23.63   | 0.031 | 0.737 |
| 3          | 68.2  | 0.9329  | 9.78E-07 | 43.99   | 0.0164              | 8.887               | 128.68  | 0.031 | 0.317 |
| 4          | 109.7 | 0.5799  | 1.55E-06 | 60.14   | 0.0475              | 26.622              | 371.88  | 0.031 | 0.185 |
| 5          | 152.8 | 0.3926  | 2.13E-06 | 75.73   | 0.0768              | 43.648              | 601.49  | 0.031 | 0.162 |
| 6          | 199.7 | 0.2946  | 2.74E-06 | 89.83   | 0.0944              | 52.422              | 739.24  | 0.031 | 0.168 |
| 7          | 242.2 | 0.2367  | 3.3E-06  | 102.12  | 0.1419              | 82.845              | 1110.50 | 0.031 | 0.143 |
| 8          | 287.5 | 0.1957  | 3.88E-06 | 114.01  | 0.1834              | 109.546             | 1436.04 | 0.031 | 0.135 |
| 9          | 334.1 | 0.1653  | 4.47E-06 | 125.58  | 0.2235              | 136.782             | 1749.37 | 0.031 | 0.132 |
| 10         | 378.3 | 0.1443  | 5.03E-06 | 135.71  | 0.2702              | 168.507             | 2115.54 | 0.031 | 0.127 |
| 11         | 427.4 | 0.1260  | 5.64E-06 | 146.50  | 0.3191              | 213.415             | 2498.20 | 0.031 | 0.127 |
| 12         | 473.0 | 0.1123  | 6.21E-06 | 156.26  | 0.3627              | 247.995             | 2838.86 | 0.031 | 0.126 |
| 13         | 523.6 | 0.1003  | 6.83E-06 | 166.45  | 0.4185              | 293.253             | 3275.75 | 0.031 | 0.125 |
| 14         | 569.8 | 0.0915  | 7.4E-06  | 175.44  | 0.4711              | 346.263             | 3687.71 | 0.031 | 0.126 |
| 15         | 618.2 | 0.0847  | 7.98E-06 | 183.28  | 0.5152              | 373.457             | 4032.89 | 0.031 | 0.124 |
| 16         | 669.7 | 0.0779  | 8.59E-06 | 191.98  | 0.5639              | 382.351             | 4413.89 | 0.031 | 0.119 |
| 17         | 716.5 | 0.0725  | 9.15E-06 | 199.66  | 0.6150              | 459.044             | 4814.35 | 0.031 | 0.124 |
| 18         | 768.1 | 0.0673  | 9.76E-06 | 207.89  | 0.6680              | 502.371             | 5228.94 | 0.031 | 0.124 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C3: Nitrogen gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.30

Hyd. Diameter ( $\mu\text{m}$ ): 55.55

Width ( $\mu\text{m}$ ): 144.79

Channel Length (m): 0.0635

| Data Point | Heat Trans. |        |                   |              |                               |                                  |         |  | Uncertainty |             |
|------------|-------------|--------|-------------------|--------------|-------------------------------|----------------------------------|---------|--|-------------|-------------|
|            | Re          | f      | Velocity<br>(m/s) | Q<br>(Watts) | coeff.<br>W/m <sup>2</sup> -K | Heat Flux<br>(W/m <sup>2</sup> ) | Nu      |  | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 13.7        | 5.8976 | 2.07              | 0.00002      | 0.018                         | 0.18                             | 0.00007 |  | 0.031       | 8.572       |
| 2          | 136.3       | 0.6298 | 15.67             | 0.0044       | 3.227                         | 34.40                            | 0.012   |  | 0.031       | 0.452       |
| 3          | 270.6       | 0.3125 | 26.39             | 0.0104       | 5.346                         | 81.32                            | 0.020   |  | 0.031       | 0.381       |
| 4          | 417.6       | 0.1965 | 36.30             | 0.0306       | 14.753                        | 239.55                           | 0.054   |  | 0.031       | 0.209       |
| 5          | 538.7       | 0.1485 | 43.60             | 0.0515       | 24.020                        | 402.95                           | 0.087   |  | 0.031       | 0.166       |
| 6          | 684.8       | 0.1145 | 51.60             | 0.0760       | 36.039                        | 594.86                           | 0.130   |  | 0.031       | 0.148       |
| 7          | 804.2       | 0.0965 | 57.62             | 0.1062       | 51.895                        | 831.49                           | 0.187   |  | 0.031       | 0.131       |
| 8          | 942.2       | 0.0809 | 64.23             | 0.1341       | 66.135                        | 1049.76                          | 0.238   |  | 0.031       | 0.125       |
| 9          | 1,069.9     | 0.0691 | 70.46             | 0.1628       | 80.462                        | 1274.17                          | 0.289   |  | 0.031       | 0.120       |
| 10         | 1,202.8     | 0.0584 | 77.36             | 0.1899       | 94.347                        | 1486.54                          | 0.338   |  | 0.031       | 0.117       |
| 11         | 1,334.3     | 0.0488 | 84.94             | 0.2154       | 107.934                       | 1686.55                          | 0.387   |  | 0.031       | 0.116       |
| 12         | 1,518.1     | 0.0415 | 93.23             | 0.2512       | 126.332                       | 1966.04                          | 0.453   |  | 0.031       | 0.114       |
| 13         | 1,700.2     | 0.0365 | 100.58            | 0.3020       | 153.837                       | 2363.86                          | 0.551   |  | 0.031       | 0.110       |
| 14         | 1,879.6     | 0.0336 | 106.10            | 0.3261       | 177.493                       | 2553.05                          | 0.636   |  | 0.031       | 0.115       |
| 15         | 2,055.4     | 0.0317 | 110.56            | 0.3509       | 196.743                       | 2746.62                          | 0.705   |  | 0.031       | 0.118       |
| 16         | 2,210.7     | 0.0305 | 113.96            | 0.3930       | 225.913                       | 3076.72                          | 0.810   |  | 0.031       | 0.117       |
| 17         | 2,379.3     | 0.0297 | 116.89            | 0.4519       | 269.163                       | 3537.78                          | 0.965   |  | 0.031       | 0.116       |
| 18         | 2,529.2     | 0.0289 | 119.57            | 0.5024       | 306.761                       | 3932.85                          | 1.099   |  | 0.031       | 0.115       |
| 19         | 2,685.9     | 0.0285 | 121.51            | 0.5472       | 338.194                       | 4283.28                          | 1.213   |  | 0.031       | 0.115       |
| 20         | 2,830.2     | 0.0280 | 123.50            | 0.6004       | 381.194                       | 4700.03                          | 1.367   |  | 0.031       | 0.115       |
| 21         | 2,970.2     | 0.0273 | 125.64            | 0.6351       | 441.417                       | 4971.35                          | 1.583   |  | 0.031       | 0.121       |

Appendix D: Single- and two-phase calculated data (continued).

Channel C3: Water tests. Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.30 Hyd. Diameter ( $\mu\text{m}$ ): 55.55

Width ( $\mu\text{m}$ ): 144.79 Channel Length (m): 0.0635

| Data Point | Re       | f      | Velocity | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|----------|--------|----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |          |        |          |         |                     |                     |        | U-f         | U_Nu  |
|            |          |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 254.69   | 0.2071 | 2.16     | 9.591   | 8468.662            | 75076               | 1.294  | 0.031       | 0.133 |
| 2          | 341.83   | 0.1257 | 2.94     | 11.646  | 12234.65            | 91167               | 1.873  | 0.031       | 0.155 |
| 3          | 385.83   | 0.1076 | 3.30     | 13.793  | 13767.28            | 107970              | 2.106  | 0.031       | 0.147 |
| 4          | 468.67   | 0.0777 | 4.08     | 14.930  | 16558.81            | 116870              | 2.538  | 0.031       | 0.165 |
| 5          | 551.18   | 0.0597 | 4.85     | 16.045  | 19521.7             | 125605              | 2.996  | 0.031       | 0.181 |
| 6          | 644.23   | 0.0474 | 5.65     | 18.901  | 21001.17            | 147962              | 3.222  | 0.031       | 0.169 |
| 7          | 763.63   | 0.0370 | 6.61     | 23.054  | 23742.47            | 180468              | 3.637  | 0.031       | 0.158 |
| 8          | 854.14   | 0.0323 | 7.29     | 27.039  | 26285.4             | 211666              | 4.020  | 0.031       | 0.149 |
| 9          | 1,000.06 | 0.0255 | 8.44     | 33.672  | 30974.09            | 263591              | 4.731  | 0.031       | 0.141 |
| 10         | 1,098.57 | 0.0229 | 9.17     | 38.108  | 33916.48            | 298314              | 5.174  | 0.031       | 0.136 |
| 11         | 1,182.92 | 0.0209 | 9.88     | 39.485  | 38567.01            | 309096              | 5.885  | 0.031       | 0.147 |
| 12         | 1,337.81 | 0.0174 | 11.08    | 47.330  | 47155.65            | 370504              | 7.188  | 0.031       | 0.147 |
| 13         | 1,438.24 | 0.0158 | 11.95    | 48.405  | 50899.79            | 378922              | 7.761  | 0.031       | 0.154 |
| 14         | 1,508.83 | 0.0151 | 12.59    | 48.099  | 51655.53            | 376527              | 7.881  | 0.031       | 0.159 |
| 15         | 1,589.52 | 0.0139 | 13.31    | 48.488  | 53528.29            | 379570              | 8.169  | 0.031       | 0.164 |
| 16         | 1,697.54 | 0.0129 | 14.09    | 53.361  | 57251.29            | 417716              | 8.729  | 0.031       | 0.159 |
| 17         | 1,946.58 | 0.0107 | 16.11    | 61.544  | 66809.04            | 481774              | 10.182 | 0.031       | 0.160 |
| 18         | 1,501.90 | 0.0140 | 13.56    | 36.140  | 38767.2             | 282911              | 5.966  | 0.031       | 0.178 |
| 19         | 1,857.84 | 0.0109 | 16.84    | 37.719  | 49054.06            | 295271              | 7.552  | 0.031       | 0.214 |
| 20         | 2,144.59 | 0.0096 | 19.39    | 38.184  | 58684.94            | 298906              | 9.032  | 0.031       | 0.249 |

Appendix D: Single- and two-phase calculated data (continued).

Channel C3: Water-argon tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 71.30

Hyd. Diameter ( $\mu\text{m}$ ): 55.55

Width ( $\mu\text{m}$ ): 144.79

Channel Length (m): 0.0635

| Data Point | G                 | x        | f      | Two-phase | Q       | h - overall             | Heat Flux        | Nu    | Uncertainty |          |
|------------|-------------------|----------|--------|-----------|---------|-------------------------|------------------|-------|-------------|----------|
|            | $\text{kg/s-m}^2$ | Quality  |        | Re-avg    | (Watts) | $\text{W/m}^2\text{-K}$ | $(\text{W/m}^2)$ |       | U f (%)     | U Nu (%) |
| 1          | 2.302             | 0.012523 | 0.2361 | 395.25    | 8.571   | 9829.1                  | 67095            | 1.503 | 0.031       | 0.169    |
| 2          | 2.615             | 0.049224 | 0.2101 | 461.41    | 10.116  | 12101.4                 | 79191            | 1.846 | 0.031       | 0.173    |
| 3          | 2.944             | 0.080939 | 0.1934 | 518.86    | 11.266  | 13003.9                 | 88192            | 1.985 | 0.031       | 0.169    |
| 4          | 2.582             | 0.143713 | 0.2371 | 454.43    | 9.703   | 11044.2                 | 75956            | 1.687 | 0.031       | 0.167    |
| 5          | 3.637             | 0.007007 | 0.1496 | 620.26    | 12.226  | 14409.2                 | 95708            | 2.205 | 0.031       | 0.177    |
| 6          | 3.729             | 0.036448 | 0.1460 | 655.30    | 12.767  | 14579.5                 | 99940            | 2.225 | 0.031       | 0.172    |
| 7          | 3.240             | 0.074612 | 0.1735 | 574.26    | 11.807  | 12620.8                 | 92425            | 1.925 | 0.031       | 0.161    |
| 8          | 3.343             | 0.111996 | 0.1735 | 598.69    | 13.203  | 13066.3                 | 103354           | 1.991 | 0.031       | 0.149    |
| 9          | 5.054             | 0.00579  | 0.1064 | 870.89    | 16.188  | 18841.9                 | 126718           | 2.880 | 0.031       | 0.177    |
| 10         | 4.451             | 0.031121 | 0.1219 | 780.34    | 15.703  | 17194.1                 | 122927           | 2.624 | 0.031       | 0.165    |
| 11         | 4.579             | 0.054454 | 0.1201 | 812.12    | 17.200  | 17694.6                 | 134645           | 2.698 | 0.031       | 0.155    |
| 12         | 4.102             | 0.097137 | 0.1377 | 741.82    | 17.748  | 16381.3                 | 138932           | 2.494 | 0.031       | 0.139    |

# Appendix D: Single- and two-phase calculated data (continued).

Channel C3: Water-helium tests.      Number of channels:      7  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):      71.30      Hyd. Diameter ( $\mu\text{m}$ ):      55.55  
Width ( $\mu\text{m}$ ):      144.79      Channel Length (m):      0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|-------------|-------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U f         | U Nu  |
|            |                     |          |        |           |         |                     |                     |       | (%)         | (%)   |
| 1          | 2.996               | 0.00742  | 0.1768 | 525.25    | 10.513  | 11953.6             | 82294               | 1.824 | 0.031       | 0.194 |
| 2          | 3.273               | 0.013586 | 0.1621 | 576.26    | 11.713  | 13009.5             | 91692               | 1.984 | 0.031       | 0.186 |
| 3          | 3.271               | 0.019718 | 0.1625 | 578.68    | 11.722  | 13006.3             | 91759               | 1.983 | 0.031       | 0.187 |
| 4          | 3.337               | 0.025468 | 0.1608 | 588.08    | 11.488  | 13132.3             | 89928               | 2.003 | 0.031       | 0.164 |
| 5          | 2.879               | 0.037514 | 0.1874 | 511.16    | 10.409  | 11515.0             | 81482               | 1.755 | 0.031       | 0.109 |
| 6          | 4.378               | 0.004962 | 0.1196 | 774.05    | 15.068  | 17707.1             | 117955              | 2.699 | 0.031       | 0.119 |
| 7          | 3.979               | 0.011132 | 0.1313 | 709.92    | 14.624  | 16016.8             | 114475              | 2.440 | 0.031       | 0.115 |
| 8          | 3.516               | 0.019138 | 0.1485 | 632.60    | 13.910  | 14282.7             | 108890              | 2.174 | 0.031       | 0.112 |
| 9          | 3.312               | 0.026466 | 0.1589 | 595.99    | 13.079  | 13444.4             | 102382              | 2.046 | 0.031       | 0.144 |
| 10         | 5.969               | 0.0019   | 0.0886 | 1,041.91  | 19.277  | 22632.4             | 150904              | 3.455 | 0.031       | 0.144 |
| 11         | 5.826               | 0.003717 | 0.0905 | 1,021.83  | 19.180  | 22208.1             | 150141              | 3.388 | 0.031       | 0.146 |
| 12         | 5.462               | 0.007894 | 0.0962 | 965.98    | 18.336  | 20896.3             | 143539              | 3.186 | 0.031       | 0.173 |



Appendix D: Single- and two-phase calculated data (continued).

