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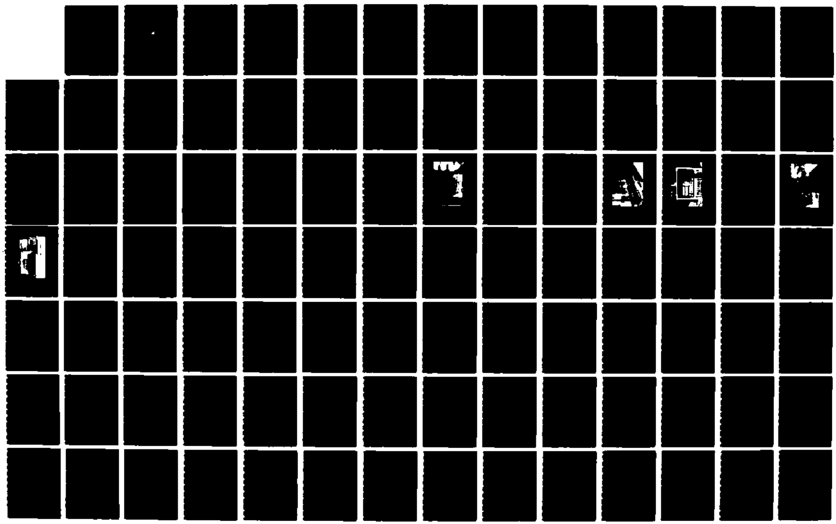

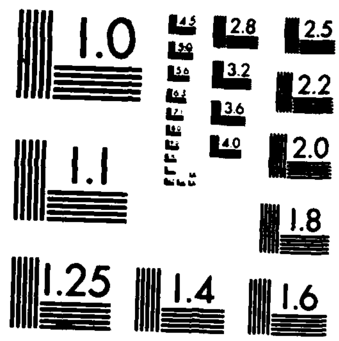

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Monterey, California

THESIS

FORCED CONVECTION HEAT TRANSFER FROM A FINNED ARRAY WITH AN ADJUSTABLE OUTER CHANNEL BOUNDARY

by

Terry L. Mellon

June 1986

Thesis Advisor: A. D. Kraus

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Forced Convection Heat Transfer from a Finned Array with an Adjustable Outer Channel Boundary

by

Terry L. Mellon
Lieutenant, USN
B.S.M.E., Vanderbilt University, Nashville, 1978

Submitted in partial fulfillment of the requirements for the degrees of

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June 1986

Author: Terry L. Mellon
Terry L. Mellon

Approved by: Allan D. Kraus
Allan D. Kraus, Thesis Advisor

P. J. Marto
Paul J. Marto, Chairman
Department of Mechanical Engineering

J N Dyer
John N. Dyer
Dean of Science and Engineering

ABSTRACT

An analysis was made of the heat transfer characteristics of an array of longitudinal fins with an adjustable outer channel boundary and a constant heat flux into the base of the array. The channel boundary could be moved to provide fin tip clearance ratios from zero to twice the fin height. Velocity variations in the inter-fin spaces and the open channel adjacent to the fin tips caused a variation in the calculated heat transfer coefficients along the height of the finned array, with the maximium coefficient occurring in the region of maximum velocity. It was shown that fin tip heat loss was a function of the clearance between the fin tip and the channel boundary, and that the maximum heat loss could occur on or near the fin tip. It was also shown how the tip heat loss affected the overall heat transfer characteristics of the array. Centerline velocity profiles and streamline profiles were developed for laminar flow with the finned array both heated and unheated. For the heated condition, two heat fluxes were used with three different clearance ratios. Temperature profiles within the fin were developed for the lower heat flux for both laminar and turbulent flow. Laminar flow results were compared to the analytical work of Acharya and Patankar.

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NOMENCLATURE

A	Crosssectional Area, in^2
c	Fin Tip to Outer Channel Boundary Distance, in
C	Dimensionless Fin Tip Clearance, c/H
C_p	Constant Pressure Specific Heat, Btu/lbm ^oF
ds	Differential Surface Area
dx	Differential Direction x
g	Acceleration of Gravity, ft/sec^2
h	Convection Heat Transfer Coefficient, Btu/hr ft^2 ^oF
$\bar{h}$	Average Heat Transfer Coefficient, Btu/hr ft^2 ^oF
H	Fin Height, in
k	Thermal Conductivity, Btu/hr ft ^oF
L	Finned Array Length, in
Q'	Heat Transfer per Unit Length, Btu/hr ft
p	Dimensionless Pressure at a Given Section, $p'/\rho(\nu/H)^2$
p'	Modified Pressure, lbf/in^2
$\bar{p}$	Mean Pressure, lbf/in^2
s	Fin Spacing, in
S	Dimensionless Fin Spacing, s/H
t	Fin Thickness, in
T	Local Air Temperature, ^oF
T_b	Finned Array Base Temperature, ^oF
T_w	Finned Array Fin Temperature, ^oF
u	x-Component of Axial Velocity, ft/sec

$\bar{u}$ Average x-Component of Axial Velocity, ft/sec

U Dimensionless u velocity, $u/(\nu/H)$

v y-Component of Axial Velocity, ft/sec

$\bar{v}$ Average y-Component of Axial Velocity, ft/sec

V Dimensionless v velocity, $v/(\nu/H)$

w z-Component of Axial Velocity, ft/sec

$\bar{w}$ Average z-Component of Axial Velocity, ft/sec

W Dimensionless u velocity, $w/(-dp/dz)(H^2/\mu)$

X Dimensionless x-direction, x/H

y Vertical Coordinate, in

Y Dimensionless Y-direction, y/H

z Axial Coordinate, in

Y Dimensionless z-direction, y/H

Greek Symbols

ρ Density, lbm/ft^3

ϕ Dimensionless Temperature, $k(T-Tw)/Q'$

μ Absolute Viscosity, lbm/ft sec

ν Kinematic Viscosity, ft^2/sec

ρ_w Density at Wall Temperature

ρ_b Density at Base Temperature

β Coefficient of Thermal Expansion, $1/^oF$

θrr Temperature Excess in the Fin, ^oF

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The author wishes to express his sincere appreciation to the staff of the Mechanical Engineering Machine Shop for their efforts in the design and construction of the test apparatus and for their patience with the seemingly endless modifications which took place.

To Professor Kraus, for his patience, encouragement and guidance throughout the course of this effort - Thank you, you helped to make it all possible.

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I. INTRODUCTION

A. BACKGROUND

The finned structures currently being used for all types of heat exchangers are comprised of a myriad of shapes and sizes, with an almost infinite variety of orientations with respect to the flow of the cooling medium. Previous investigations have not focused specifically on the experimental heat transfer characteristics of longitudinal fins encased in a variable geometry enclosure, i.e., fins operating with an adjustable outer channel boundary. Therefore, this study has been undertaken to further the understanding of the forced convection heat transfer performance of a longitudinal finned array with a moveable outer channel boundary. The study is conducted for laminar as well as for turbulent flow conditions.

B. PROBLEM FORMULATION

An analytical but seminal study of "Laminar Mixed Convection in a Shrouded Fin Array" was accomplished by Acharaya and Patankar [Ref. 1]. The first objective of this current study was the design and construction of a test apparatus capable of closely approximating Acharya and Patankar's analytical work, thus helping to verify the analytical results and to establish the credibility of the equipment design. After verification of laminar results, the same equipment was to be capable of producing turbulent flow in the finned array. It was felt that the high velocities inherent to a turbulent flow field should enchance the local heat transfer characteristics in regions of high velocity. The effect on the overall heat transfer performance of the array was also to be determined.

The basic aspects of the design were established in very general terms. It was necessary to have (1) an array of longitudinal fins, (2) a known heat input into the array, (3) an adjustable outer channel boundary, (4) induced air flow (either turbulent or laminar), and (5) some means of measuring velocity and temperature.

Given a finned surface with the accompanying channel boundary at some position that includes a fin-tip clearance (Figure 1.1), the air flow is in the longitudinal direction, along the length of the fins. The air will seek the path of least resistance, and will flow through the relatively large plenum area above the array. Theoretically, if the fin spacing could be reduced, then it logically follows that the flow imbalance would become even more severe. When combined with viscous effects, this flow imbalance will give rise to relatively low velocities near the fin base, and to relatively larger velocities near the fin tip.

If adjacent to the fin, the effect of increased velocities is to enhance the local heat transfer coefficient. Acharya and Patankar have analytically verified this effect for laminar flow conditions. However, the overall heat transfer effectiveness of the array is degraded because of low velocity areas near the base [Ref. 2]. The effect of turbulent flow is to be determined.

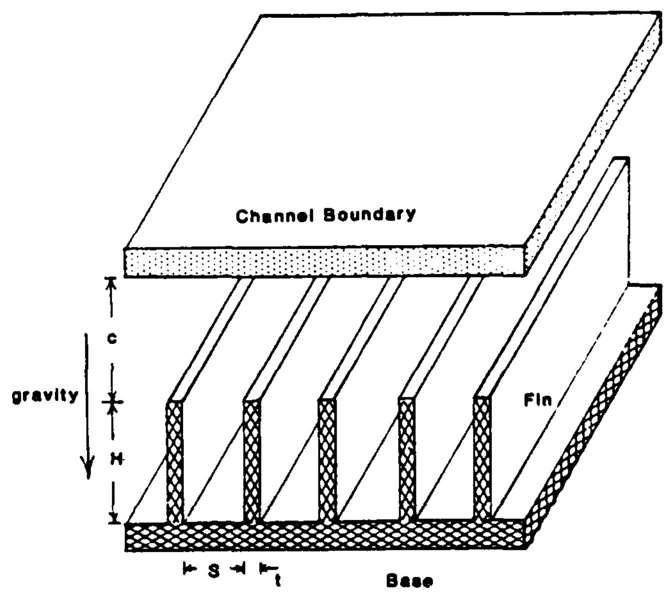


Figure 1.1 Shrouded Fin Array and Nomenclature.

C. THEORY AND ASSUMPTIONS

The elliptical flow field vastly complicates heat transfer calculations. However, the geometrical similarities of the physical problem can be used to define a typical study module, which is based on inter-fin channel symmetry lines and physical boundaries (Figure 1.2).

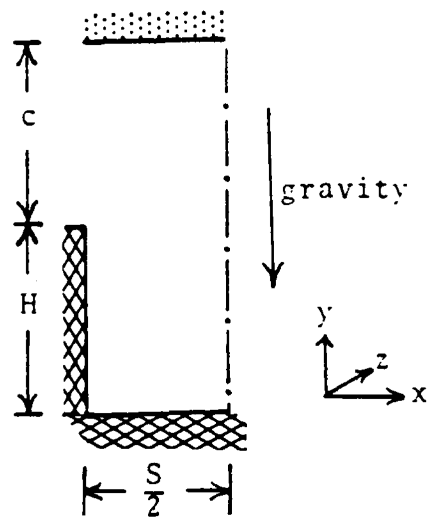


Figure 1.2 Study and Computations Typical Module.

Certain assumptions are necessary for both laminar and turbulent flow conditions. These assumptions are as follows:

1. Only fully-developed thermal and hydrodynamic conditions are considered.

2. The outer channel boundary is considered to be adiabatic when under steady state conditions.

3. The base surface and fins transfer heat at a uniform rate per unit axial length.

4. At any given cross-section, the temperature of the fin and base surface is considered to be uniform.

5. The Prandtl number of air is assumed to be 0.7, to match the work of Acharya and Patankar.

6. The thin fin assumption is valid, i.e., $t/h \ll 1$ and $t/s \ll 1$.

These assumptions are used primarily to establish the analytical problem, which in turn establishes the characteristics of the test equipment.

D. ANALYSIS

The fully-developed profiles and thermal boundary conditions imply that the temperature rise in the z-direction is linear. The overall heat balance of the domain of a particular module gives the rate of change of temperature in the z-direction as:

$$\frac{\partial T}{\partial z} = \frac{dT_w}{dz} = \frac{Q'}{\rho C_p (s/2)(H+c)w} \qquad (1.1).$$

With dimensionless variables defined by

$$X = \frac{x}{H} \qquad Y = \frac{y}{H} \qquad S = \frac{s}{H} \qquad C = \frac{c}{H} \qquad (1.2a)$$

$$U = \frac{u}{(\nu/H)} \qquad V = \frac{v}{(\nu/H)} \qquad W = \frac{w}{(-dp/dz)(H^2/\mu)} \qquad (1.2b)$$

$$P = \frac{p'}{(\nu/H)^2 \rho} \qquad \phi = \frac{(T-T_w)k}{Q'} \qquad (1.2c),$$

the conservation equations for mass, momentum and energy then become

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1.3}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \tag{1.4}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} + Gr^+\phi \tag{1.5}$$

$$U\frac{\partial W}{\partial X} + V\frac{\partial W}{\partial Y} = 1 + \frac{\partial^2 W}{\partial X^2} + \frac{\partial^2 W}{\partial Y^2} \tag{1.6}$$

$$U\frac{\partial \phi}{\partial X} + V\frac{\partial \phi}{\partial Y} = \frac{1}{Pr}\left(\frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2}\right) - \frac{2}{Pr}\left(\frac{(W/\bar{W})}{S(1+c)}\right) \tag{1.7}$$

with equations 1.2a through 1.7 being defined by Acharya and Patankar [Ref. 1].

For fully developed conditions only the magnitude of the modified Grashof number governs the heat transfer results for a fixed duct length and fin spacing [Ref. 1]. Also, the Reynolds number is not a significant factor because of the fully-developed flow condition [Ref. 3]. The modified Grashof number is defined by Acharya and Patankar [Ref. 1] as:

$$Gr^+ = \frac{g\beta Q' H^3}{\nu^2 k} \tag{1.8}$$

and is a function of the following variables:

1. The thermal properties of the cooling medium, specifically the kinematic viscosity, the thermal conductivity, and the coefficient of thermal expansion.

2. The energy transferred into the array per unit axial length.

3. The characteristic dimension, i.e., height of the fin.

With the problem thus defined, a test apparatus was designed and constructed.

II. EQUIPMENT DESIGN AND MEASUREMENT DEVICES

A. TEMPERATURE MEASUREMENT THEORY.

The Murray-Gardner Assumptions are essential to classical fin theory (Table 1)[Ref. 4:p. 344]. It is these assumptions which make an analytical solution to the problem of fin temperature and heat transfer rate possible. Consider an extended surface in constant temperature surroundings (T_s) with a known temperature at the base of the fin (T_b) (Figure 2.1).

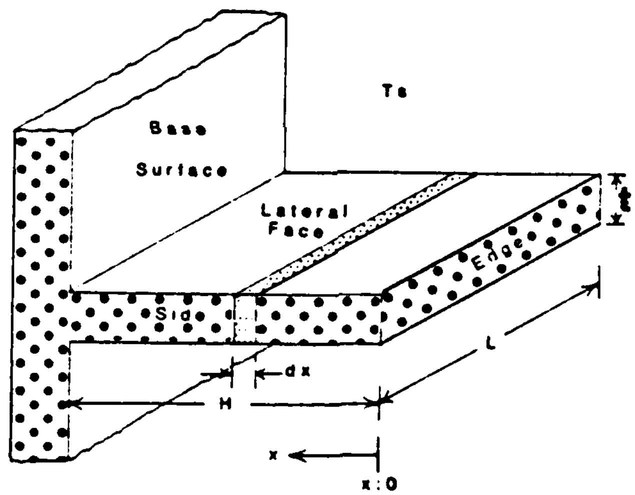


Figure 2.1 Extended Surface Profile, Terminology, and Coordinate System.

A differential element, dx, will have a cross sectional area normal to the path of heat flow given by

$$A = tL \tag{2.1}$$

TABLE 1

MURRAY-GARDNER ASSUMPTIONS FOR EXTENDED SURFACES

1. The heat flow is steady, i.e., the temperature in the fin does not vary with time.

2. The fin material is homogeneous; the thermal conductivity is constant and uniform.

3. The coefficient of heat transfer is constant and uniform over the entire face surface of the fin.

4. The temperature of the surrounding fluid is constant and uniform. Because one is dealing with cooling, this temperature is always assumed to be lower than that at any point on the fin.

5. There are no temperature gradients within the fin other than along its height. This requires that the fin length and height be great when compared with the width.

6. There is no bond resistance to the flow of heat at the base of the fin.

7. The temperature at the base of the fin is uniform and constant.

8. There are no heat sources within the fin itself.

9. Unless otherwise noted, there is a negligible amount of heat transferred by convection from the edge and sides of the fin.

and differential surface area

$$dS=2(L+t)dx \tag{2.2a}$$

which reduces to

$$dS=2Ldx \tag{2.2b}$$

if assumptions 5 and 9 of TABLE 1 are honored.

Define the temperature excess as the difference between the fin temperature at any point and the constant temperature surroundings as

$$\theta = T - T_s \tag{2.3a}$$

so that

$$d\theta = dT \tag{2.3b}$$

A simple energy balance on the differential element yields

$$-kA\frac{dT}{dx} = -kA\frac{dT}{dx} - \frac{d}{dx}\left(kA\frac{dt}{dx}\right) + 2hL\ (T - T_s)dx \tag{2.4}.$$

The differential equation for temperature excess is

$$\frac{d^2\theta}{dx^2} - m^2\theta = 0 \tag{2.5}$$

where

$$m = \left(\frac{2h}{kt}\right)^{\frac{1}{2}} \tag{2.6}.$$

The general solution to the differential equation is of the form

$$\theta(x) = C_1e^{mx} + C_2e^{-mx} \tag{2.7}$$

where the arbitrary constants C_1 and C_2 are evaluated from the boundary conditions

$$\theta = \theta_b \quad \text{at} \quad x=b \tag{2.8a}$$

$$\frac{d\theta}{dx} = 0 \quad \text{at} \quad x=0 \tag{2.8b}$$

and the particular solution is

$$\theta(x) = \theta_b \frac{\cosh mx}{\cosh mb} \tag{2.9}$$

The heat flow into the base of the fin is obtained by the derivative of equation (2.9) multiplied by the quantity $k{\cdot}A=ktL$ and evaluated at $x=b$ so that

$$q_b = ktL\theta_b \tanh mb \tag{2.10}$$

The evaluation of the temperature profile and the heat transfer at the base thus involves an evaluation of equation 2.6. This is, in turn, a function of the still-unknown surface heat transfer convection coefficient. Typical values of the convection coefficient for forced convection in gases are 50 W/m^2K - 250 W/m^2K [Ref. 5:p. 9], which is approximately 9 $BTU/hrft^2F$ - 44 $BTU/hrft^2F$. Obviously, either the convection coefficient must be determined, or some other means of determining the value of m as given by equation (2.6) must be obtained.

Examination of equation 2.9 indicates that if the temperature at two points on the fin is a known quantity, then m can be calculated by the relatively simple solution of two simultaneous equations. Thus, the first item of the equipment design is the determination of temperature measurement locations and appropriate devices.

B. LONGITUDINAL FIN ARRAY AND THERMOCOUPLE PLACEMENT

A longitudinal fin assembly with fins of rectangular profile was obtained and configured to match the requirements of the testing procedure (Figure 2.2).

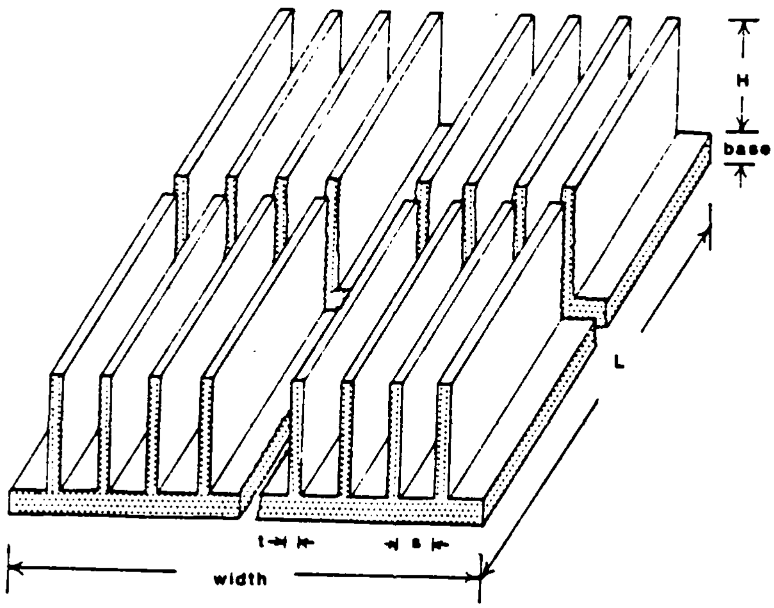
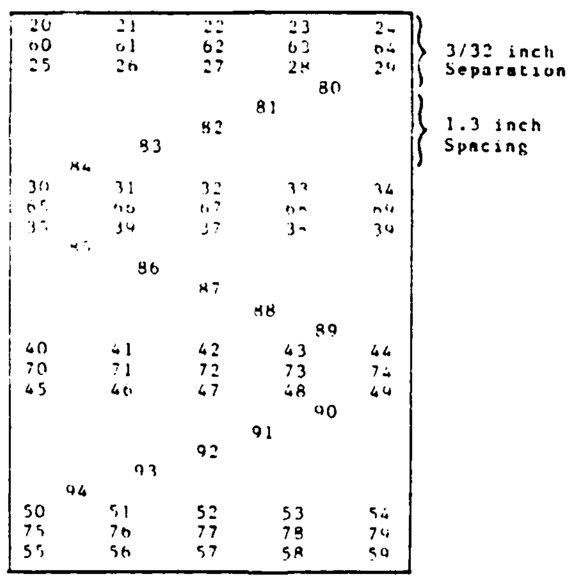


Figure 2.2 Longitudinal Fin Assembly.

The nominal length of the assembly is 15 inches with a mean fin height of 0.9177 inches and a mean fin spacing of 0.3072 inches. The mean fin thickness is 0.0838 inches, and the mean base thickness is 0.2060 inches. Appendix A presents a listing of the actual dimensions as measured on the array, including the mean values and standard deviations of each dimension. The assembly is extruded commercial aluminum.

To facilitate temperature measurement, 75 copper-constantin thermocouples were mounted in and on the array. At twenty locations, 0.035-inch holes were drilled to a depth of 0.0375 inches and 0.7500 inches with a longitudinal separation of 0.1875 inches, for a total of 40 thermocouples. An additional 35 thermocouples were surface-mounted to the fin base (Figure 2.3). Thus, 75 thermocouples, numbered 20-94, were available to obtain a two-dimensional temperature profile of the finned array.



Trailing Edge - Bottom View

#0 -#4: Set at 3/8 inch depth.
#5 -#9: Set at 3/4 inch depth.
Above 60; Surface mounted.

Figure 2.3 Thermocouple Placement Map.

An Autodata Nine data recorder with a 100 channel capability was used to record temperatures. Five additional thermocouples were used, four to provide the bulk temperature of the air downstream of the array, and a final thermocouple to provide ambient temperature. With the thermocouples installed a means of heating the unit was necessary.

C. SILICON PAD HEATER

The analytical work of Acharya and Patankar was presented for modified Grashof numbers of 10^4, 10^6, and 10^7. Assuming that air at $100^\circ F$ is the cooling medium, then the heat input can be calculated to size the heater. From Acharya and Patankar, the modified Grashof number is

$$Gr^+ = \frac{g\beta Q' H^3}{\nu^2 k} \tag{2.11}$$

However, the value of

$$\frac{g\beta\rho^2}{\mu^2} \tag{2.12}$$

is a tabulated quantity, yielding

$$Gr^+ = \left(\frac{g\beta\rho}{\mu^2}\right)\left(\frac{H^3 Q'}{k}\right) \tag{2.13}$$

Rearranging terms yields

$$Q' = \left(\frac{Gr^+ k}{H^3}\right)\left(\frac{\mu^2}{g\beta\rho^2}\right) \tag{2.14}$$

To size the silicon heater Q' was calculated in (Btu/hr-ft) and Watts (Table 2).

TABLE 2
PRELIMINARY CALCULATIONS OF HEAT INPUT TO MATCH MODIFIED GRASHOF NUMBERS.

air @ 70°F	$\frac{g\beta\rho^2}{\mu^2} = 2.38(10^6)\ \frac{1}{ft^3\,{}^\circ F}$	
	$k = 0.148\ \frac{Btu}{hr\,ft^3\,{}^\circ F}$	
fin array		H = .9177 in = .0765 ft
	Q'	Q'
Gr^+	(Btu/hr ft)	(W)
10^4	.1390	.5930
10^6	13.90	59.30
10^7	139.0	593.0

Cost and physical size requirements prohibited the use of a silicon pad heater capable of producing 600 watts. The size is nominally 6.5 x 15 inches. A heater was readily available with a nominal maximum rating of 450 W, which easily met the requirements of $Gr^+=10^4$ and $Gr^+=10^6$. Therefore, the 450W heater was chosen. Also, the power listings of Table 2 are only preliminary calculations, and the actual determination of the modified Grashof number will be an iterative process.

D. OUTER CHANNEL BOUNDARY AND INLET BELL

The design of the outer channel boundary was straight forward. The channel was to be movable and to provide a fin tip clearance of zero to twice the fin height. The physical dimensions of the channel , nominally 6.5 inches by 15 inches, and the requirement to keep it parallel to the finned array necessitated the use of machine screws. Standard 3/4-inch by 10 TPI screw threads were chosen. Positional accuracy of at least a tenth of an inch was possible, and the screws were readily available (Figure 2.4).

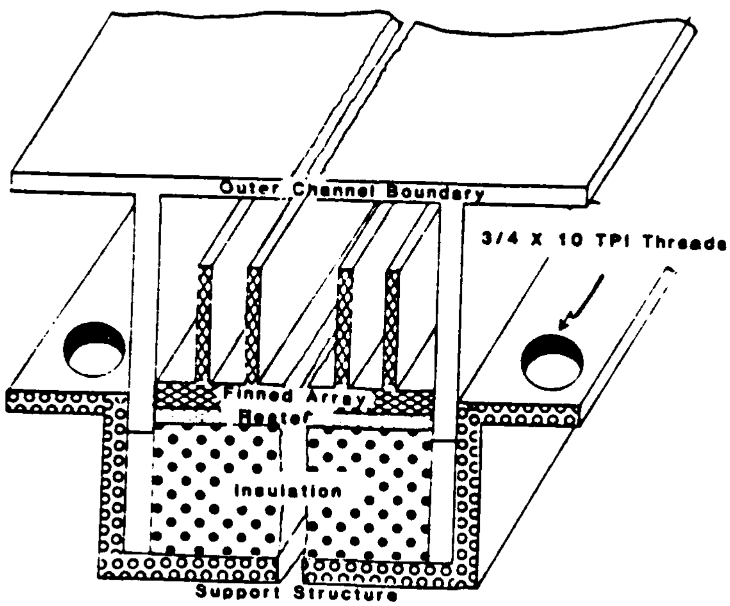


Figure 2.4 Finned Array and Outer Channel Boundary.

The inlet bell was configured to match the array inlet using

$$\frac{h}{h + 2r} = \frac{\pi}{\pi + 2} \tag{2.15}$$

attributable to Moffatt [Ref. 5]. The enclosure hieght is H, and the radius of curvature of the inlet bell is r.

For purposes of this test equipment r was chosen as the mean value for a clearance ratio of one, and the width of the array for a radius of curvature of approximately 2.5 inches. This averaging process led to a decrease in air flow for the outer fins. However, because only the center channels and fins were used, this was not thought to be a problem.

As the outer channel boundary was required to move, a gap was necessary on the lower part of the bell. This gap was sealed with putty during test runs to give a smooth inlet surface. Assembly of the finned array, the heater, all thermocouples, the support base, and the outer channel boundary (Figure 2.5) completed approximately 70 percent of the construction process.

E. DUCTING AND FAN ASSEMBLY

The connecting duct had to satisfy three requirements: (1) provide an adequate sealing surface at the moveable channel boundary, (2) be long enough to minimize the effect of the fan on the velocity profile at the exit plane of the finned array, and (3) not become unreasonably long.

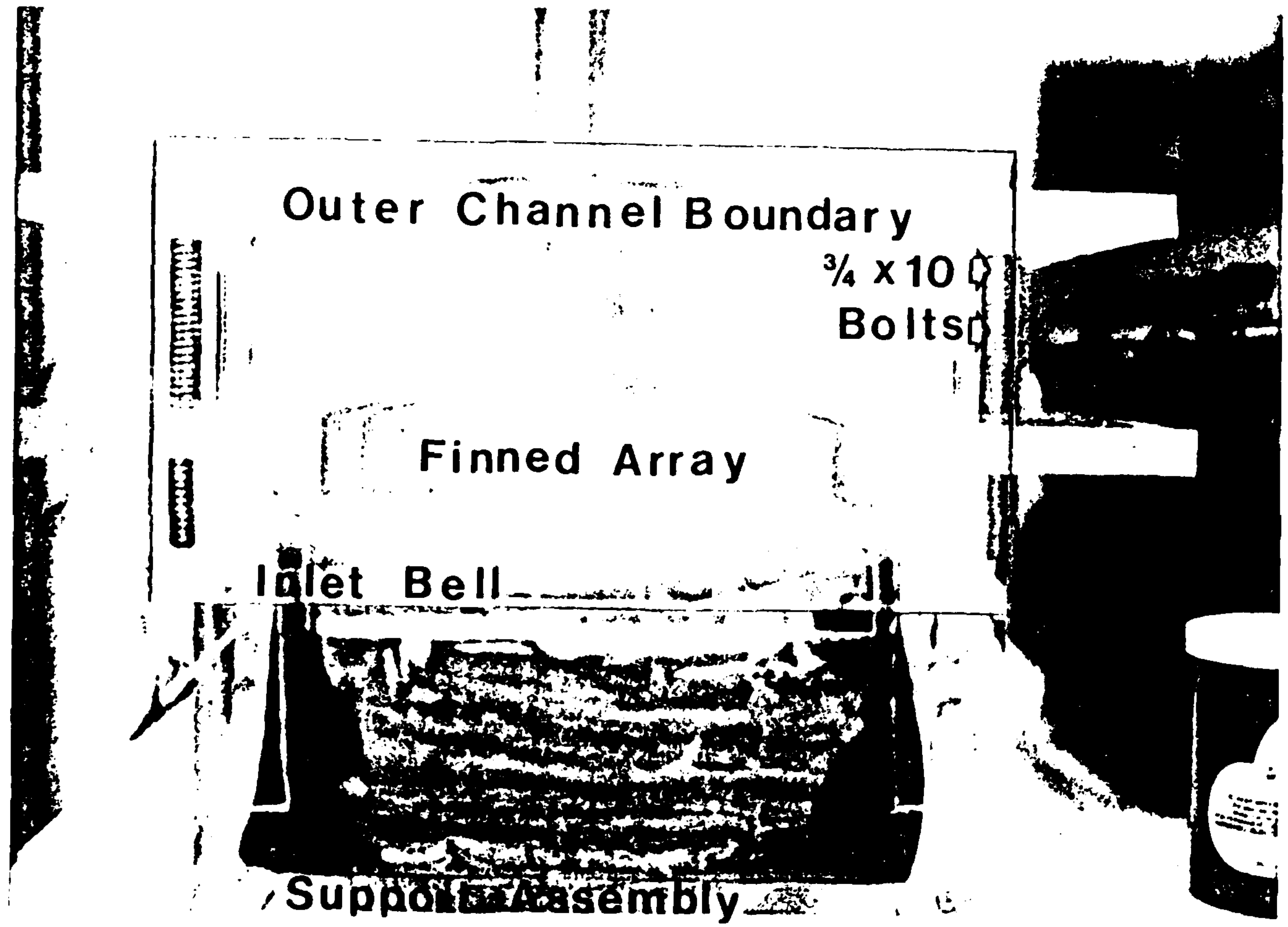


Figure 2.5 Test Assembly with Finned Array, Inlet Bell, Support Assembly, Insulation, Outer Channel Boundary, and Adjusting Bolts.

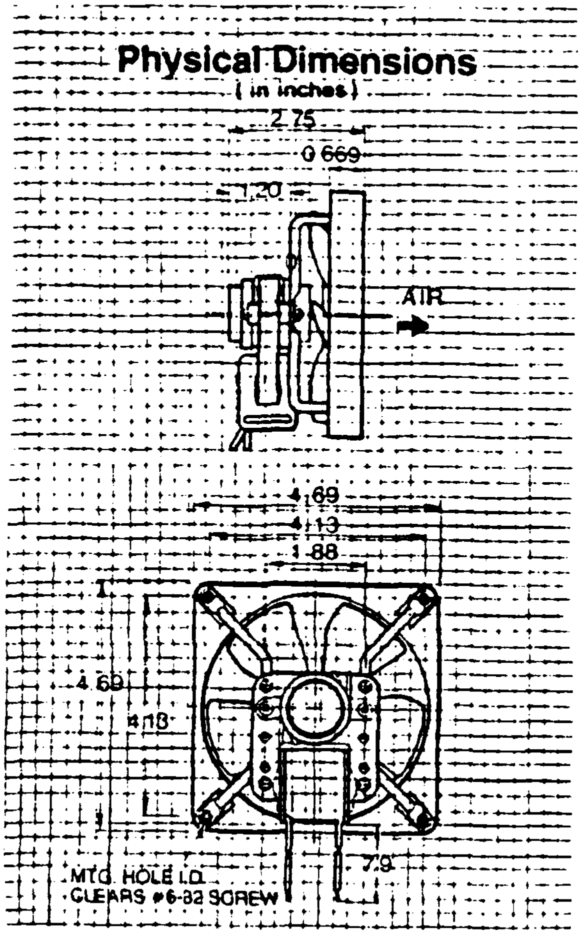
A length of ten fan diameter was chosen as a manageable value for the duct length. The inlet side of the duct was merely sized to fit the exit of the test assembly. The outlet of the duct was sized to match the fan.

The fan chosen was a 115V, 60Hz, alternating current unit capable of delivering 65 SCFM if flow was unrestricted (Figure 2.6). As a hotwire anemometer was being used to measure the velocity field directly, it was unnecessary to calculate fan discharge curves for different pressures and temperatures. It was necessary, however, to be able to control the flow rate through the test assembly. Two methods were available: (1) control the voltage and current to the fan itself, or (2) provide some means of controlling the outlet flow of the fan.

The method chosen was a set of sliding doors at the exit of the fan. These doors were capable of providing flow of approximately zero to full-fan capacity. Figure 2.7 illustrates the final construction of the test unit.