Channel C3: Water-Nitrogen tests.      Number of channels:      7  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      71.30      Hyd. Diameter ( $\mu\text{m}$ ):      55.55  
 Width ( $\mu\text{m}$ ):      144.79      Channel Length (m):      0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty    |                 |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|----------------|-----------------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U <sub>f</sub> | U <sub>Nu</sub> |
|            |                     |          |        |           |         |                     |                     |       | (%)            | (%)             |
| 1          | 3.898               | 0.003579 | 0.1450 | 639.90    | 13.236  | 15835.0             | 103616              | 2.442 | 0.031          | 0.178           |
| 2          | 3.462               | 0.00787  | 0.1614 | 579.96    | 12.440  | 15428.7             | 97379               | 2.386 | 0.031          | 0.180           |
| 3          | 3.724               | 0.015218 | 0.1462 | 649.47    | 16.026  | 17121.8             | 125452              | 2.657 | 0.031          | 0.155           |
| 4          | 3.832               | 0.029329 | 0.1429 | 683.72    | 16.806  | 17506.3             | 131557              | 2.752 | 0.031          | 0.151           |
| 5          | 3.643               | 0.059135 | 0.1539 | 675.23    | 16.017  | 15884.5             | 125383              | 2.570 | 0.031          | 0.144           |
| 6          | 3.530               | 0.089339 | 0.1625 | 681.80    | 15.715  | 15019.9             | 123019              | 2.505 | 0.031          | 0.139           |
| 7          | 4.911               | 0.005354 | 0.1104 | 843.71    | 20.281  | 21857.2             | 158759              | 3.361 | 0.031          | 0.157           |
| 8          | 4.597               | 0.012501 | 0.1178 | 801.64    | 19.112  | 20784.8             | 149613              | 3.216 | 0.031          | 0.158           |
| 9          | 4.676               | 0.022712 | 0.1161 | 830.49    | 19.868  | 21095.2             | 155525              | 3.294 | 0.031          | 0.154           |
| 10         | 4.676               | 0.046326 | 0.1183 | 855.12    | 20.069  | 20521.2             | 157101              | 3.278 | 0.031          | 0.149           |
| 11         | 6.219               | 0.00446  | 0.0881 | 1,055.34  | 23.063  | 25481.0             | 180542              | 3.920 | 0.031          | 0.164           |
| 12         | 6.133               | 0.009414 | 0.0890 | 1,055.36  | 23.424  | 26596.2             | 183365              | 4.107 | 0.031          | 0.166           |
| 13         | 6.323               | 0.016965 | 0.0871 | 1,094.49  | 23.110  | 26650.4             | 180905              | 4.146 | 0.031          | 0.170           |

## Appendix D: Single- and two-phase calculated data (continued).

Channel D: Argon gas tests.                      Number of channels:                      7  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):                      111.330                      Hyd. Diameter ( $\mu\text{m}$ ):                      111.88  
Width ( $\mu\text{m}$ ):                      112.43                      Channel Length (m):                      0.0635

| Data Point |         |        |          |         | Heat Trans.         |                     |          |             |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|----------|-------------|-------|
|            | Re      | f      | Velocity | Q       | coeff.              | Heat Flux           | Nu       | Uncertainty |       |
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |          | U-f         | U-Nu  |
| 1          | 58.7    | 3.3451 | 5.60     | 0.0013  | 0.770               | 8.72                | 0.004785 | 0.031       | 0.435 |
| 2          | 218.2   | 0.7173 | 16.11    | 0.0087  | 4.412               | 58.71               | 0.027371 | 0.031       | 0.250 |
| 3          | 529.8   | 0.2529 | 31.03    | 0.0218  | 10.060              | 146.68              | 0.062344 | 0.031       | 0.246 |
| 4          | 845.5   | 0.1565 | 42.16    | 0.0480  | 21.842              | 322.55              | 0.135005 | 0.031       | 0.188 |
| 5          | 1,110.7 | 0.1292 | 48.52    | 0.0967  | 45.952              | 649.31              | 0.283043 | 0.031       | 0.137 |
| 6          | 1,375.0 | 0.1068 | 54.74    | 0.1242  | 59.131              | 833.79              | 0.363849 | 0.031       | 0.136 |
| 7          | 1,627.7 | 0.0971 | 58.74    | 0.1513  | 71.962              | 1015.55             | 0.442667 | 0.031       | 0.135 |
| 8          | 1,854.1 | 0.0964 | 60.27    | 0.1883  | 90.734              | 1264.27             | 0.557738 | 0.031       | 0.131 |
| 9          | 2,061.8 | 0.0935 | 62.11    | 0.2197  | 107.940             | 1475.13             | 0.663109 | 0.031       | 0.131 |
| 10         | 2,275.8 | 0.0885 | 64.58    | 0.2563  | 128.131             | 1720.45             | 0.786900 | 0.031       | 0.130 |
| 11         | 2,456.0 | 0.0835 | 66.94    | 0.2966  | 150.431             | 1991.22             | 0.923672 | 0.031       | 0.127 |
| 12         | 2,605.3 | 0.0800 | 68.82    | 0.3325  | 172.898             | 2232.12             | 1.061144 | 0.031       | 0.126 |
| 13         | 2,752.9 | 0.0776 | 70.28    | 0.3935  | 206.376             | 2641.98             | 1.266700 | 0.031       | 0.121 |
| 14         | 2,891.3 | 0.0753 | 71.79    | 0.4887  | 276.694             | 3281.34             | 1.695315 | 0.031       | 0.117 |
| 15         | 3,027.6 | 0.0717 | 73.88    | 0.5211  | 307.172             | 3498.25             | 1.880421 | 0.031       | 0.120 |
| 16         | 3,162.0 | 0.0683 | 75.69    | 0.5134  | 353.991             | 3446.84             | 2.176506 | 0.031       | 0.136 |
| 17         | 3,249.6 | 0.0678 | 76.31    | 0.5743  | 389.913             | 3855.97             | 2.395539 | 0.031       | 0.133 |
| 18         | 3,315.6 | 0.0674 | 76.83    | 0.6220  | 422.455             | 4176.18             | 2.594776 | 0.031       | 0.132 |

Appendix D: Single- and two-phase calculated data (continued).

Channel D: Helium gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.330

Hyd. Diameter ( $\mu\text{m}$ ): 111.88

Width ( $\mu\text{m}$ ): 112.43

Channel Length (m): 0.0635

| Data Point | Re    | f       | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   |                                  | Nu        | Uncertainty |             |
|------------|-------|---------|-------------------|--------------|-------------------------------|----------------------------------|-----------|-------------|-------------|
|            |       |         |                   |              | coeff.<br>W/m <sup>2</sup> -K | Heat Flux<br>(W/m <sup>2</sup> ) |           | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 6.1   | 16.8991 | 5.80              |              |                               |                                  |           |             |             |
| 2          | 25.4  | 4.1034  | 18.50             | 0.0022       | 1.429                         | 14.88                            | 0.0010358 | 0.031       | 0.913       |
| 3          | 80.5  | 1.3737  | 40.82             | 0.0359       | 27.583                        | 240.80                           | 0.0198963 | 0.031       | 0.207       |
| 4          | 133.2 | 0.8840  | 54.94             | 0.0749       | 62.608                        | 503.06                           | 0.0450715 | 0.031       | 0.183       |
| 5          | 193.7 | 0.5781  | 70.38             | 0.1112       | 94.419                        | 746.64                           | 0.0679435 | 0.031       | 0.181       |
| 6          | 254.7 | 0.4479  | 82.17             | 0.1488       | 127.660                       | 998.79                           | 0.0918378 | 0.031       | 0.179       |
| 7          | 315.7 | 0.3660  | 92.60             | 0.1792       | 151.275                       | 1202.89                          | 0.1088589 | 0.031       | 0.178       |
| 8          | 377.3 | 0.3101  | 102.21            | 0.2565       | 241.071                       | 1722.08                          | 0.1731385 | 0.031       | 0.175       |
| 9          | 435.9 | 0.2712  | 110.55            | 0.3187       | 316.914                       | 2139.75                          | 0.2274170 | 0.031       | 0.177       |
| 10         | 506.7 | 0.2366  | 119.67            | 0.3949       | 411.565                       | 2651.33                          | 0.2951677 | 0.031       | 0.180       |
| 11         | 565.2 | 0.2145  | 126.59            | 0.4496       | 479.984                       | 3018.81                          | 0.3442281 | 0.031       | 0.182       |
| 12         | 630.1 | 0.1979  | 132.81            | 0.5090       | 558.547                       | 3417.14                          | 0.4006518 | 0.031       | 0.185       |
| 13         | 700.6 | 0.1808  | 139.84            | 0.5743       | 645.429                       | 3855.78                          | 0.4630899 | 0.031       | 0.187       |
| 14         | 772.7 | 0.1668  | 146.42            | 0.6487       | 752.082                       | 4355.47                          | 0.5397323 | 0.031       | 0.191       |
| 15         | 643.8 | 0.1426  | 176.93            | 0.8884       | 425.075                       | 6059.35                          | 0.6869200 | 0.031       | 0.191       |

# Appendix D: Single- and two-phase calculated data (continued).

Channel D: Nitrogen gas tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.330 Hyd. Diameter ( $\mu\text{m}$ ): 111.88Width ( $\mu\text{m}$ ): 112.43 Channel Length (m): 0.0635

| Data Point |         |        |          |         | Heat Trans.         |                     |         |       |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|---------|-------|-------|
|            | Re      | f      | Velocity | Q       | coeff.              | Heat Flux           | Nu      | U-f   | U-Nu  |
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |         | (%)   | (%)   |
| 1          | 31.6    | 2.7850 | 4.11     | 0.00021 | 0.175               | 1.42                | 0.00074 | 0.031 | 2.208 |
| 2          | 123.2   | 0.7501 | 13.67    | 0.0067  | 4.542               | 44.84               | 0.019   | 0.031 | 0.293 |
| 3          | 370.1   | 0.2578 | 31.78    | 0.0343  | 22.899              | 230.19              | 0.096   | 0.031 | 0.192 |
| 4          | 670.3   | 0.1543 | 46.81    | 0.0858  | 59.938              | 575.91              | 0.252   | 0.031 | 0.160 |
| 5          | 911.9   | 0.1205 | 56.16    | 0.1545  | 118.912             | 1037.28             | 0.498   | 0.031 | 0.148 |
| 6          | 1,156.7 | 0.0992 | 64.26    | 0.2195  | 175.207             | 1473.38             | 0.733   | 0.031 | 0.146 |
| 7          | 1,389.0 | 0.0872 | 70.50    | 0.2812  | 230.763             | 1888.02             | 0.966   | 0.031 | 0.147 |
| 8          | 1,629.9 | 0.0809 | 75.08    | 0.3301  | 267.535             | 2216.17             | 1.121   | 0.031 | 0.146 |
| 9          | 1,812.4 | 0.0792 | 77.30    | 0.3803  | 311.593             | 2553.29             | 1.305   | 0.031 | 0.147 |
| 10         | 1,996.0 | 0.0807 | 78.09    | 0.4441  | 369.164             | 2981.71             | 1.547   | 0.031 | 0.147 |
| 11         | 2,170.1 | 0.0810 | 79.05    | 0.5041  | 424.130             | 3384.22             | 1.777   | 0.031 | 0.148 |
| 12         | 2,371.0 | 0.0787 | 81.18    | 0.5791  | 497.651             | 3887.71             | 2.086   | 0.031 | 0.150 |
| 13         | 2,483.3 | 0.0782 | 82.00    | 0.6321  | 554.603             | 4243.71             | 2.325   | 0.031 | 0.151 |
| 14         | 2,646.2 | 0.0763 | 83.70    | 0.7075  | 632.410             | 4749.75             | 2.652   | 0.031 | 0.153 |

Appendix D: Single- and two-phase calculated data (continued).

Channel D: Water tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.330      Hyd. Diameter ( $\mu\text{m}$ ): 111.88

Width ( $\mu\text{m}$ ): 112.43      Channel Length (m): 0.0635

| Data Point | Re       | f      | Velocity | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|----------|--------|----------|---------|---------------------|---------------------|--------|-------------|-------|
|            |          |        |          |         |                     |                     |        | U-f         | U_Nu  |
|            |          |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | (%)         | (%)   |
| 1          | 253.61   | 0.4144 | 1.76     | 12.216  | 11086.42            | 82016               | 1.974  | 0.031       | 0.146 |
| 2          | 315.30   | 0.2832 | 2.23     | 14.150  | 14989.65            | 95000               | 2.675  | 0.031       | 0.169 |
| 3          | 386.91   | 0.1980 | 2.77     | 16.316  | 19955.32            | 109541              | 3.567  | 0.031       | 0.193 |
| 4          | 372.09   | 0.2313 | 2.66     | 16.035  | 17059.65            | 107658              | 3.048  | 0.031       | 0.171 |
| 5          | 478.25   | 0.1515 | 3.42     | 19.532  | 23338.2             | 131133              | 4.171  | 0.031       | 0.190 |
| 6          | 499.75   | 0.1528 | 3.54     | 21.467  | 22222.78            | 144123              | 3.967  | 0.031       | 0.167 |
| 7          | 582.68   | 0.1183 | 4.13     | 24.400  | 26450.31            | 163814              | 4.722  | 0.031       | 0.174 |
| 8          | 612.39   | 0.1137 | 4.34     | 25.359  | 30201.02            | 170253              | 5.391  | 0.031       | 0.189 |
| 9          | 668.95   | 0.1027 | 4.69     | 28.657  | 29717.12            | 192398              | 5.299  | 0.031       | 0.167 |
| 10         | 719.88   | 0.0937 | 5.08     | 29.223  | 28203.05            | 196193              | 5.032  | 0.031       | 0.158 |
| 11         | 747.00   | 0.0899 | 5.27     | 29.452  | 29399.86            | 197735              | 5.246  | 0.031       | 0.163 |
| 12         | 796.45   | 0.0833 | 5.64     | 30.090  | 31314.47            | 202015              | 5.589  | 0.031       | 0.170 |
| 13         | 856.01   | 0.0785 | 5.99     | 33.708  | 31303.81            | 226307              | 5.580  | 0.031       | 0.154 |
| 14         | 902.12   | 0.0730 | 6.31     | 34.680  | 32648.08            | 232835              | 5.820  | 0.031       | 0.156 |
| 15         | 1,000.25 | 0.0641 | 7.02     | 36.872  | 36049.17            | 247553              | 6.429  | 0.031       | 0.162 |
| 16         | 1,041.60 | 0.0637 | 7.17     | 40.326  | 33565.31            | 270737              | 5.972  | 0.031       | 0.141 |
| 17         | 1,069.31 | 0.0638 | 7.39     | 39.818  | 34029.8             | 267331              | 6.058  | 0.031       | 0.145 |
| 18         | 1,190.55 | 0.0544 | 8.29     | 41.605  | 36750.92            | 279327              | 6.547  | 0.031       | 0.151 |
| 19         | 1,217.63 | 0.0553 | 8.49     | 41.501  | 39271.36            | 278629              | 6.997  | 0.031       | 0.160 |
| 20         | 1,370.01 | 0.0482 | 9.67     | 42.114  | 44373.74            | 282741              | 7.917  | 0.031       | 0.179 |
| 21         | 1,544.59 | 0.0327 | 11.50    | 19.728  | 54468.39            | 132446              | 9.776  | 0.031       | 0.463 |
| 22         | 1,665.79 | 0.0318 | 12.41    | 20.612  | 84942.1             | 138387              | 15.246 | 0.031       | 0.652 |
| 23         | 1,781.85 | 0.0312 | 13.29    | 21.454  | 115172.8            | 144035              | 20.674 | 0.031       | 0.831 |
| 24         | 1,848.16 | 0.0321 | 13.80    | 21.801  | 156643.4            | 146367              | 28.119 | 0.031       | 1.095 |
| 25         | 1,959.30 | 0.0315 | 14.63    | 22.665  | 195107.6            | 152169              | 35.025 | 0.031       | 1.304 |
| 26         | 2,021.15 | 0.0323 | 15.11    | 23.158  | 221995              | 155478              | 39.855 | 0.031       | 1.448 |
| 27         | 2,152.49 | 0.0313 | 16.12    | 24.324  | 267507.7            | 163304              | 48.033 | 0.031       | 1.656 |