F. AUTODATA NINE

The Autodata Nine is a self-contained, 100-channel, data-recording device (Figure 2.8). Channels are on 10 wafer-style boards so that the master unit may be used to measure either voltages or temperatures with the appropriate value taken directly as output. For this test equipment, 80 channels were configured for thermocouples with direct



115 Volts, 60 Hz, Alternating Current
Rated @ 65 SCFM for Unrestricted Flow

Figure 2.6 Cooling Fan Characteristics.

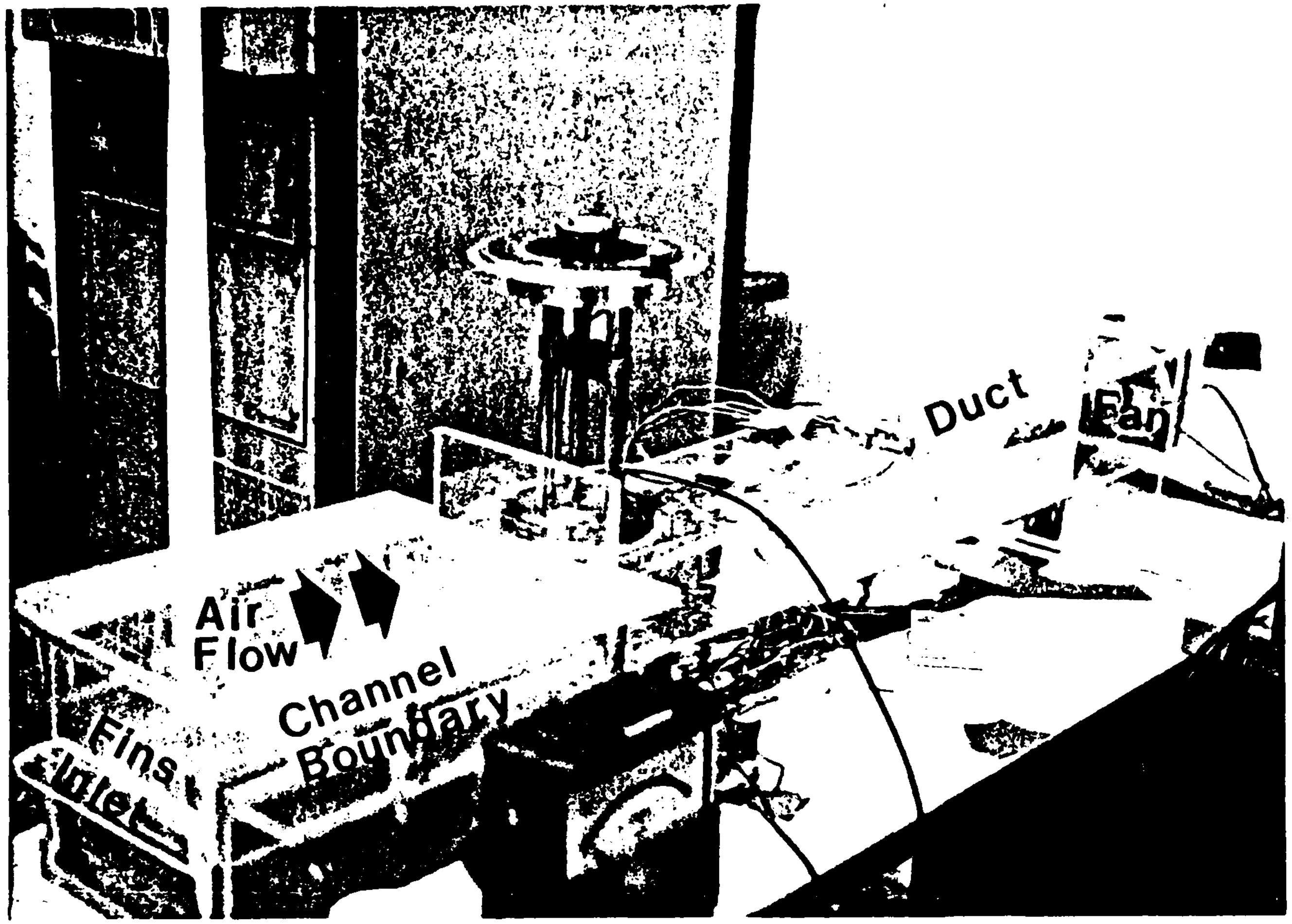


Figure 2.7 Final Assembly - Showing All Components.

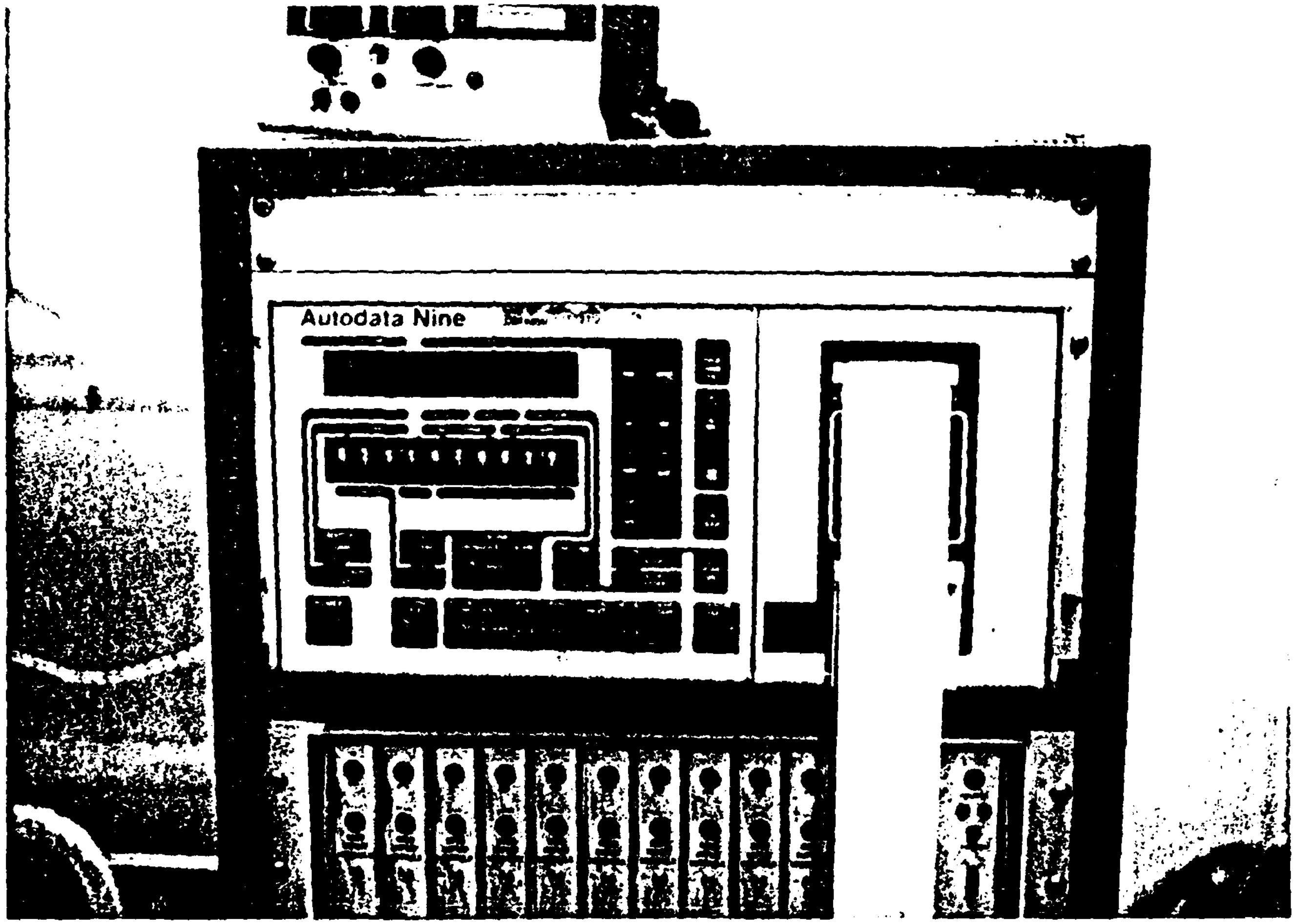


Figure 2.8 Autodata Nine Data Recorder.

readout of temperatures in ^{o}F. All 80 thermocouples and the Autodata Nine were calibrated as a system (Appendix B).

G. HOTWIRE ANEMOMETER

Use of the Hotwire Anemometer and associative equipment was generously provided by Professor P. Ligrani, of the Naval Postgraduate School. The equipment consisted of six major items: (1) hotwire probe, (2) traversing mechanism (Figure 2.9), (3) resistance bridge, (4) amplifier/filter display unit, (5) oscilloscope, and (6) manometer (Figure 2.10). The oscilloscope was not an essential item, but provided a visual indication of turbulent versus laminar flow.

The basics of the hotwire operation are in terms of electrical resistance. The wire is heated by an initial electric current and cooled by the incident flow. From the resistance of the wire, the flow velocity may be deduced. The hotwire is extremely sensitive to air motion perpendicular to the wire. It is not sensitive to air motion parallel to the wire. This information was used to aid in determining the secondary velocities of the flow field in the channel.

The hotwire is calibrated as a system using the pressure difference of the manometer. Appendix C contains a sample hotwire calibration with (1) the calibration program input, (2) the Program Listing, and (3) the program output.

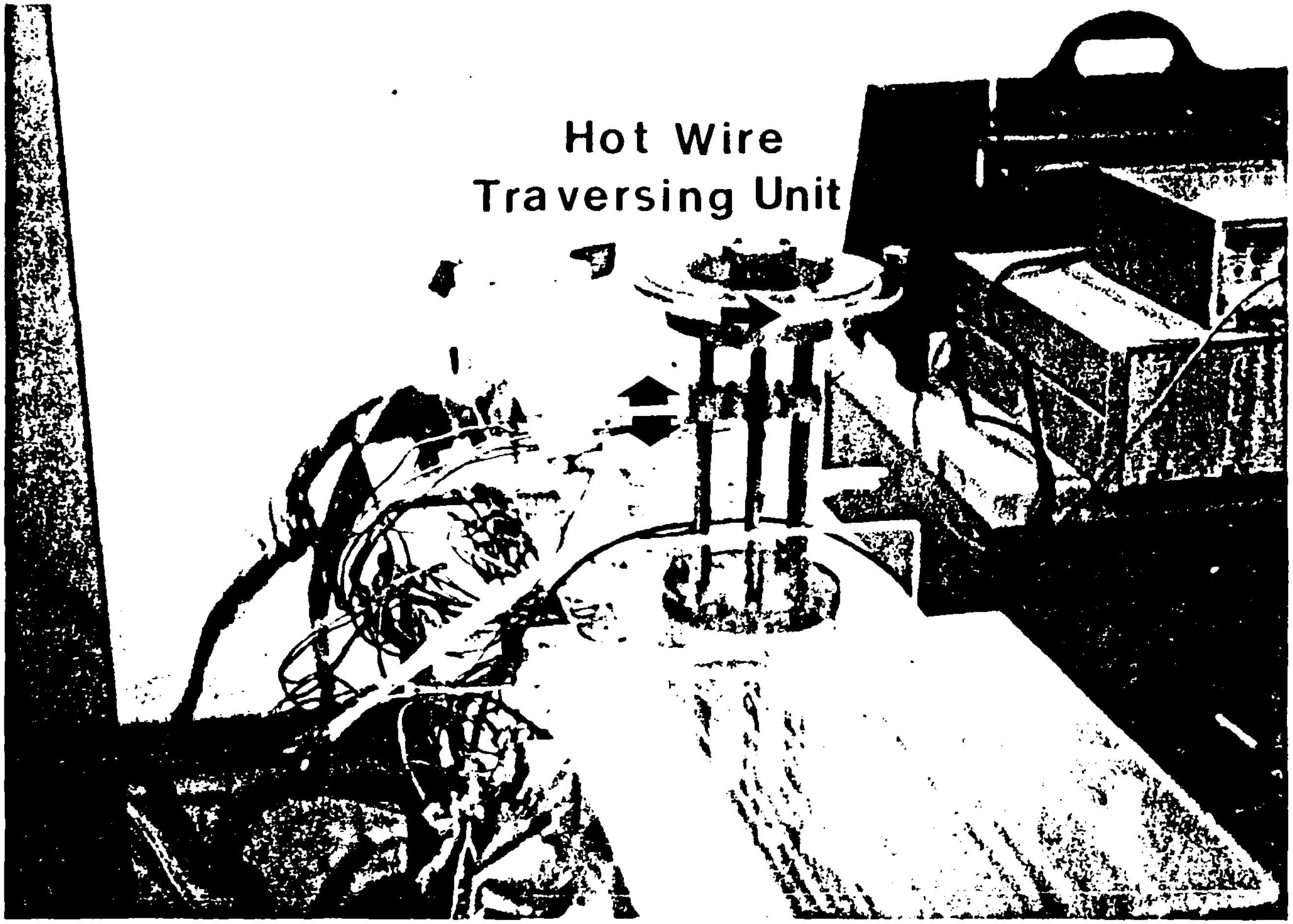


Figure 2.9 Hot Wire Anemometer Traversing Mechanism.

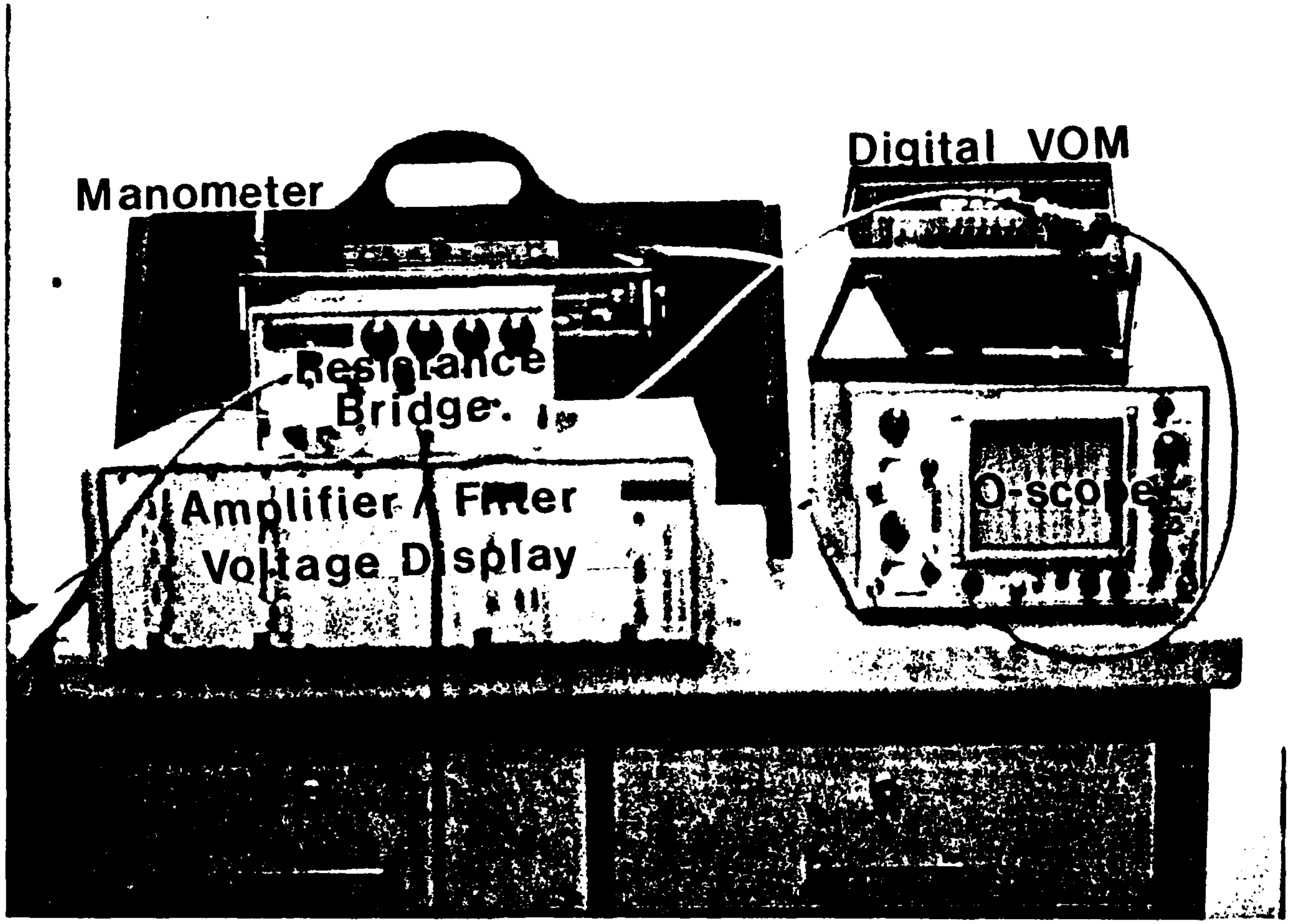


Figure 2.10 Hot Wire Anemometer Equipment.

H. SUMMARY

The equipment is varied, and a summary is provided in TABLE 3. Some items were rather crude in the initial design phase, others became superfluous as the testing progressed, and in some cases the entire test apparatus would have been made more efficient by the use of additional items. Specifics of equipment discrepancies will be discussed more fully in Chapter VI.

TABLE 3

EQUIPMENT LIST

Test Unit	Aluminum finned array 6.5 x 15 Outer channel boundary, plexiglass Support structure, plexiglass Insulation
Autodata Nine	80 copper constantine thermocouples
Anemometer	Hotwire probe Resistance bridge Digital voltage/ohm/amp meter Amplifier/filter/display for resistance bridge Oscilloscope Manometer with pressure tap Traversing mechanism
Silicon heater	Digital voltage/ohm/amp meter Analog amp meter 0-10 amps Rheostat
Fan	4-inch AC 65 SCFM fan Ducting, plexiglass Doors, plexiglass

III. LAMINAR FLOW

A. PURPOSE

Laminar flow work was done in order to provide a usable comparison to the analytical presentation of Acharya and Patankar [Ref. 1]. Specifically, comparisons at modified Grashof Numbers 10^4 and 10^6 were used with the dimensionless parameters as set forth in Reference 1. Within the accuracy and precision limitations of the equipment used, in almost all cases the correlations between test and analytical data were very good. While only figures (not tables) will be presented here, a complete listing of the data obtained for each Grashof Number as well as for each clearance ratio is included in Appendices D and E. Comparisons are presented for both centerline velocity profiles as well as for the streamline profile. An original test case is presented for a clearance ratio of 0.0, with the test unit both heated and unheated. The two heat conditions were essential in order to verify that the hot wire anemometer was capable of the precision required for further comparison.

Figure 3.1 indicates the general relationship between hotwire output voltage and actual centerline velocity in feet per second. The calculation of velocity as a function of voltage may be found in Appendix C. Note that this

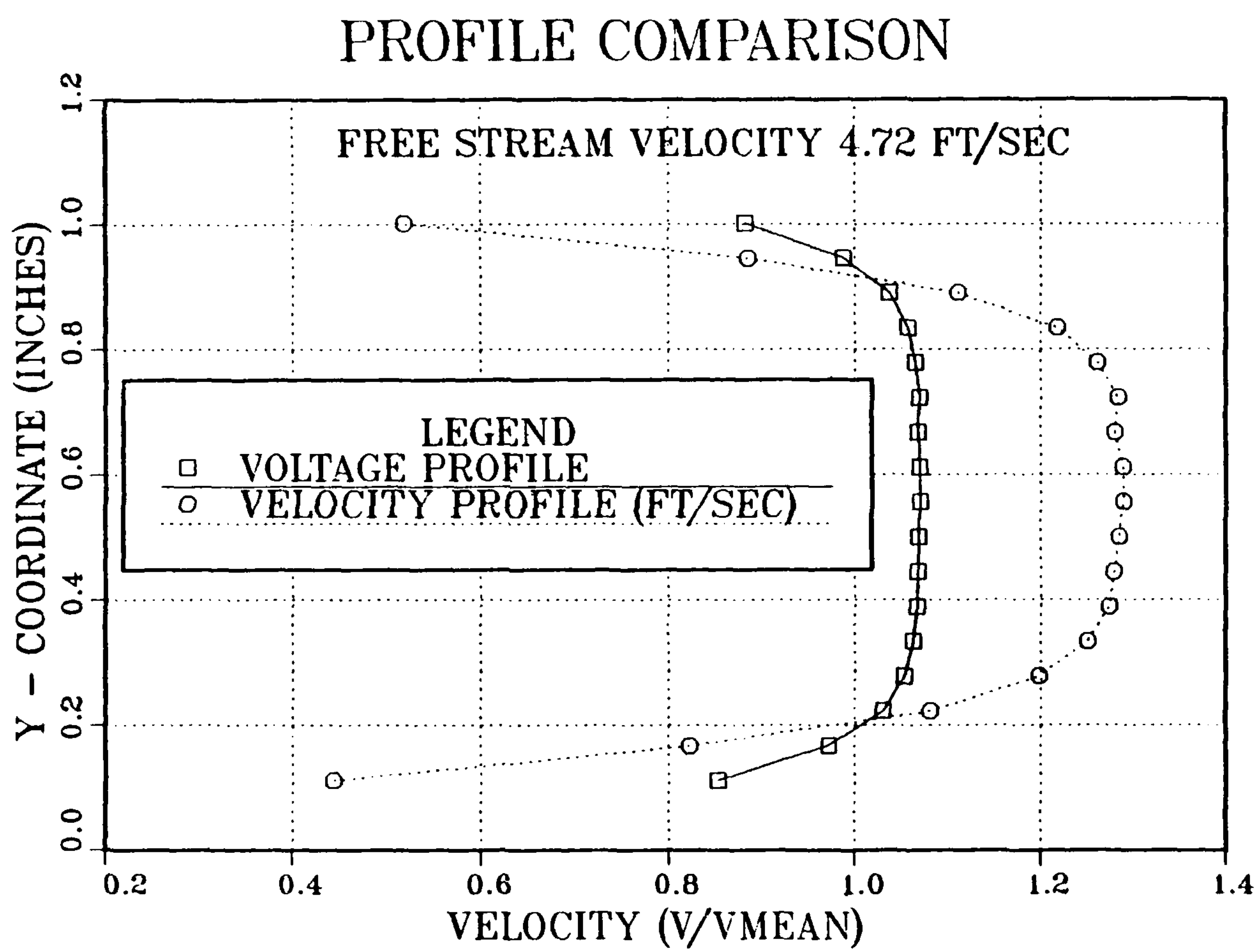


Figure 3.1 Comparison of a Centerline Velocity Profile to the Original Hot Wire Voltage Readings Profile.

figure is plotted for a velocity ratio in the axial direction; however, the perpendicular direction does not represent a ratio. Figure 3.2 offers a comparison of the centerline velocity profiles for an unheated as well as for a heated test. The unheated profile very closely approximates the expected result for pure laminar flow in a duct. The heated profile, however, suggests that an offset of the velocity profile is caused by secondary flow effects, accompanied by a general increase in the velocity ratio. For the same free-stream velocity through the finned array, the increase in mean velocity for the heated case is approximately 2 percent. This increase is due solely to the fact that the finned array is being heated.

The secondary velocities are caused by buoyancy effects, and are readily apparent in Figure 3.3, which shows both the classic streamline profile for flow in a duct, and the streamline profile for $Gr^{+}=10^{4}$. The classic profile is lost because buoyancy effects have superimposed a secondary rotational flow velocity field on the primary velocity field through the duct. Because the actual flow direction cannot be determined, the direction must be assumed.

For laminar flow work the oscilloscope was an invaluable tool. Having a direct visual indication of laminar versus turbulent velocities, which was evident in the quiescent profile of the oscilloscope trace, ensured that the required laminar conditions were met.

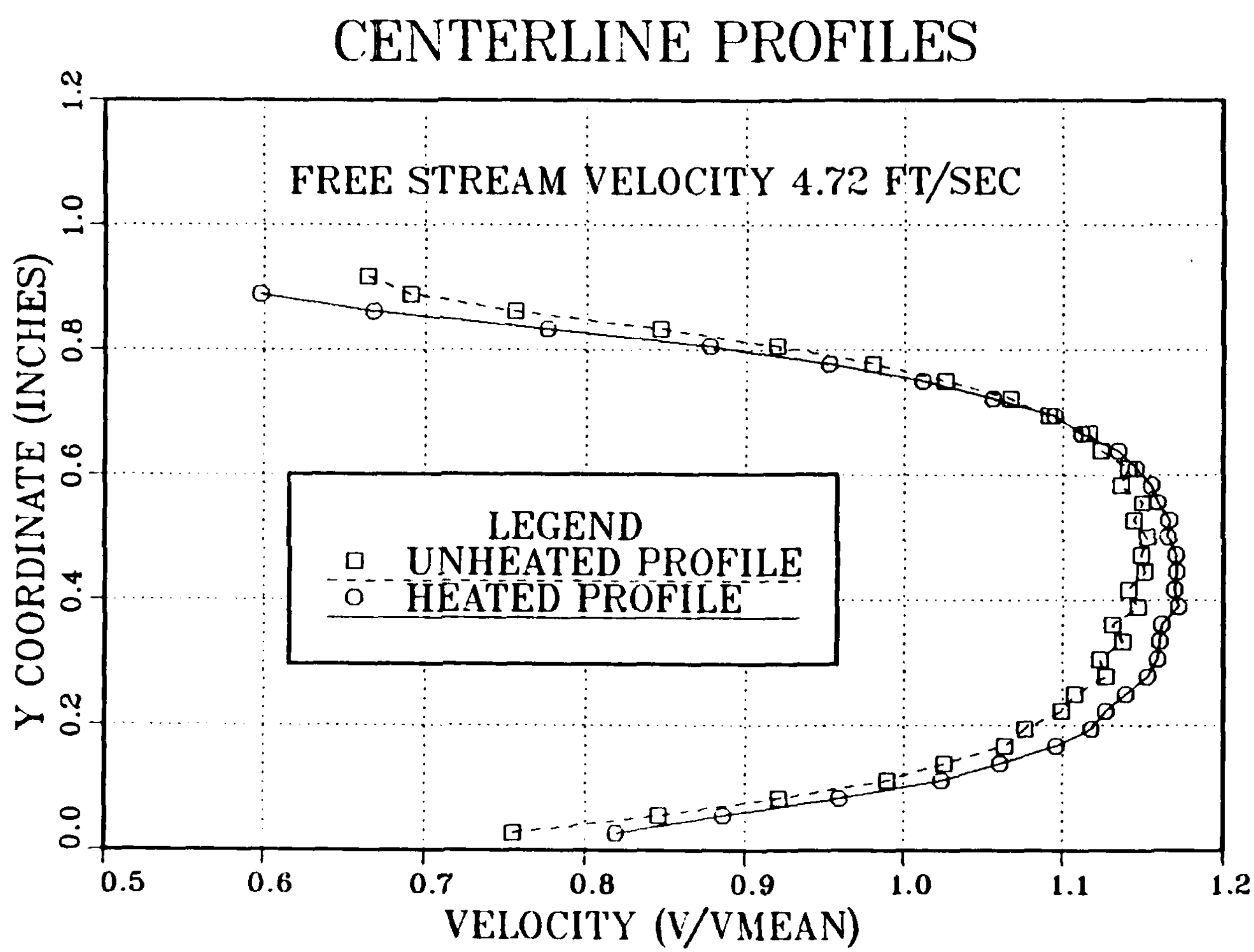


Figure 3.2 Comparison of Centerline Velocity Profiles for a Heated and Unheated Case.

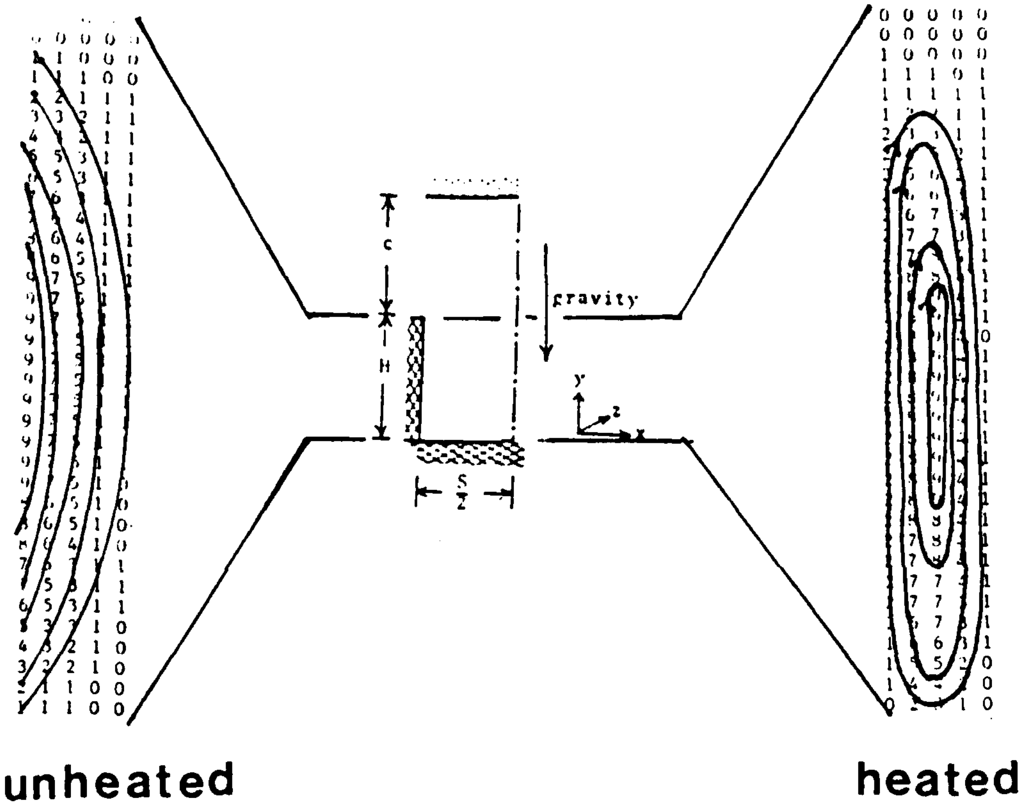


Figure 3.3 Streamline Profiles for Heated
Unheated Case.

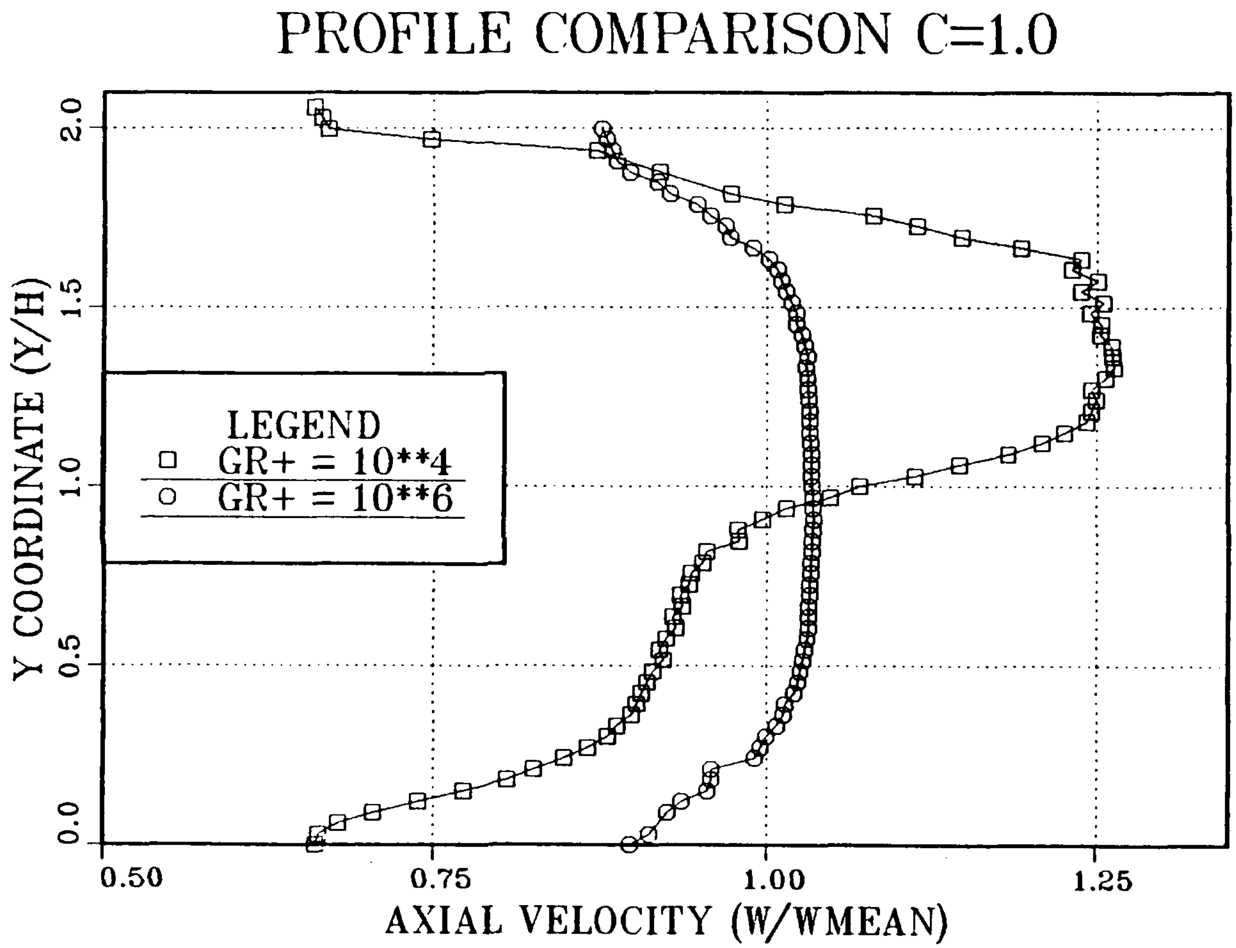


Figure 3.18 Profile Comparison for C=1.0.

IV. TURBULENT FLOW

A. PURPOSE

The purpose of the turbulent flow testing was threefold: (1) the development of turbulent velocity streamline profiles and centerline velocity profiles similar to those determined for laminar flow, (2) the development of temperature profiles within the fin for comparison to the temperature profiles for laminar flow, and (3) the development of convection heat transfer coefficients for the turbulent flow case for comparison to the coefficients that Acharya and Patankar derived analytically for laminar flow. Unfortunately, for turbulent flow there is no analytical work for comparison. Therefore, the assumption is that errors detected during laminar testing will also carry over into the turbulent setting.

In order to ensure comparability, the same modified Grashof Numbers 10^4 and 10^6 were used, as were the dimensionless parameters stated by Acharya and Patankar [Ref. 1]. While only figures will be presented here, a complete listing of the data obtained for each Grashof Number as well as for each clearance ratio is included in Appendices F and G. Comparisons are presented for centerline velocity profiles as well as for streamline profiles. As was evident with the laminar flow results, the velocities are caused by buoyancy effects. As the actual flow direction cannot be determined, the direction of the secondary flow is assumed. The relative lack of quiescence in the "trace" of the oscilloscope offerred additional verification of turbulent testing.

B. MODIFIED GRASHOF NUMBER 10^4

Three tests were conducted at $Gr^+=10^4$, with clearance parameters of 0.0, 0.4, and 1.0. The relative strength of the secondary flow is indicated on each figure. As anticipated, there is a general increase in the strength of the secondary field as flow resistance decreases. The orientation of the hot wire probe for the different readings necessary to measure the relative strength of the secondary field was outlined in Chapter III, "Laminar Flow".

1. Clearance Parameter = 0.0, 0.4, and 1.0

Figures 4.1, 4.2, and 4.3 present the streamline profiles for $Gr^+=10^4$ and C=0.0, C=0.4 and C=1.0 respectively. The relatively high velocities in the turbulent velocity field cause more :catter to the data, but the profiles are appropriate for an average flow through the duct. As the clearance is increased, the mean velocity down the channel decreases, the velocity perturbations decrease slightly, and the scatter is less evident. Once again, streamlines are sketched by hand as an approximation of the computer output. In this case actual locations are at the

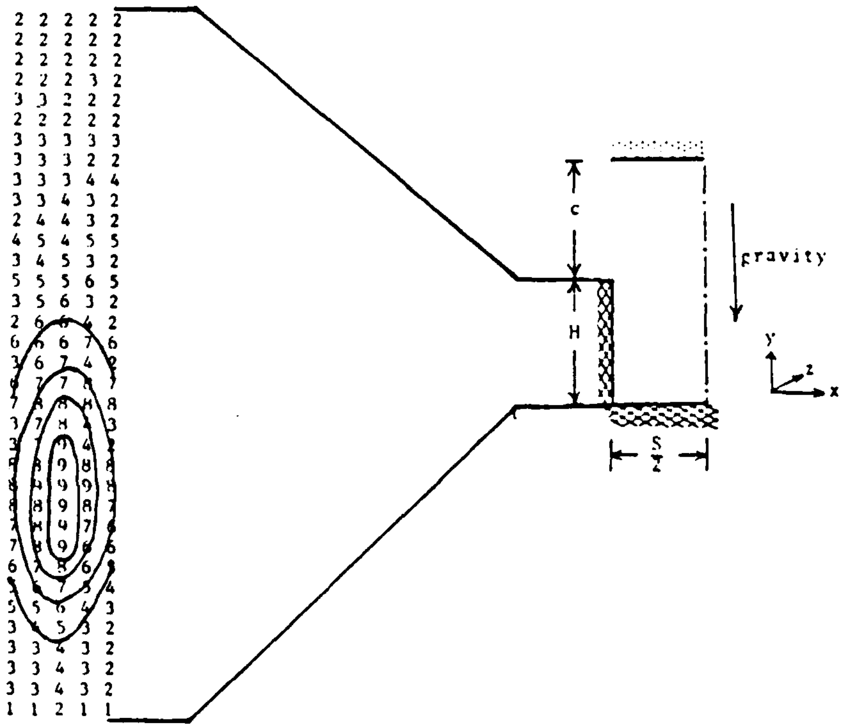


Figure 4.1 Streamlines for $Gr^{+}=10^{4}$, C=0.0, Turbulent Flow.

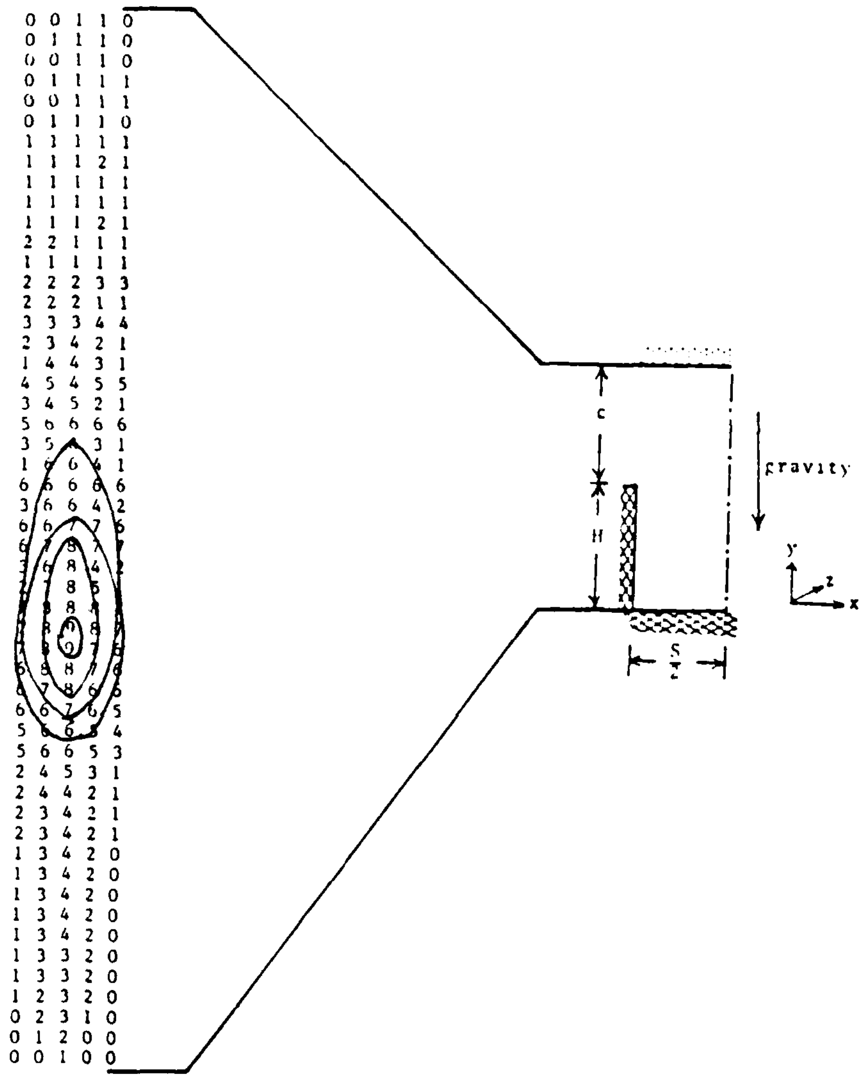


Figure 4.2 Streamlines for $Gr^{+}=10^{4}$, C=0.4, Turbulent Flow.

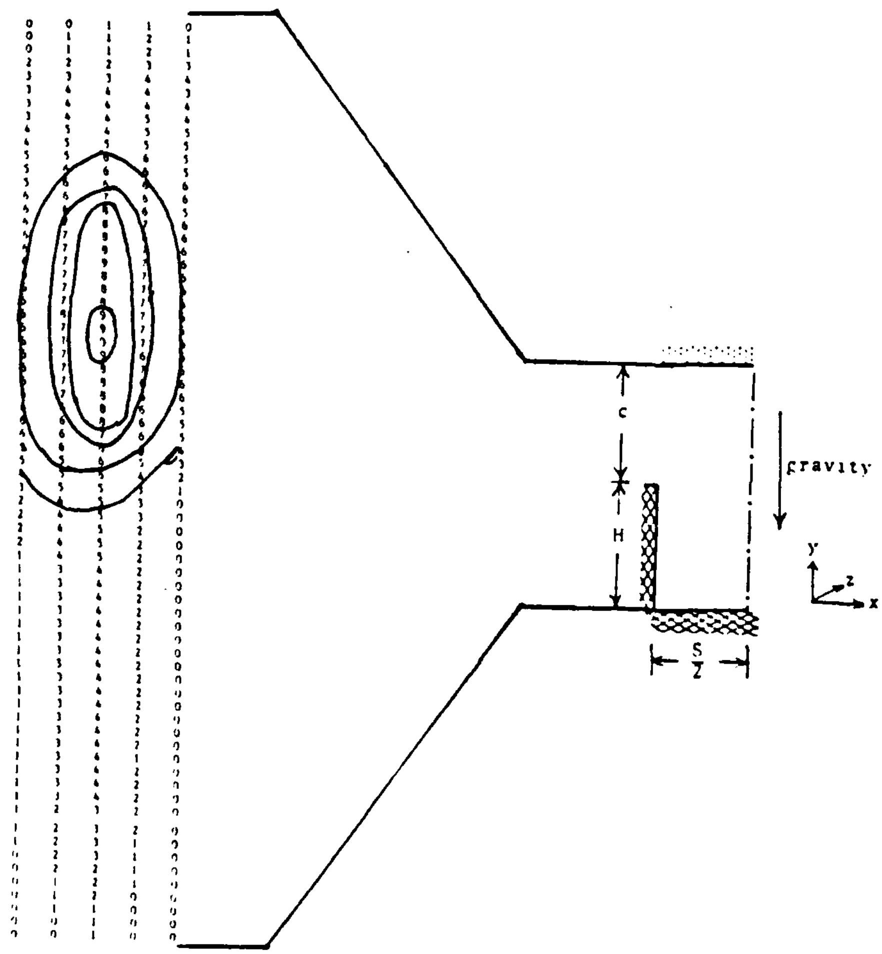


Figure 4.3 Streamlines for $Gr^{+}=10^{4}$, C=1.0, Turbulent Flow.

discretion of the individual doing the drawing. The resolution of the streamlines in the vicinity of either the solid boundaries or the lines of symmetry is very poor. This result was expected and is consistent with the laminar flow findings.

2. Centerline Velocity Profiles

Figure 4.4 illustrates the centerline velocity profiles for $Gr^{+}=10^{4}$ and clearance ratios C=0.0, C=0.4 and C=1.0. Examination of the illustration indicates that the velocity profile was not fully developed for either C=0.0 or C=0.4. It was not possible for the profile for C=1.0 to be fully developed even though the figure indicates fully-developed conditions. The flatness of the C=1.0 profile is accounted for by the separation distance from the exit plane of the finned array to the hot wire probe. As previsouly discussed, the separation distance allows the "wake" of the exiting flow to impinge on the probe of the hot wire anemometer. This means that the velocity as measured can never truly go to zero at the boundaries, which, in turn, leads to a relatively high mean velocity. Because all figures are based on the mean velocity, the ratios produced by the test are always lower than any analytically-derived value.

Also, when the hot wire probe was reoriented to determine the relative strength of the secondary flow, the "wake" had the effect of increasing the secondary flow percentage.

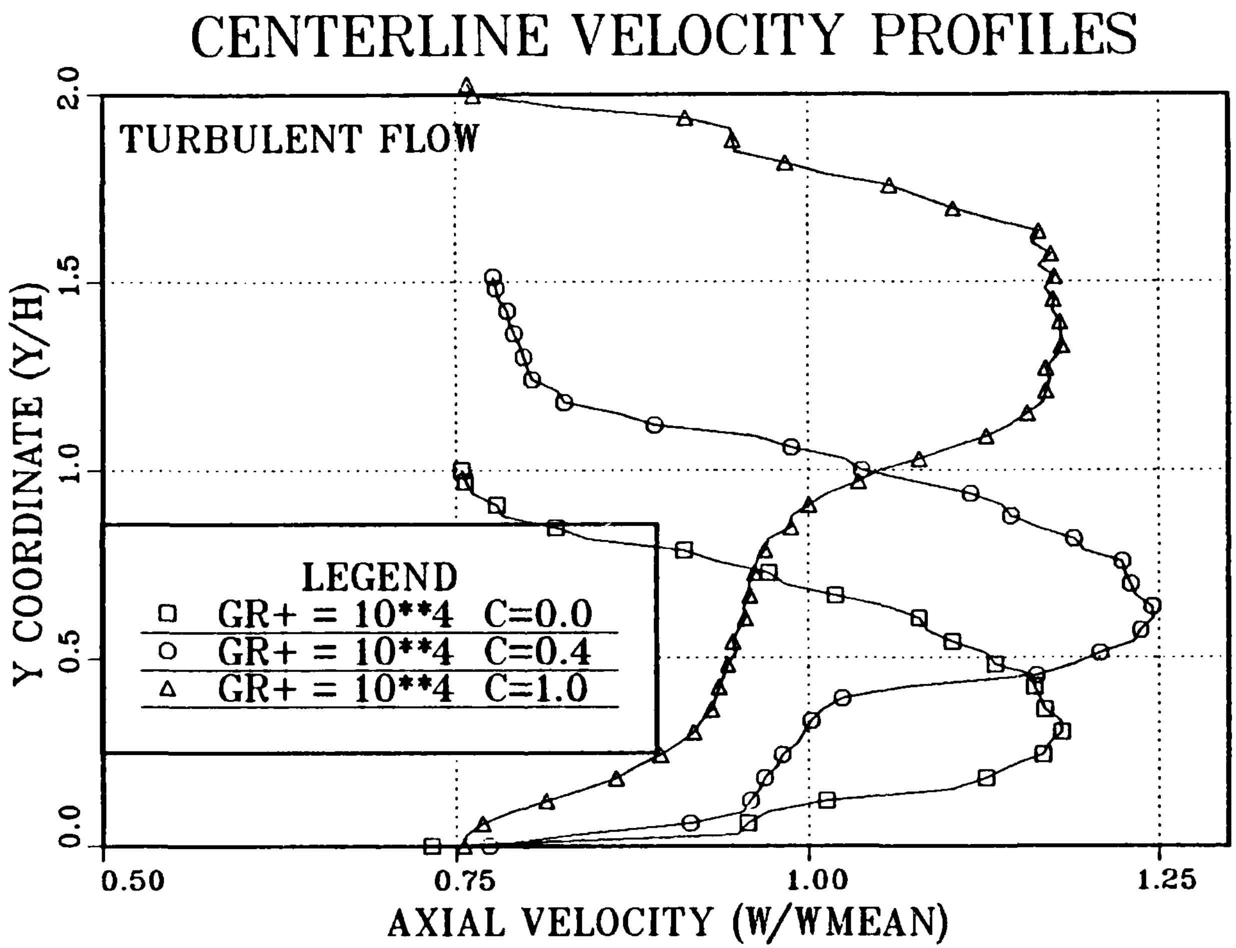


Figure 4.4 Turbulent Centerline Velocity Profiles, $Gr^{+}=10^{4}$, C=0.0, C=0.4, and C=1.0.

C. MODIFIED GRASHOF NUMBER 10^6

1. Clearance Parameter Equal 0.0, 0.4, and 1.0

As with a modified Grashof Number of 10^4, three test runs were conducted. Figures 4.5, 4.6, and 4.7 are the streamline profiles for C=0.0, C=0.4 and C=1.0 respectively. For these tests the magnitude of the relative strength of the secondary flow is greater than the strength of the secodary flow encountered for $Gr^+=10^4$. This result was expected but the strength of the secondary flow did not increase as much as expected.

2. Centerline Velocity Profile

Figure 4.8 shows the centerline velocity profiles for $Gr^+=10^6$, and for clearance parameters C=0.0, C=0.4, and C=1. These centerline velocities show the characteristics discussed previously for $GR^+=10^4$.

D. CENTERLINE VELOCITY PROFILE COMPARISON

Figures 4.9, 4.10 and 4.11 indicate the differences in the centerline velocity profiles due to a change in the Grashof number. Even though the free-stream velocity was not intentionally changed during these tests, it was necessary to recalibrate the hot wire anemometer. The changes in the profiles due to recalibration are minimal when compared to other effects (i.e. the heat input). Thus, the figures give a very good indication of how the

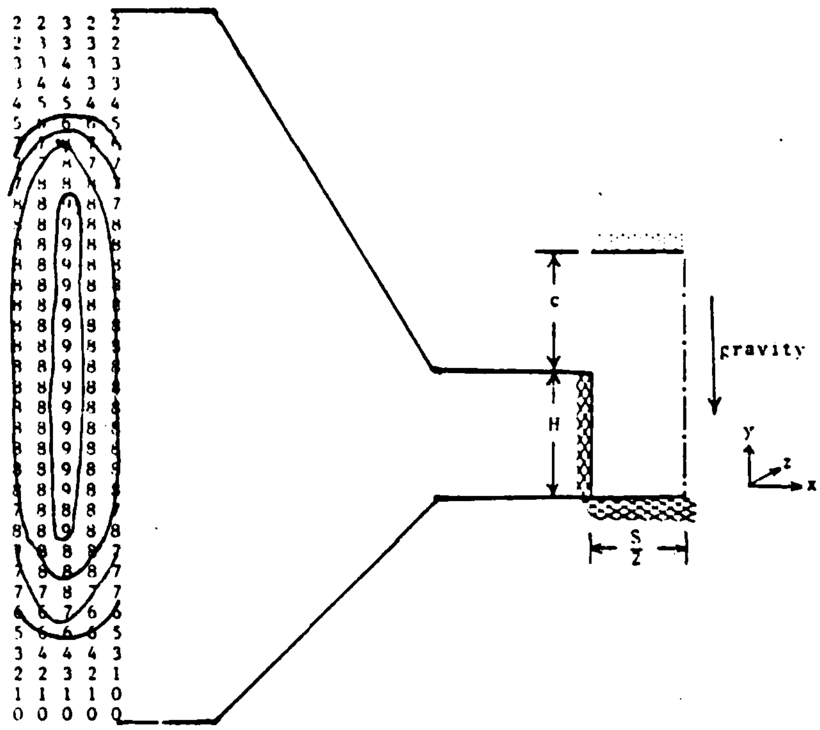


Figure 4.5 Streamlines for $Gr^{+}=10^{6}$, C=0.0, Turbulent Flow.

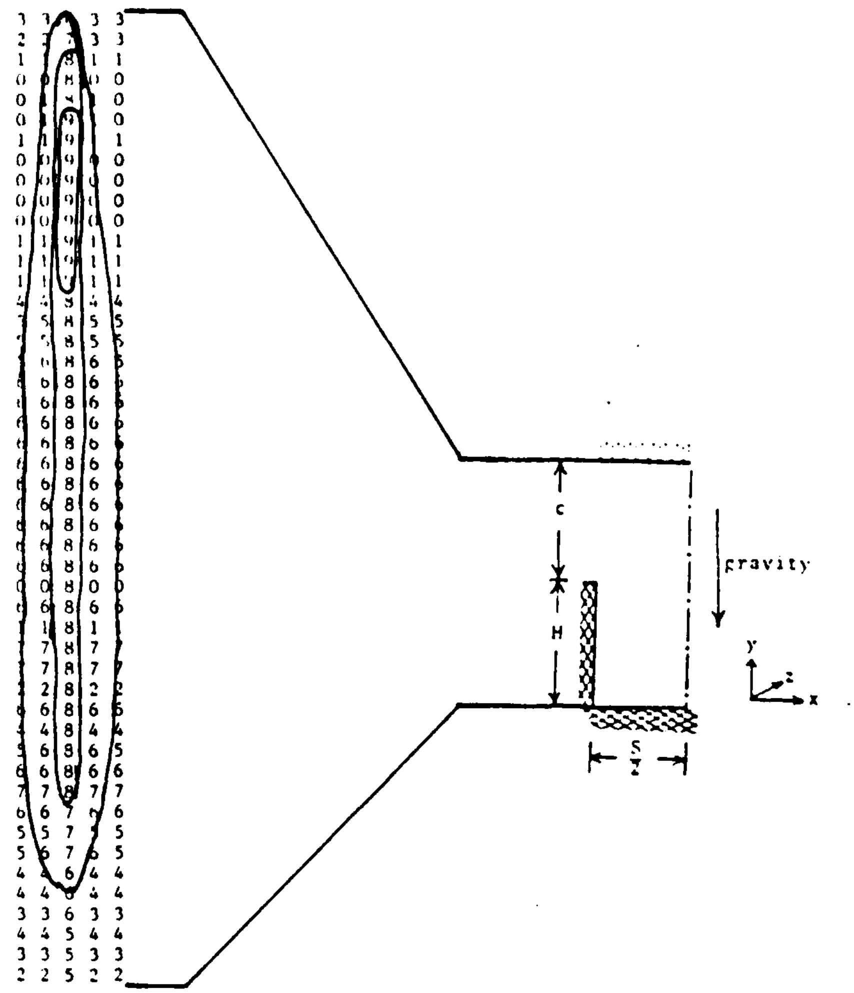


Figure 4.6 Streamlines for $Gr^{+}=10^{6}$, C=0.4, Turbulent Flow.

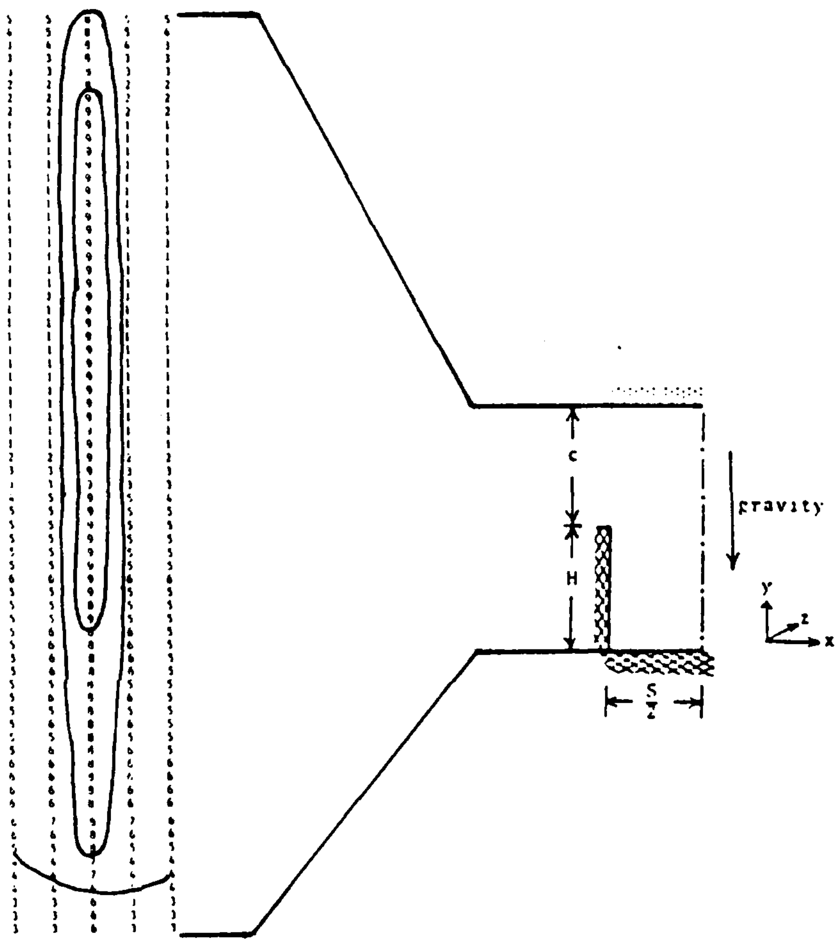


Figure 4.7 Streamlines for $Gr^{+}=10^{6}$, C=1.0, Turbulent Flow.

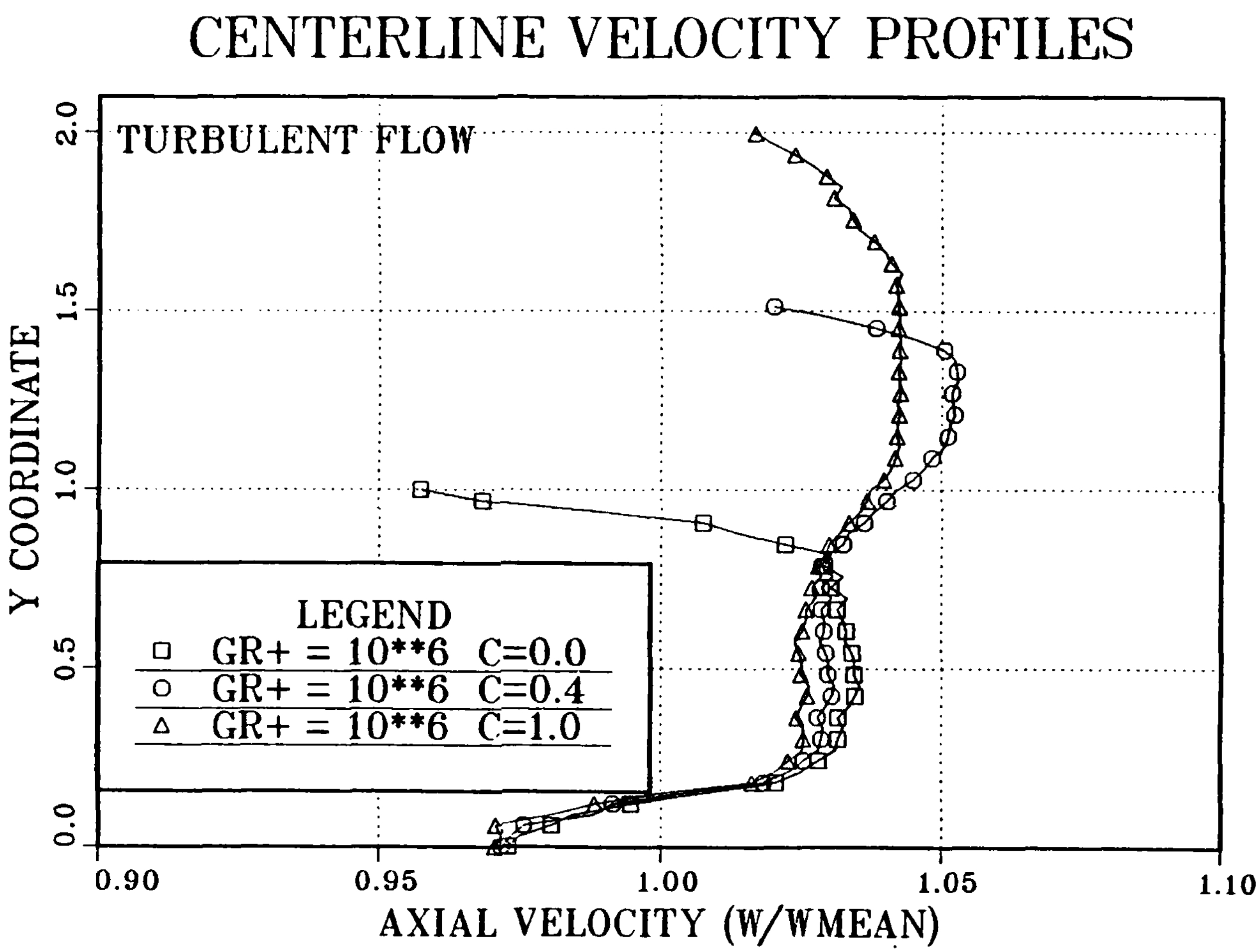


Figure 4.8 Turbulent Centerline Velocity Profiles, $Gr^{+}=10^{6}$, C=0.0, C=0.4, and C=1.0.

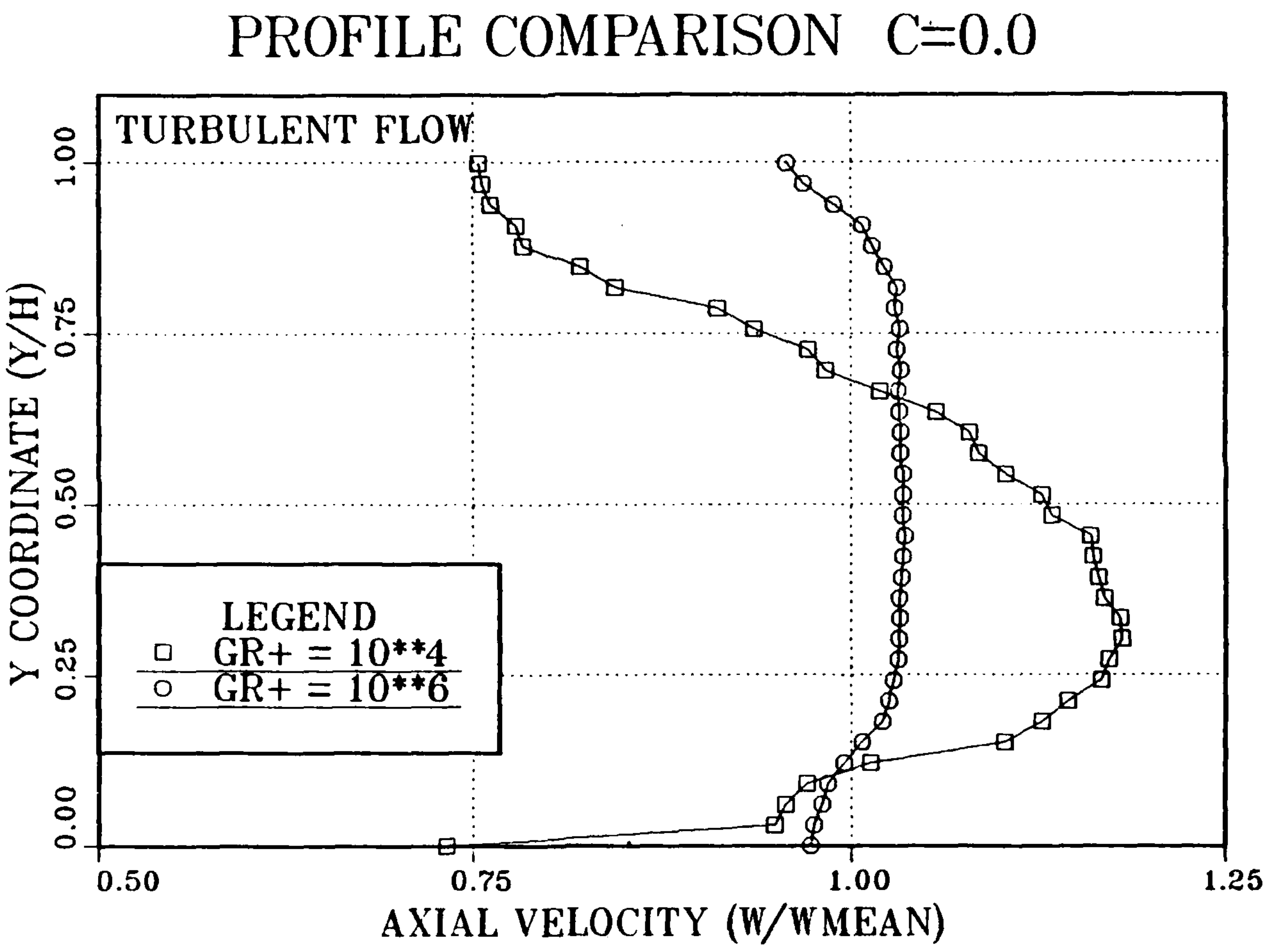


Figure 4.9 Profile Comparison for C=0.0.

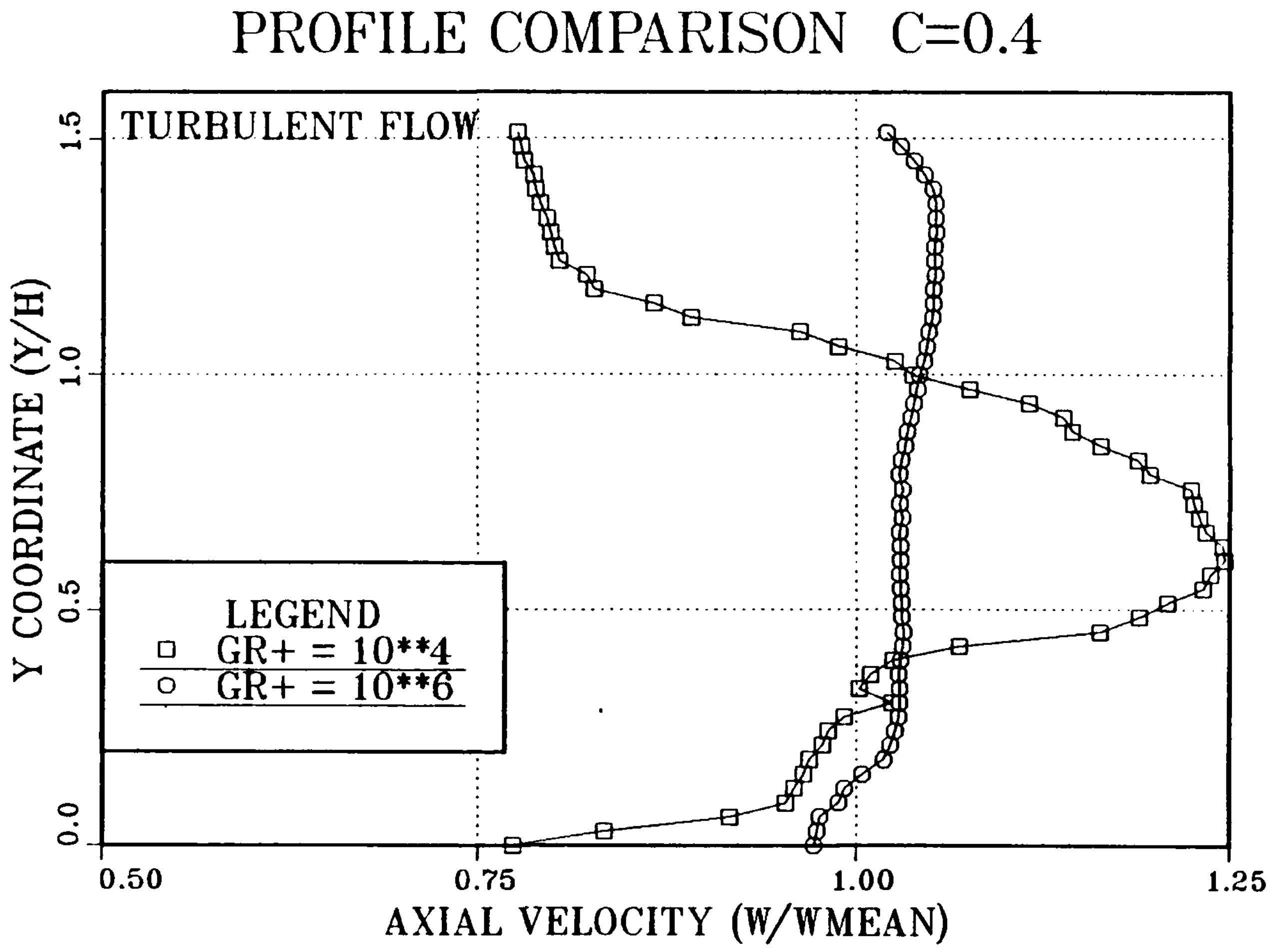


Figure 4.10 Profile Comparison for C=0.4.