# Appendix D: Single- and two-phase calculated data (continued).

Channel D: Water-argon tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.330 Hyd. Diameter ( $\mu\text{m}$ ): 111.88Width ( $\mu\text{m}$ ): 112.43 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|-------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | U f         | U Nu  |
|            |                     |          |        |           |         |                     |                     |        | (%)         | (%)   |
| 1          | 2.089               | 0.010879 | 0.2092 | 393.82    | 10.488  | 18.501              | 70416               | 3.292  | 0.031       | 0.274 |
| 2          | 2.473               | 0.019053 | 0.1791 | 463.81    | 11.976  | 22.525              | 80402               | 4.011  | 0.031       | 0.291 |
| 3          | 2.350               | 0.0423   | 0.1903 | 447.37    | 12.235  | 19.518              | 82141               | 3.471  | 0.031       | 0.249 |
| 4          | 1.929               | 0.086342 | 0.2378 | 375.39    | 10.946  | 14.708              | 73490               | 2.611  | 0.031       | 0.211 |
| 5          | 2.009               | 0.108608 | 0.2349 | 389.53    | 11.180  | 15.522              | 75060               | 2.757  | 0.031       | 0.218 |
| 6          | 2.867               | 0.008244 | 0.1512 | 543.40    | 15.792  | 22.709              | 106027              | 4.039  | 0.031       | 0.225 |
| 7          | 2.281               | 0.022761 | 0.1895 | 440.14    | 13.199  | 18.628              | 88615               | 3.307  | 0.031       | 0.221 |
| 8          | 2.512               | 0.038094 | 0.1729 | 490.26    | 15.076  | 19.693              | 101215              | 3.493  | 0.031       | 0.205 |
| 9          | 2.418               | 0.063983 | 0.1804 | 482.85    | 15.724  | 18.302              | 105564              | 3.239  | 0.031       | 0.183 |
| 10         | 2.492               | 0.085507 | 0.1798 | 495.99    | 15.918  | 18.412              | 106868              | 3.260  | 0.031       | 0.183 |
| 11         | 3.147               | 0.006462 | 0.1390 | 590.19    | 16.472  | 26.123              | 110592              | 4.651  | 0.031       | 0.247 |
| 12         | 3.187               | 0.015389 | 0.1390 | 595.63    | 16.049  | 27.724              | 107751              | 4.939  | 0.031       | 0.268 |
| 13         | 2.914               | 0.032671 | 0.1535 | 548.97    | 14.859  | 23.801              | 99760               | 4.237  | 0.031       | 0.250 |
| 14         | 3.018               | 0.054392 | 0.1493 | 577.41    | 16.637  | 24.557              | 111695              | 4.365  | 0.031       | 0.231 |
| 15         | 9.379               | 0.075048 | 0.0538 | 1.639.05  | 25.307  | 78.799              | 169907              | 14.144 | 0.031       | 0.484 |
| 16         | 10.324              | 0.074836 | 0.0491 | 1.793.54  | 25.729  | 100.909             | 172739              | 18.124 | 0.031       | 0.603 |
| 17         | 10.151              | 0.083385 | 0.0503 | 1.767.26  | 25.802  | 106.564             | 173226              | 19.137 | 0.031       | 0.632 |
| 18         | 9.410               | 0.099106 | 0.0552 | 1.640.06  | 24.478  | 106.964             | 164337              | 19.209 | 0.031       | 0.666 |
| 19         | 10.363              | 0.098665 | 0.0504 | 1.796.23  | 25.587  | 163.369             | 171787              | 29.355 | 0.031       | 0.963 |
| 20         | 10.671              | 0.041946 | 0.0461 | 1.845.36  | 26.333  | 159.679             | 176793              | 28.683 | 0.031       | 0.916 |
| 21         | 12.822              | 0.003898 | 0.0361 | 2.263.41  | 29.610  | 221.563             | 198792              | 39.695 | 0.031       | 1.126 |
| 22         | 12.669              | 0.009661 | 0.0367 | 2.242.86  | 29.715  | 244.239             | 199503              | 43.747 | 0.031       | 1.235 |
| 23         | 11.989              | 0.019546 | 0.0391 | 2.127.16  | 28.979  | 226.844             | 194556              | 40.625 | 0.031       | 1.176 |
| 24         | 12.806              | 0.025104 | 0.0369 | 2.266.55  | 29.576  | 242.217             | 198569              | 43.392 | 0.031       | 1.231 |
| 25         | 12.458              | 0.037847 | 0.0384 | 2.207.01  | 29.019  | 228.972             | 194827              | 41.020 | 0.031       | 1.186 |
| 26         | 2.564               | 0.259557 | 0.2434 | 453.17    | 10.399  | 19.229              | 69815               | 3.454  | 0.031       | 0.291 |
| 27         | 2.827               | 0.251281 | 0.2178 | 500.87    | 11.679  | 20.470              | 78408               | 3.676  | 0.031       | 0.277 |
| 28         | 2.516               | 0.300019 | 0.2601 | 448.83    | 10.803  | 18.321              | 72530               | 3.289  | 0.031       | 0.267 |
| 29         | 2.477               | 0.330442 | 0.2746 | 444.65    | 10.859  | 17.222              | 72903               | 3.091  | 0.031       | 0.251 |
| 30         | 2.757               | 0.306307 | 0.2376 | 495.91    | 12.245  | 19.622              | 82210               | 3.520  | 0.031       | 0.253 |
| 31         | 2.371               | 0.37896  | 0.3069 | 429.03    | 10.731  | 17.145              | 72044               | 3.076  | 0.031       | 0.252 |
| 32         | 2.366               | 0.393901 | 0.3138 | 429.98    | 10.928  | 16.653              | 73371               | 2.987  | 0.031       | 0.241 |
| 33         | 2.497               | 0.398719 | 0.2967 | 458.52    | 11.989  | 18.426              | 80488               | 3.301  | 0.031       | 0.242 |
| 34         | 2.679               | 0.380372 | 0.2685 | 491.55    | 12.804  | 20.061              | 85962               | 3.594  | 0.031       | 0.246 |
| 35         | 2.848               | 0.374718 | 0.2553 | 512.17    | 12.377  | 22.515              | 83095               | 4.042  | 0.031       | 0.285 |

Appendix D: Single- and two-phase calculated data (continued).

Channel D: Water-helium tests.

Number of channels: 7

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 111.330 Hyd. Diameter ( $\mu\text{m}$ ): 111.88

Width ( $\mu\text{m}$ ): 112.43 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | U f (%)     | U Nu (%) |
| 1          | 2.231               | 0.001031 | 0.1913 | 426.51    | 11.970  | 21975.3             | 80364               | 3.905  | 0.031       | 0.283    |
| 2          | 2.251               | 0.002322 | 0.1884 | 433.58    | 12.061  | 22957.7             | 80974               | 4.076  | 0.031       | 0.292    |
| 3          | 1.700               | 0.013091 | 0.2487 | 332.01    | 9.473   | 13764.5             | 63596               | 2.440  | 0.031       | 0.227    |
| 4          | 2.200               | 0.020904 | 0.1977 | 420.98    | 11.224  | 16564.4             | 75355               | 2.943  | 0.031       | 0.232    |
| 5          | 2.641               | 0.000826 | 0.1629 | 500.70    | 13.924  | 22348.6             | 93484               | 3.974  | 0.031       | 0.250    |
| 6          | 2.463               | 0.002059 | 0.1737 | 470.15    | 13.365  | 21247.7             | 89727               | 3.776  | 0.031       | 0.247    |
| 7          | 2.436               | 0.004182 | 0.1748 | 468.04    | 13.283  | 20663.3             | 89179               | 3.670  | 0.031       | 0.242    |
| 8          | 2.555               | 0.006948 | 0.1683 | 487.70    | 13.544  | 21047.3             | 90933               | 3.740  | 0.031       | 0.242    |
| 9          | 2.723               | 0.009657 | 0.1601 | 513.92    | 13.685  | 21719.1             | 91876               | 3.864  | 0.031       | 0.248    |
| 10         | 2.522               | 0.014943 | 0.1726 | 479.40    | 13.060  | 18631.3             | 87683               | 3.313  | 0.031       | 0.225    |
| 11         | 3.564               | 0.00063  | 0.1240 | 657.80    | 16.526  | 31265.0             | 110954              | 5.576  | 0.031       | 0.293    |
| 12         | 3.168               | 0.001686 | 0.1393 | 586.10    | 14.820  | 28210.7             | 99497               | 5.030  | 0.031       | 0.295    |
| 13         | 3.632               | 0.002604 | 0.1221 | 669.36    | 16.360  | 32135.2             | 109839              | 5.732  | 0.031       | 0.304    |
| 14         | 3.521               | 0.005046 | 0.1265 | 647.41    | 15.441  | 28175.1             | 103665              | 5.027  | 0.031       | 0.285    |
| 15         | 3.512               | 0.007718 | 0.1271 | 646.01    | 15.467  | 27105.7             | 103845              | 4.836  | 0.031       | 0.275    |
| 16         | 12.117              | 0.006072 | 0.0383 | 2,143.26  | 27.175  | 149225.5            | 182449              | 26.729 | 0.031       | 0.835    |
| 17         | 12.645              | 0.00677  | 0.0368 | 2,230.58  | 27.565  | 161444.8            | 185066              | 28.926 | 0.031       | 0.889    |
| 18         | 12.621              | 0.007934 | 0.0369 | 2,224.57  | 27.543  | 151802.9            | 184917              | 27.201 | 0.031       | 0.838    |
| 19         | 12.446              | 0.008825 | 0.0375 | 2,192.62  | 27.186  | 151164.9            | 182522              | 27.088 | 0.031       | 0.845    |
| 20         | 12.287              | 0.010233 | 0.0381 | 2,162.37  | 26.976  | 140769.3            | 181108              | 25.228 | 0.031       | 0.795    |

Appendix D: Single- and two-phase calculated data (continued).

Channel D: Water-Nitrogen tests.      Number of channels:      7  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      111.330      Hyd. Diameter ( $\mu\text{m}$ ):      111.88  
 Width ( $\mu\text{m}$ ):      112.43      Channel Length (m):      0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu      | Uncertainty    |                 |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|---------|----------------|-----------------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |         | U <sub>f</sub> | U <sub>Nu</sub> |
|            |                     |          |        |           |         |                     |                     |         | (%)            | (%)             |
| 1          | 2.215               | 0.005014 | 0.1950 | 422.01    | 12.598  | 29001.3             | 84582               | 5.182   | 0.031          | 0.350           |
| 2          | 1.914               | 0.011472 | 0.2268 | 367.57    | 10.433  | 24109.1             | 70047               | 4.334   | 0.031          | 0.351           |
| 3          | 2.035               | 0.031934 | 0.2212 | 392.73    | 10.172  | 23154.1             | 68293               | 4.254   | 0.031          | 0.347           |
| 4          | 2.162               | 0.052226 | 0.2118 | 427.48    | 10.742  | 22184.2             | 72119               | 4.157   | 0.031          | 0.316           |
| 5          | 1.874               | 0.087209 | 0.2488 | 391.77    | 9.819   | 16317.7             | 65924               | 3.163   | 0.031          | 0.257           |
| 6          | 2.988               | 0.003938 | 0.1463 | 561.31    | 16.569  | 29811.0             | 111241              | 5.329   | 0.031          | 0.277           |
| 7          | 2.606               | 0.008974 | 0.1675 | 495.20    | 14.168  | 26176.3             | 95121               | 4.699   | 0.031          | 0.284           |
| 8          | 2.750               | 0.017302 | 0.1584 | 532.33    | 15.117  | 27534.2             | 101490              | 4.977   | 0.031          | 0.280           |
| 9          | 2.883               | 0.027687 | 0.1524 | 565.18    | 15.774  | 27644.6             | 105904              | 5.047   | 0.031          | 0.270           |
| 10         | 2.271               | 0.050656 | 0.1948 | 463.24    | 13.048  | 20351.4             | 87602               | 3.794   | 0.031          | 0.241           |
| 11         | 3.383               | 0.003138 | 0.1293 | 634.36    | 18.466  | 30998.2             | 123979              | 5.537   | 0.031          | 0.260           |
| 12         | 3.666               | 0.005736 | 0.1191 | 692.02    | 20.117  | 35408.3             | 135059              | 6.338   | 0.031          | 0.271           |
| 13         | 3.175               | 0.017002 | 0.1369 | 615.51    | 17.864  | 26372.5             | 119933              | 4.764   | 0.031          | 0.230           |
| 14         | 11.399              | 0.030025 | 0.0440 | 1,966.22  | 19.820  | 232363.5            | 133070              | 43.100  | 0.031          | 1.759           |
| 15         | 11.496              | 0.032527 | 0.0436 | 1,992.63  | 19.680  | 376414.8            | 132129              | 69.973  | 0.031          | 2.857           |
| 16         | 11.498              | 0.036541 | 0.0437 | 2,004.72  | 19.602  | 531532.8            | 131602              | 99.179  | 0.031          | 4.045           |
| 17         | 11.121              | 0.040682 | 0.0453 | 1,951.09  | 19.364  | 641054.1            | 130008              | 120.078 | 0.031          | 4.936           |
| 18         | 10.892              | 0.0464   | 0.0464 | 1,924.04  | 19.072  | 564549.6            | 128046              | 106.339 | 0.031          | 4.415           |
| 19         | 10.402              | 0.055856 | 0.0490 | 1,857.64  | 18.648  | 483437.1            | 125196              | 91.915  | 0.031          | 3.867           |
| 20         | 2.323               | 0.189694 | 0.2452 | 501.63    | 8.321   | 18697.1             | 55867               | 4.094   | 0.031          | 0.347           |
| 21         | 2.602               | 0.17327  | 0.2150 | 550.13    | 9.353   | 21649.7             | 62795               | 4.652   | 0.031          | 0.357           |
| 22         | 2.219               | 0.20768  | 0.2625 | 489.58    | 7.804   | 20722.9             | 52396               | 4.635   | 0.031          | 0.406           |
| 23         | 8.174               | 0.0249   | 0.0439 | 3,591.24  | 60.536  | 48,689              | 412894              | 20.402  | 0.031          | 0.409           |
| 24         | 8.018               | 0.0306   | 0.0442 | 3,525.12  | 57.016  | 44,591              | 388883              | 18.799  | 0.031          | 0.393           |



Appendix D: Single- and two-phase calculated data (continued).