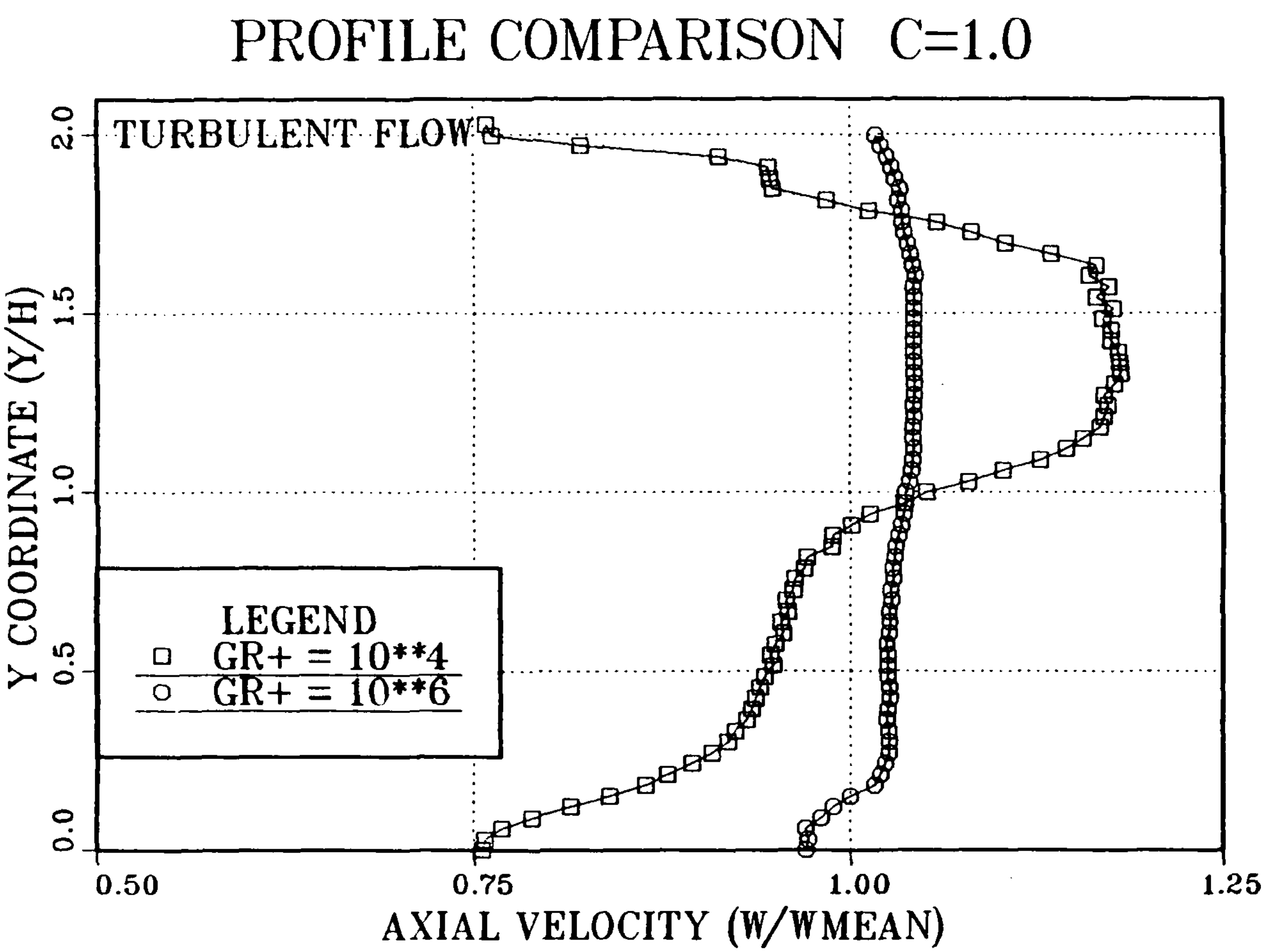


Figure 4.11 Profile Comparison for C=1.0.

centerline velocity profile would change for an increase in the heat flow.

E. TURBULENT-LAMINAR FLOW COMPARISON

The following figures are provided for a quick visual comparison of the laminar and turbulent flow. Figures 4.12, 4.13, and 4.14 are for $Gr^{+}=10^{4}$ and $C=0.0$, $C=0.4$, and $C=1.0$ respectively. Figures 4.15, 4.16, and 4.17 are for $Gr^{+}=10^{6}$ with the same clearance ratios.

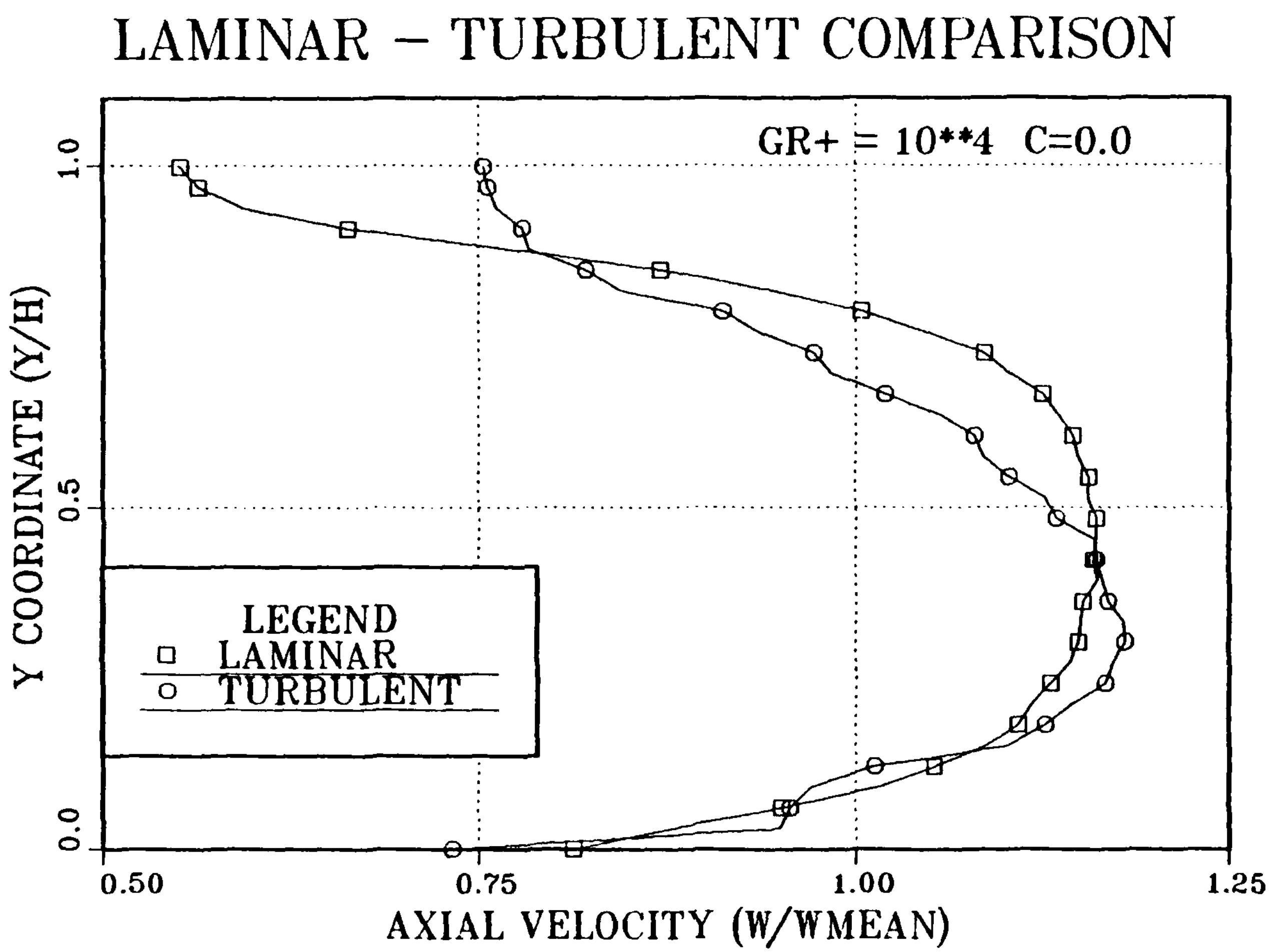


Figure 4.12 Laminar-Turbulent Comparison $Gr^{+}=10^{4}$, C=0.0.

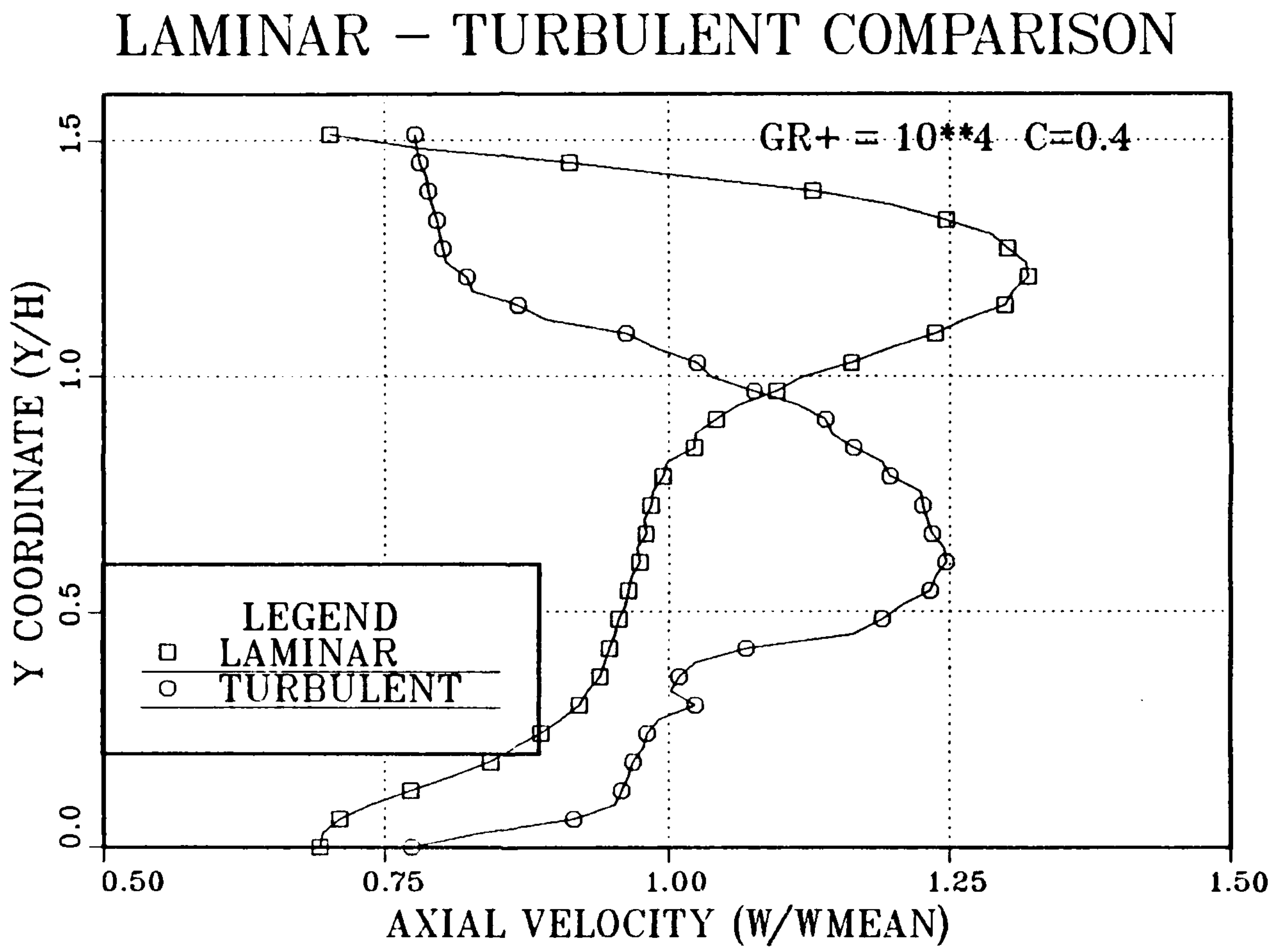


Figure 4.13 Laminar-Turbulent Comparison $Gr^{+}=10^{4}$, C=0.4.

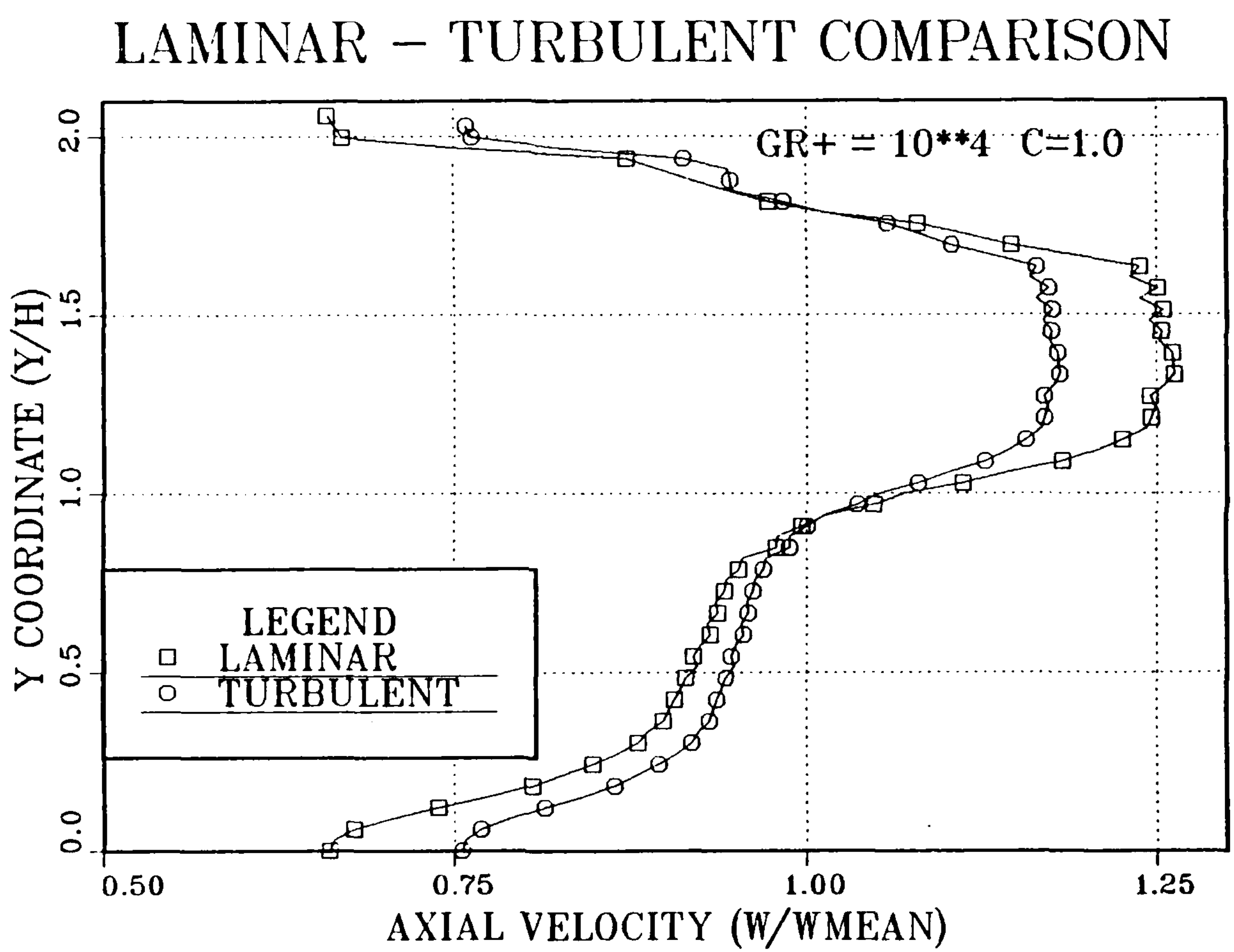


Figure 4.14 Laminar-Turbulent Comparison $Gr^{+}=10^{4}$, C=1.0.

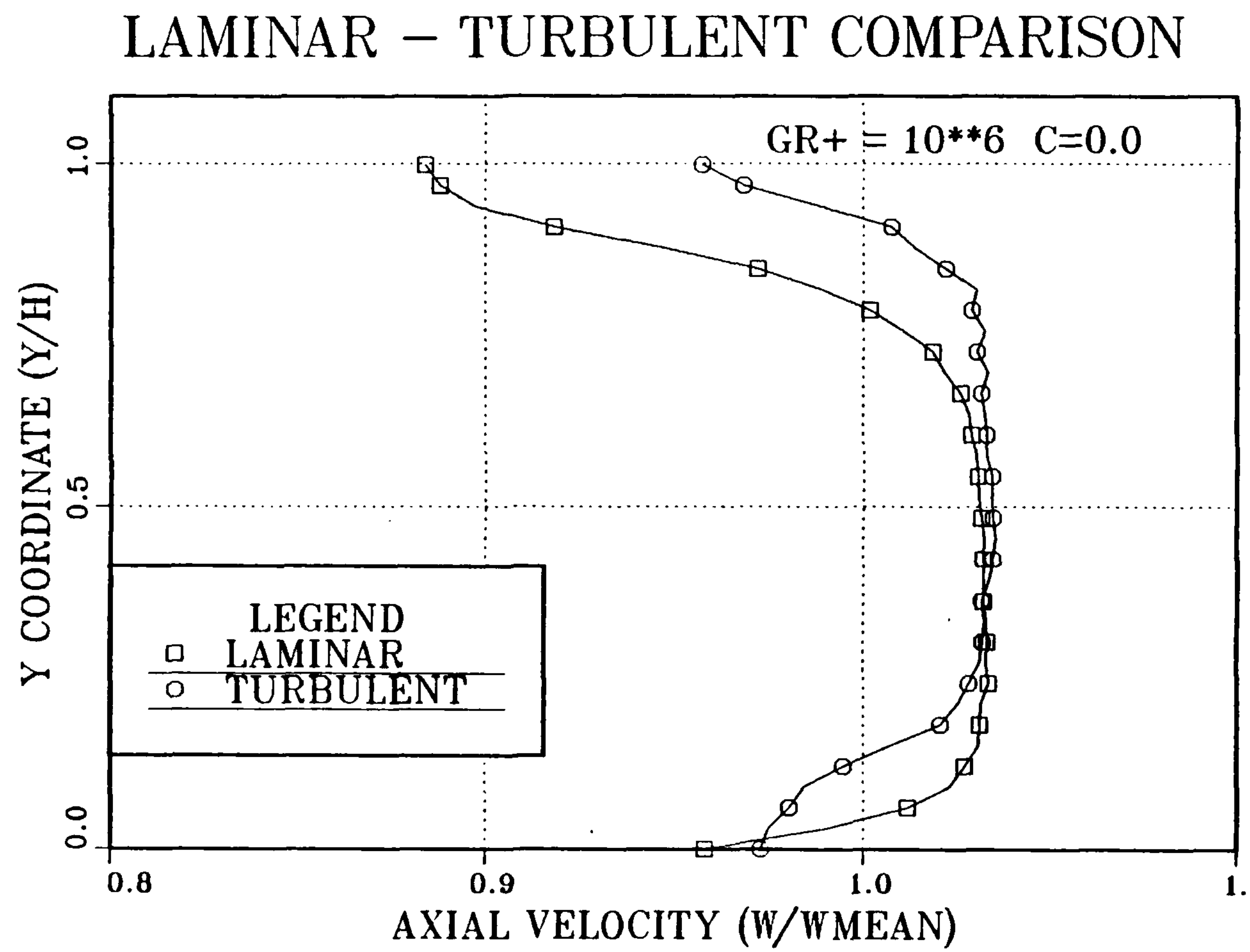


Figure 4.15 Laminar-Turbulent Comparison $Gr^{+}=10^{6}$, C=0.0.

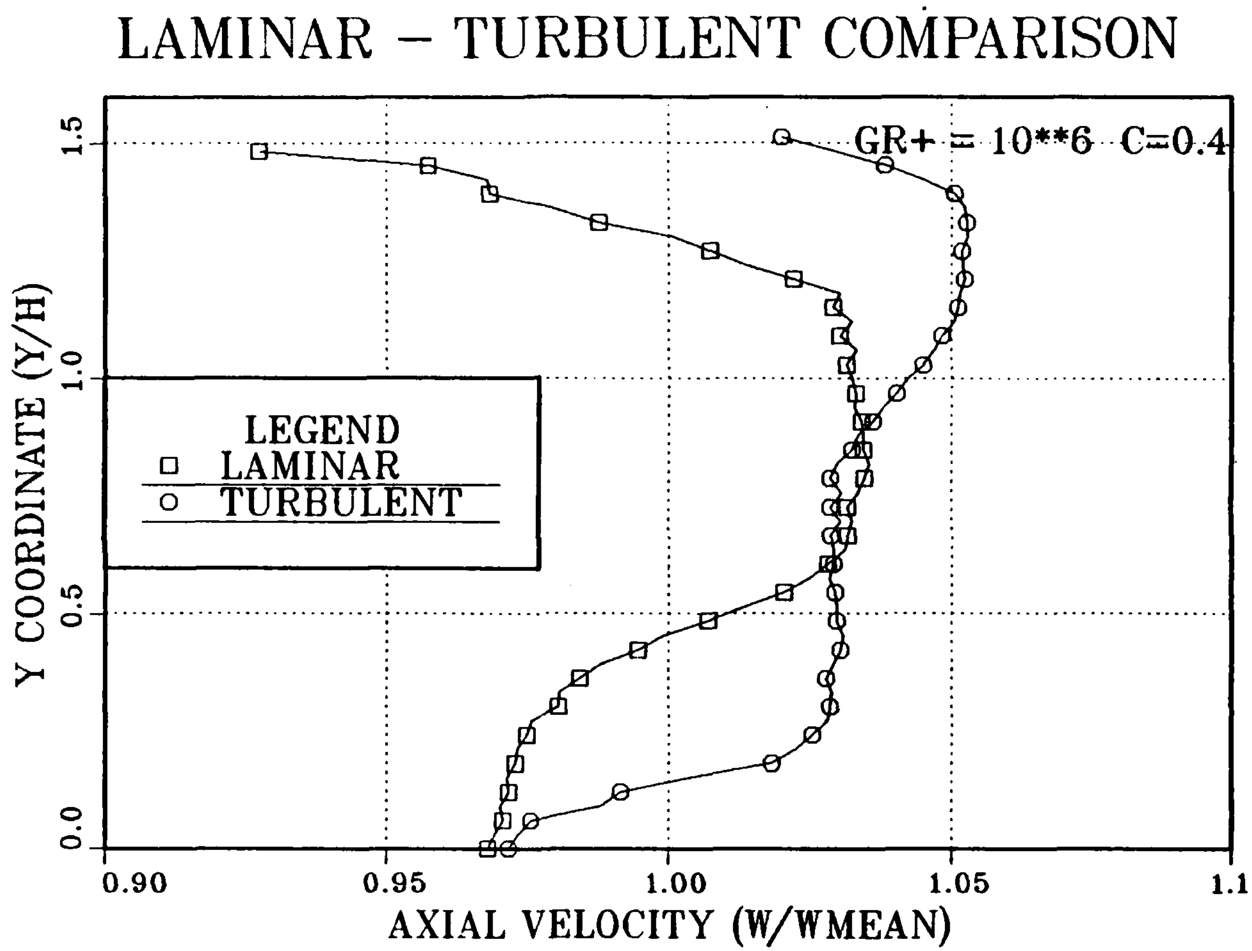


Figure 4.16 Laminar-Turbulent Comparison $Gr^{+}=10^{6}$, C=0.4.

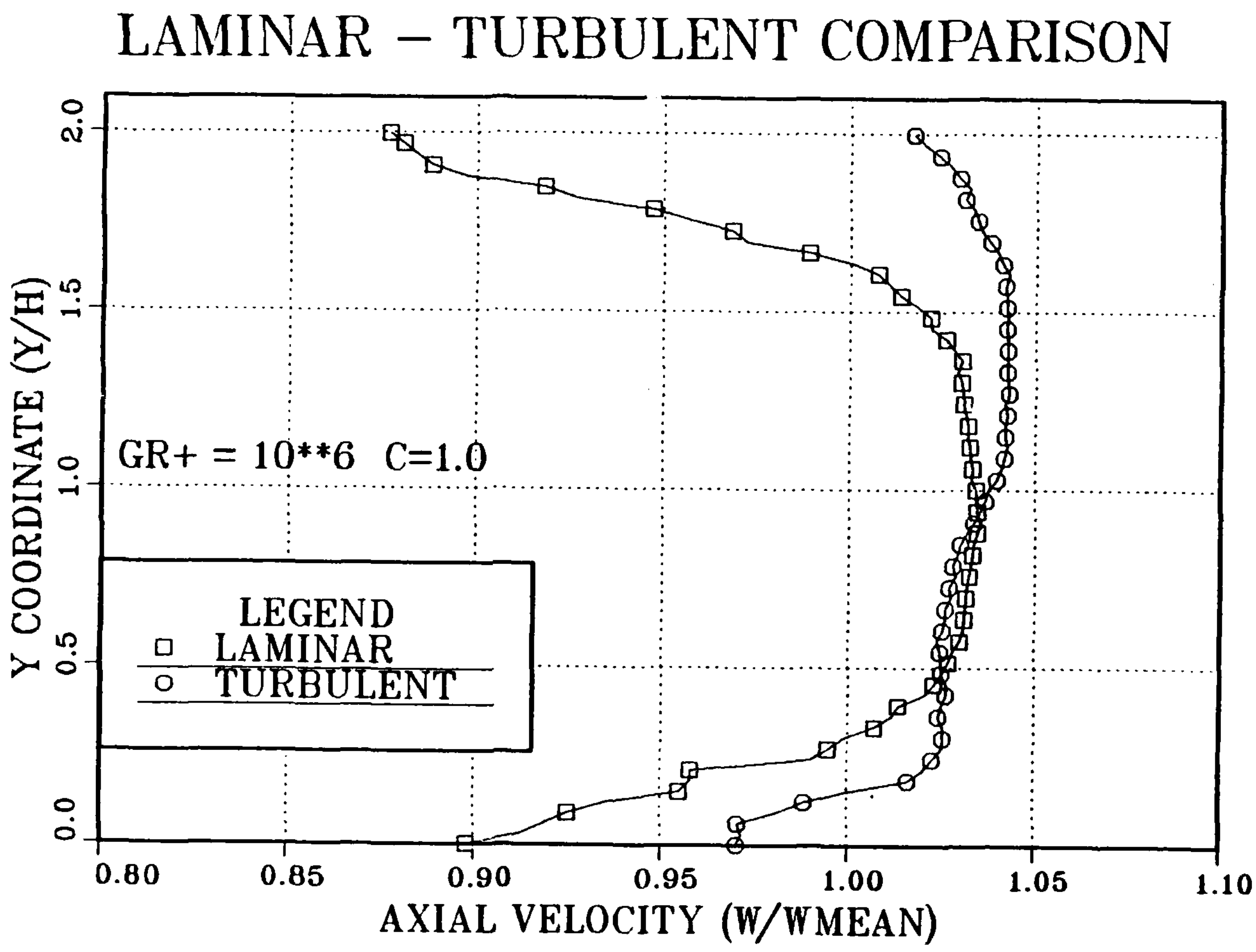


Figure 4.17 Laminar-Turbulent Comparison $Gr^{+}=10^{6}$, C=1.0.

V. TEMPERATURE PROFILES

A. PURPOSE

Development of temperature profiles along the length of the fin was essential to the determination of the convection heat transfer coefficients. Temperature profiles were developed directly from the temperature readings recorded for steady state conditions. Profiles are presented only for $Gr^{+}=10^{4}$ for laminar and turbulent flow with clearance ratios C=0.0, C=0.4, and C=1.0. As in Chapters III and IV, only figures will be presented here, a partial listing of the temperatures being available in Tables 4 and 5. Table 4 contains the information for laminar flow, and Table 5 contains information for turbulent flow.

B. LAMINAR FLOW

Figure 5.1 is presented as a reminder of how the thermocouples were mounted on the longitudinal finned array. Figures 5.2, 5.3, and 5.4 show the temperature profiles obtained under laminar flow conditions for the three clearance ratios. The sinusoidal temperature pattern on the surface was a function of the silicon pad heater. Note that the pattern was no longer evident for thermocouples mounted at the 3/8-inch depth or the 3/4-inch depth. The temperatures are plotted as the differences based on the

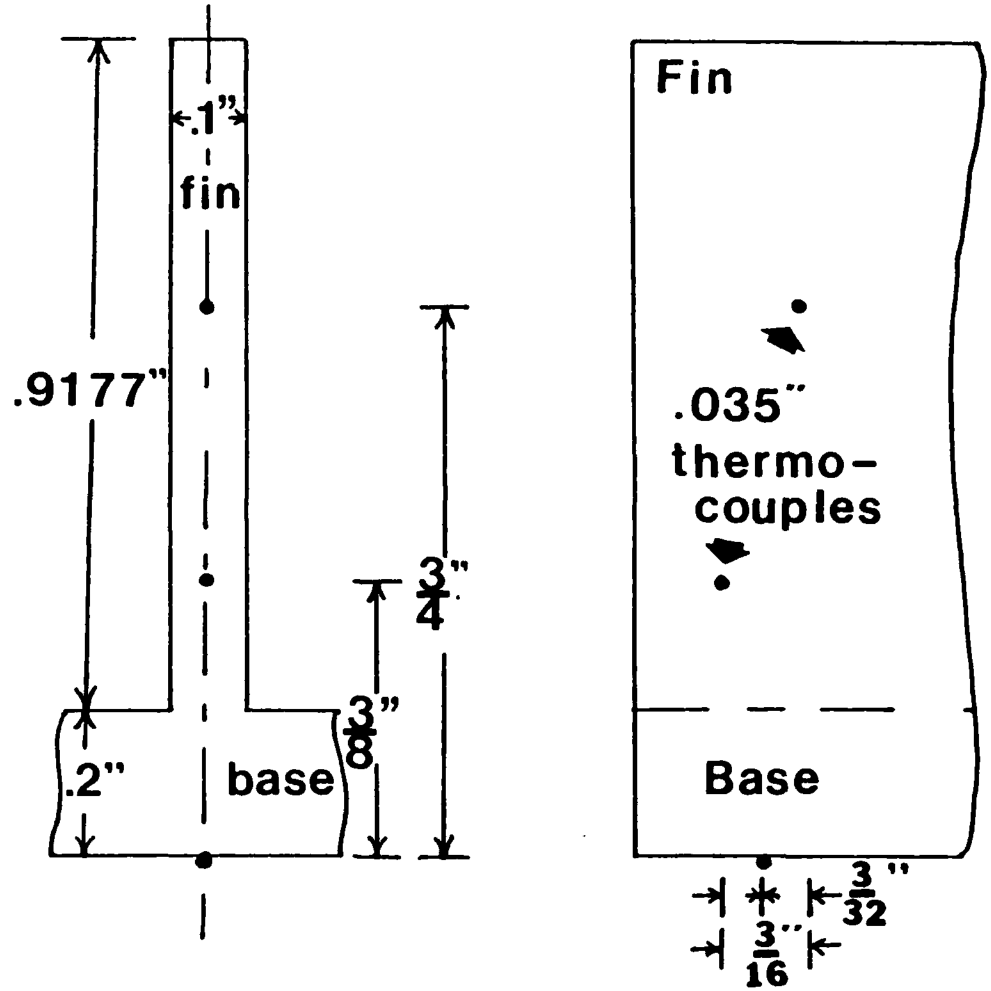


Figure 5.1 Fin Thermocouple Placement.

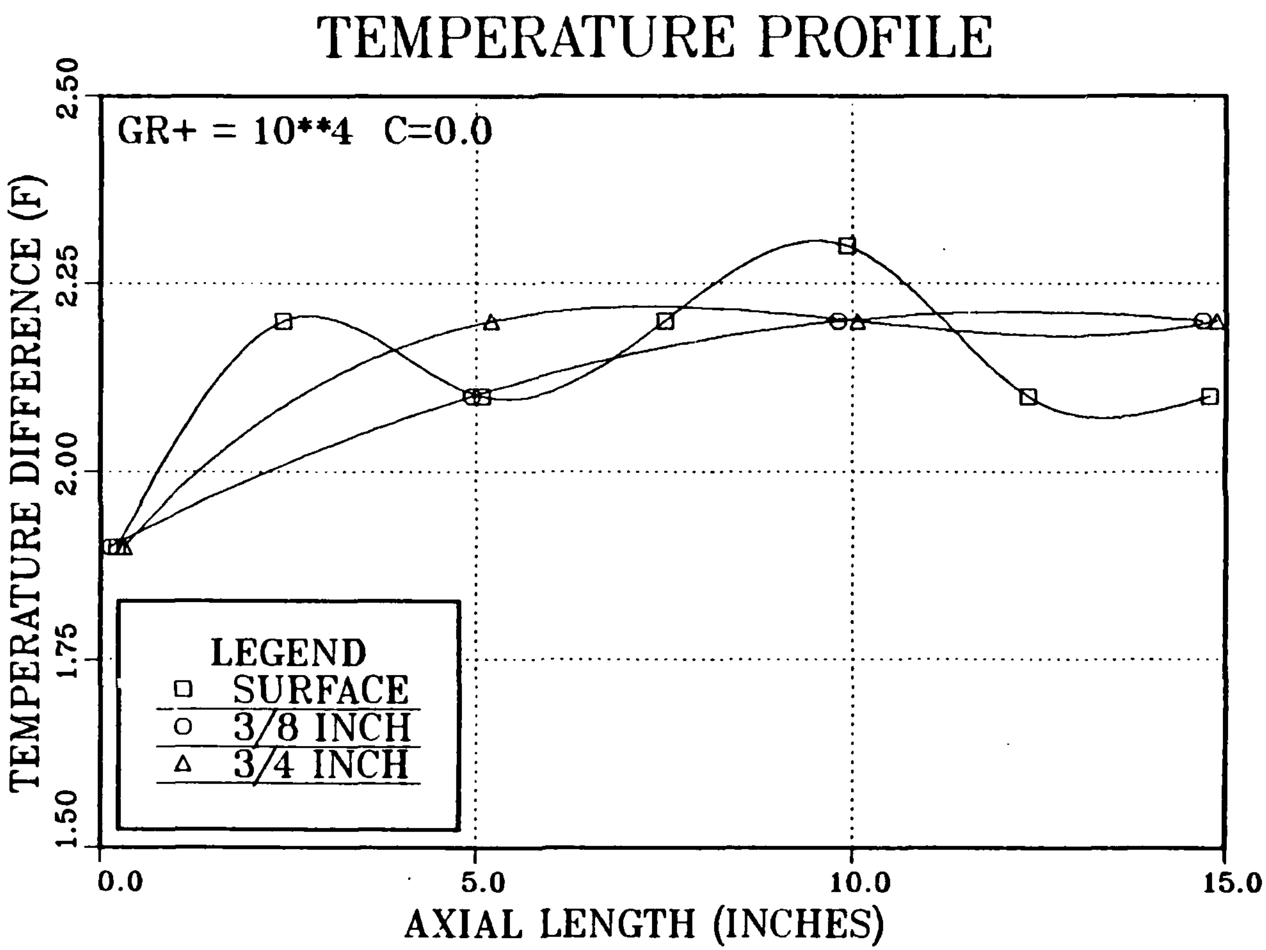


Figure 5.2 Temperature Profile $Gr^{+}=10^{4}$, C=0.0, Laminar Flow.

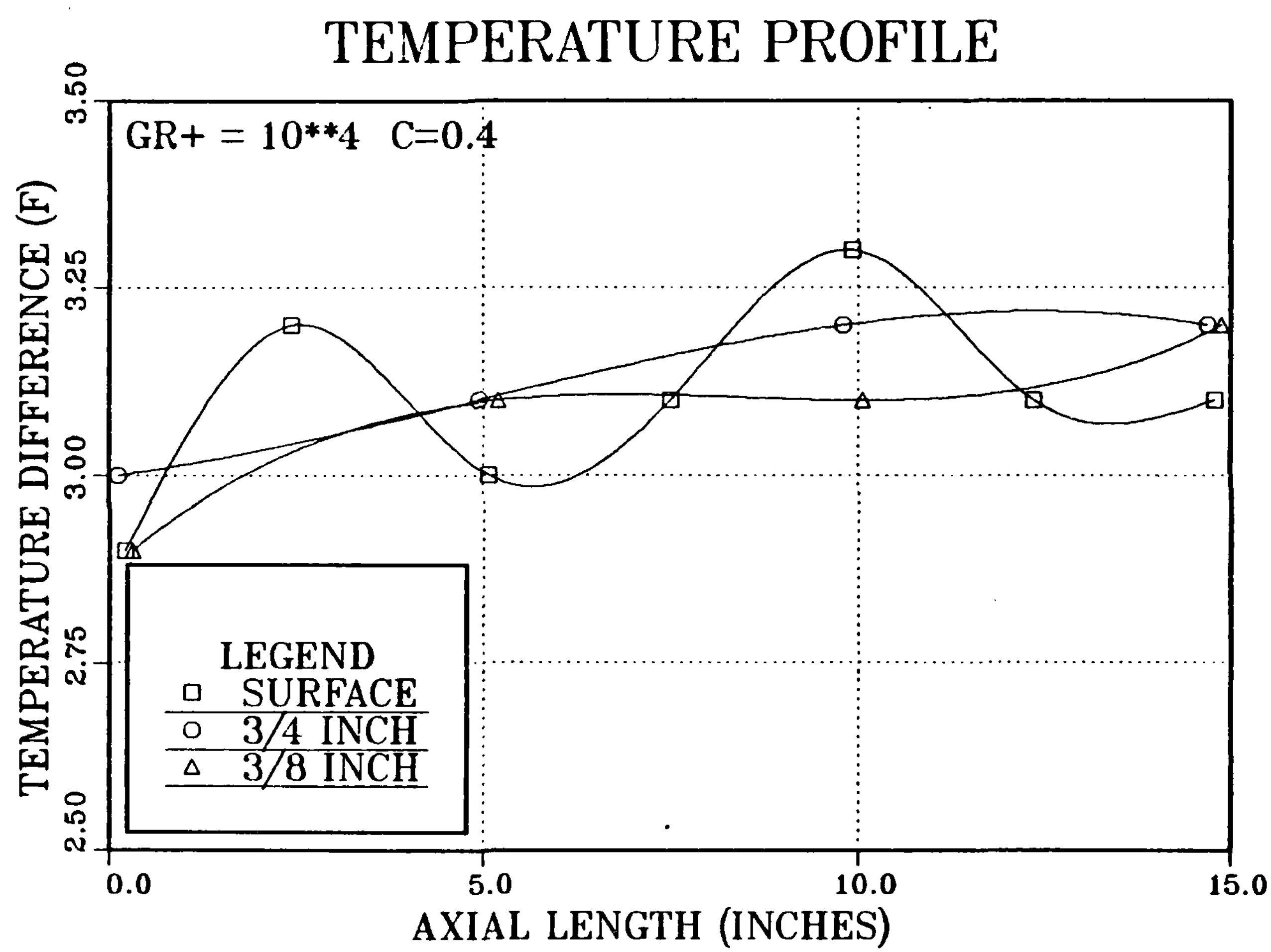


Figure 5.3 Temperature Profile $Gr^{+}=10^{4}$, C=0.4, Laminar Flow.

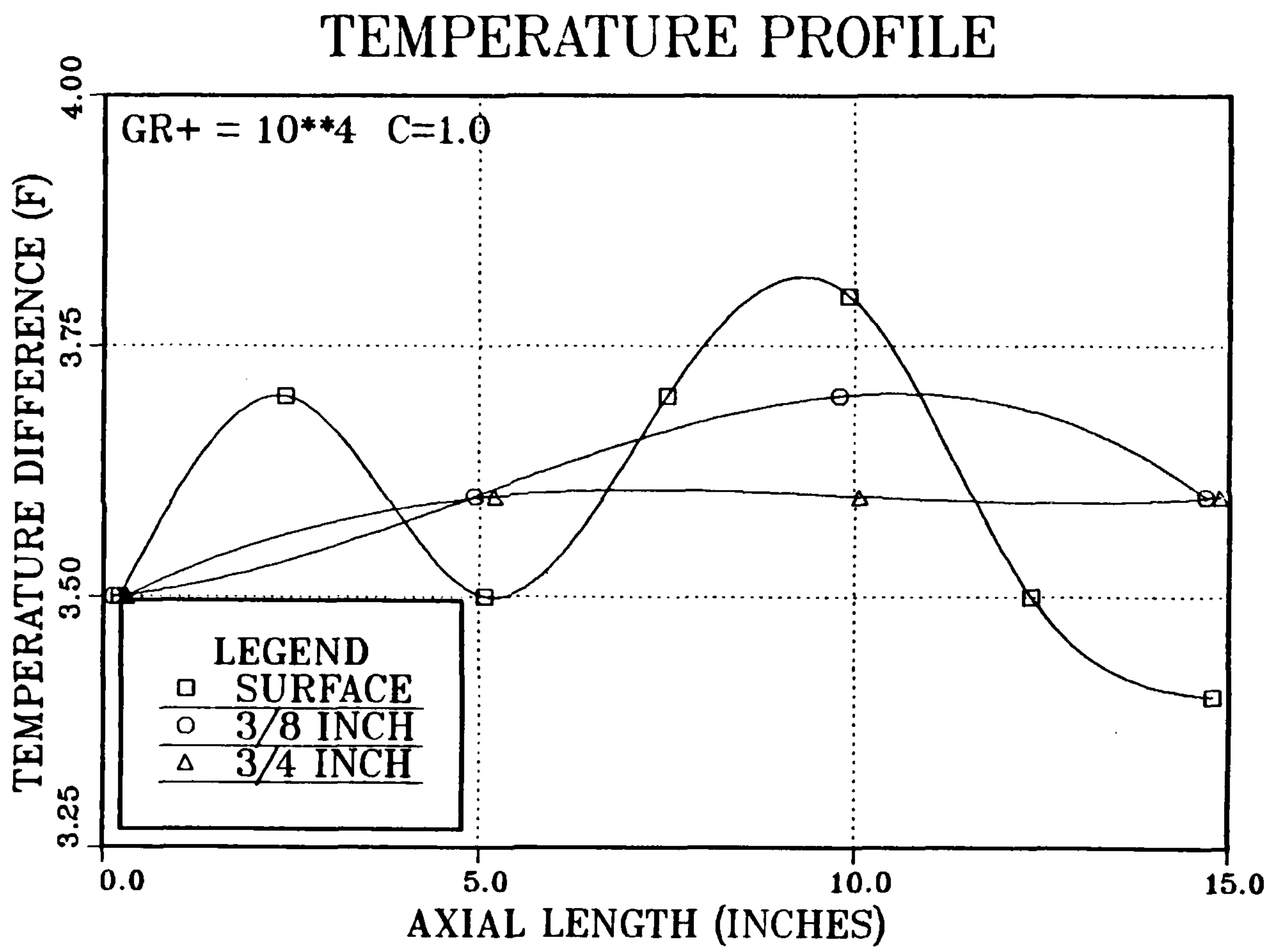


Figure 5.4 Temperature Profile $Gr^{+}=10^{4}$, C=1.0, Laminar Flow.

initial temperature of the assembly. This latter value was used as a base value because of the ease of calculation. To have used the surrounding temperature would have required actual calculation of each temperature. However, use of the initial array temperature necessitates only the calculation of one temperature, with all subsequent values based on this value.

There was a general increase of all temperatures along the fin as the fin tip clearance was increased. This was expected because of the flow rate disparity previously discussed. It remains to be determined how the temperature increase will effect the heat transfer coefficient.

C. TURBULENT FLOW

As evidenced in Figures 5.5, 5.6, and 5.7, the temperature increase under turbulent flow conditions was less than the increase under laminar conditions. This finding was to be expected and was the result of the increased air flow for turbulent conditions. The temperature profiles are important only in that they allow calculation of the convection coefficients at each point.

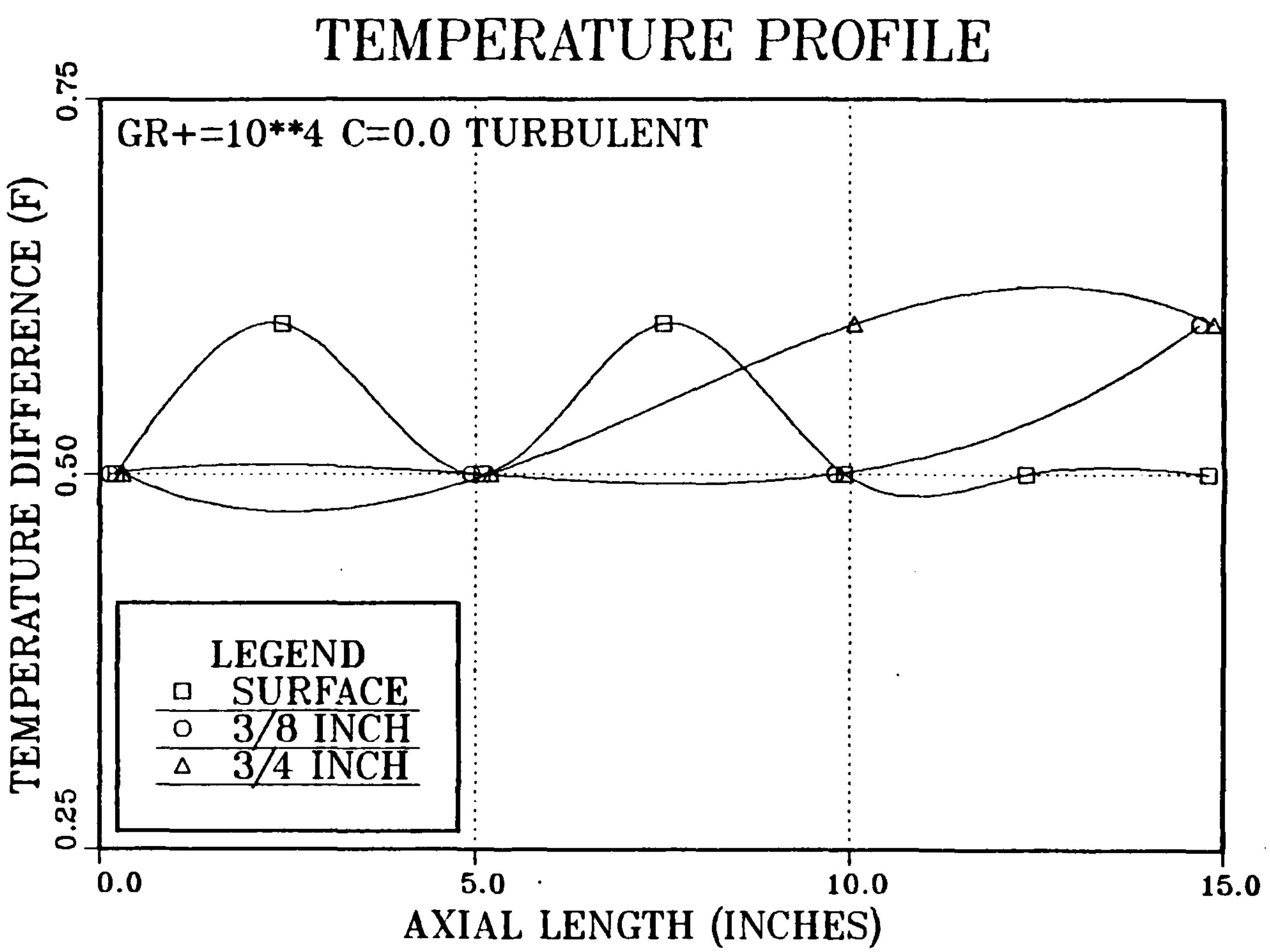


Figure 5.5 Temperature Profile $Gr^{+}=10^{4}$, C=0.0, Turbulent Flow.

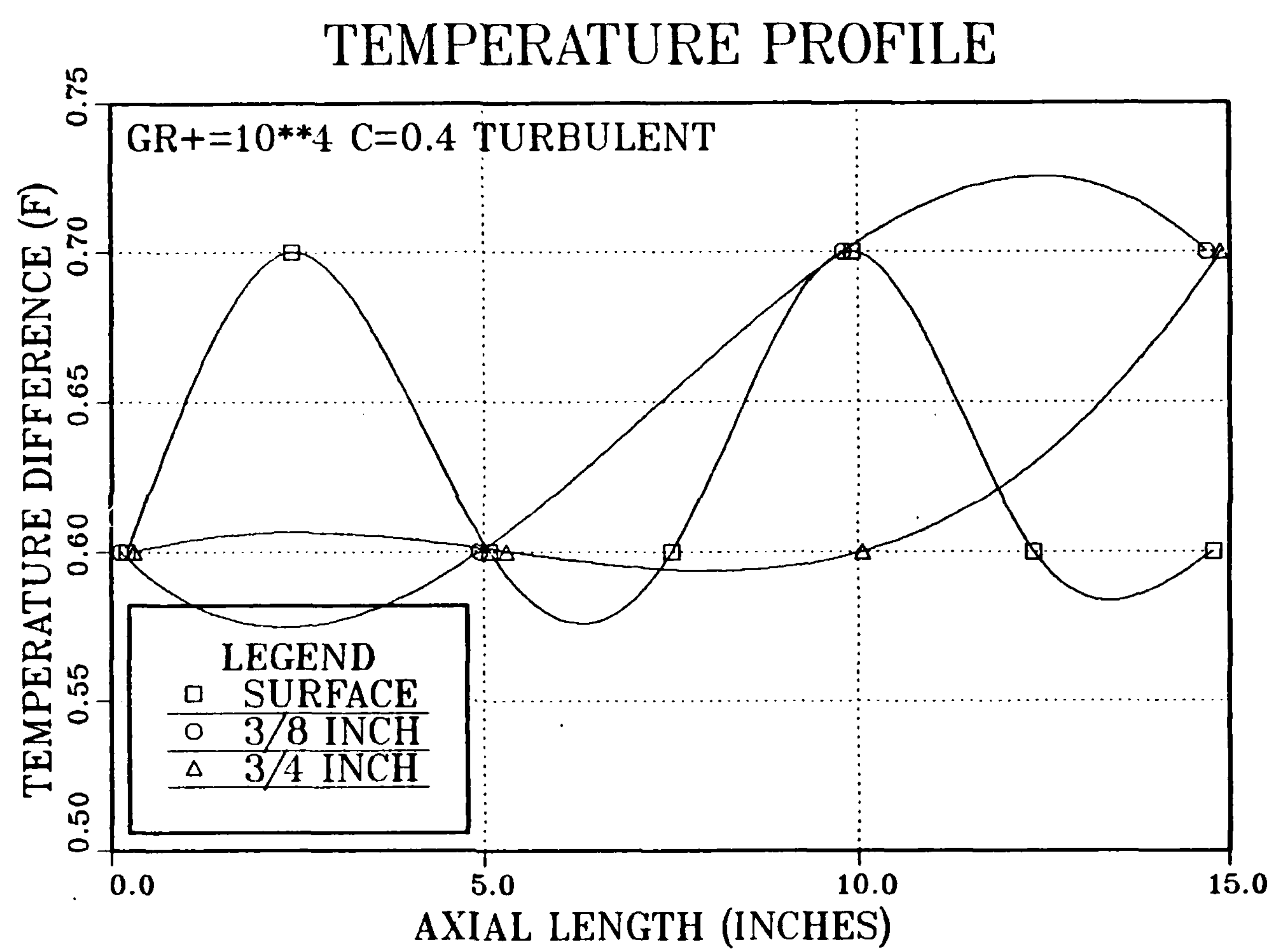


Figure 5.6 Temperature Profile $Gr^{+}=10^{4}$, C=0.4, Turbulent Flow.

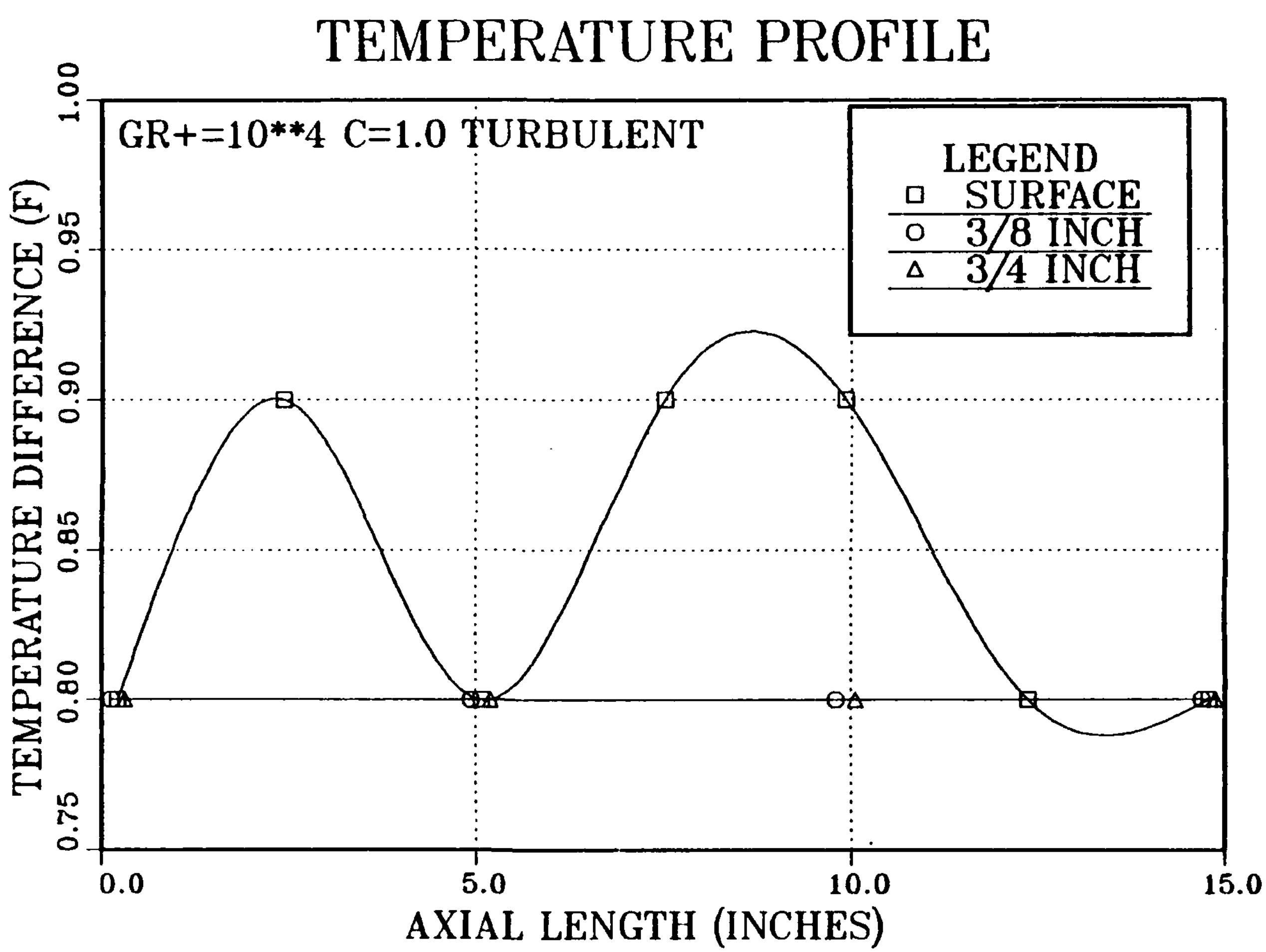


Figure 5.7 Temperature Profile $Gr^{+}=10^{4}$, C=1.0, Turbulent Flow.

VI. CONVECTION COEFFICIENTS

A. BACKGROUND

Results for the laminar flow convection heat transfer coefficients are presented in two forms. First, as a comparison to the analytical work of Acharya and Patankar, and second as a summary on a single figure. Note that figures are presented for the dimensionless y coordinate, and for the ratio of the local heat transfer coefficient to the average coefficient. The average heat transfer coefficient was easily determined because the rate of heat transfer into the fin and the fin area were known quantities. Turbulent flow results are presented only in summary form.

Determination of the local heat transfer coefficients was incorporated in the following two-step process: (1) calculation of initial local coefficients and (2) calculation of heat transfer rates. If the sum of the calculated heat transfer rates did not equal the known rate, then step 1 was repeated. The assumptions were that the rate of heat transfer from the fin at the base was zero, and that the shape of the heat transfer coefficient curve would be similar to the shape of the velocity curve.

The fin was treated as a set of ten, separate, cascaded, sub-fins [Ref. 4][Ref. 7]. Needed coefficients were then calculated for each of the ten sub-fins. From the heat transfer coefficients, heat transfer rates were calculated and summed to check against the known value. If the two values did not match, the entire process was repeated.

First guess values for the local heat transfer coefficient were determined using

$$\theta(x) = \theta_b \frac{\cosh mx}{\cosh mb} \tag{6.1}$$

with

$$m = \left(\frac{2h}{kt}\right)^{\frac{1}{2}} \tag{6.2}$$

Because the fin, above the base, was approximately isothermal, (actual fin temperatures are given in TABLES 4 and 5) the temperature ratios were very nearly unity, causing errors in the thermocouple readings to be accentuated. Equation 6.1 is predicated on the assumption of a constant surface heat transfer coefficient which was not the case for the overall tests. However for the small sub-fins, the equation was applicable (i.e. the convection was constant for the small fin.

B. LAMINAR FLOW

Laminar flow comparison results are presented in Figure 6.1 for $Gr^+=10^4$ and C=0.0. Comparisons for C=0.4 and C=1.0 are presented in Figures 6.2 and 6.3 respectively. In each case, the test values for the convection coefficients are

TABLE 4

CALCULATED STEADY STATE FIN TEMPERATURES FOR LAMINAR FLOW

	Approximate Position (in)			
	0	5	10	15
Clearance C=0.0				
Depth	Temperature (^{o}F)			
3/4 inch	71.3	71.6	71.7	70.7
3/8 inch	71.5	71.7	71.8	71.6
Clearance C=0.4				
Depth	Temperature (^{o}F)			
3/4 inch	72.3	72.5	72.6	73.0
3/8 inch	72.6	72.7	72.8	72.6
Clearance C=1.0				
Depth	Temperature (^{o}F)			
3/4 inch	72.9	73.0	73.1	73.4
3/8 inch	73.1	73.2	73.3	73.0

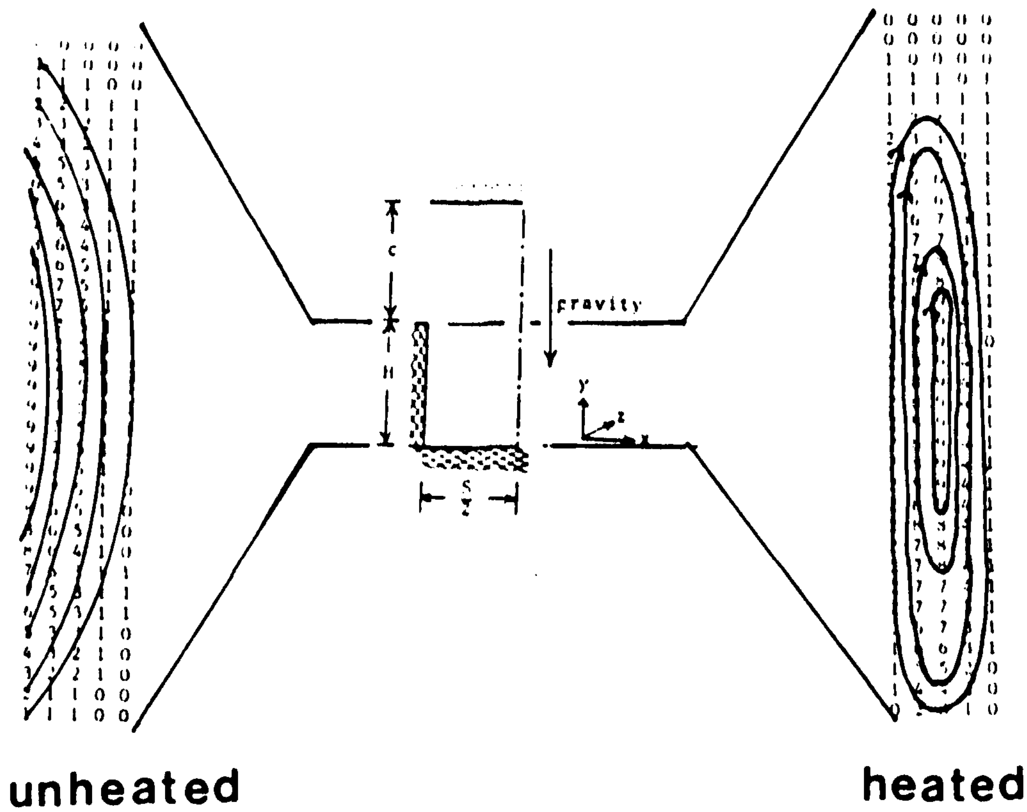


Figure 3.3 Streamline Profiles for Heated Unheated Case.

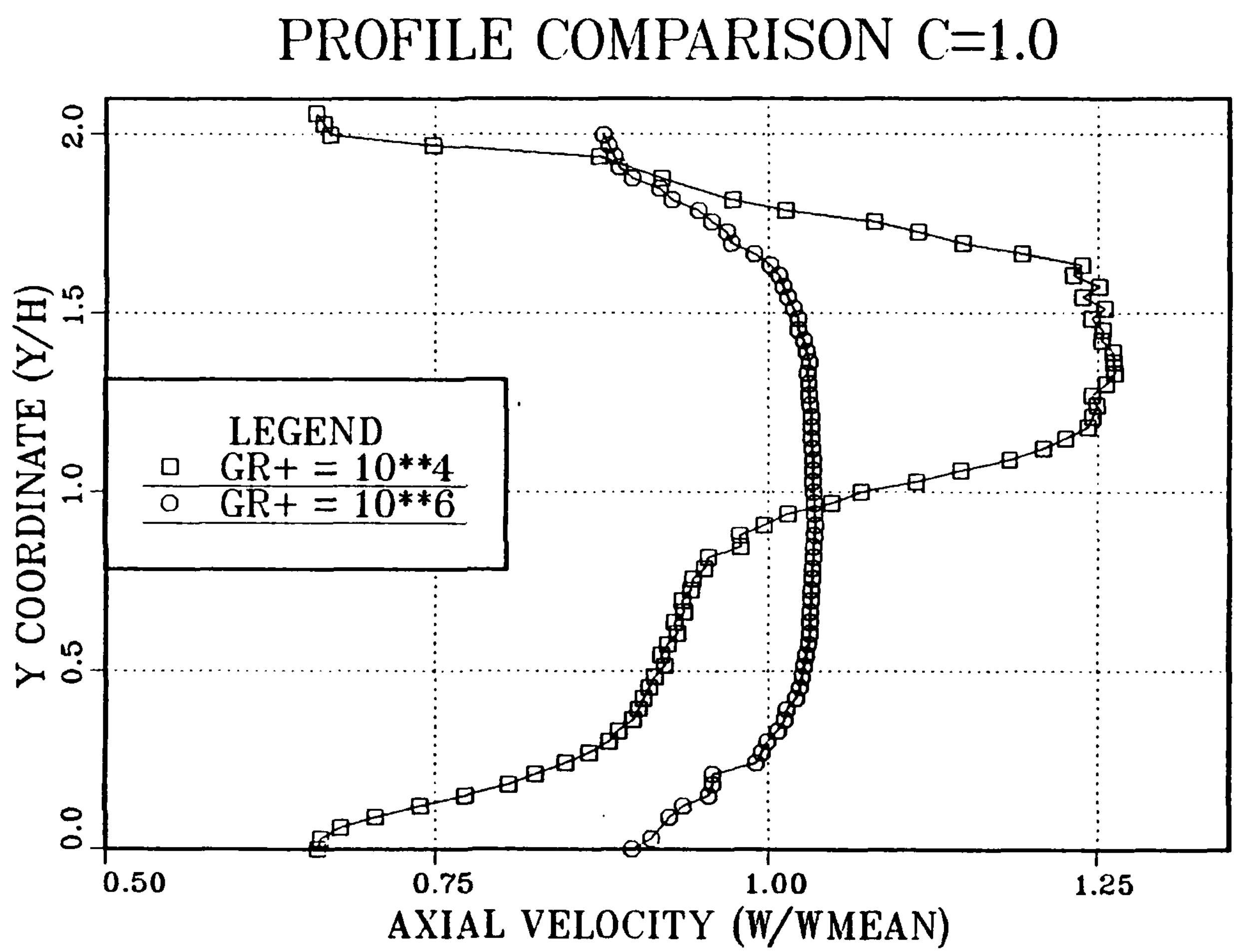


Figure 3.18 Profile Comparison for C=1.0.

IV. TURBULENT FLOW

A. PURPOSE

The purpose of the turbulent flow testing was threefold: (1) the development of turbulent velocity streamline profiles and centerline velocity profiles similar to those determined for laminar flow, (2) the development of temperature profiles within the fin for comparison to the temperature profiles for laminar flow, and (3) the development of convection heat transfer coefficients for the turbulent flow case for comparison to the coefficients that Acharya and Patankar derived analytically for laminar flow. Unfortunately, for turbulent flow there is no analytical work for comparison. Therefore, the assumption is that errors detected during laminar testing will also carry over into the turbulent setting.

In order to ensure comparability, the same modified Grashof Numbers 10^4 and 10^6 were used, as were the dimensionless parameters stated by Acharya and Patankar [Ref. 1]. While only figures will be presented here, a complete listing of the data obtained for each Grashof Number as well as for each clearance ratio is included in Appendices F and G. Comparisons are presented for centerline velocity profiles as well as for streamline profiles. As was evident with the laminar flow results, the velocities are caused by buoyancy effects. As the actual flow direction cannot be determined, the direction of the secondary flow is assumed. The relative lack of quiescence in the "trace" of the oscilloscope offerred additional verification of turbulent testing.

B. MODIFIED GRASHOF NUMBER 10^4

Three tests were conducted at $Gr^+=10^4$, with clearance parameters of 0.0, 0.4, and 1.0. The relative strength of the secondary flow is indicated on each figure. As anticipated, there is a general increase in the strength of the secondary field as flow resistance decreases. The orientation of the hot wire probe for the different readings necessary to measure the relative strength of the secondary field was outlined in Chapter III, "Laminar Flow".

1. Clearance Parameter = 0.0, 0.4, and 1.0

Figures 4.1, 4.2, and 4.3 present the streamline profiles for $Gr^+=10^4$ and C=0.0, C=0.4, and C=1.0 respectively. The relatively high velocities in the turbulent velocity field cause more scatter to the data, but the profiles are appropriate for an average flow through the duct. As the clearance is increased, the mean velocity down the channel decreases, the velocity perturbations decrease slightly, and the scatter is less evident. Once again, streamlines are sketched by hand as an approximation of the computer output. In this case actual locations are at the

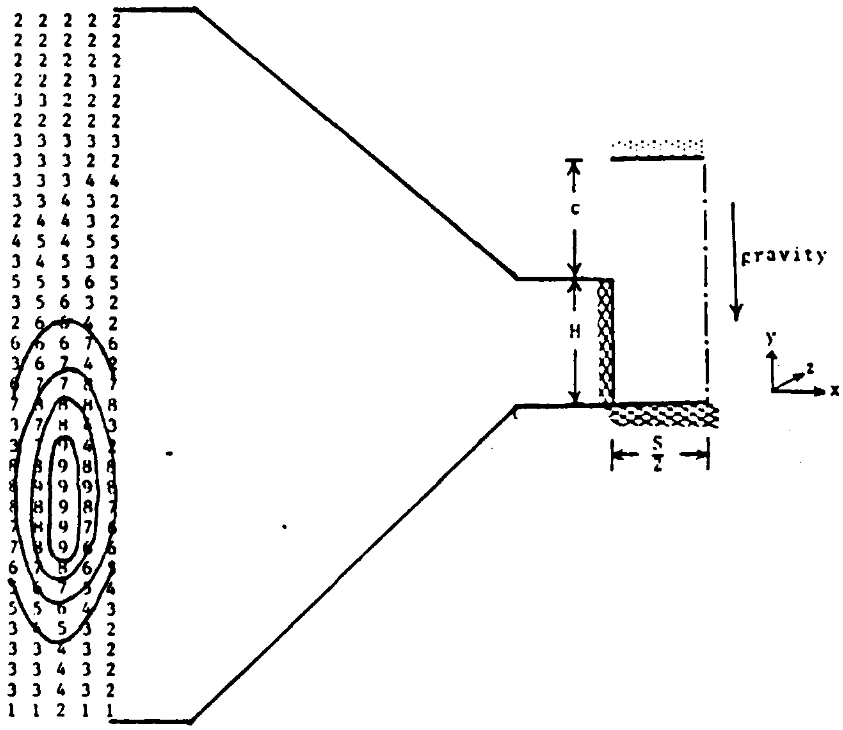


Figure 4.1 Streamlines for $Gr^{+}=10^{4}$, C=0.0, Turbulent Flow.