Channel E: Argon gas tests.                      Number of channels:                      9  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):                      74.910                      Hyd. Diameter ( $\mu\text{m}$ ):                      79.991  
 Width ( $\mu\text{m}$ ):                      85.81                      Channel Length (m):                      0.0635

| Data Point | Heat Trans. |        |          |         |                     |                     |          |             |       |
|------------|-------------|--------|----------|---------|---------------------|---------------------|----------|-------------|-------|
|            | Re          | f      | Velocity | Q       | coeff.              | Heat Flux           | Nu       | Uncertainty |       |
|            |             |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |          | U-f         | U-Nu  |
| 1          | 56.9        | 0.7871 | 8.30     | 0.0004  | 0.250               | 3.02                | 0.001107 | 0.031       | 1.220 |
| 2          | 124.1       | 0.4542 | 15.01    | 0.0026  | 1.698               | 21.32               | 0.007506 | 0.031       | 0.388 |
| 3          | 242.2       | 0.2484 | 24.03    | 0.0059  | 3.763               | 49.27               | 0.016621 | 0.031       | 0.333 |
| 4          | 670.4       | 0.0839 | 48.46    | 0.0396  | 28.604              | 331.19              | 0.125786 | 0.031       | 0.163 |
| 5          | 984.3       | 0.0581 | 61.15    | 0.0686  | 50.870              | 573.26              | 0.223470 | 0.031       | 0.150 |
| 6          | 1,330.2     | 0.0490 | 69.58    | 0.1123  | 86.576              | 938.01              | 0.379936 | 0.031       | 0.139 |
| 7          | 1,595.3     | 0.0427 | 76.10    | 0.1480  | 117.783             | 1236.17             | 0.516616 | 0.031       | 0.136 |
| 8          | 1,857.5     | 0.0397 | 80.35    | 0.1857  | 151.493             | 1551.63             | 0.664470 | 0.031       | 0.136 |
| 9          | 2,074.2     | 0.0398 | 81.67    | 0.2206  | 180.918             | 1842.54             | 0.793715 | 0.031       | 0.135 |
| 10         | 2,270.6     | 0.0391 | 83.40    | 0.2629  | 218.840             | 2196.08             | 0.960098 | 0.031       | 0.135 |
| 11         | 2,443.7     | 0.0376 | 85.70    | 0.2996  | 251.080             | 2503.03             | 1.101827 | 0.031       | 0.135 |
| 12         | 2,601.3     | 0.0360 | 88.21    | 0.3423  | 292.292             | 2859.95             | 1.282884 | 0.031       | 0.135 |
| 13         | 2,718.5     | 0.0349 | 90.00    | 0.3830  | 331.911             | 3199.55             | 1.457166 | 0.031       | 0.135 |
| 14         | 2,822.1     | 0.0340 | 91.56    | 0.4199  | 372.545             | 3508.08             | 1.636273 | 0.031       | 0.137 |
| 15         | 2,907.7     | 0.0333 | 92.87    | 0.4636  | 418.266             | 3873.20             | 1.837930 | 0.031       | 0.138 |
| 16         | 3,000.0     | 0.0318 | 95.24    | 0.4943  | 453.425             | 4129.74             | 1.993284 | 0.031       | 0.140 |
| 17         | 3,054.3     | 0.0312 | 96.40    | 0.5343  | 502.941             | 4464.03             | 2.212036 | 0.031       | 0.142 |
| 18         | 3,094.4     | 0.0307 | 97.44    | 0.5686  | 545.138             | 4750.35             | 2.399041 | 0.031       | 0.143 |
| 19         | 3,115.5     | 0.0303 | 98.14    | 0.6030  | 588.852             | 5037.59             | 2.592562 | 0.031       | 0.145 |

Appendix D: Single- and two-phase calculated data (continued).

Channel E: Helium gas tests.      Number of channels:      9  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      74.910      Hyd. Diameter ( $\mu\text{m}$ ):      79.991  
 Width ( $\mu\text{m}$ ):      85.81      Channel Length (m):      0.0635

| Data Point | Re    | f      | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   | Heat Flux<br>(W/m <sup>2</sup> ) | Nu        | Uncertainty |             |
|------------|-------|--------|-------------------|--------------|-------------------------------|----------------------------------|-----------|-------------|-------------|
|            |       |        |                   |              | coeff.<br>W/m <sup>2</sup> -K |                                  |           | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 8.2   | 4.7520 | 10.44             | 0.0000       | 0.004                         | 0.05                             | 0.0000021 | 0.031       | 93.291      |
| 2          | 18.2  | 3.2159 | 18.14             | 0.0006       | 0.398                         | 4.88                             | 0.0002063 | 0.031       | 2.022       |
| 3          | 31.4  | 2.0670 | 25.99             | 0.0023       | 1.644                         | 19.51                            | 0.0008500 | 0.031       | 0.862       |
| 4          | 79.4  | 0.9333 | 45.38             | 0.0266       | 21.738                        | 221.99                           | 0.0111929 | 0.031       | 0.208       |
| 5          | 137.5 | 0.5052 | 64.75             | 0.0416       | 33.034                        | 347.14                           | 0.0170264 | 0.031       | 0.219       |
| 6          | 195.4 | 0.3484 | 80.08             | 0.0477       | 36.032                        | 398.68                           | 0.0185993 | 0.031       | 0.255       |
| 7          | 253.6 | 0.2713 | 92.70             | 0.0813       | 65.293                        | 679.45                           | 0.0336546 | 0.031       | 0.203       |
| 8          | 306.3 | 0.2247 | 103.33            | 0.1278       | 111.144                       | 1067.59                          | 0.0571766 | 0.031       | 0.172       |
| 9          | 368.1 | 0.1891 | 113.95            | 0.1551       | 134.506                       | 1295.99                          | 0.0692060 | 0.031       | 0.169       |
| 10         | 428.6 | 0.1643 | 123.43            | 0.1909       | 170.121                       | 1594.71                          | 0.0875112 | 0.031       | 0.164       |
| 11         | 491.1 | 0.1448 | 132.48            | 0.2240       | 202.283                       | 1871.33                          | 0.1040654 | 0.031       | 0.162       |
| 12         | 547.1 | 0.1311 | 140.04            | 0.2619       | 242.418                       | 2187.79                          | 0.1246809 | 0.031       | 0.159       |
| 13         | 610.3 | 0.1186 | 148.03            | 0.2906       | 276.671                       | 2427.36                          | 0.1423544 | 0.031       | 0.161       |
| 14         | 547.6 | 0.1609 | 160.40            | 0.7424       | 349.572                       | 5063.88                          | 0.5643628 | 0.031       | 0.159       |
| 15         | 672.9 | 0.1092 | 155.04            | 0.3228       | 303.508                       | 2696.40                          | 0.1562152 | 0.031       | 0.158       |
| 16         | 732.6 | 0.1013 | 161.63            | 0.3675       | 356.285                       | 3070.11                          | 0.1833413 | 0.031       | 0.157       |
| 17         | 796.1 | 0.0954 | 167.29            | 0.4160       | 416.391                       | 3475.62                          | 0.2142466 | 0.031       | 0.157       |
| 18         | 862.0 | 0.0892 | 173.61            | 0.4504       | 453.954                       | 3762.95                          | 0.2336700 | 0.031       | 0.159       |
| 19         | 929.3 | 0.0840 | 179.65            | 0.5242       | 563.300                       | 4378.90                          | 0.2897979 | 0.031       | 0.160       |

Appendix D: Single- and two-phase calculated data (continued).

Channel E: Nitrogen gas tests.      Number of channels:      9  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      74.910      Hyd. Diameter ( $\mu\text{m}$ ):      79.991  
 Width ( $\mu\text{m}$ ):      85.81      Channel Length (m):      0.0635

| Data Point |         |        |          | Heat Trans. |         |           |         | Uncertainty |       |
|------------|---------|--------|----------|-------------|---------|-----------|---------|-------------|-------|
|            | Re      | f      | Velocity | Q           | coeff.  | Heat Flux | Nu      | U-f         | U-Nu  |
|            |         |        | (m/s)    | (Watts)     | W/m2-K  | (W/m^2)   |         | (%)         | (%)   |
|            |         |        |          |             |         |           |         |             |       |
| 1          | 45.1    | 1.3736 | 7.21     | 0.00022     | 0.121   | 1.81      | 0.00037 | 0.031       | 5.006 |
| 2          | 88.4    | 0.8327 | 12.30    | 0.0021      | 1.136   | 17.55     | 0.003   | 0.031       | 1.032 |
| 3          | 169.3   | 0.4564 | 19.89    | 0.0060      | 3.224   | 50.18     | 0.010   | 0.031       | 0.705 |
| 4          | 374.9   | 0.2138 | 34.10    | 0.0223      | 12.371  | 185.92    | 0.038   | 0.031       | 0.444 |
| 5          | 637.6   | 0.1101 | 50.53    | 0.0594      | 36.477  | 496.33    | 0.110   | 0.031       | 0.313 |
| 6          | 844.3   | 0.0867 | 59.30    | 0.0992      | 62.504  | 828.46    | 0.189   | 0.031       | 0.270 |
| 7          | 1.096.7 | 0.0669 | 69.53    | 0.1442      | 93.936  | 1205.09   | 0.284   | 0.031       | 0.258 |
| 8          | 1.255.5 | 0.0584 | 75.43    | 0.1693      | 117.794 | 1414.74   | 0.356   | 0.031       | 0.263 |
| 9          | 1,491.6 | 0.0500 | 83.00    | 0.2120      | 152.776 | 1770.95   | 0.461   | 0.031       | 0.262 |
| 10         | 1,663.3 | 0.0458 | 87.77    | 0.2436      | 179.600 | 2035.44   | 0.542   | 0.031       | 0.264 |
| 11         | 1.825.8 | 0.0440 | 90.67    | 0.2759      | 205.738 | 2305.18   | 0.621   | 0.031       | 0.265 |
| 12         | 1,943.9 | 0.0428 | 92.68    | 0.3070      | 232.004 | 2564.57   | 0.700   | 0.031       | 0.263 |
| 13         | 2,105.6 | 0.0420 | 94.64    | 0.3490      | 267.851 | 2915.57   | 0.808   | 0.031       | 0.264 |
| 14         | 2.236.0 | 0.0401 | 97.40    | 0.3841      | 299.654 | 3209.15   | 0.904   | 0.031       | 0.265 |
| 15         | 2,341.3 | 0.0391 | 99.25    | 0.4195      | 331.761 | 3504.29   | 1.001   | 0.031       | 0.266 |
| 16         | 2,458.7 | 0.0376 | 101.64   | 0.4700      | 378.093 | 3926.13   | 1.140   | 0.031       | 0.264 |
| 17         | 2,550.9 | 0.0368 | 103.36   | 0.5325      | 440.377 | 4449.02   | 1.327   | 0.031       | 0.261 |
| 18         | 2,644.9 | 0.0355 | 105.51   | 0.5866      | 495.384 | 4900.63   | 1.493   | 0.031       | 0.261 |
| 19         | 2,737.8 | 0.0347 | 107.25   | 0.6434      | 555.359 | 5374.75   | 1.673   | 0.031       | 0.263 |

Appendix D: Single- and two-phase calculated data (continued).

Channel E: Water tests.

Number of channels: 9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.910      Hyd. Diameter ( $\mu\text{m}$ ): 79.991

Width ( $\mu\text{m}$ ): 85.81      Channel Length (m): 0.0635

| Data Point | Re       | f      | Velocity | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |       |
|------------|----------|--------|----------|---------|---------------------|---------------------|-------|-------------|-------|
|            |          |        |          |         |                     |                     |       | U-f         | U_Nu  |
|            |          |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | (%)         | (%)   |
| 1          | 322.80   | 0.1357 | 3.28     | 11.378  | 10410.22            | 95051               | 1.333 | 0.031       | 0.127 |
| 2          | 401.18   | 0.1000 | 4.13     | 13.315  | 15030.75            | 111235              | 1.926 | 0.031       | 0.152 |
| 3          | 523.65   | 0.0651 | 5.46     | 16.133  | 20767.85            | 134778              | 2.666 | 0.031       | 0.171 |
| 4          | 523.12   | 0.0713 | 5.52     | 15.107  | 21801.61            | 126207              | 2.802 | 0.031       | 0.190 |
| 5          | 599.17   | 0.0585 | 6.36     | 16.398  | 25710.04            | 136992              | 3.306 | 0.031       | 0.206 |
| 6          | 689.54   | 0.0513 | 7.16     | 21.014  | 28933.08            | 175557              | 3.712 | 0.031       | 0.181 |
| 7          | 798.70   | 0.0437 | 7.97     | 29.405  | 34474.82            | 245652              | 4.403 | 0.031       | 0.153 |
| 8          | 890.00   | 0.0385 | 8.93     | 30.500  | 38928.53            | 254804              | 4.975 | 0.031       | 0.166 |
| 9          | 932.80   | 0.0370 | 9.33     | 30.777  | 40368.2             | 257119              | 5.157 | 0.031       | 0.171 |
| 10         | 1.016.27 | 0.0333 | 10.19    | 31.711  | 43412.88            | 264917              | 5.548 | 0.031       | 0.179 |
| 11         | 1.137.37 | 0.0303 | 11.12    | 32.042  | 46454.04            | 267685              | 5.919 | 0.031       | 0.190 |
| 12         | 1.181.94 | 0.0295 | 11.56    | 31.728  | 47760.01            | 265062              | 6.086 | 0.031       | 0.197 |
| 13         | 1.226.75 | 0.0291 | 11.97    | 31.726  | 49018.13            | 265044              | 6.245 | 0.031       | 0.203 |
| 14         | 1.276.90 | 0.0283 | 12.45    | 31.534  | 50241.68            | 263439              | 6.400 | 0.031       | 0.209 |
| 15         | 1.334.82 | 0.0271 | 13.00    | 31.735  | 52399.8             | 265123              | 6.674 | 0.031       | 0.217 |
| 16         | 1.388.89 | 0.0264 | 13.50    | 31.982  | 54001.98            | 267186              | 6.877 | 0.031       | 0.222 |
| 17         | 1.502.67 | 0.0245 | 14.39    | 37.381  | 57361.04            | 312292              | 7.292 | 0.031       | 0.202 |
| 18         | 1.575.97 | 0.0232 | 15.09    | 38.036  | 59343.02            | 317763              | 7.543 | 0.031       | 0.206 |
| 19         | 1.644.87 | 0.0220 | 15.74    | 38.709  | 63047.47            | 323381              | 8.014 | 0.031       | 0.214 |
| 20         | 1.730.75 | 0.0211 | 16.57    | 39.196  | 66401.86            | 327449              | 8.440 | 0.031       | 0.223 |

Appendix D: Single- and two-phase calculated data (continued).

Channel E: Water-argon tests.

Number of channels: 9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.910 Hyd. Diameter ( $\mu\text{m}$ ): 79.991

Width ( $\mu\text{m}$ ): 85.81 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U f (%)     | U Nu (%) |
| 1          | 6.228               | 0.007187 | 0.1002 | 822.96    | 14.410  | 28950.8             | 137581              | 3.693 | 0.031       | 0.454    |
| 2          | 6.067               | 0.014325 | 0.1031 | 805.91    | 13.550  | 27260.6             | 129370              | 3.476 | 0.031       | 0.457    |
| 3          | 5.325               | 0.032079 | 0.1193 | 709.20    | 12.103  | 23568.4             | 115553              | 3.004 | 0.031       | 0.443    |
| 4          | 4.994               | 0.068938 | 0.1311 | 670.93    | 11.795  | 20587.1             | 112611              | 2.623 | 0.031       | 0.401    |
| 5          | 5.155               | 0.115199 | 0.1336 | 693.52    | 12.394  | 21238.0             | 118337              | 2.707 | 0.031       | 0.394    |
| 6          | 5.998               | 0.143928 | 0.1192 | 803.58    | 14.450  | 22849.5             | 137964              | 2.914 | 0.031       | 0.369    |
| 7          | 5.527               | 0.198647 | 0.1390 | 736.41    | 12.800  | 20704.3             | 122207              | 2.644 | 0.031       | 0.378    |
| 8          | 5.010               | 0.290717 | 0.1707 | 677.91    | 12.578  | 17791.7             | 120087              | 2.270 | 0.031       | 0.334    |
| 9          | 8.568               | 0.005491 | 0.0727 | 1,132.51  | 21.338  | 38521.1             | 203731              | 4.913 | 0.031       | 0.410    |
| 10         | 9.015               | 0.009792 | 0.0692 | 1,195.45  | 22.365  | 40258.2             | 213532              | 5.133 | 0.031       | 0.409    |
| 11         | 8.948               | 0.017771 | 0.0699 | 1,192.59  | 22.217  | 39415.9             | 212120              | 5.023 | 0.031       | 0.404    |
| 12         | 8.827               | 0.041314 | 0.0720 | 1,186.50  | 22.306  | 37192.7             | 212971              | 4.737 | 0.031       | 0.382    |
| 13         | 8.370               | 0.071618 | 0.0776 | 1,137.07  | 22.117  | 33965.9             | 211169              | 4.322 | 0.031       | 0.354    |
| 14         | 8.385               | 0.101394 | 0.0804 | 1,133.47  | 21.704  | 32778.8             | 207226              | 4.174 | 0.031       | 0.351    |
| 15         | 8.510               | 0.133176 | 0.0820 | 1,152.65  | 22.144  | 31916.1             | 211424              | 4.065 | 0.031       | 0.337    |
| 16         | 12.474              | 0.003446 | 0.0510 | 1,609.79  | 23.268  | 49284.1             | 222157              | 6.301 | 0.031       | 0.490    |
| 17         | 12.653              | 0.006997 | 0.0503 | 1,639.25  | 23.785  | 49852.5             | 227088              | 6.371 | 0.031       | 0.486    |
| 18         | 12.533              | 0.012729 | 0.0509 | 1,629.50  | 23.418  | 50513.3             | 223584              | 6.454 | 0.031       | 0.498    |
| 19         | 11.806              | 0.031952 | 0.0546 | 1,549.54  | 22.999  | 46433.0             | 219582              | 5.928 | 0.031       | 0.468    |
| 20         | 11.136              | 0.055562 | 0.0590 | 1,470.72  | 22.683  | 43557.5             | 216569              | 5.558 | 0.031       | 0.445    |
| 21         | 10.392              | 0.089591 | 0.0652 | 1,380.98  | 22.365  | 39208.6             | 213536              | 5.001 | 0.031       | 0.409    |
| 22         | 4.992               | 0.260945 | 0.1699 | 653.61    | 11.871  | 21748.2             | 113340              | 2.784 | 0.031       | 0.418    |
| 23         | 4.815               | 0.282549 | 0.1811 | 631.72    | 11.644  | 22060.6             | 111174              | 2.824 | 0.031       | 0.429    |
| 24         | 4.505               | 0.326471 | 0.2061 | 591.49    | 10.923  | 20120.4             | 104292              | 2.576 | 0.031       | 0.418    |
| 25         | 4.566               | 0.344577 | 0.2082 | 601.61    | 11.168  | 19835.1             | 106626              | 2.539 | 0.031       | 0.405    |
| 26         | 4.955               | 0.324258 | 0.1866 | 650.85    | 12.024  | 22214.8             | 114804              | 2.844 | 0.031       | 0.419    |
| 27         | 5.184               | 0.346127 | 0.1837 | 683.62    | 12.672  | 21314.2             | 120991              | 2.729 | 0.031       | 0.387    |
| 28         | 4.592               | 0.3938   | 0.2217 | 611.17    | 11.665  | 18661.0             | 111377              | 2.388 | 0.031       | 0.369    |
| 29         | 4.979               | 0.371236 | 0.2016 | 647.92    | 11.513  | 21789.2             | 109923              | 2.794 | 0.031       | 0.431    |
| 30         | 5.119               | 0.394619 | 0.2021 | 671.24    | 12.201  | 20735.2             | 116493              | 2.657 | 0.031       | 0.392    |

## Appendix D: Single- and two-phase calculated data (continued).

Channel E: Water-helium tests. Number of channels: 9

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 74.910 Hyd. Diameter ( $\mu\text{m}$ ): 79.991Width ( $\mu\text{m}$ ): 85.81 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu     | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|--------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |        | U f (%)     | U Nu (%) |
| 1          | 6.134               | 0.000746 | 0.1023 | 800.92    | 12.841  | 28451.7             | 122601              | 3.633  | 0.031       | 0.250    |
| 2          | 6.599               | 0.001452 | 0.0947 | 865.77    | 13.844  | 30312.1             | 132181              | 3.869  | 0.031       | 0.247    |
| 3          | 5.766               | 0.003037 | 0.1082 | 758.60    | 12.143  | 25734.9             | 115937              | 3.284  | 0.031       | 0.240    |
| 4          | 6.939               | 0.00562  | 0.0912 | 902.95    | 13.570  | 29642.2             | 129565              | 3.787  | 0.031       | 0.249    |
| 5          | 6.677               | 0.010206 | 0.0958 | 863.64    | 12.470  | 27242.6             | 119062              | 3.483  | 0.031       | 0.251    |
| 6          | 6.485               | 0.021816 | 0.1004 | 834.13    | 11.774  | 23485.9             | 112410              | 3.004  | 0.031       | 0.234    |
| 7          | 6.182               | 0.033362 | 0.1072 | 790.35    | 10.909  | 20924.0             | 104151              | 2.679  | 0.031       | 0.228    |
| 8          | 8.655               | 0.000578 | 0.0711 | 1,151.87  | 21.823  | 37094.5             | 208363              | 4.727  | 0.031       | 0.194    |
| 9          | 8.618               | 0.001019 | 0.0712 | 1,150.75  | 21.588  | 36906.1             | 206113              | 4.702  | 0.031       | 0.195    |
| 10         | 8.530               | 0.001972 | 0.0717 | 1,144.30  | 21.139  | 36123.5             | 201828              | 4.600  | 0.031       | 0.196    |
| 11         | 8.427               | 0.004342 | 0.0724 | 1,135.46  | 20.894  | 34785.8             | 199486              | 4.427  | 0.031       | 0.191    |
| 12         | 8.284               | 0.008146 | 0.0739 | 1,116.68  | 20.386  | 32778.9             | 194639              | 4.172  | 0.031       | 0.186    |
| 13         | 7.160               | 0.019455 | 0.0863 | 967.63    | 17.857  | 26219.7             | 170495              | 3.336  | 0.031       | 0.173    |
| 14         | 11.360              | 0.000457 | 0.0554 | 1,479.04  | 23.534  | 45278.4             | 224693              | 5.783  | 0.031       | 0.222    |
| 15         | 11.427              | 0.000814 | 0.0547 | 1,498.86  | 23.693  | 45206.5             | 226210              | 5.770  | 0.031       | 0.221    |
| 16         | 11.504              | 0.0014   | 0.0542 | 1,511.48  | 23.076  | 44250.8             | 220322              | 5.647  | 0.031       | 0.223    |
| 17         | 11.058              | 0.003639 | 0.0565 | 1,455.32  | 21.808  | 41253.1             | 208217              | 5.263  | 0.031       | 0.221    |
| 18         | 10.568              | 0.006733 | 0.0591 | 1,394.47  | 20.961  | 38689.9             | 200132              | 4.935  | 0.031       | 0.216    |
| 19         | 9.822               | 0.013858 | 0.0640 | 1,298.01  | 19.948  | 34416.8             | 190453              | 4.389  | 0.031       | 0.204    |
| 20         | 37.627              | 0.001858 | 0.0399 | 5,055.33  | 66.396  | 78629.4             | 633927              | 10.012 | 0.031       | 0.165    |
| 21         | 37.218              | 0.002879 | 0.0400 | 4,972.80  | 61.903  | 70146.1             | 591031              | 8.937  | 0.031       | 0.165    |
| 22         | 36.041              | 0.003956 | 0.0404 | 4,827.05  | 62.405  | 71215.5             | 595827              | 9.071  | 0.031       | 0.163    |
| 23         | 35.254              | 0.005103 | 0.0406 | 4,728.15  | 60.463  | 69852.0             | 577281              | 8.896  | 0.031       | 0.165    |
| 24         | 34.423              | 0.006289 | 0.0409 | 4,593.99  | 56.931  | 63749.6             | 543558              | 8.123  | 0.031       | 0.165    |
| 25         | 53.416              | 0.000604 | 0.0366 | 7,122.66  | 81.433  | 85108.0             | 777496              | 10.845 | 0.031       | 0.166    |
| 26         | 52.832              | 0.001333 | 0.0367 | 7,061.31  | 82.945  | 86925.6             | 791932              | 11.074 | 0.031       | 0.164    |
| 27         | 51.241              | 0.002087 | 0.0370 | 6,846.96  | 81.473  | 84418.4             | 777875              | 10.755 | 0.031       | 0.162    |
| 28         | 50.549              | 0.002832 | 0.0369 | 6,869.00  | 79.115  | 82722.3             | 755366              | 10.520 | 0.031       | 0.164    |
| 29         | 48.880              | 0.003665 | 0.0373 | 6,633.22  | 75.715  | 78941.3             | 722902              | 10.041 | 0.031       | 0.165    |
| 30         | 47.653              | 0.004541 | 0.0375 | 6,465.20  | 78.338  | 80115.9             | 747941              | 10.190 | 0.031       | 0.158    |
| 31         | 66.651              | 0.000497 | 0.0346 | 8,853.35  | 81.637  | 99461.4             | 779448              | 12.679 | 0.031       | 0.201    |
| 32         | 64.656              | 0.001092 | 0.0349 | 8,595.13  | 80.782  | 98923.3             | 771278              | 12.609 | 0.031       | 0.199    |
| 33         | 64.025              | 0.001682 | 0.0350 | 8,509.78  | 81.183  | 100085.8            | 775113              | 12.758 | 0.031       | 0.198    |

Appendix D: Single- and two-phase calculated data (continued).

Channel E: Water-Nitrogen tests.      Number of channels:      9  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      74.910      Hyd. Diameter ( $\mu\text{m}$ ):      79.991  
 Width ( $\mu\text{m}$ ):      85.81      Channel Length (m):      0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|-------------|-------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U f         | U Nu  |
|            |                     |          |        |           |         |                     |                     |       | (%)         | (%)   |
| 1          | 5.339               | 0.003374 | 0.1147 | 718.78    | 13.955  | 23791.7             | 133237              | 3.039 | 0.031       | 0.194 |
| 2          | 5.300               | 0.008109 | 0.1154 | 720.61    | 13.281  | 23017.2             | 126804              | 2.952 | 0.031       | 0.197 |
| 3          | 4.858               | 0.016291 | 0.1267 | 667.43    | 12.027  | 21252.8             | 114830              | 2.747 | 0.031       | 0.201 |
| 4          | 5.678               | 0.032358 | 0.1112 | 784.97    | 13.069  | 24073.6             | 124777              | 3.164 | 0.031       | 0.210 |
| 5          | 5.058               | 0.06762  | 0.1294 | 724.77    | 11.772  | 19820.9             | 112395              | 2.699 | 0.031       | 0.193 |
| 6          | 4.787               | 0.110264 | 0.1431 | 717.11    | 10.776  | 16831.6             | 102888              | 2.396 | 0.031       | 0.182 |
| 7          | 7.290               | 0.002999 | 0.0836 | 984.75    | 20.836  | 31271.8             | 198938              | 3.992 | 0.031       | 0.172 |
| 8          | 7.236               | 0.006644 | 0.0849 | 976.75    | 19.249  | 31126.2             | 183788              | 3.989 | 0.031       | 0.185 |
| 9          | 7.968               | 0.010006 | 0.0769 | 1,085.26  | 21.237  | 34036.9             | 202760              | 4.373 | 0.031       | 0.183 |
| 10         | 7.377               | 0.023078 | 0.0839 | 1,020.52  | 19.405  | 29828.0             | 185277              | 3.880 | 0.031       | 0.177 |
| 11         | 7.593               | 0.048074 | 0.0833 | 1,079.83  | 19.721  | 29869.2             | 188291              | 3.981 | 0.031       | 0.175 |
| 12         | 7.386               | 0.075474 | 0.0879 | 1,082.40  | 19.133  | 26499.5             | 182677              | 3.630 | 0.031       | 0.162 |
| 13         | 10.469              | 0.00182  | 0.0587 | 1,398.47  | 26.738  | 42193.0             | 255289              | 5.385 | 0.031       | 0.182 |
| 14         | 10.611              | 0.004108 | 0.0577 | 1,430.27  | 26.633  | 43035.6             | 254286              | 5.501 | 0.031       | 0.186 |
| 15         | 10.415              | 0.007857 | 0.0588 | 1,412.61  | 26.013  | 41018.3             | 248363              | 5.260 | 0.031       | 0.183 |
| 16         | 10.510              | 0.017202 | 0.0585 | 1,446.98  | 26.224  | 40338.7             | 250375              | 5.216 | 0.031       | 0.179 |
| 17         | 10.219              | 0.035881 | 0.0612 | 1,434.49  | 25.034  | 37126.8             | 239013              | 4.889 | 0.031       | 0.174 |
| 18         | 9.607               | 0.054546 | 0.0661 | 1,377.33  | 23.837  | 34120.1             | 227589              | 4.576 | 0.031       | 0.168 |
| 19         | 4.004               | 0.215805 | 0.1953 | 668.82    | 8.354   | 16709.2             | 79762               | 2.683 | 0.031       | 0.224 |
| 20         | 4.858               | 0.182026 | 0.1550 | 777.08    | 10.215  | 21268.0             | 97525               | 3.283 | 0.031       | 0.232 |
| 21         | 4.230               | 0.215897 | 0.1874 | 696.82    | 8.350   | 17712.5             | 79720               | 2.849 | 0.031       | 0.237 |
| 22         | 4.759               | 0.1945   | 0.1631 | 760.42    | 9.479   | 20204.1             | 90506               | 3.170 | 0.031       | 0.238 |
| 23         | 4.482               | 0.214879 | 0.1773 | 734.24    | 8.923   | 18700.2             | 85193               | 3.005 | 0.031       | 0.234 |
| 24         | 4.753               | 0.204562 | 0.1653 | 767.93    | 9.577   | 20172.1             | 91439               | 3.203 | 0.031       | 0.235 |
| 25         | 4.764               | 0.208432 | 0.1663 | 770.64    | 9.413   | 17964.9             | 89868               | 2.866 | 0.031       | 0.216 |
| 26         | 4.208               | 0.243076 | 0.1969 | 708.73    | 8.085   | 15338.5             | 77197               | 2.553 | 0.031       | 0.215 |
| 27         | 4.452               | 0.232695 | 0.1844 | 737.05    | 8.503   | 15966.6             | 81181               | 2.625 | 0.031       | 0.214 |
| 28         | 4.275               | 0.245873 | 0.1954 | 719.04    | 8.157   | 15409.0             | 77877               | 2.575 | 0.031       | 0.215 |
| 29         | 4.925               | 0.224881 | 0.1645 | 809.63    | 9.766   | 18184.4             | 93242               | 2.960 | 0.031       | 0.211 |

Appendix D: Single- and two-phase calculated data (continued).