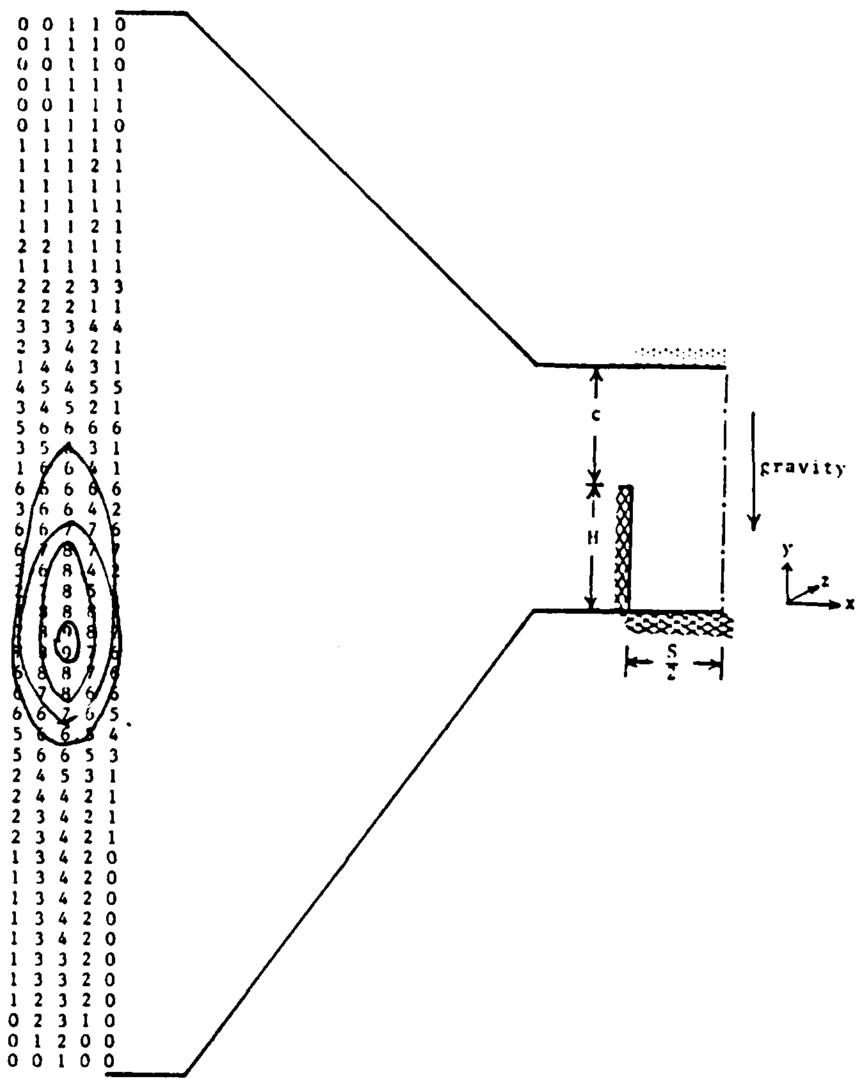


Figure 4.2 Streamlines for $Gr^{+}=10^{4}$, C=0.4, Turbulent Flow.

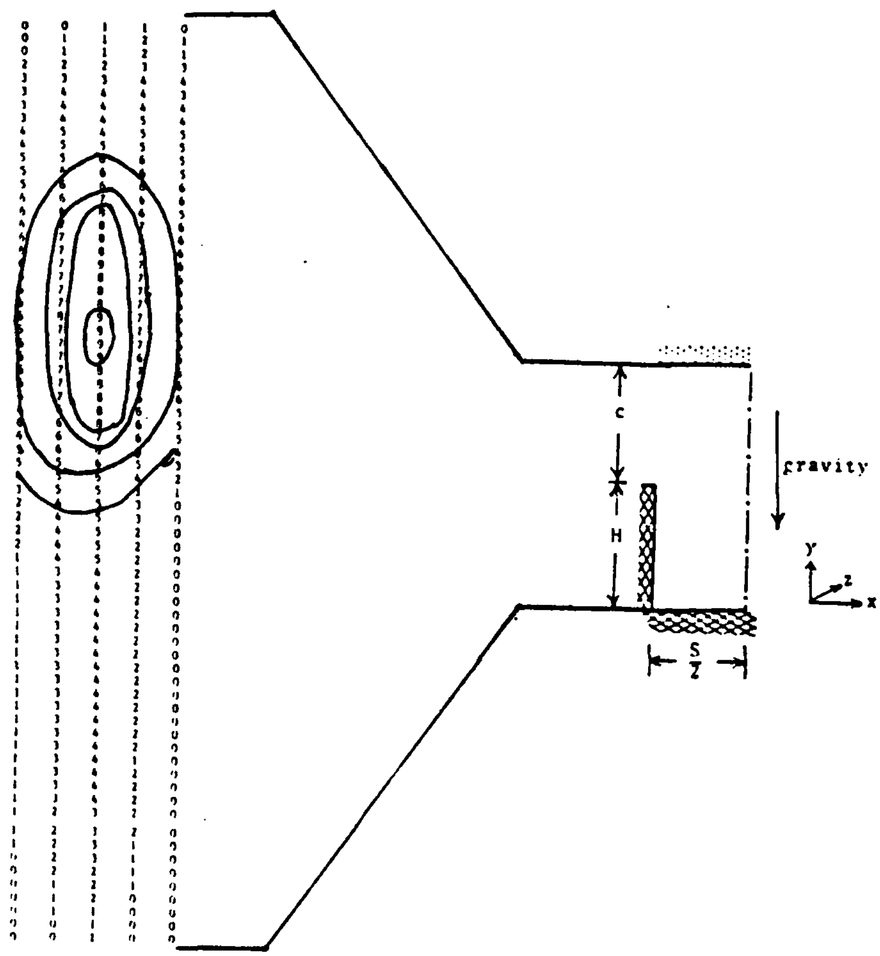


Figure 4.3 Streamlines for $Gr^{+}=10^{4}$, C=1.0, Turbulent Flow.

discretion of the individual doing the drawing. The resolution of the streamlines in the vicinity of either the solid boundaries or the lines of symmetry is very poor. This result was expected and is consistent with the laminar flow findings.

2. Centerline Velocity Profiles

Figure 4.4 illustrates the centerline velocity profiles for $Gr^{+}=10^{4}$ and clearance ratios C=0.0, C=0.4 and C=1.0. Examination of the illustration indicates that the velocity profile was not fully developed for either C=0.0 or C=0.4. It was not possible for the profile for C=1.0 to be fully developed even though the figure indicates fully-developed conditions. The flatness of the C=1.0 profile is accounted for by the separation distance from the exit plane of the finned array to the hot wire probe. As previsouly discussed, the separation distance allows the "wake" of the exiting flow to impinge on the probe of the hot wire anemometer. This means that the velocity as measured can never truly go to zero at the boundaries, which, in turn, leads to a relatively high mean velocity. Because all figures are based on the mean velocity, the ratios produced by the test are always lower than any analytically-derived value.

Also, when the hot wire probe was reoriented to determine the relative strength of the secondary flow, the "wake" had the effect of increasing the secondary flow percentage.

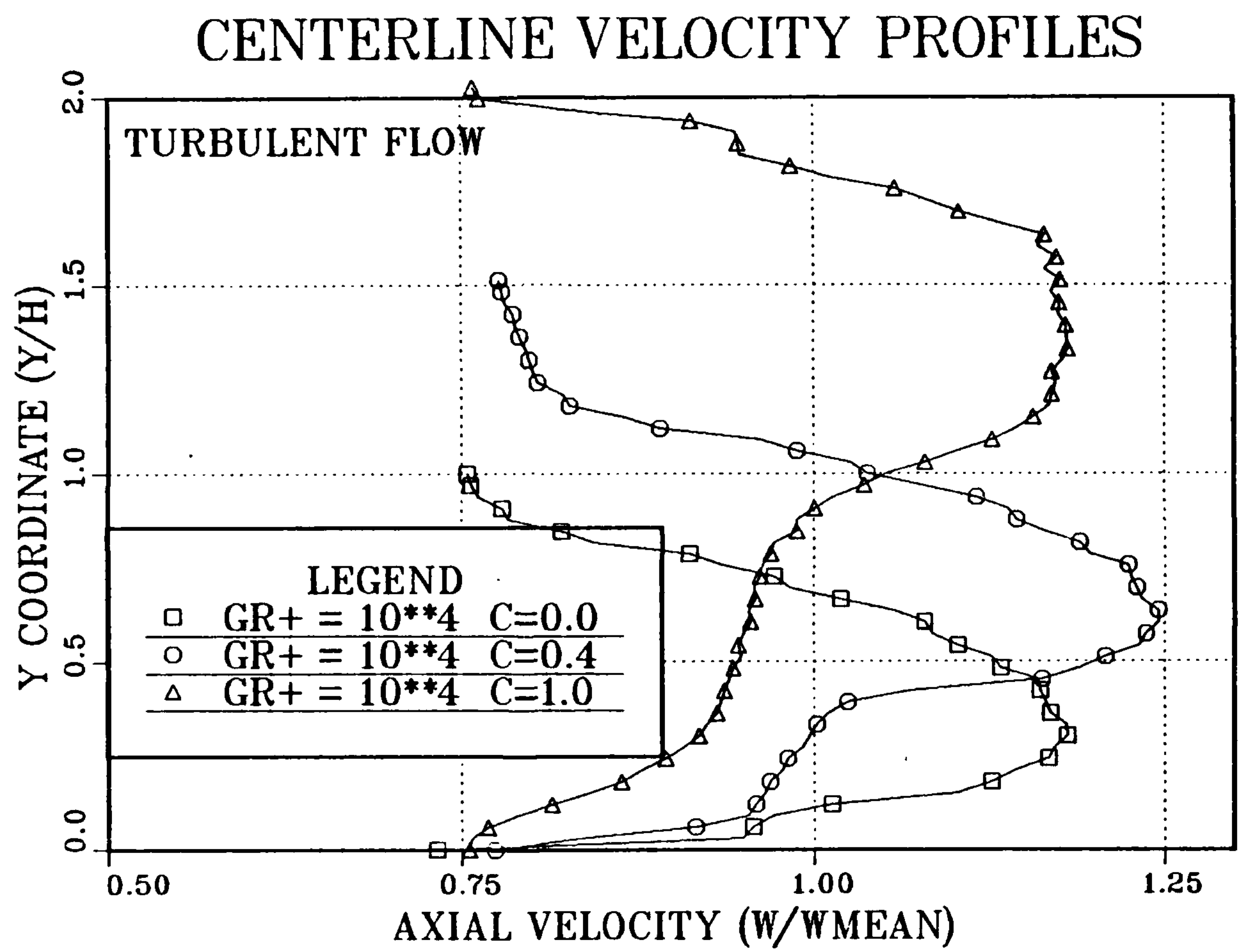


Figure 4.4 Turbulent Centerline Velocity Profiles, $Gr^{+}=10^{4}$, C=0.0, C=0.4, and C=1.0.

C. MODIFIED GRASHOF NUMBER 10^6

1. Clearance Parameter Equal 0.0, 0.4, and 1.0

As with a modified Grashof Number of 10^4, three test runs were conducted. Figures 4.5, 4.6, and 4.7 are the streamline profiles for C=0.0, C=0.4 and C=1.0 respectively. For these tests the magnitude of the relative strength of the secondary flow is greater than the strength of the secodary flow encountered for $Gr^+=10^4$. This result was expected but the strength of the secondary flow did not increase as much as expected.

2. Centerline Velocity Profile

Figure 4.8 shows the centerline velocity profiles for $Gr^+=10^6$, and for clearance parameters C=0.0, C=0.4, and C=1. These centerline velocities show the characteristics discussed previously for $GR^+=10^4$.

D. CENTERLINE VELOCITY PROFILE COMPARISON

Figures 4.9, 4.10 and 4.11 indicate the differences in the centerline velocity profiles due to a change in the Grashof number. Even though the free-stream velocity was not intentionally changed during these tests, it was necessary to recalibrate the hot wire anemometer. The changes in the profiles due to recalibration are minimal when compared to other effects (i.e. the heat input). Thus, the figures give a very good indication of how the

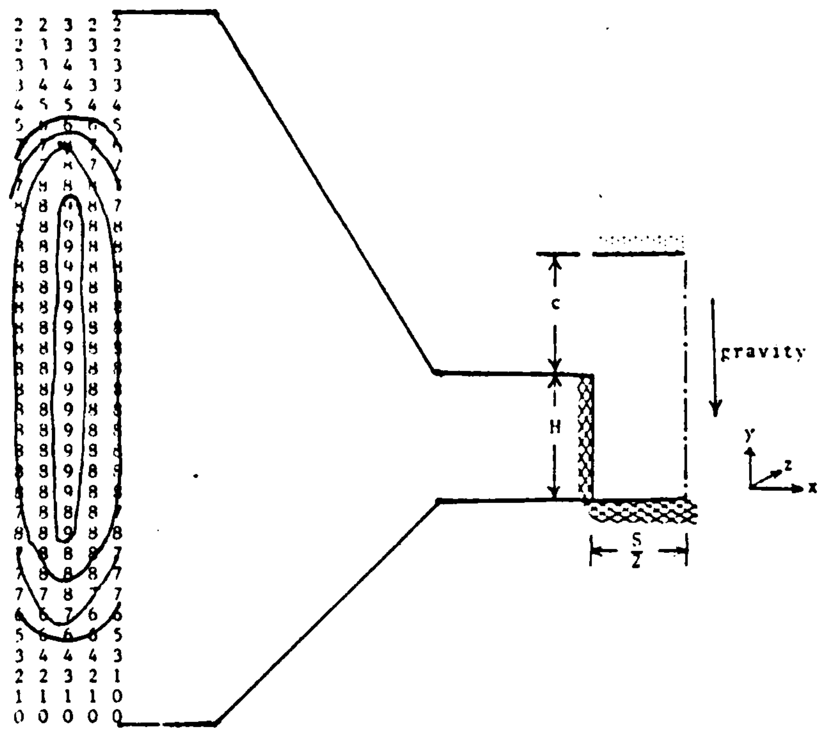


Figure 4.5 Streamlines for $Gr^{+}=10^{6}$, C=0.0, Turbulent Flow.

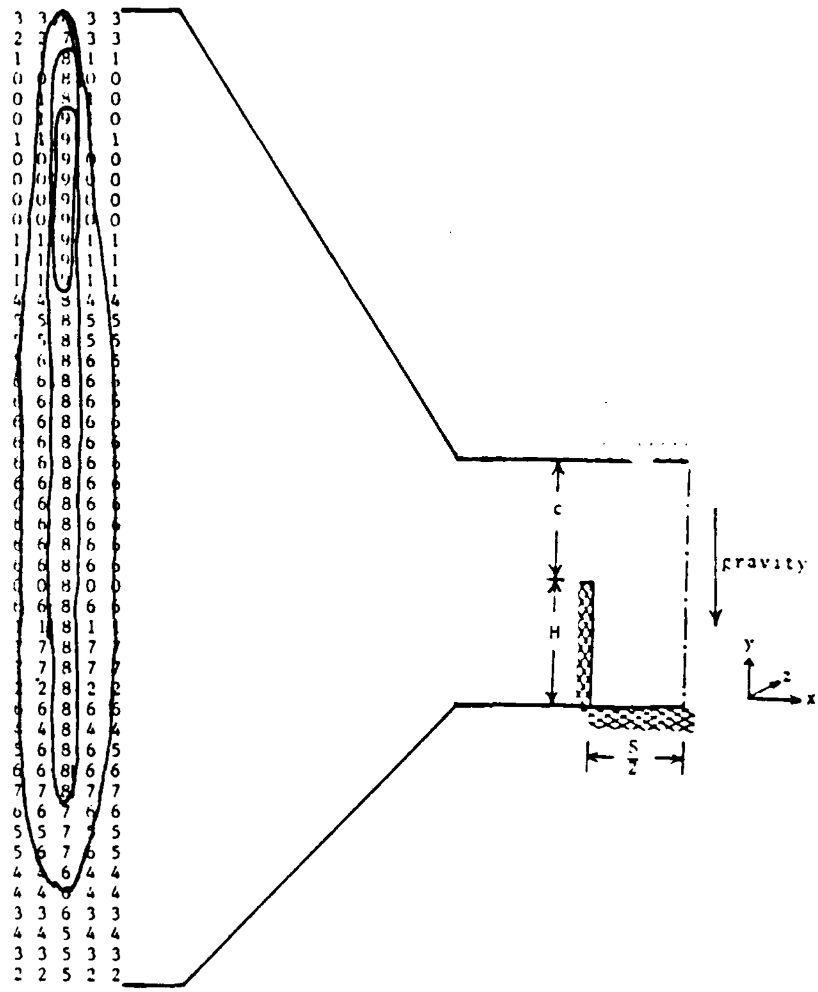


Figure 4.6 Streamlines for $Gr^{+}=10^{6}$, C=0.4, Turbulent Flow.

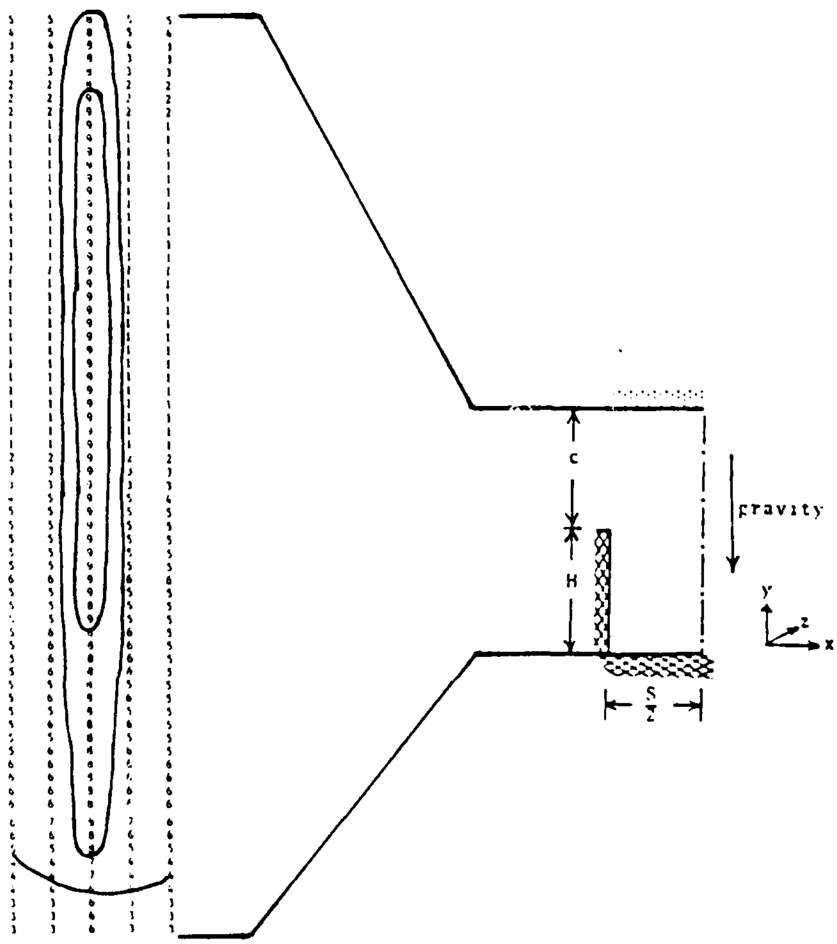


Figure 4.7 Streamlines for $Gr^{+}=10^{6}$, C=1.0, Turbulent Flow.

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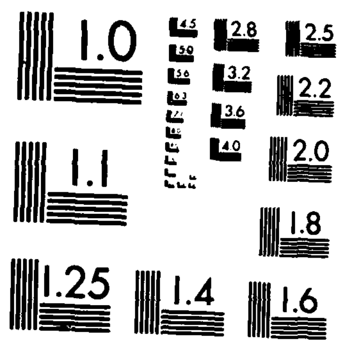

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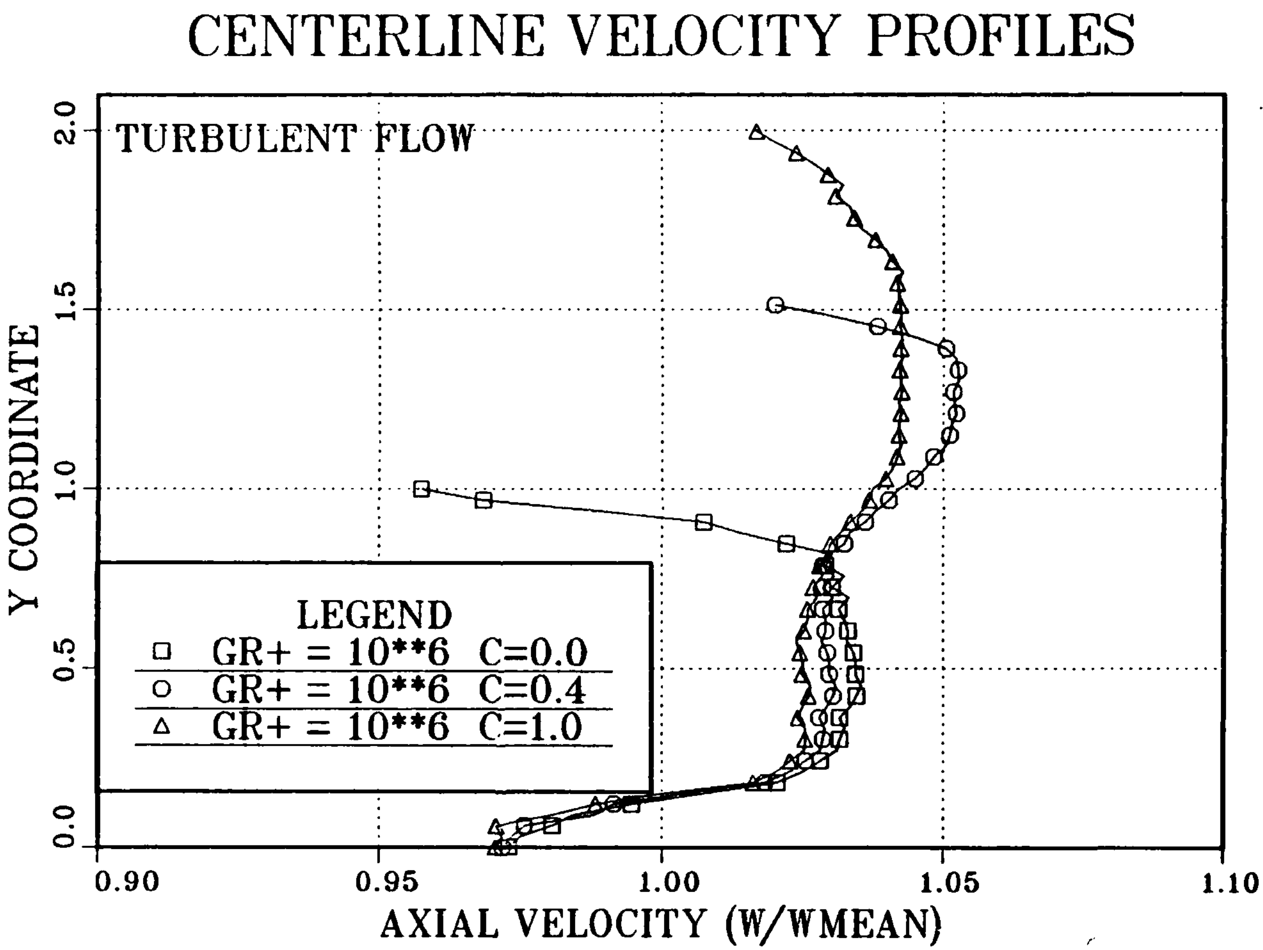


Figure 4.8 Turbulent Centerline Velocity Profiles, $Gr^{+}=10^{6}$, C=0.0, C=0.4, and C=1.0.

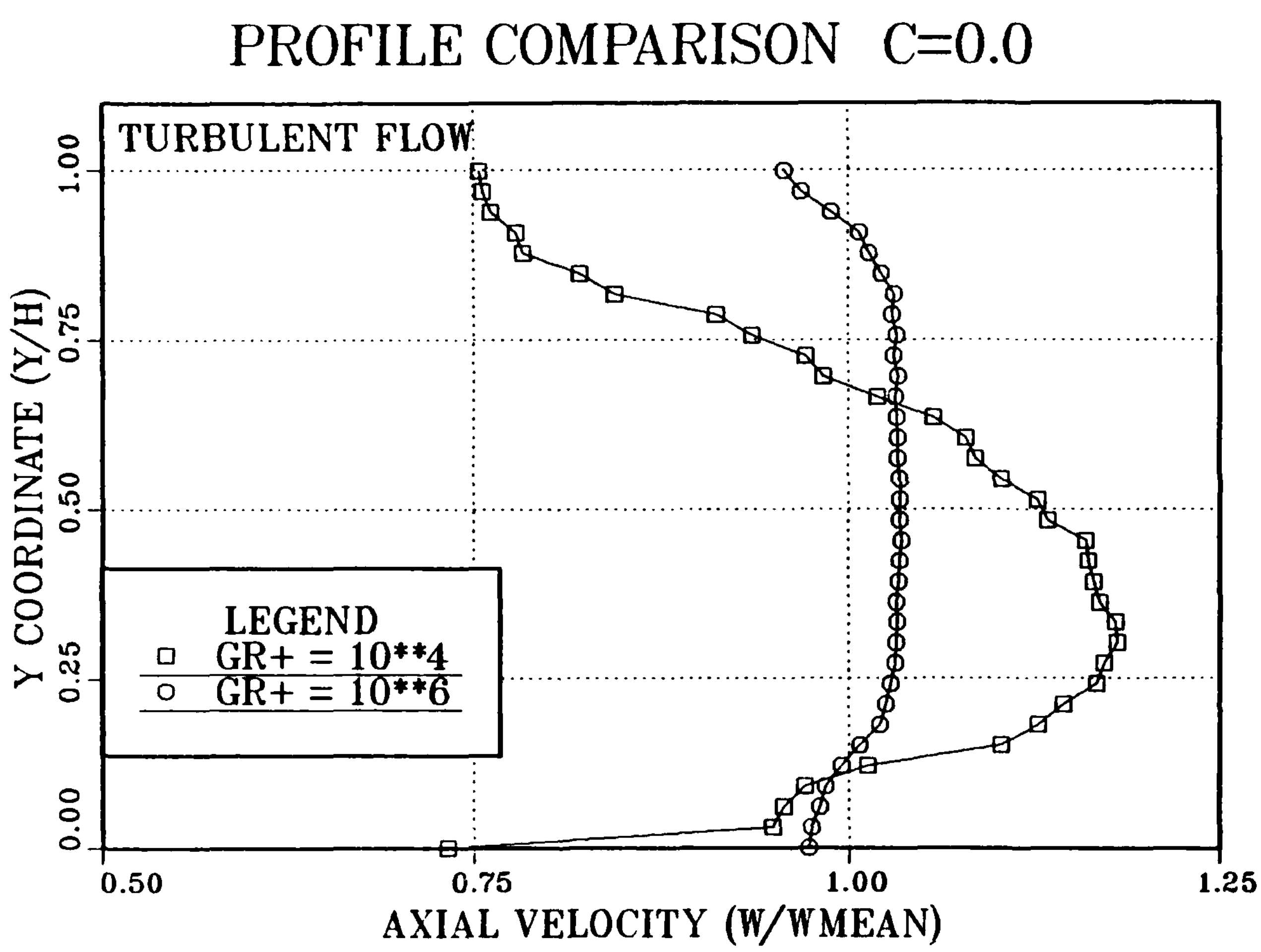


Figure 4.9 Profile Comparison for C=0.0.

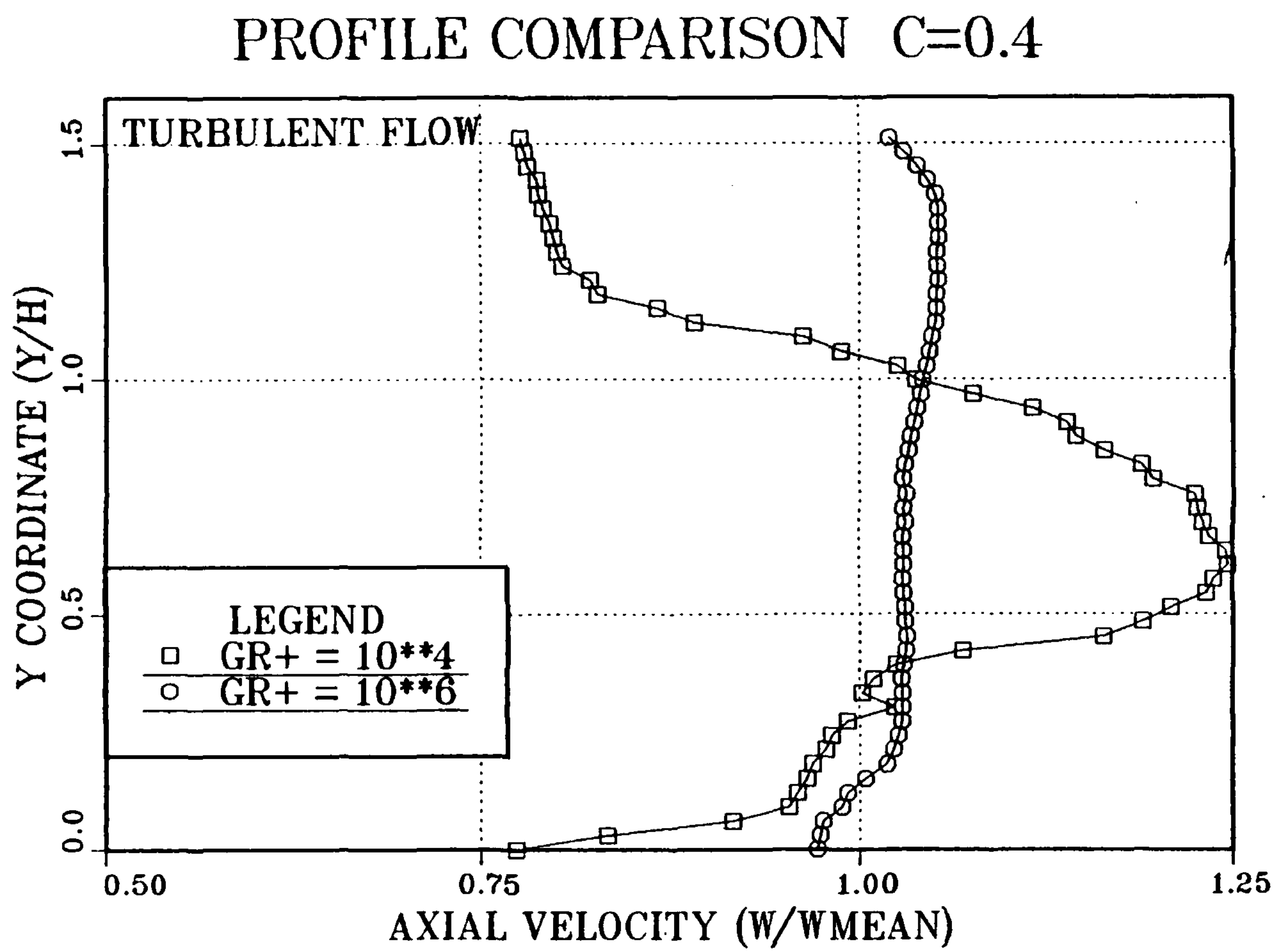


Figure 4.10 Profile Comparison for C=0.4.

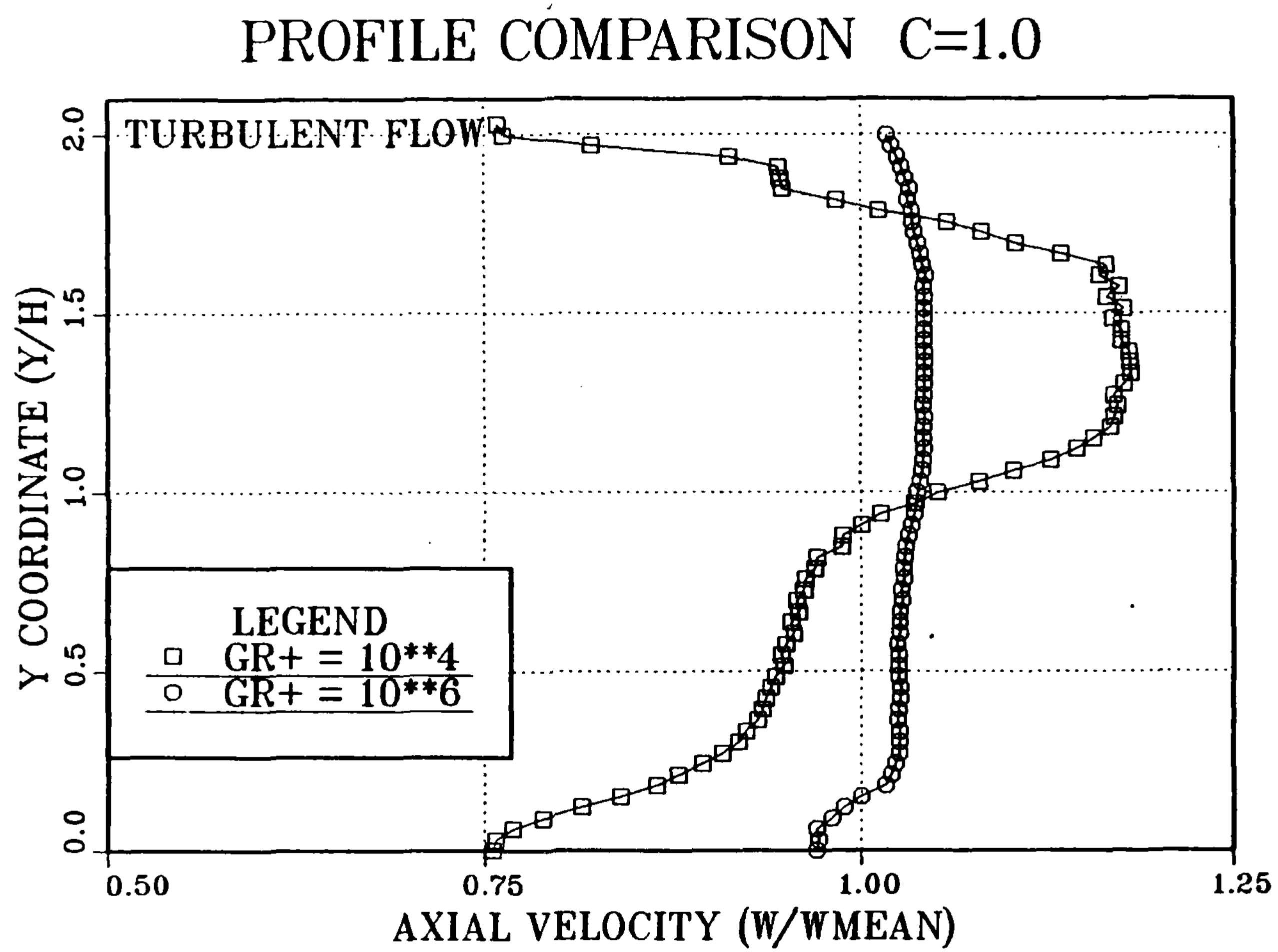


Figure 4.11 Profile Comparison for C=1.0.

centerline velocity profile would change for an increase in the heat flow.

E. TURBULENT-LAMINAR FLOW COMPARISON

The following figures are provided for a quick visual comparison of the laminar and turbulent flow. Figures 4.12, 4.13, and 4.14 are for $Gr^{+}=10^{4}$ and C=0.0, C=0.4, and C=1.0 respectively. Figures 4.15, 4.16, and 4.17 are for $Gr^{+}=10^{6}$ with the same clearance ratios.

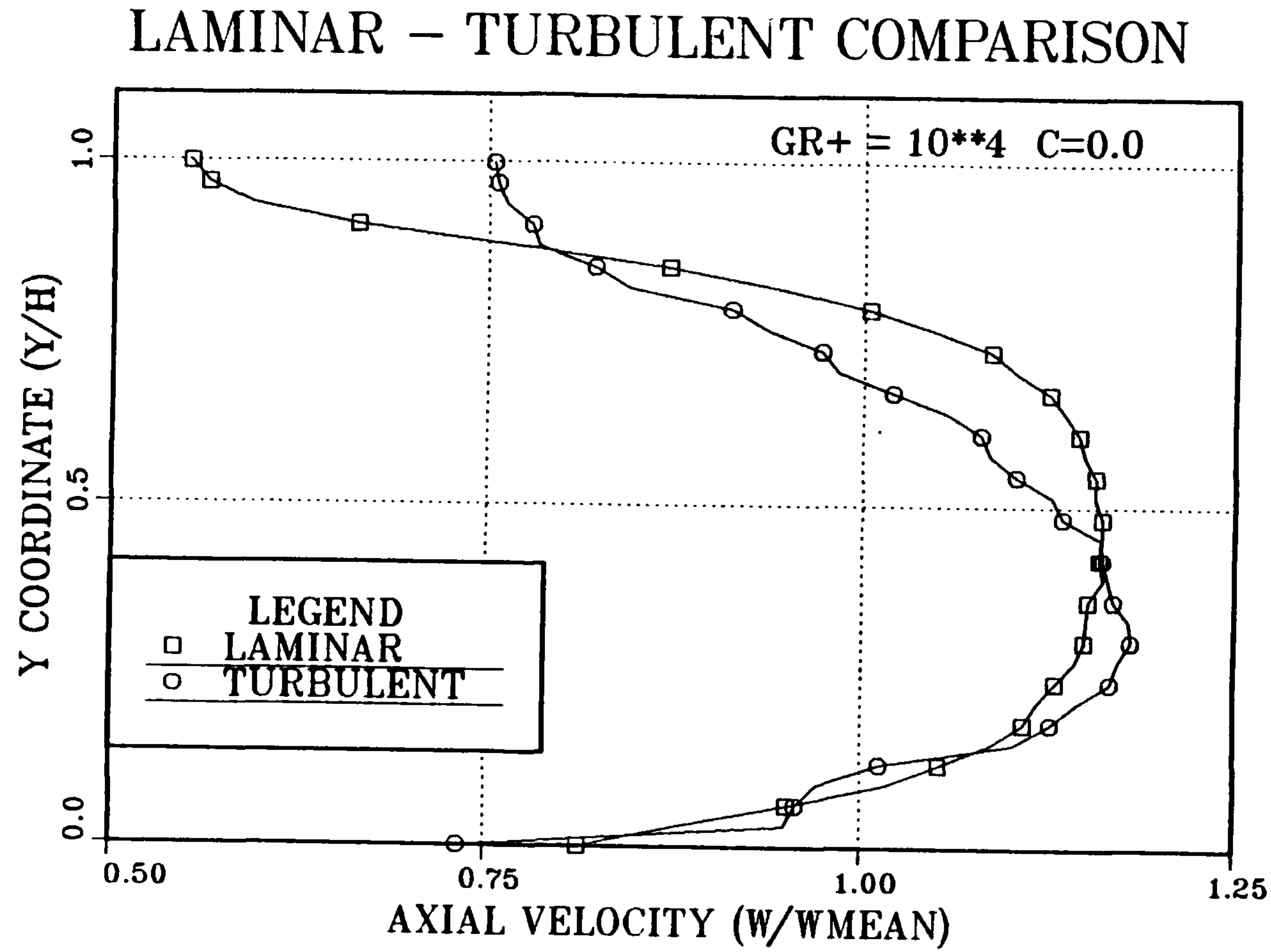


Figure 4.12 Laminar-Turbulent Comparison $Gr^{+}=10^{4}$, C=0.0.

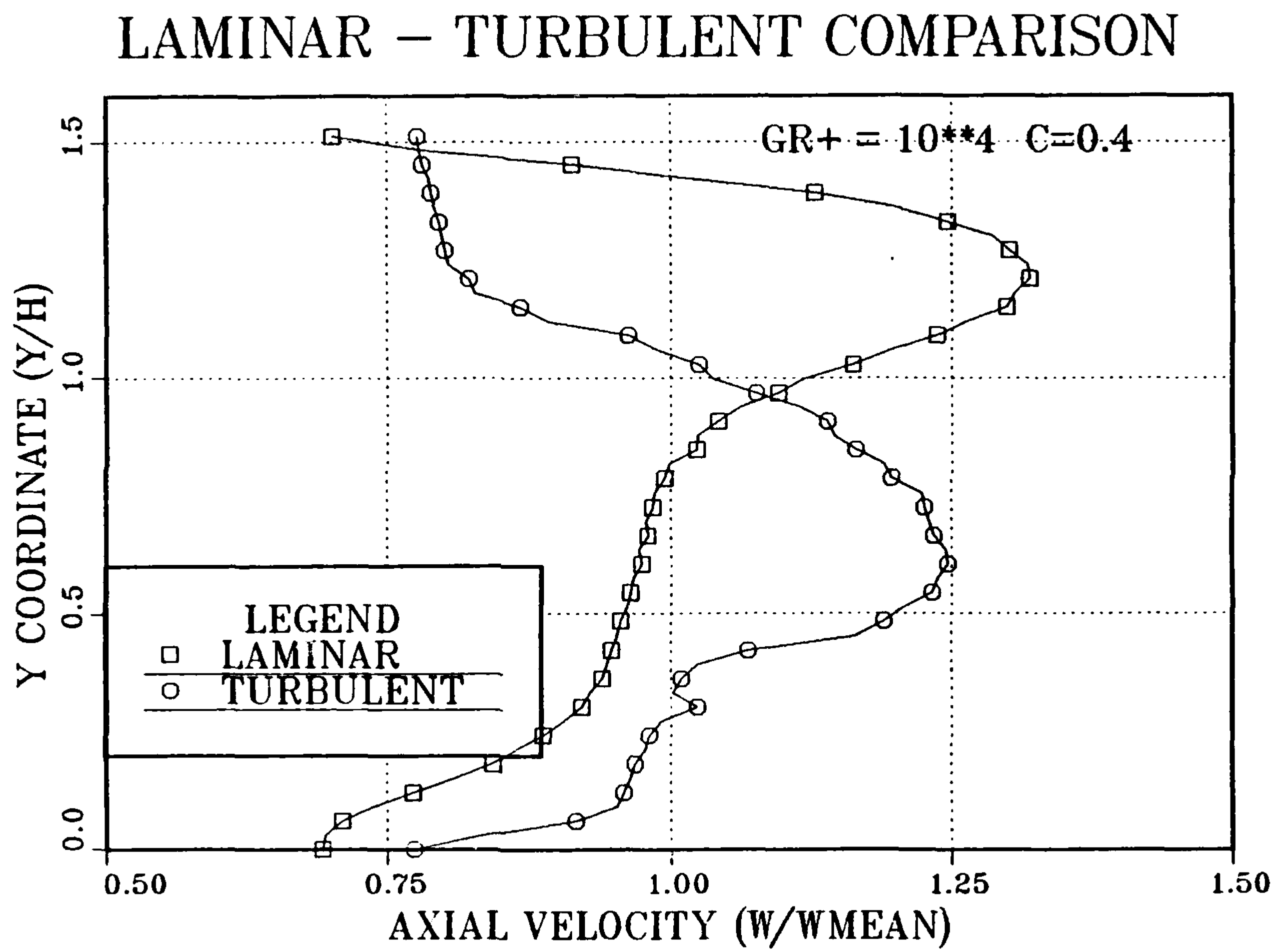


Figure 4.13 Laminar-Turbulent Comparison $Gr^{+}=10^{4}$, C=0.4.

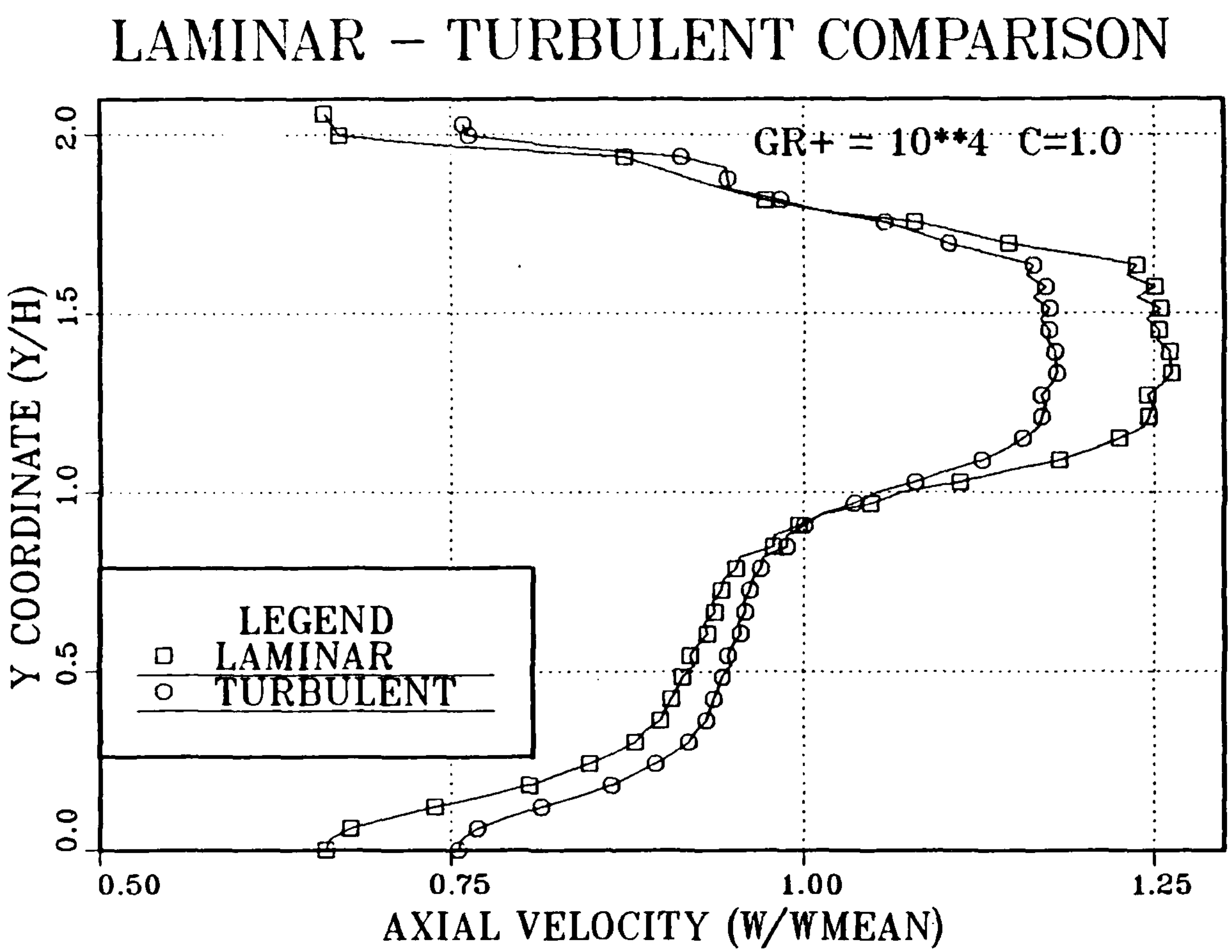


Figure 4.14 Laminar-Turbulent Comparison $Gr^{+}=10^{4}$, C=1.0.

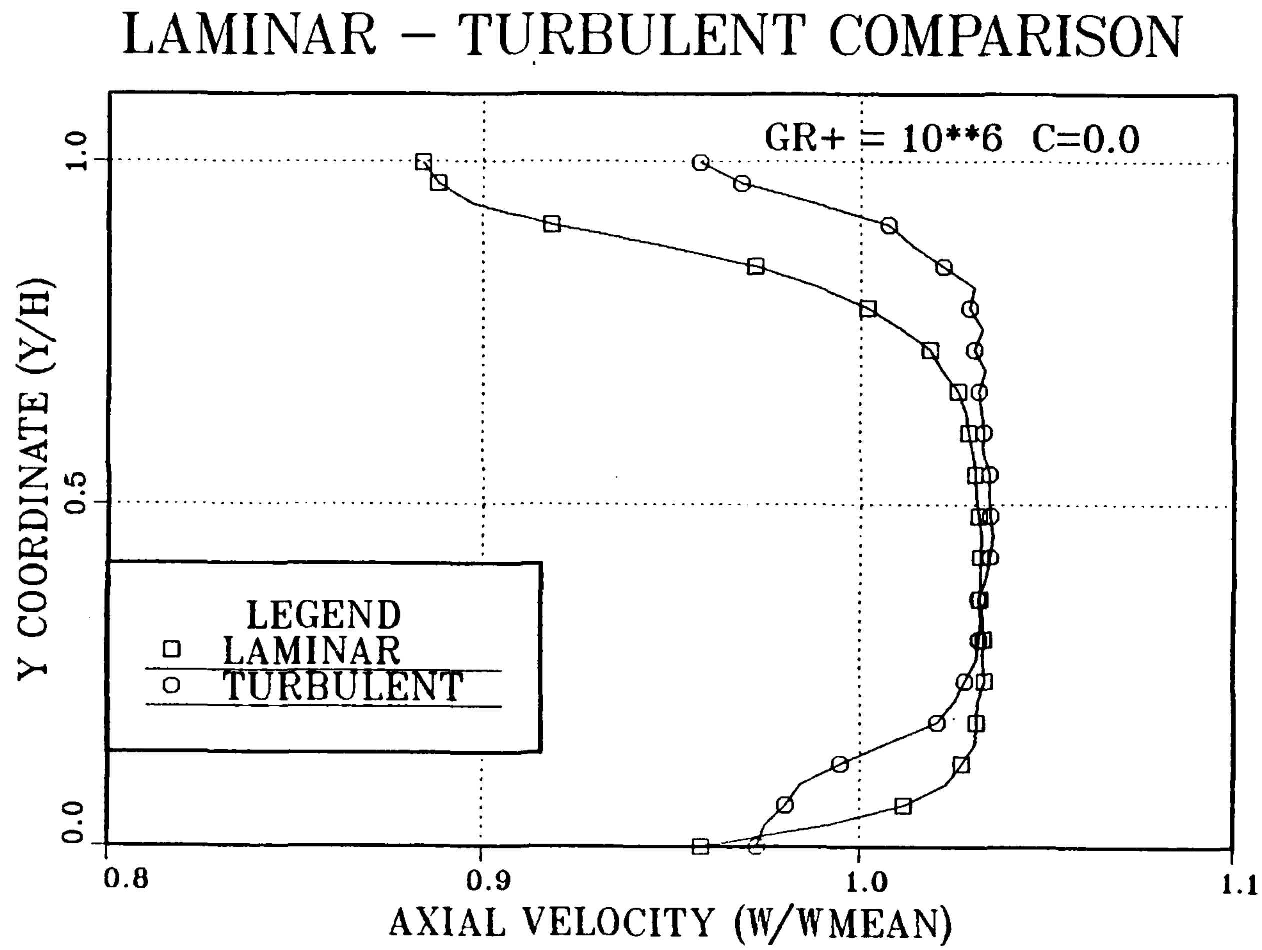


Figure 4.15 Laminar-Turbulent Comparison $Gr^{+}=10^{6}$, C=0.0.

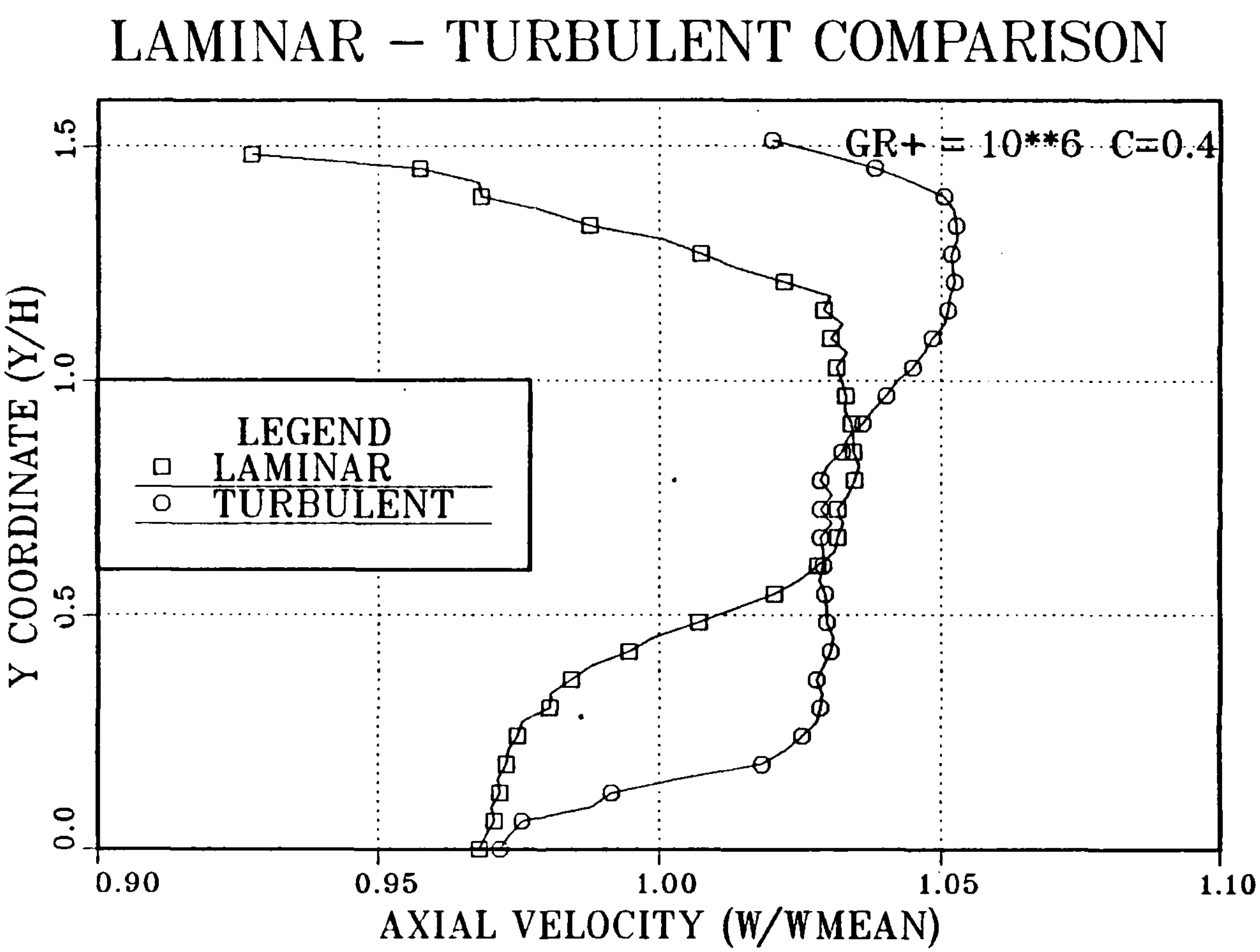


Figure 4.16 Laminar-Turbulent Comparison $Gr^{+}=10^{6}$, C=0.4.

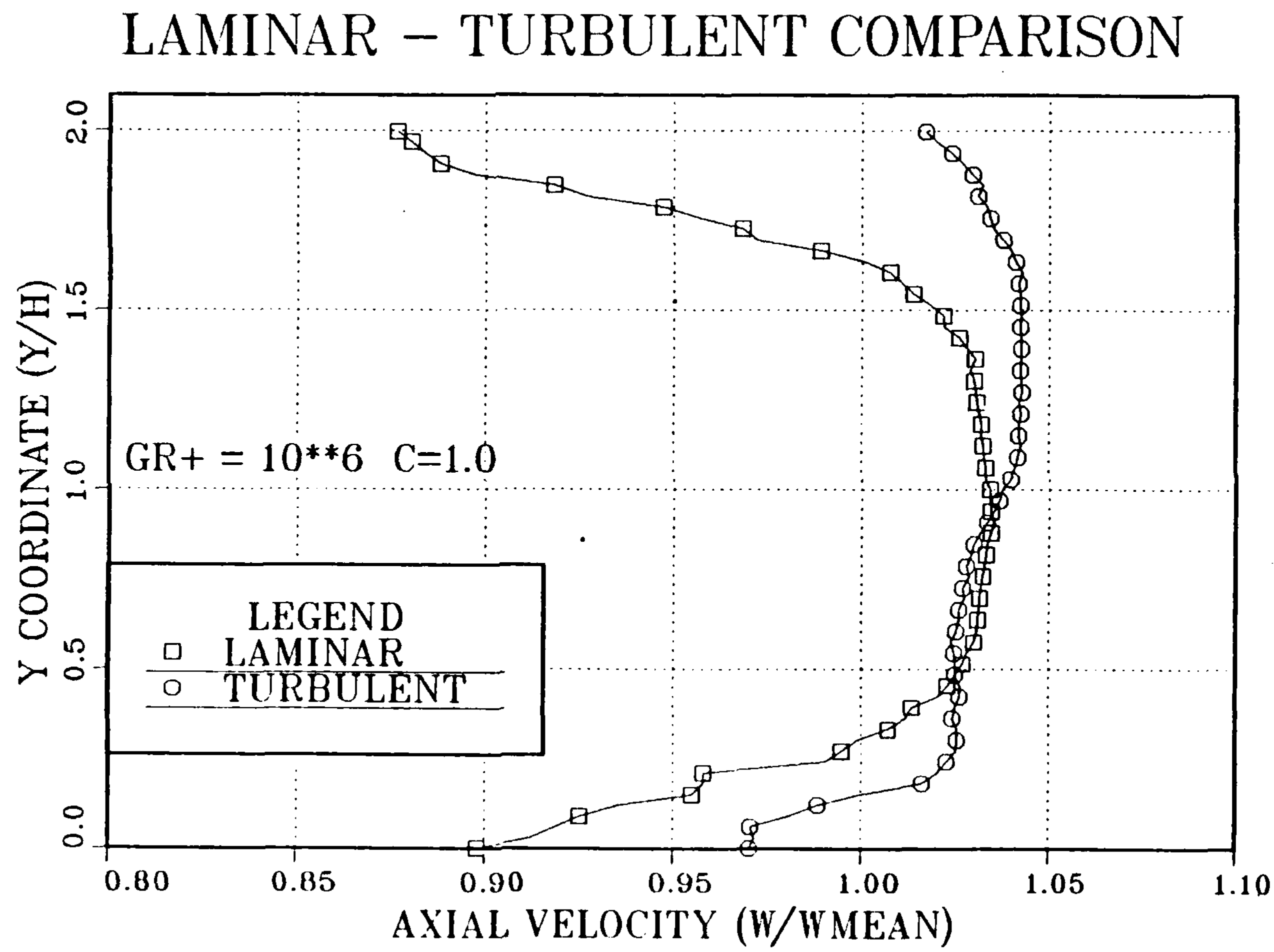


Figure 4.17 Laminar-Turbulent Comparison $Gr^{+}=10^{6}$, C=1.0.

V. TEMPERATURE PROFILES

A. PURPOSE

Development of temperature profiles along the length of the fin was essential to the determination of the convection heat transfer coefficients. Temperature profiles were developed directly from the temperature readings recorded for steady state conditions. Profiles are presented only for $Gr^{+}=10^{4}$ for laminar and turbulent flow with clearance ratios C=0.0, C=0.4, and C=1.0. As in Chapters III and IV, only figures will be presented here, a partial listing of the temperatures being available in Tables 4 and 5. Table 4 contains the information for laminar flow, and Table 5 contains information for turbulent flow.

B. LAMINAR FLOW

Figure 5.1 is presented as a reminder of how the thermocouples were mounted on the longitudinal finned array. Figures 5.2, 5.3, and 5.4 show the temperature profiles obtained under laminar flow conditions for the three clearance ratios. The sinusoidal temperature pattern on the surface was a function of the silicon pad heater. Note that the pattern was no longer evident for thermocouples mounted at the 3/8-inch depth or the 3/4-inch depth. The temperatures are plotted as the differences based on the

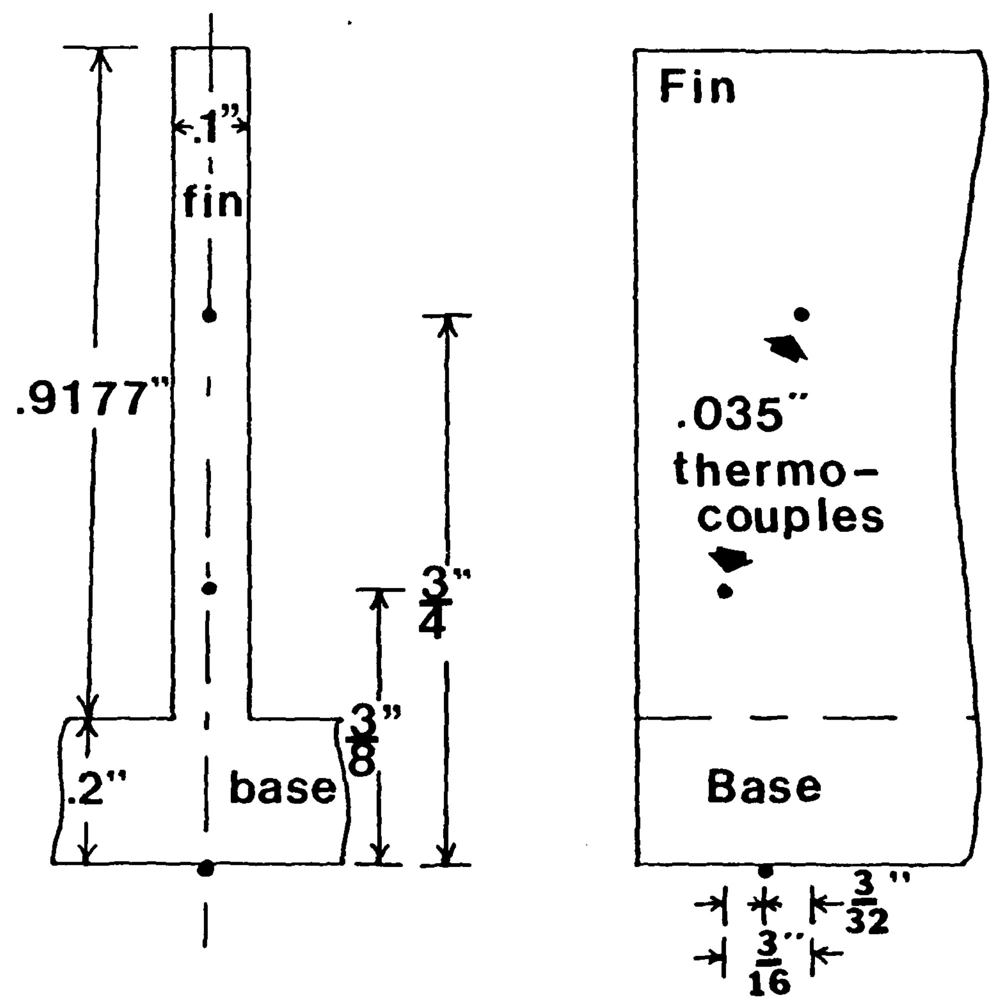


Figure 5.1 Fin Thermocouple Placement.

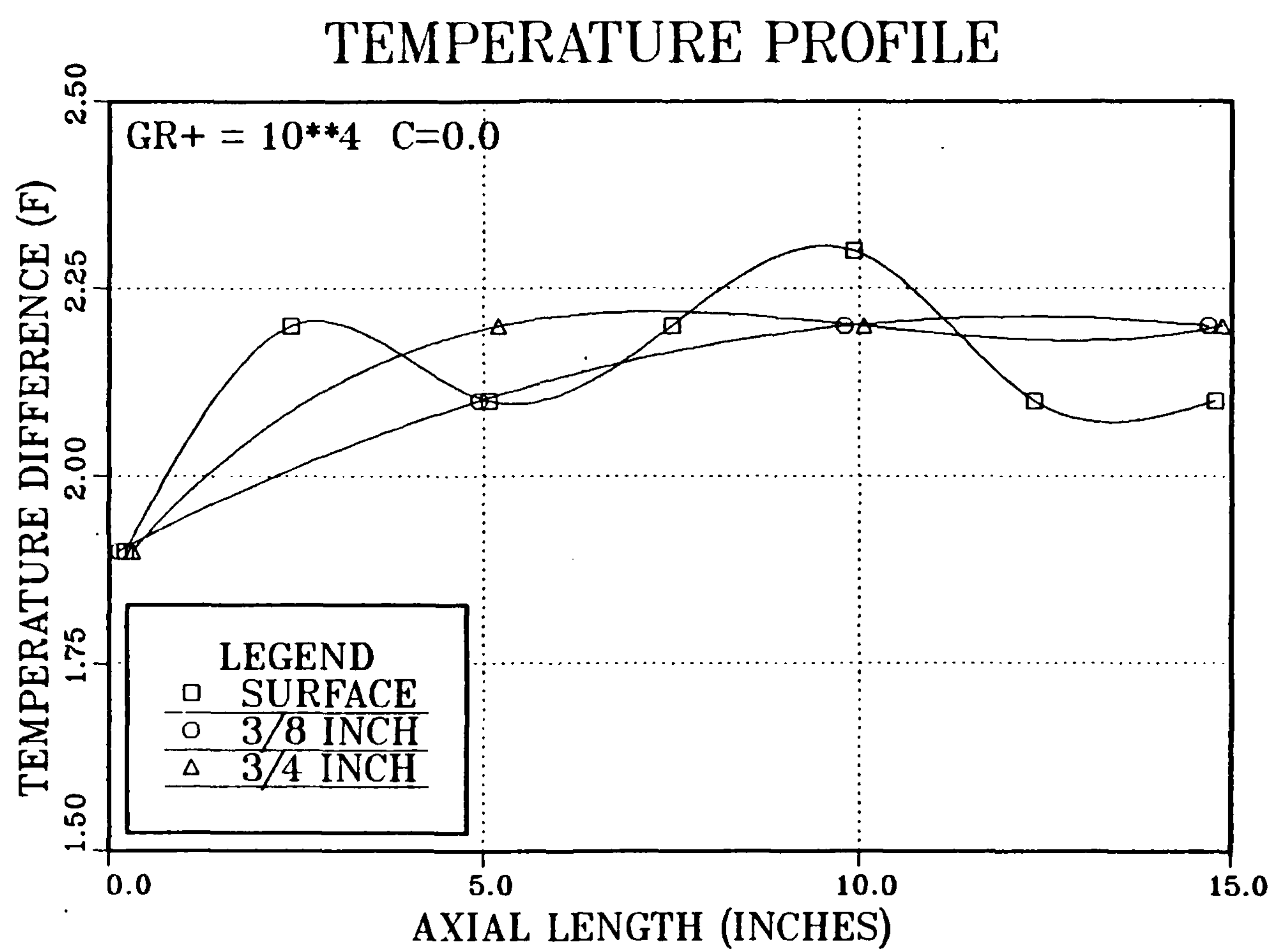


Figure 5.2 Temperature Profile $Gr^{+}=10^{4}$, C=0.0, Laminar Flow.