Channel F: Argon gas tests.                      Number of channels:                      11  
Channel Dimensions:  
Depth ( $\mu\text{m}$ ):                      54.090                      Hyd. Diameter ( $\mu\text{m}$ ):                      55.99  
Width ( $\mu\text{m}$ ):                      58.02                      Channel Length (m):                      0.0635

| Data Point |         |        |          |         | Heat Trans.         |                     |          |       |       |
|------------|---------|--------|----------|---------|---------------------|---------------------|----------|-------|-------|
|            | Re      | f      | Velocity | Q       | coeff.              | Heat Flux           | Nu       | U-f   | U-Nu  |
|            |         |        | (m/s)    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |          |       |       |
| 1          | 145.7   | 0.1223 | 24.67    | 0.0008  | 0.551               | 8.28                | 0.001706 | 0.031 | 1.137 |
| 2          | 347.7   | 0.0853 | 38.84    | 0.0061  | 4.396               | 63.99               | 0.013568 | 0.031 | 0.367 |
| 3          | 701.6   | 0.0483 | 57.31    | 0.0273  | 21.578              | 287.59              | 0.066371 | 0.031 | 0.187 |
| 4          | 1.078.9 | 0.0330 | 72.52    | 0.0579  | 48.464              | 609.87              | 0.148828 | 0.031 | 0.154 |
| 5          | 1.410.0 | 0.0283 | 80.73    | 0.0897  | 76.046              | 944.59              | 0.233531 | 0.031 | 0.144 |
| 6          | 1.907.0 | 0.0190 | 100.20   | 0.1361  | 118.997             | 1432.59             | 0.365207 | 0.031 | 0.141 |
| 7          | 2.087.5 | 0.0184 | 102.90   | 0.1640  | 146.931             | 1726.11             | 0.450804 | 0.031 | 0.141 |
| 8          | 2.174.9 | 0.0184 | 103.58   | 0.1842  | 167.045             | 1939.67             | 0.512552 | 0.031 | 0.140 |
| 9          | 2.306.9 | 0.0177 | 106.40   | 0.2159  | 194.249             | 2273.51             | 0.596349 | 0.031 | 0.139 |
| 10         | 2.423.4 | 0.0167 | 110.05   | 0.2660  | 241.600             | 2800.32             | 0.741957 | 0.031 | 0.133 |
| 11         | 2.521.8 | 0.0158 | 113.72   | 0.3013  | 279.402             | 3171.87             | 0.858105 | 0.031 | 0.134 |
| 12         | 2.576.9 | 0.0152 | 116.18   | 0.3248  | 308.825             | 3419.38             | 0.948449 | 0.031 | 0.136 |
| 13         | 2.604.6 | 0.0149 | 117.89   | 0.3697  | 348.375             | 3892.05             | 1.070968 | 0.031 | 0.133 |
| 14         | 2.613.0 | 0.0146 | 119.28   | 0.4038  | 386.212             | 4251.42             | 1.187753 | 0.031 | 0.133 |
| 15         | 2.670.9 | 0.0137 | 123.44   | 0.4438  | 429.733             | 4672.60             | 1.322483 | 0.031 | 0.134 |
| 16         | 5.082.5 | 0.0557 | 108.95   | 1.0864  | 459.665             | 7409.76             | 6.401325 | 0.031 | 0.135 |
| 17         | 2.676.9 | 0.0133 | 125.11   | 0.4768  | 472.083             | 5019.47             | 1.453480 | 0.031 | 0.139 |
| 18         | 2.680.5 | 0.0129 | 127.17   | 0.4950  | 504.079             | 5211.54             | 1.552640 | 0.031 | 0.139 |
| 19         | 2.686.9 | 0.0125 | 129.58   | 0.5337  | 551.076             | 5618.95             | 1.699199 | 0.031 | 0.139 |



Appendix D: Single- and two-phase calculated data (continued).

Channel F: Helium gas tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.090

Hyd. Diameter ( $\mu\text{m}$ ): 55.99

Width ( $\mu\text{m}$ ): 58.02

Channel Length (m): 0.0635

| Data Point | Re      | f      | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   | Heat Flux<br>(W/m <sup>2</sup> ) | Nu        | Uncertainty |             |
|------------|---------|--------|-------------------|--------------|-------------------------------|----------------------------------|-----------|-------------|-------------|
|            |         |        |                   |              | coeff.<br>W/m <sup>2</sup> -K |                                  |           | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 9.2     | 6.8701 | 11.31             |              |                               |                                  |           |             |             |
| 2          | 26.7    | 2.2902 | 23.32             |              |                               |                                  |           |             |             |
| 3          | 44.7    | 1.2444 | 33.34             | 0.0007       | 0.396                         | 7.30                             | 0.0001439 | 0.031       | 3.030       |
| 4          | 115.8   | 0.4706 | 58.88             | 0.0193       | 13.787                        | 203.61                           | 0.0049957 | 0.031       | 0.275       |
| 5          | 192.3   | 0.2823 | 78.38             | 0.0310       | 22.614                        | 326.18                           | 0.0081979 | 0.031       | 0.275       |
| 6          | 256.9   | 0.1983 | 94.74             | 0.0517       | 39.278                        | 544.46                           | 0.0142169 | 0.031       | 0.222       |
| 7          | 347.8   | 0.1431 | 113.22            | 0.0933       | 74.924                        | 982.58                           | 0.0270628 | 0.031       | 0.173       |
| 8          | 426.5   | 0.1130 | 128.20            | 0.0934       | 71.515                        | 983.37                           | 0.0258719 | 0.031       | 0.201       |
| 9          | 501.2   | 0.0940 | 141.65            | 0.1528       | 126.215                       | 1608.59                          | 0.0455413 | 0.031       | 0.155       |
| 10         | 584.7   | 0.0791 | 155.34            | 0.2166       | 186.704                       | 2280.65                          | 0.0672798 | 0.031       | 0.137       |
| 11         | 669.6   | 0.0681 | 168.26            | 0.2632       | 235.164                       | 2771.07                          | 0.0846366 | 0.031       | 0.134       |
| 12         | 741.6   | 0.0606 | 179.04            | 0.3002       | 272.230                       | 3160.98                          | 0.0979149 | 0.031       | 0.132       |
| 13         | 825.5   | 0.0541 | 190.15            | 0.3522       | 317.155                       | 3708.04                          | 0.1140706 | 0.031       | 0.128       |
| 14         | 905.9   | 0.0488 | 200.81            | 0.3860       | 353.058                       | 4063.47                          | 0.1269252 | 0.031       | 0.128       |
| 15         | 983.7   | 0.0446 | 210.66            | 0.4182       | 382.957                       | 4402.76                          | 0.1376618 | 0.031       | 0.129       |
| 16         | 1.053.5 | 0.0418 | 218.11            | 0.4552       | 420.105                       | 4792.10                          | 0.1509887 | 0.031       | 0.128       |
| 17         | 1.140.2 | 0.0384 | 228.13            | 0.5178       | 488.405                       | 5451.28                          | 0.1754492 | 0.031       | 0.126       |
| 18         | 1.224.0 | 0.0356 | 237.50            | 0.5582       | 530.240                       | 5876.87                          | 0.1905295 | 0.031       | 0.126       |
| 19         | 1.297.5 | 0.0334 | 245.52            | 0.6142       | 597.175                       | 6466.18                          | 0.2145224 | 0.031       | 0.126       |

## Appendix D: Single- and two-phase calculated data (continued).

Channel F: Nitrogen gas tests.      Number of channels:      11  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      54.090      Hyd. Diameter ( $\mu\text{m}$ ):      55.99  
 Width ( $\mu\text{m}$ ):      58.02      Channel Length (m):      0.0635

| Data Point | Re      | f      | Velocity<br>(m/s) | Q<br>(Watts) | Heat Trans.                   | Heat Flux<br>(W/m <sup>2</sup> ) | Nu      | Uncertainty |             |
|------------|---------|--------|-------------------|--------------|-------------------------------|----------------------------------|---------|-------------|-------------|
|            |         |        |                   |              | coeff.<br>W/m <sup>2</sup> -K |                                  |         | U-f<br>(%)  | U-Nu<br>(%) |
| 1          | 55.0    | 0.7152 | 5.07E-07          | 11.22        | 0.00020                       | 0.145                            | 2.08    | 0.031       | 2.675       |
| 2          | 194.5   | 0.2003 | 1.83E-06          | 28.30        | 0.0042                        | 3.197                            | 43.84   | 0.031       | 0.464       |
| 3          | 501.1   | 0.0716 | 4.89E-06          | 53.88        | 0.0270                        | 22.831                           | 284.57  | 0.031       | 0.206       |
| 4          | 778.8   | 0.0464 | 7.86E-06          | 70.36        | 0.0524                        | 45.597                           | 552.20  | 0.031       | 0.178       |
| 5          | 999.7   | 0.0373 | 1.04E-05          | 80.61        | 0.0834                        | 75.777                           | 878.47  | 0.031       | 0.158       |
| 6          | 1,252.1 | 0.0298 | 1.36E-05          | 92.02        | 0.1152                        | 105.620                          | 1213.18 | 0.031       | 0.152       |
| 7          | 1,481.4 | 0.0251 | 1.66E-05          | 101.56       | 0.1459                        | 133.787                          | 1536.01 | 0.031       | 0.149       |
| 8          | 1,678.1 | 0.0222 | 1.95E-05          | 109.12       | 0.1766                        | 162.516                          | 1859.72 | 0.031       | 0.146       |
| 9          | 1,828.3 | 0.0208 | 2.21E-05          | 113.71       | 0.2040                        | 189.818                          | 2148.03 | 0.031       | 0.145       |
| 10         | 1,966.4 | 0.0204 | 2.53E-05          | 115.91       | 0.2395                        | 224.041                          | 2521.75 | 0.031       | 0.143       |
| 11         | 2,059.9 | 0.0203 | 2.81E-05          | 117.16       | 0.2742                        | 259.282                          | 2887.32 | 0.031       | 0.141       |
| 12         | 2,140.1 | 0.0200 | 3.1E-05           | 118.66       | 0.3147                        | 302.902                          | 3313.19 | 0.031       | 0.139       |
| 13         | 2,223.9 | 0.0193 | 3.39E-05          | 121.36       | 0.3514                        | 344.821                          | 3699.41 | 0.031       | 0.139       |
| 14         | 2,303.8 | 0.0186 | 3.76E-05          | 124.10       | 0.3909                        | 385.943                          | 4115.64 | 0.031       | 0.139       |
| 15         | 2,368.9 | 0.0178 | 3.96E-05          | 127.21       | 0.4199                        | 419.024                          | 4421.19 | 0.031       | 0.138       |
| 16         | 2,430.3 | 0.0172 | 4.31E-05          | 129.97       | 0.4595                        | 465.332                          | 4837.73 | 0.031       | 0.139       |
| 17         | 2,470.5 | 0.0167 | 4.62E-05          | 132.06       | 0.4987                        | 514.966                          | 5250.84 | 0.031       | 0.139       |
| 18         | 2,512.6 | 0.0161 | 5.06E-05          | 134.80       | 0.5464                        | 571.531                          | 5752.65 | 0.031       | 0.140       |

Appendix D: Single- and two-phase calculated data (continued).

Channel F: Water tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.090      Hyd. Diameter ( $\mu\text{m}$ ): 55.99

Width ( $\mu\text{m}$ ): 58.02      Channel Length (m): 0.0635

| Data Point | Re     | f      | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |       |
|------------|--------|--------|---------|---------------------|---------------------|-------|-------------|-------|
|            |        |        |         |                     |                     |       | U-f         | U_Nu  |
|            |        |        | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | (%)         | (%)   |
| 1          | 364.88 | 0.0723 | 10.245  | 15,046              | 107865              | 1.340 | 0.031       | 0.152 |
| 2          | 398.96 | 0.0641 | 11.237  | 17,194              | 118310              | 1.531 | 0.031       | 0.157 |
| 3          | 431.38 | 0.0570 | 12.115  | 18,967              | 127553              | 1.689 | 0.031       | 0.161 |
| 4          | 415.62 | 0.0631 | 11.621  | 18,533              | 122346              | 1.651 | 0.031       | 0.163 |
| 5          | 450.05 | 0.0561 | 12.956  | 20,932              | 136404              | 1.866 | 0.031       | 0.165 |
| 6          | 468.74 | 0.0539 | 13.164  | 22,716              | 138591              | 2.024 | 0.031       | 0.175 |
| 7          | 441.04 | 0.0629 | 12.216  | 21,959              | 128611              | 1.958 | 0.031       | 0.182 |
| 8          | 457.32 | 0.0599 | 12.562  | 22,796              | 132250              | 2.034 | 0.031       | 0.183 |
| 9          | 574.01 | 0.0394 | 15.313  | 29,028              | 161218              | 2.591 | 0.031       | 0.191 |
| 10         | 551.25 | 0.0438 | 14.411  | 27,937              | 151722              | 2.495 | 0.031       | 0.196 |
| 11         | 511.03 | 0.0523 | 12.944  | 25,983              | 136279              | 2.321 | 0.031       | 0.203 |
| 12         | 530.98 | 0.0502 | 12.858  | 26,750              | 135370              | 2.392 | 0.031       | 0.210 |
| 13         | 648.20 | 0.0346 | 15.320  | 32,911              | 161294              | 2.944 | 0.031       | 0.217 |
| 14         | 572.29 | 0.0454 | 12.758  | 26,782              | 134314              | 2.398 | 0.031       | 0.214 |
| 15         | 651.52 | 0.0365 | 14.272  | 32,113              | 150261              | 2.876 | 0.031       | 0.228 |
| 16         | 674.09 | 0.0353 | 14.434  | 33,609              | 151966              | 3.011 | 0.031       | 0.236 |

Appendix D: Single- and two-phase calculated data (continued).

Channel F: Water-argon tests.      Number of channels:      11  
 Channel Dimensions:  
 Depth ( $\mu\text{m}$ ):      54.090      Hyd. Diameter ( $\mu\text{m}$ ):      55.99  
 Width ( $\mu\text{m}$ ):      58.02      Channel Length (m):      0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U f (%)     | U Nu (%) |
| 1          | 6.009               | 0.011125 | 0.1432 | 576.32    | 12.011  | 18469.8             | 126450              | 1.642 | 0.031       | 0.159    |
| 2          | 5.904               | 0.021073 | 0.1467 | 568.39    | 11.283  | 17774.6             | 118785              | 1.580 | 0.031       | 0.163    |
| 3          | 6.953               | 0.0269   | 0.1247 | 672.58    | 13.488  | 20120.2             | 142003              | 1.787 | 0.031       | 0.156    |
| 4          | 6.032               | 0.045597 | 0.1460 | 585.69    | 11.318  | 16633.3             | 119153              | 1.477 | 0.031       | 0.155    |
| 5          | 5.847               | 0.057341 | 0.1525 | 567.75    | 11.008  | 15708.6             | 115895              | 1.395 | 0.031       | 0.151    |
| 6          | 6.072               | 0.068745 | 0.1484 | 590.64    | 11.238  | 16621.6             | 118312              | 1.476 | 0.031       | 0.156    |
| 7          | 7.098               | 0.067649 | 0.1265 | 691.92    | 13.273  | 19097.9             | 139739              | 1.696 | 0.031       | 0.152    |
| 8          | 6.078               | 0.091009 | 0.1513 | 593.58    | 11.229  | 15676.4             | 118219              | 1.392 | 0.031       | 0.149    |
| 9          | 6.501               | 0.095887 | 0.1419 | 636.35    | 12.194  | 16565.5             | 128379              | 1.471 | 0.031       | 0.145    |
| 10         | 6.582               | 0.106942 | 0.1423 | 642.75    | 12.043  | 16334.5             | 126791              | 1.451 | 0.031       | 0.146    |
| 11         | 7.132               | 0.10611  | 0.1304 | 700.62    | 13.500  | 17586.2             | 142127              | 1.561 | 0.031       | 0.140    |
| 12         | 6.727               | 0.128932 | 0.1433 | 654.23    | 12.127  | 16392.9             | 127677              | 1.457 | 0.031       | 0.146    |
| 13         | 31.165              | 0.017103 | 0.0284 | 2,923.20  | 43.282  | 50059.2             | 455682              | 4.462 | 0.031       | 0.141    |
| 14         | 31.196              | 0.035853 | 0.0286 | 2,956.84  | 46.586  | 57607.9             | 490467              | 5.130 | 0.031       | 0.143    |
| 15         | 30.715              | 0.055196 | 0.0295 | 2,927.99  | 47.424  | 60080.0             | 499285              | 5.348 | 0.031       | 0.144    |
| 16         | 30.535              | 0.074868 | 0.0303 | 2,914.96  | 47.661  | 61297.7             | 501778              | 5.457 | 0.031       | 0.145    |
| 17         | 30.226              | 0.094422 | 0.0313 | 2,877.65  | 46.443  | 58768.9             | 488954              | 5.234 | 0.031       | 0.144    |
| 18         | 29.246              | 0.117489 | 0.0337 | 2,747.15  | 40.863  | 47466.4             | 430207              | 4.234 | 0.031       | 0.141    |
| 19         | 63.081              | 0.008676 | 0.0385 | 5,851.46  | 66.229  | 74780.1             | 697268              | 6.672 | 0.031       | 0.157    |
| 20         | 60.942              | 0.01822  | 0.0388 | 5,712.27  | 67.491  | 80039.2             | 710560              | 7.134 | 0.031       | 0.157    |
| 21         | 60.823              | 0.027982 | 0.0390 | 5,670.12  | 63.486  | 72318.4             | 668390              | 6.450 | 0.031       | 0.158    |
| 22         | 59.453              | 0.038084 | 0.0393 | 5,556.20  | 64.597  | 74126.5             | 680093              | 6.611 | 0.031       | 0.155    |
| 23         | 58.733              | 0.048643 | 0.0395 | 5,496.93  | 63.203  | 73330.6             | 665407              | 6.539 | 0.031       | 0.157    |
| 24         | 57.933              | 0.059349 | 0.0398 | 5,395.78  | 60.110  | 67800.5             | 632849              | 6.050 | 0.031       | 0.158    |
| 25         | 85.558              | 0.005987 | 0.0356 | 7,958.35  | 81.870  | 86958.5             | 861937              | 7.756 | 0.031       | 0.161    |
| 26         | 85.171              | 0.01313  | 0.0357 | 7,941.59  | 83.927  | 89335.7             | 883594              | 7.967 | 0.031       | 0.158    |
| 27         | 83.159              | 0.02042  | 0.0360 | 7,752.45  | 82.982  | 87501.9             | 873651              | 7.804 | 0.031       | 0.157    |
| 28         | 82.574              | 0.02753  | 0.0359 | 7,828.88  | 81.104  | 86317.9             | 853881              | 7.685 | 0.031       | 0.159    |
| 29         | 80.429              | 0.035373 | 0.0363 | 7,615.76  | 78.179  | 83158.8             | 823081              | 7.405 | 0.031       | 0.160    |
| 30         | 79.007              | 0.043493 | 0.0365 | 7,479.80  | 81.496  | 85378.5             | 858001              | 7.604 | 0.031       | 0.153    |
| 31         | 106.654             | 0.004932 | 0.0337 | 9,882.57  | 81.998  | 99551.4             | 863285              | 8.883 | 0.031       | 0.193    |
| 32         | 104.011             | 0.010782 | 0.0340 | 9,645.79  | 81.565  | 99557.5             | 858731              | 8.883 | 0.031       | 0.191    |
| 33         | 103.536             | 0.01652  | 0.0341 | 9,600.53  | 82.396  | 101355.0            | 867479              | 9.044 | 0.031       | 0.190    |

Appendix D: Single- and two-phase calculated data (continued).

Channel F: Water-helium tests.

Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.090

Hyd. Diameter ( $\mu\text{m}$ ): 55.99

Width ( $\mu\text{m}$ ): 58.02

Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |       |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|-------------|-------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U f         | U Nu  |
|            |                     |          |        |           |         |                     |                     |       | (%)         | (%)   |
| 1          | 6.427               | 0.001368 | 0.1306 | 625.35    | 13.300  | 21013.8             | 140020              | 1.865 | 0.031       | 0.162 |
| 2          | 7.013               | 0.002162 | 0.1199 | 681.76    | 13.673  | 21116.2             | 143948              | 1.874 | 0.031       | 0.160 |
| 3          | 6.023               | 0.003809 | 0.1405 | 582.73    | 11.036  | 17843.0             | 116188              | 1.584 | 0.031       | 0.168 |
| 4          | 6.898               | 0.003821 | 0.1231 | 665.34    | 12.727  | 20883.4             | 133992              | 1.855 | 0.031       | 0.170 |
| 5          | 5.976               | 0.005908 | 0.1424 | 576.54    | 10.681  | 16951.1             | 112447              | 1.506 | 0.031       | 0.166 |
| 6          | 6.748               | 0.005732 | 0.1269 | 646.62    | 11.828  | 19234.0             | 124523              | 1.710 | 0.031       | 0.170 |
| 7          | 7.506               | 0.007325 | 0.1152 | 713.35    | 12.405  | 20446.1             | 130601              | 1.819 | 0.031       | 0.173 |
| 8          | 7.071               | 0.010534 | 0.1226 | 672.77    | 11.704  | 18795.8             | 123224              | 1.672 | 0.031       | 0.170 |
| 9          | 6.508               | 0.013425 | 0.1338 | 618.23    | 10.619  | 16936.2             | 111802              | 1.507 | 0.031       | 0.169 |
| 10         | 6.672               | 0.014565 | 0.1309 | 632.41    | 10.756  | 17105.9             | 113238              | 1.522 | 0.031       | 0.169 |
| 11         | 6.675               | 0.016876 | 0.1317 | 630.25    | 10.490  | 16618.4             | 110437              | 1.480 | 0.031       | 0.170 |
| 12         | 7.090               | 0.01769  | 0.1247 | 666.33    | 10.981  | 17478.0             | 115607              | 1.557 | 0.031       | 0.171 |
| 13         | 6.580               | 0.0229   | 0.1348 | 619.37    | 10.158  | 15424.7             | 106941              | 1.374 | 0.031       | 0.165 |
| 14         | 30.189              | 0.003716 | 0.0286 | 2,860.57  | 45.098  | 55767.7             | 474800              | 4.965 | 0.031       | 0.143 |
| 15         | 29.190              | 0.005826 | 0.0295 | 2,781.26  | 45.091  | 57124.9             | 474727              | 5.082 | 0.031       | 0.144 |
| 16         | 28.479              | 0.008052 | 0.0303 | 2,716.86  | 44.480  | 57207.4             | 468295              | 5.089 | 0.031       | 0.145 |
| 17         | 27.658              | 0.01035  | 0.0313 | 2,631.05  | 42.533  | 53822.2             | 447798              | 4.790 | 0.031       | 0.144 |
| 18         | 26.155              | 0.013177 | 0.0337 | 2,454.29  | 36.582  | 42494.1             | 385141              | 3.787 | 0.031       | 0.141 |
| 19         | 62.589              | 0.000877 | 0.0385 | 5,805.35  | 65.717  | 74202.2             | 691879              | 6.620 | 0.031       | 0.157 |
| 20         | 59.943              | 0.001858 | 0.0388 | 5,617.75  | 66.396  | 78740.1             | 699027              | 7.017 | 0.031       | 0.157 |
| 21         | 59.292              | 0.002879 | 0.0390 | 5,526.04  | 61.903  | 70515.5             | 651727              | 6.288 | 0.031       | 0.158 |
| 22         | 57.416              | 0.003956 | 0.0393 | 5,364.07  | 62.405  | 71611.2             | 657015              | 6.384 | 0.031       | 0.155 |
| 23         | 56.162              | 0.005103 | 0.0395 | 5,254.17  | 60.463  | 70152.1             | 636565              | 6.253 | 0.031       | 0.157 |
| 24         | 54.839              | 0.006289 | 0.0398 | 5,105.08  | 56.931  | 64214.5             | 599378              | 5.727 | 0.031       | 0.158 |
| 25         | 85.097              | 0.000604 | 0.0356 | 7,915.08  | 81.433  | 86494.8             | 857340              | 7.714 | 0.031       | 0.161 |
| 26         | 84.165              | 0.001333 | 0.0357 | 7,846.90  | 82.945  | 88290.8             | 873259              | 7.873 | 0.031       | 0.158 |
| 27         | 81.632              | 0.002087 | 0.0360 | 7,608.70  | 81.473  | 85910.1             | 857758              | 7.661 | 0.031       | 0.157 |
| 28         | 80.529              | 0.002832 | 0.0359 | 7,633.20  | 79.115  | 84200.8             | 832938              | 7.495 | 0.031       | 0.159 |
| 29         | 77.869              | 0.003665 | 0.0363 | 7,371.19  | 75.715  | 80537.9             | 797140              | 7.170 | 0.031       | 0.160 |
| 30         | 75.915              | 0.004541 | 0.0365 | 7,184.48  | 78.338  | 82069.7             | 824751              | 7.306 | 0.031       | 0.153 |
| 31         | 106.181             | 0.000497 | 0.0337 | 9,838.31  | 81.637  | 99114.1             | 859493              | 8.843 | 0.031       | 0.193 |
| 32         | 103.002             | 0.001092 | 0.0340 | 9,551.36  | 80.782  | 98601.4             | 850484              | 8.797 | 0.031       | 0.191 |
| 33         | 101.997             | 0.001682 | 0.0341 | 9,456.52  | 81.183  | 99863.4             | 854712              | 8.909 | 0.031       | 0.190 |

# Appendix D: Single- and two-phase calculated data (continued).

Channel F: Water-Nitrogen tests. Number of channels: 11

Channel Dimensions:

Depth ( $\mu\text{m}$ ): 54.090 Hyd. Diameter ( $\mu\text{m}$ ): 55.99

Width ( $\mu\text{m}$ ): 58.02 Channel Length (m): 0.0635

| Data Point | G                   | x        | f      | Two-phase | Q       | h - overall         | Heat Flux           | Nu    | Uncertainty |          |
|------------|---------------------|----------|--------|-----------|---------|---------------------|---------------------|-------|-------------|----------|
|            | kg/s-m <sup>2</sup> | Quality  |        | Re-avg    | (Watts) | W/m <sup>2</sup> -K | (W/m <sup>2</sup> ) |       | U f (%)     | U Nu (%) |
| 1          | 5.707               | 0.00757  | 0.1469 | 563.39    | 12.111  | 18931.9             | 127509              | 1.691 | 0.031       | 0.160    |
| 2          | 5.799               | 0.011406 | 0.1460 | 571.21    | 11.444  | 18317.7             | 120489              | 1.643 | 0.031       | 0.165    |
| 3          | 6.052               | 0.015963 | 0.1401 | 600.45    | 11.806  | 18617.0             | 124295              | 1.677 | 0.031       | 0.163    |
| 4          | 6.287               | 0.020555 | 0.1356 | 625.96    | 12.244  | 19072.0             | 128909              | 1.726 | 0.031       | 0.161    |
| 5          | 6.083               | 0.027987 | 0.1411 | 610.28    | 11.410  | 18289.9             | 120130              | 1.667 | 0.031       | 0.166    |
| 6          | 11.154              | 0.018141 | 0.0760 | 1112.10   | 21.195  | 32464.9             | 223147              | 2.929 | 0.031       | 0.159    |
| 7          | 5.806               | 0.049745 | 0.1517 | 592.21    | 10.364  | 16531.9             | 109114              | 1.540 | 0.031       | 0.166    |
| 8          | 6.262               | 0.066768 | 0.1424 | 651.93    | 11.259  | 16544.1             | 118535              | 1.567 | 0.031       | 0.154    |
| 9          | 7.358               | 0.051975 | 0.1207 | 746.93    | 12.840  | 19938.1             | 135182              | 1.863 | 0.031       | 0.163    |
| 10         | 7.257               | 0.046232 | 0.1219 | 731.37    | 12.743  | 19811.3             | 134163              | 1.841 | 0.031       | 0.163    |
| 11         | 6.092               | 0.039917 | 0.1454 | 605.95    | 10.579  | 17727.7             | 111381              | 1.638 | 0.031       | 0.174    |
| 12         | 20.576              | 0.083603 | 0.0462 | 2098.13   | 30.131  | 42521.8             | 317227              | 4.120 | 0.031       | 0.155    |
| 13         | 30.899              | 0.008625 | 0.0284 | 2922.27   | 42.640  | 49316.8             | 448925              | 4.432 | 0.031       | 0.141    |
| 14         | 30.636              | 0.018254 | 0.0286 | 2955.33   | 45.138  | 55816.9             | 475218              | 5.057 | 0.031       | 0.143    |
| 15         | 29.868              | 0.028381 | 0.0295 | 2926.44   | 45.153  | 57203.8             | 475383              | 5.231 | 0.031       | 0.144    |
| 16         | 29.392              | 0.03889  | 0.0303 | 2913.94   | 44.565  | 57316.6             | 469189              | 5.296 | 0.031       | 0.145    |
| 17         | 28.799              | 0.04955  | 0.0313 | 2877.79   | 42.638  | 53954.3             | 448898              | 5.040 | 0.031       | 0.144    |
| 18         | 27.528              | 0.062411 | 0.0337 | 2749.46   | 36.696  | 42626.9             | 386345              | 4.040 | 0.031       | 0.141    |
| 19         | 62.807              | 0.004357 | 0.0385 | 5850.35   | 65.731  | 74217.6             | 692023              | 6.649 | 0.031       | 0.157    |
| 20         | 60.387              | 0.009194 | 0.0388 | 5710.17   | 66.425  | 78774.8             | 699335              | 7.083 | 0.031       | 0.157    |
| 21         | 59.972              | 0.01419  | 0.0390 | 5667.23   | 61.945  | 70563.7             | 652172              | 6.379 | 0.031       | 0.158    |
| 22         | 58.321              | 0.019412 | 0.0393 | 5552.78   | 62.464  | 71678.4             | 657632              | 6.511 | 0.031       | 0.155    |
| 23         | 57.304              | 0.024928 | 0.0395 | 5493.19   | 60.536  | 70237.0             | 637336              | 6.414 | 0.031       | 0.157    |
| 24         | 56.214              | 0.030582 | 0.0398 | 5392.04   | 57.016  | 64310.4             | 600272              | 5.908 | 0.031       | 0.158    |
| 25         | 85.301              | 0.003003 | 0.0356 | 7957.17   | 81.445  | 86507.2             | 857463              | 7.738 | 0.031       | 0.161    |
| 26         | 84.612              | 0.006608 | 0.0357 | 7939.12   | 82.971  | 88318.7             | 873535              | 7.925 | 0.031       | 0.158    |
| 27         | 82.310              | 0.010316 | 0.0360 | 7748.88   | 81.513  | 85952.6             | 858182              | 7.741 | 0.031       | 0.157    |
| 28         | 81.438              | 0.013957 | 0.0359 | 7824.23   | 79.168  | 84257.3             | 833497              | 7.601 | 0.031       | 0.159    |
| 29         | 79.006              | 0.018005 | 0.0363 | 7610.33   | 75.781  | 80607.9             | 797833              | 7.302 | 0.031       | 0.160    |
| 30         | 77.289              | 0.02223  | 0.0365 | 7473.77   | 78.422  | 82158.1             | 825638              | 7.473 | 0.031       | 0.153    |
| 31         | 106.391             | 0.002472 | 0.0337 | 9881.21   | 81.647  | 99125.7             | 859594              | 8.865 | 0.031       | 0.193    |
| 32         | 103.450             | 0.00542  | 0.0340 | 9642.96   | 80.803  | 98626.9             | 850704              | 8.845 | 0.031       | 0.191    |
| 33         | 102.680             | 0.008329 | 0.0341 | 9596.33   | 81.216  | 99903.3             | 855054              | 8.984 | 0.031       | 0.190    |

## BIBLIOGRAPHY

- Anderson, T.M., and I. Mudawar, 1989, "Microelectronic Cooling by Enhanced Pool Boiling of a Dielectric Fluorocarbon Liquid," *J Heat Transfer*, v111, August, pp. 752-759.
- Babin, B.R., G.P. Peterson, and D. Wu, 1990, "Steady-State Modeling and Testing of a Micro Heat Pipe," *J Heat Transfer*, v112, pp. 595-601.
- Badran, B., J.M. Albayyari, F.M. Gerner, P. Ramadas, T. Henderson, and K.W. Baker, 1993, "Liquid-Metal Micro Heat Pipes," *Heat Pipes and Capillary Pumped Loops*, ASME HTD-v236, pp. 71-85.
- Bailey, Darin K., 1996, "An Apparatus for the Study of Friction and Heat Transfer in Microchannels," Masters of Science Thesis, Louisiana Tech University.
- Baker, Ovid, 1954, "Simultaneous Flow of Oil and Gas," *The Oil and Gas Journal*, July 26, pp. 185-195.
- Barron, Randall F., 1985, *Cryogenic Systems*, 2nd ed., Oxford Univ. Press, New York.
- Bowers, M.B., and I. Mudawar, 1994, "High Flux Boiling Low Flow Rate, Low Pressure Drop Mini-Channel and Micro-Channel Heat Sinks," *Int J Heat Mass Transfer*, v37, n2, pp. 321-332.
- Cao, Y., A. Faghri, and E.T. Mahefkey, 1993, "Micro/Miniature Heat Pipes and Operating Limitations," *Heat Pipes and Capillary Pumped Loops*, ASME HTD-v236, pp. 55-62.
- Chapra, Steven C., and Raymond P. Canale, 1985, *Numerical Methods for Engineers*, McGraw-Hill, New York.
- Choi, S.B., 1991, "Friction Factors and Heat Transfer in Microtubes," Doctor of Engineering Dissertation, Louisiana Tech University.
- Collier, J. G., 1981, *Convective Boiling and Condensation*, McGraw-Hill, New York NY.

- Cotter, T.P., 1984, "Principles and Prospects for Micro Heat Pipes," *Proc 5th Int Heat Pipe Conf*, Tsukuba, Japan, pp. 328-335.
- Drost, M.K., M.R. Beckett, and R.S. Wegeng, 1994, "Thermodynamic Evaluation of a Microscale Heat Pump," *Microscale Heat Transfer*, ASME HTD-Vol. 291, pp. 35-43.
- Duncan, A.B., and G.P. Peterson, 1994, "Review of Microscale Heat Transfer," *Appl Mech Rev*, v47, n9, September, pp. 397-428.
- Gerner, F.M., J.P. Longtin, H.T. Henderson, W.M. Hsieh, P. Ramadas, and S. Chang, 1992, "Flow and Heat Transfer Limitations in Micro Heat Pipes," *Topics in Heat Transfer - v3*, ASME HTD-v206-3, pp. 99-104.
- Harley, J., J. Pfahler, H. Bau, and J. Zemel, 1989a, "Transport Processes in Micron and Submicron Channels," *Convection Heat Transfer and Transport Processes*, ASME HTD - Vol. 116, pp. 1-5.
- Harley, J., and H. Bau, 1989b, "Fluid Flow in Micron and Submicron Size Channels," *Proceedings of the 1989 Micro Electro Mechanical Systems Workshop*, Salt Lake City, Utah, February 20-22, pp. 25-28.
- Hartnett, J. P., and M. Kostic, 1989, "Heat Transfer in Newtonian and Non-Newtonian Fluids in Rectangular Channels," *Adv Heat Transfer*, v19, pp. 247-356.
- Hayduk, W., 1981, *Encyclopedia of Fluid Mechanics, Vol. 1: Flow Phenomena and Measurement; Chapter 3: Correlation for Molecular Diffusivities in Liquids*, Gulf Press, Houston, Texas.
- He, J.G., 1988, "Experimental Investigation for Enhancing Effect of Polymeric Additives on Subcooled Nucleate Flow Boiling with Higher Velocity," Master of Science Thesis, Tsinghua University, Beijing, China.
- Holman, Jack Phillip, 1984, *Experimental Methods for Engineers*, 4<sup>th</sup> ed., McGraw-Hill, New York.
- Incropera, Frank W., and David P. DeWitt, 1985, *Fundamentals of Heat and Mass Transfer*, 2<sup>nd</sup> ed., John Wiley and Sons, New York.
- Khrustalev, D., and A. Faghri, 1994, "Thermal Analysis of a Micro Heat Pipe," *J Heat Transfer*, v116, February, pp. 189-198.



- Lockhart, R. W., and R. C. Martinelli, 1949, "Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes," *Chem Engr Progress*, v45, n1, pp. 41-48.
- Little, W.A., 1990a, "Advances in Joule-Thompson Cooling," *Adv Cryo Engr*, v35, Plenum Press, New York, pp. 1305-1314.
- Little, W.A., 1990b, "Microminiature Refrigerators for Joule-Thompson Cooling of Electronic Chips and Devices," *Adv Cryo Engr*, v35, Plenum Press, New York, pp. 1325-1333.
- Little, W.A., 1984, "Microminiature Refrigeration," *Rev Sci Instrum*, v55, n5, pp. 661-680.
- Longtin, J.P., Badran, B., and F.M. Gerner, 1992, "A One-Dimensional Model of a Micro Heat Pipe during Steady-State Operation," *Heat Transfer on the Microscale*, ASME HTD - v 200, pp. 23-33.
- Mallik, A.K., G.P. Peterson, and M.H. Weichold, 1992, "On the Use of Micro Heat Pipes as Integral Part of Semiconductor Devices," *J Elec Packaging*, v114, pp. 436-442.
- Martinelli, R. C., L. M. K. Boelter, T. H. M. Taylor, E. G. Thomsen, and E. H. Morrin, 1944, "Isothermal Pressure Drop for Two-Phase Two-Component flow in a Horizontal Pipe," *Trans ASME*, February, pp.139-151.
- Martinelli, R. C., and D. B. Nelson, 1948, "Prediction of Pressure Drop During Forced Circulation Boiling of Water," *Trans ASME*, August, pp. 695-702.
- Marto, P.J., and Lt. V.J. Lepere, USN, 1982, "Pool Boiling Heat Transfer From Enhanced Surfaces to Dielectric Fluids," *J Heat Transfer*, v104, pp. 292-299.
- McAdams, W. H., W. K. Woods, and L. C. Heroman, Jr., 1942, "Vaporization Inside Horizontal Tubes - II - Benzene-Oil Mixtures," *Trans ASME*, v64, pg. 193.
- Mudawar, I., and T.M. Anderson, 1993, "Optimization of Enhanced Surfaces for High Flux Chip Cooling by Pool Boiling," *J Electronic Packaging*, v115, pp. 89-100.
- Mudawar, I., and T.M. Anderson, 1990, "Parametric Investigation Into the Effects of Pressure, Subcooling, Surface Augmentation and Choice of Coolant on Pool Boiling in the Design of Cooling Systems for High-Power-Density Electronic Chips," *J Electronic Packaging*, v112, pp. 375-382.

- Mudawar, I., and M.B. Bowers, 1995, "Parametric Study of Ultra-High CHF in Highly Subcooled Water Flow Inside Small Diameter Tubes," Engineering Foundation Conference on Convective Flow Boiling, Banff, Alberta, April 30 - May 5, Paper II-9.
- Peng, X.F., and B.-X. Wang, 1993, "Forced Convection and Flow Boiling Heat Transfer for Liquid Flowing through Microchannels," *Int J Heat Mass Transfer*, v36, n14, pp. 3421-3427.
- Peterson, G.P., 1992, "Overview of Micro Heat Pipe Research and Development," *Appl Mech Rev*, v45, n5, pp. 175-189.
- Peterson, G.P., A.B. Duncan, and M.H. Weichold, 1993, "Experimental Investigation of Micro Heat Pipes Fabricated in Silicon Wafers," *J Heat Transfer*, v115, August, pp. 751-756.
- Peterson, G.P., A.B. Duncan, A.S. Ahmed, A.K. Mallik, and M.H. Weichold, 1991, "Experimental Investigation of Micro Heat Pipes in Silicon Wafers," *Micromechanical Sensors, Actuators, and Systems*, ASME DSC-v32, pp. 341-348.
- Pfahler, J., J. Harley, H. Bau, and J.N. Zemel, 1991, "Gas and Liquid Flow in Small Channels," *Micromechanical Sensors, Actuators, and Systems*, ASME DSC - v 32, 49-60.
- Pfahler, J., J. Harley, H. Bau, and J.N. Zemel, 1990a, "Liquid and Gas Transport in Small Channels," *Microstructures, Sensors and Actuators*, ASME DSC-v19, Dallas, Texas, Nov. 25-30, 149-157.
- Pfahler, J., J. Harley, H. Bau, and J.N. Zemel, 1990b, "Liquid Transport in Micron and Submicron Channels," *Sensors and Actuators*, A21-23, 431-434.
- Reid, Robert C., John M. Prausnitz, and Bruce E. Poling, 1987, *The Properties of Gases and Liquids*, 4<sup>th</sup> ed., McGraw-Hill, New York.
- Schenck, Hilbert Jr., 1968, *Theories of Engineering Experimentation*, 2<sup>nd</sup> ed., McGraw-Hill, New York.
- Sonntag, Richard E., and Gordon J. Van Wylen, 1991, *Introduction to Thermodynamics: Classical and Statistical*, 3rd ed., John Wiley and Sons, New York.

- Stanley, R. S., T. A. Ameel, and R.O. Warrington, 1996, "Convective Flow Boiling in Microgeometries: A Review and Applications," *Convective Flow Boiling*, Proceedings of the First International Conference on Convective Flow Boiling, Ed. John Chen, pp. 305-310.
- Suo, M., and P. Griffith, 1964, "Two-Phase Flow in Capillary Tubes," *J Basic Engr*, September, pp. 576-582.
- Swanson, L.W., and G.P. Peterson, 1995, "The Interfacial Thermodynamics of Micro Heat Pipes," *J Heat Transfer*, v117, February, pp. 195-201.
- Swanson, L.W., and G.P. Peterson, 1993, "The Interfacial Thermodynamics of the Capillary Structures in Micro Heat Pipes," *Heat Transfer on the Microscale*, ASME HTD - v253, pp.45-51.
- White, Frank M., 1986, *Fluid Mechanics*, 2<sup>nd</sup> ed., McGraw-Hill, New York.
- Wright, N., and B. Gebhart, 1989, "Enhanced Boiling on Microconfigured Surfaces," *J Electronic Packaging*, v111, pp. 112-120.
- Wu, P., and W.A. Little, 1983, "Measurement of Friction Factor for the Flow of Gases in Very Fine Channels Used for Microminature Joule-Thompson Refrigerators," *Cryogenics*, May, pp. 273-277.
- Wu, D., and G.P. Peterson, 1991a, "Transient Experimental Investigation of Micro Heat Pipes," *AIAA J ThermoPhysics*, v5, n4, Oct.-Dec., pp. 539-544.
- Wu, D., and G.P. Peterson, 1991b, "Investigation of the Transient Characteristics of a Micro Heat Pipe," *AIAA J Thermophysics*, v5, n2, April-June, pp. 129-134.
- Yu, D., R.O. Warrington, R.F. Barron, and T.A. Ameel, 1995, "An Experimental and Theoretical Investigation of Fluid Flow and Heat Transfer in Microtubes," 4th ASME/JSME Thermal Engineering Joint Conference, March, Maui, Hawaii.
- Zhukov, V.M., and I.L. Yarmak, 1990, "Transient Heat Transfer in Two-Phase Cryogenic Liquid Forced Flows Under Step Heat Flux in Narrow Channels," *Cryogenics*, v30, pp. 82-286.

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