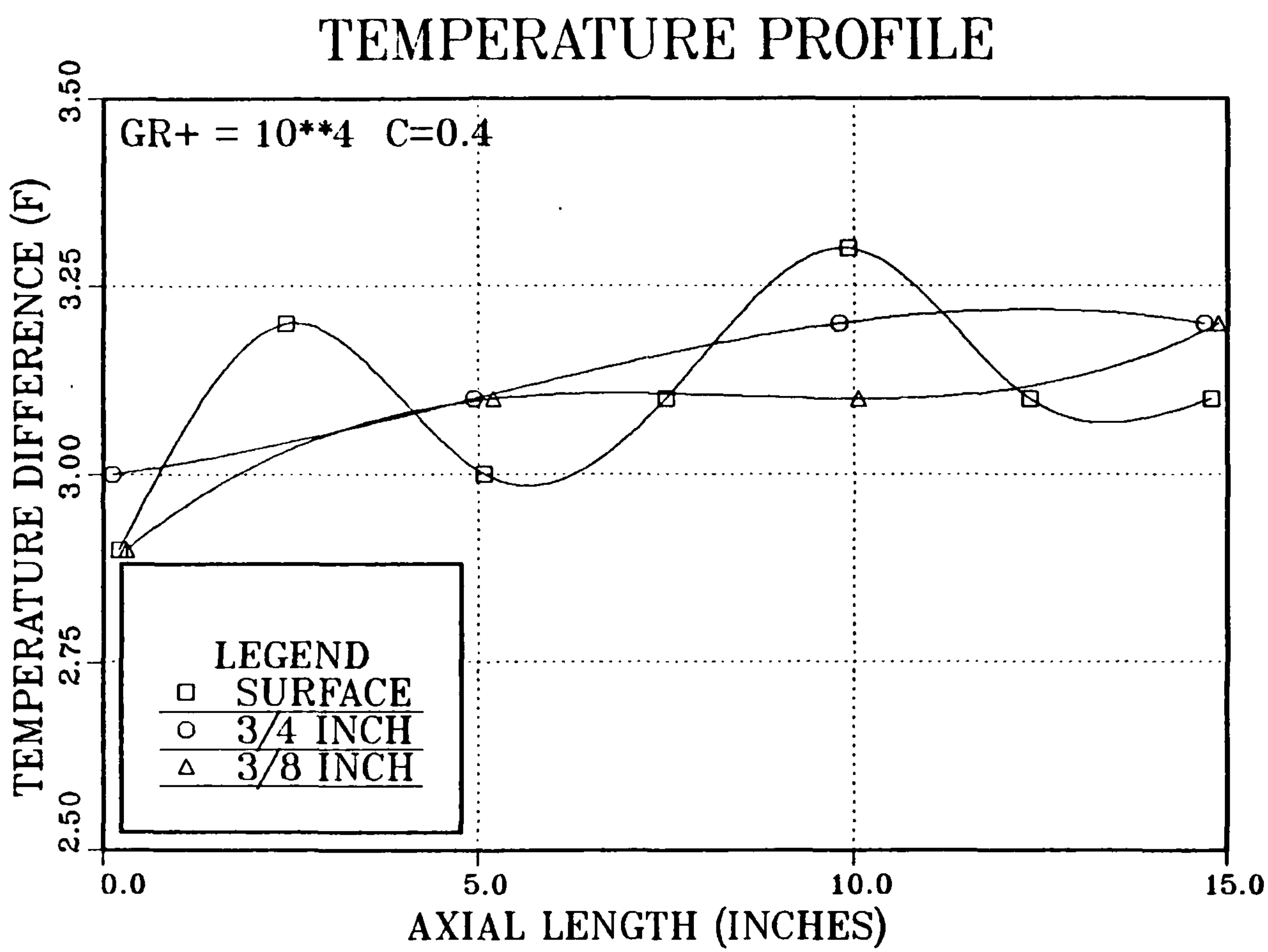


Figure 5.3 Temperature Profile $Gr^{+}=10^{4}$, C=0.4, Laminar Flow.

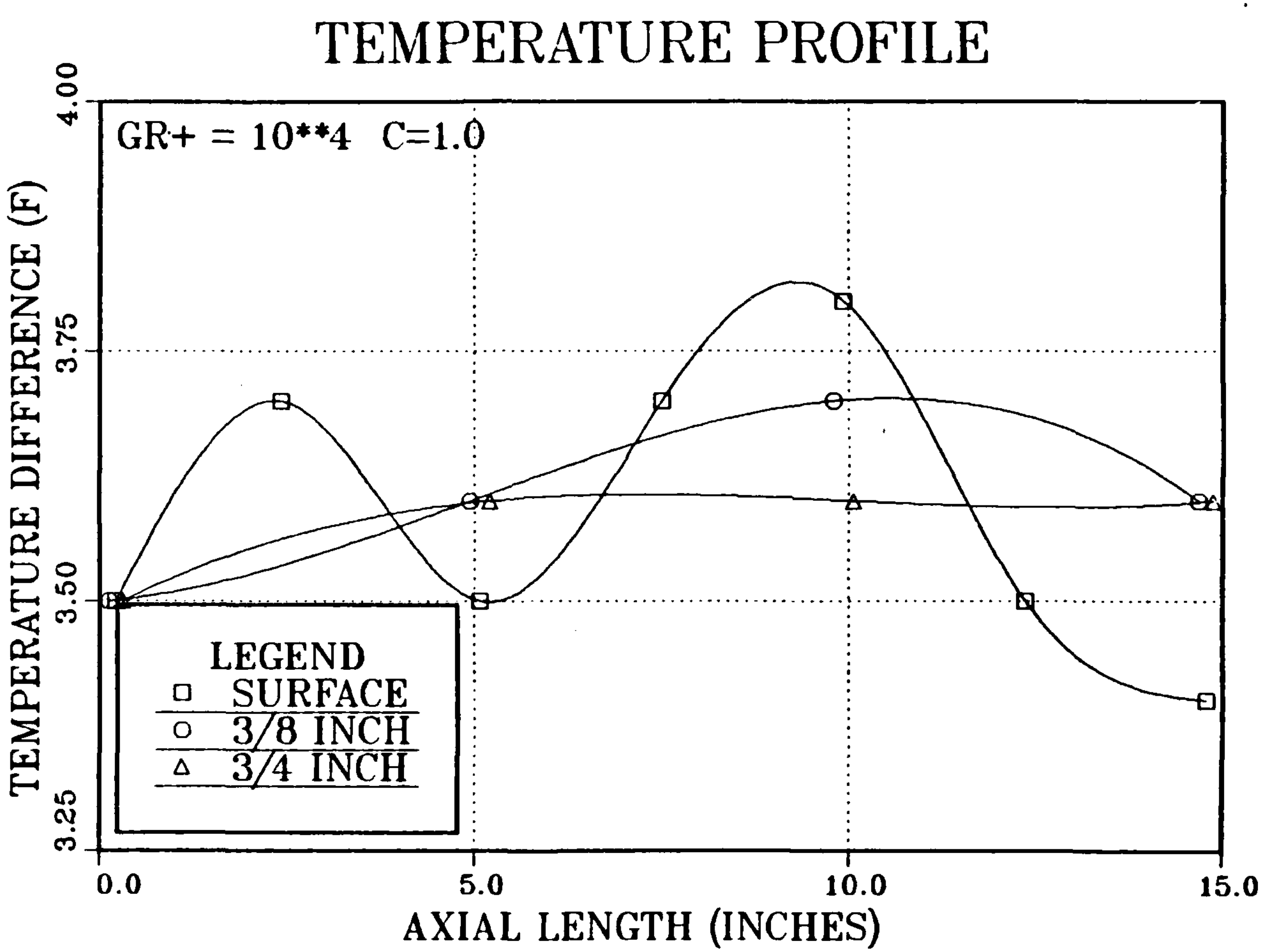


Figure 5.4 Temperature Profile $Gr^{+}=10^{4}$, C=1.0, Laminar Flow.

initial temperature of the assembly. This latter value was used as a base value because of the ease of calculation. To have used the surrounding temperature would have required actual calculation of each temperature. However, use of the initial array temperature necessitates only the calculation of one temperature, with all subsequent values based on this value.

There was a general increase of all temperatures along the fin as the fin tip clearance was increased. This was expected because of the flow rate disparity previously discussed. It remains to be determined how the temperature increase will effect the heat transfer coefficient.

C. TURBULENT FLOW

As evidenced in Figures 5.5, 5.6, and 5.7, the temperature increase under turbulent flow conditions was less than the increase under laminar conditions. This finding was to be expected and was the result of the increased air flow for turbulent conditions. The temperature profiles are important only in that they allow calculation of the convection coefficients at each point.

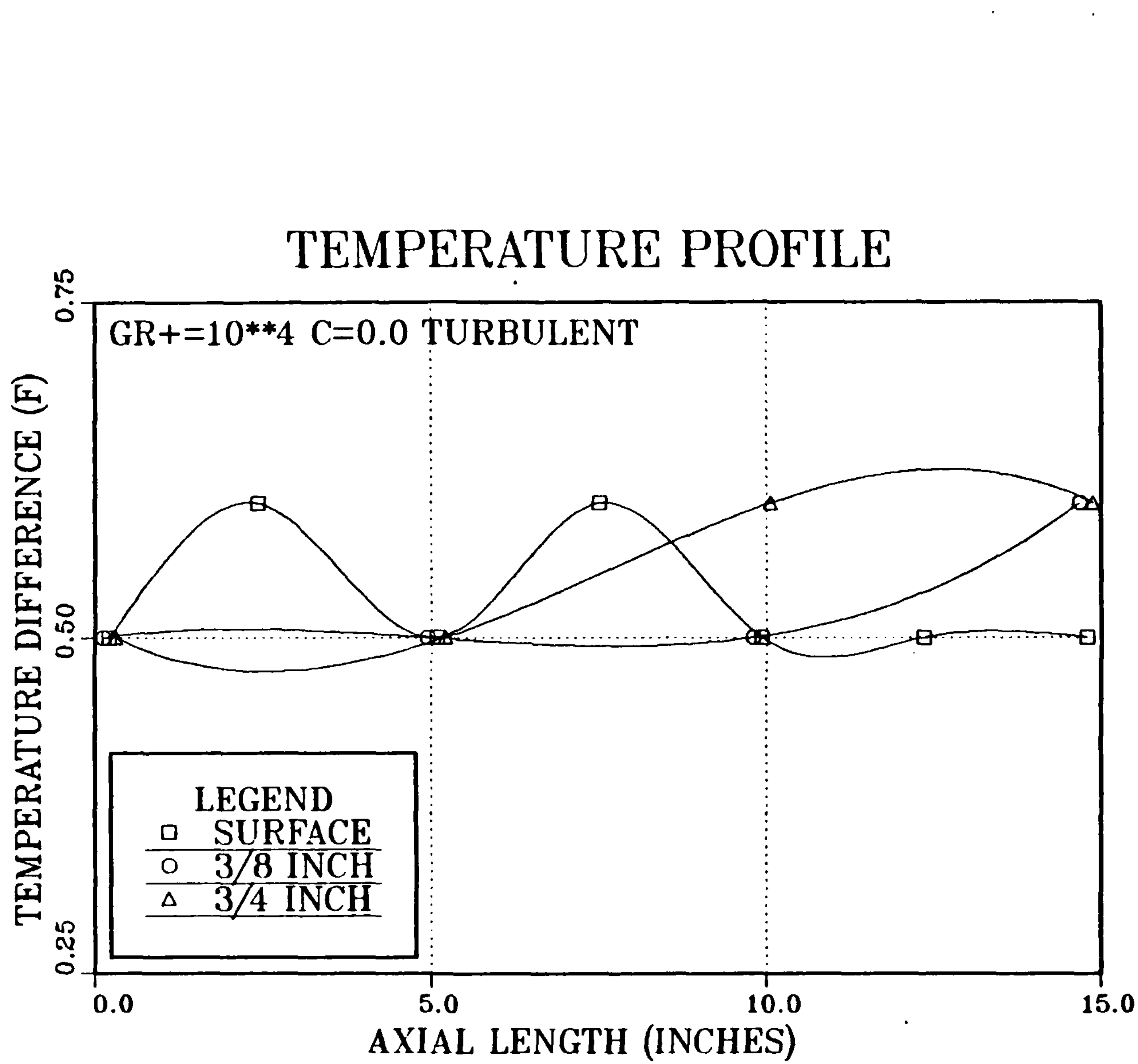


Figure 5.5 Temperature Profile $Gr^{+}=10^{4}$, C=0.0, Turbulent Flow.

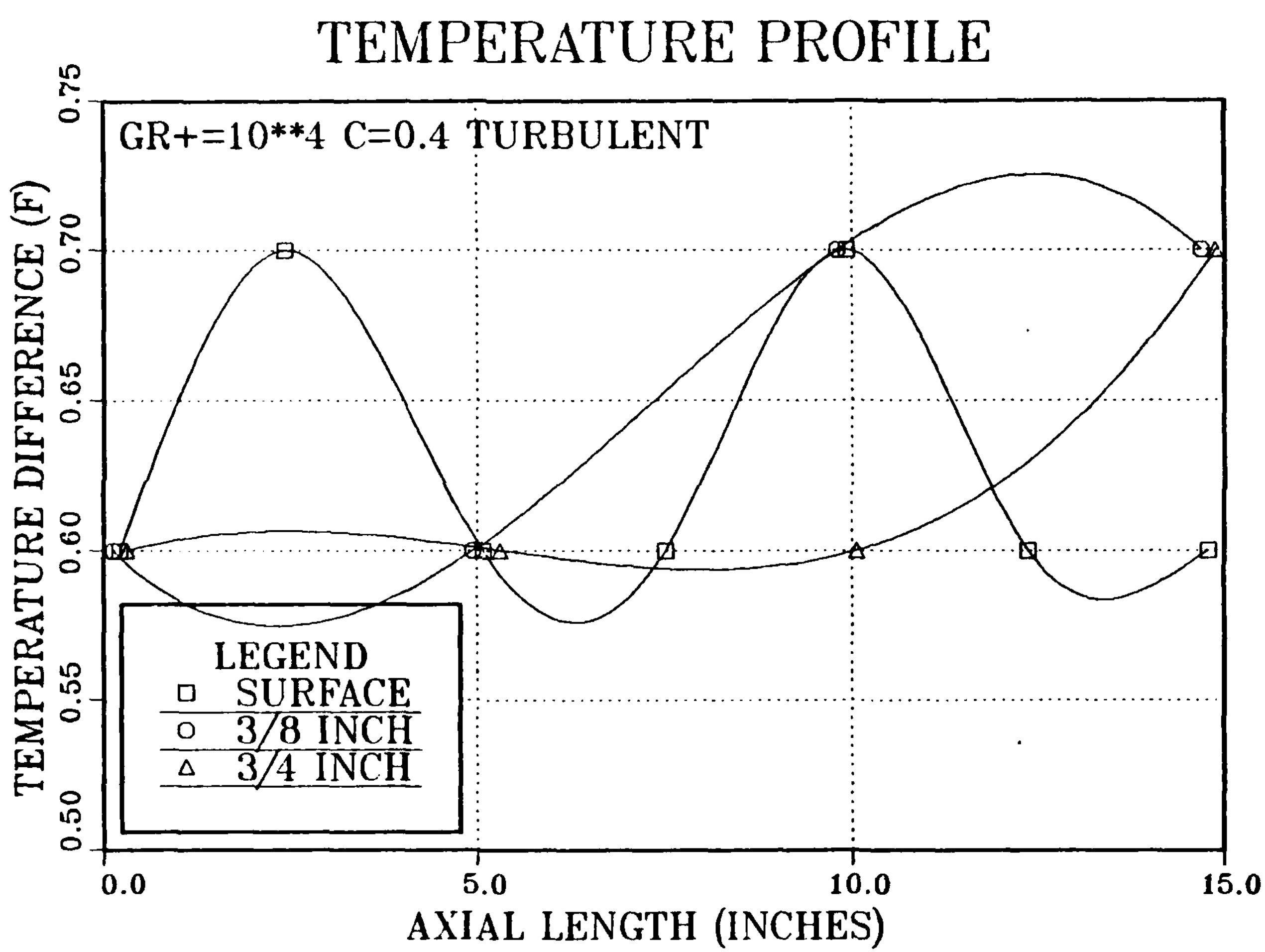


Figure 5.6 Temperature Profile $Gr^{+}=10^{4}$, C=0.4, Turbulent Flow.

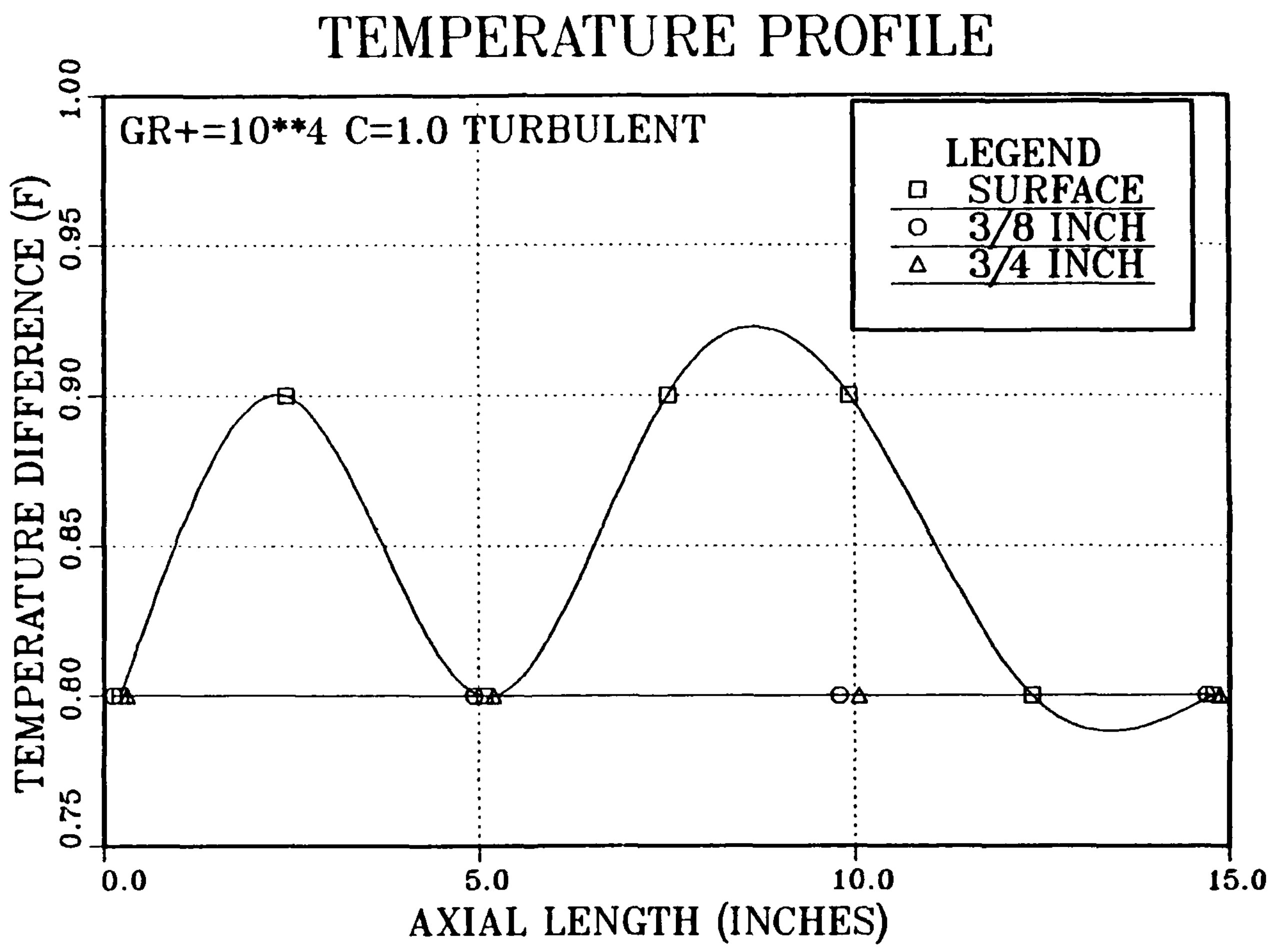


Figure 5.7 Temperature Profile $Gr^{+}=10^{4}$, C=1.0, Turbulent Flow.

VI. CONVECTION COEFFICIENTS

A. BACKGROUND

Results for the laminar flow convection heat transfer coefficients are presented in two forms. First, as a comparison to the analytical work of Acharya and Patankar, and second as a summary on a single figure. Note that figures are presented for the dimensionless y coordinate, and for the ratio of the local heat transfer coefficient to the average coefficient. The average heat transfer coefficient was easily determined because the rate of heat transfer into the fin and the fin area were known quantities. Turbulent flow results are presented only in summary form.

Determination of the local heat transfer coefficients was incorporated in the following two-step process: (1) calculation of initial local coefficients and (2) calculation of heat transfer rates. If the sum of the calculated heat transfer rates did not equal the known rate, then step 1 was repeated. The assumptions were that the rate of heat transfer from the fin at the base was zero, and that the shape of the heat transfer coefficient curve would be similar to the shape of the velocity curve.

The fin was treated as a set of ten, separate, cascaded, sub-fins [Ref. 4][Ref. 7]. Needed coefficients were then calculated for each of the ten sub-fins. From the heat transfer coefficients, heat transfer rates were calculated and summed to check against the known value. If the two values did not match, the entire process was repeated.

First guess values for the local heat transfer coefficient were determined using

$$\theta(x) = \theta_b \frac{\cosh mx}{\cosh mb} \tag{6.1}$$

with

$$m = \left(\frac{2h}{kt}\right)^{\frac{1}{2}} \tag{6.2}$$

Because the fin, above the base, was approximately isothermal, (actual fin temperatures are given in TABLES 4 and 5) the temperature ratios were very nearly unity, causing errors in the thermocouple readings to be accentuated. Equation 6.1 is predicated on the assumption of a constant surface heat transfer coefficient which was not the case for the overall tests. However for the small sub-fins, the equation was applicable (i.e. the convection was constant for the small fin.

B. LAMINAR FLOW

Laminar flow comparison results are presented in Figure 6.1 for $Gr^{+}=10^{4}$ and C=0.0. Comparisons for C=0.4 and C=1.0 are presented in Figures 6.2 and 6.3 respectively. In each case, the test values for the convection coefficients are

TABLE 4

CALCULATED STEADY STATE FIN TEMPERATURES FOR LAMINAR FLOW

	Approximate Position (in)			
	0	5	10	15
	Clearance C=0.0			
Depth	Temperature (^{o}F)			
3/4 inch	71.3	71.6	71.7	70.7
3/8 inch	71.5	71.7	71.8	71.6
	Clearance C=0.4			
Depth	Temperature (^{o}F)			
3/4 inch	72.3	72.5	72.6	73.0
3/8 inch	72.6	72.7	72.8	72.6
	Clearance C=1.0			
Depth	Temperature (^{o}F)			
3/4 inch	72.9	73.0	73.1	73.4
3/8 inch	73.1	73.2	73.3	73.0

TABLE 5

CALCULATED STEADY STATE FIN TEMPERATURES FOR TURBULENT FLOW

	Approximate Position (in)			
	0	5	10	15
Clearance C=0.0				
Depth	Temperature (^{o}F)			
3/4 inch	70.9	70.9	71.1	71.4
3/8 inch	71.1	71.1	71.1	71.0
Clearance C=0.4				
Depth	Temperature (^{o}F)			
3/4 inch	71.0	71.0	71.1	71.5
3/8 inch	71.2	71.2	71.3	71.1
Clearance C=1.0				
Depth	Temperature (^{o}F)			
3/4 inch	71.2	71.2	71.3	71.6
3/8 inch	71.4	71.4	71.4	71.2

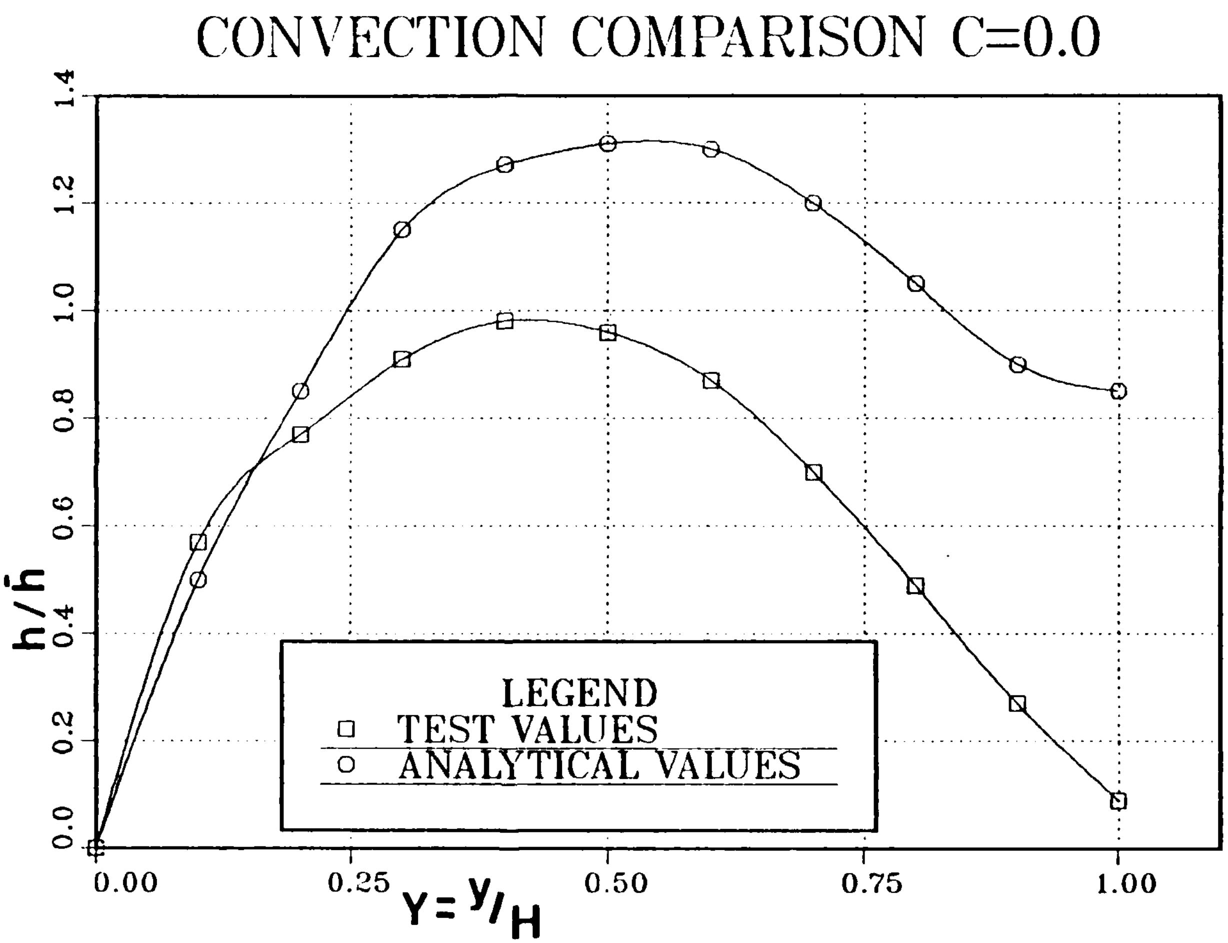


Figure 6.1 Test Results and Analytical Convection Heat Transfer Coefficient Comparison for C=0.0.

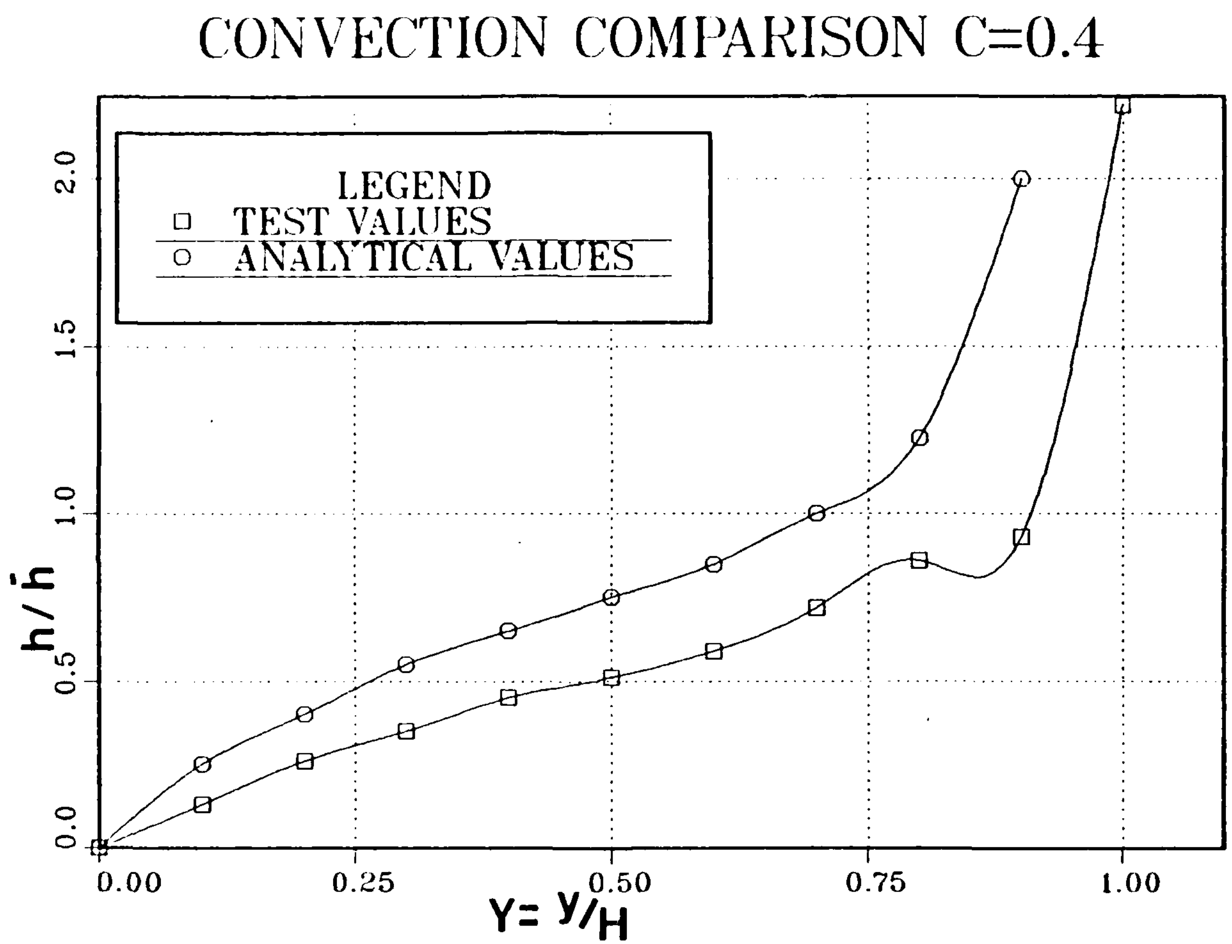


Figure 6.2 Test Results and Analytical Convection Heat Transfer Coefficient Comparison for C=0.4.

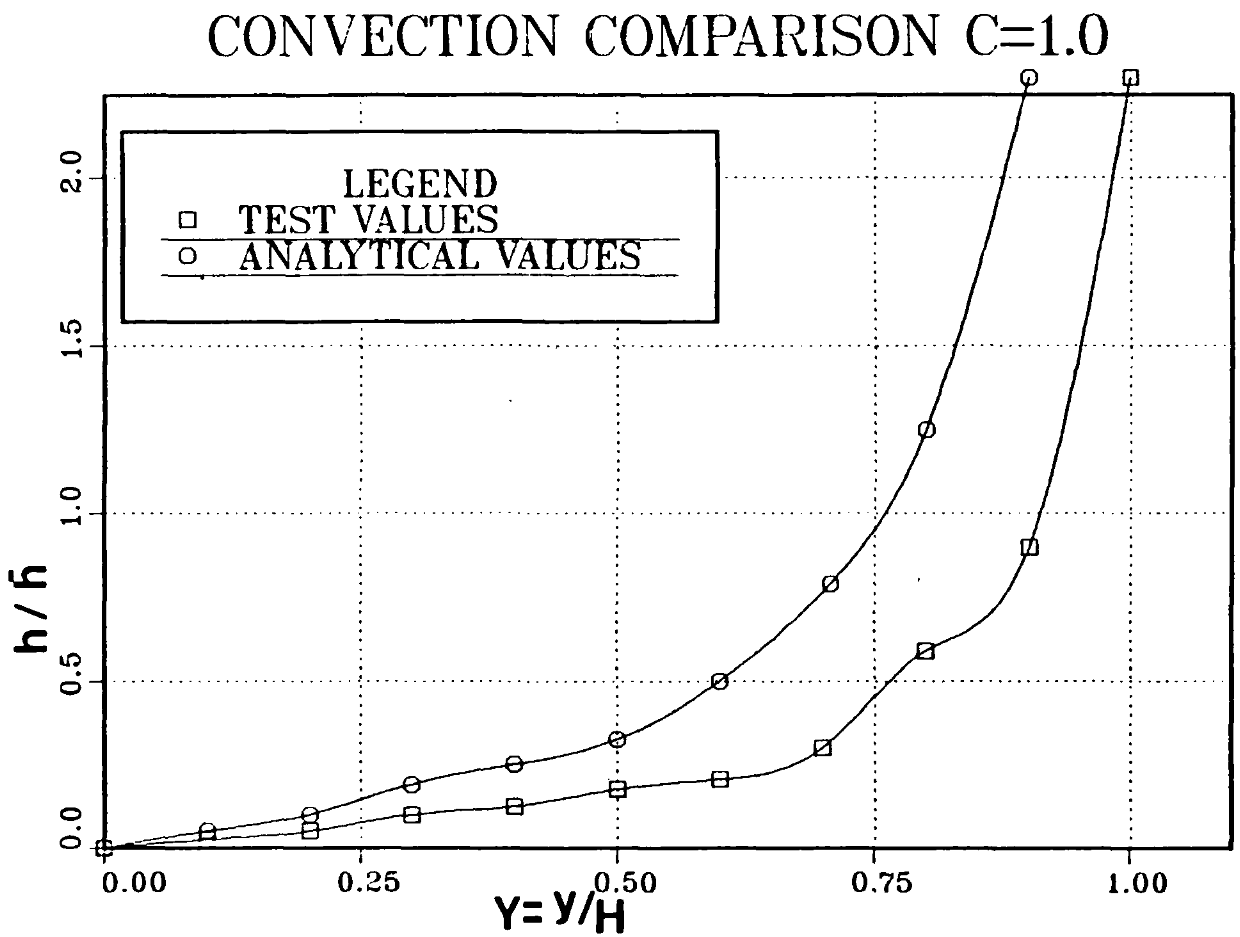


Figure 6.3 Test Results and Analytical Convection Heat Transfer Coefficient Comparison for C=1.0.

lower than for the analytical values. As discussed above, the convection coefficients are dependent on several calculated values. An error in the heat flux into the fin carries over into the calculated heat transfer coefficients. Appendix D contains the calculated heat flux for $Gr^{+}=10^{4}$, while Appendix E offers the heat flux calculations for $Gr^{+}=10^{6}$. The laminar flow convection heat transfer coefficient ratios are presented in Figure 6.4.

C. TURBULENT FLOW

For turbulent flow, there are no analytical results which may be used for comparison. However, the same calculation techniques that were used for laminar flow were repeated here. Therefore, the form of the convection coefficient ratio curve should be accurate. Errors in the actual numbers were discussed previously. The turbulent flow convection coefficient ratio results are presented in Figure 6.5.

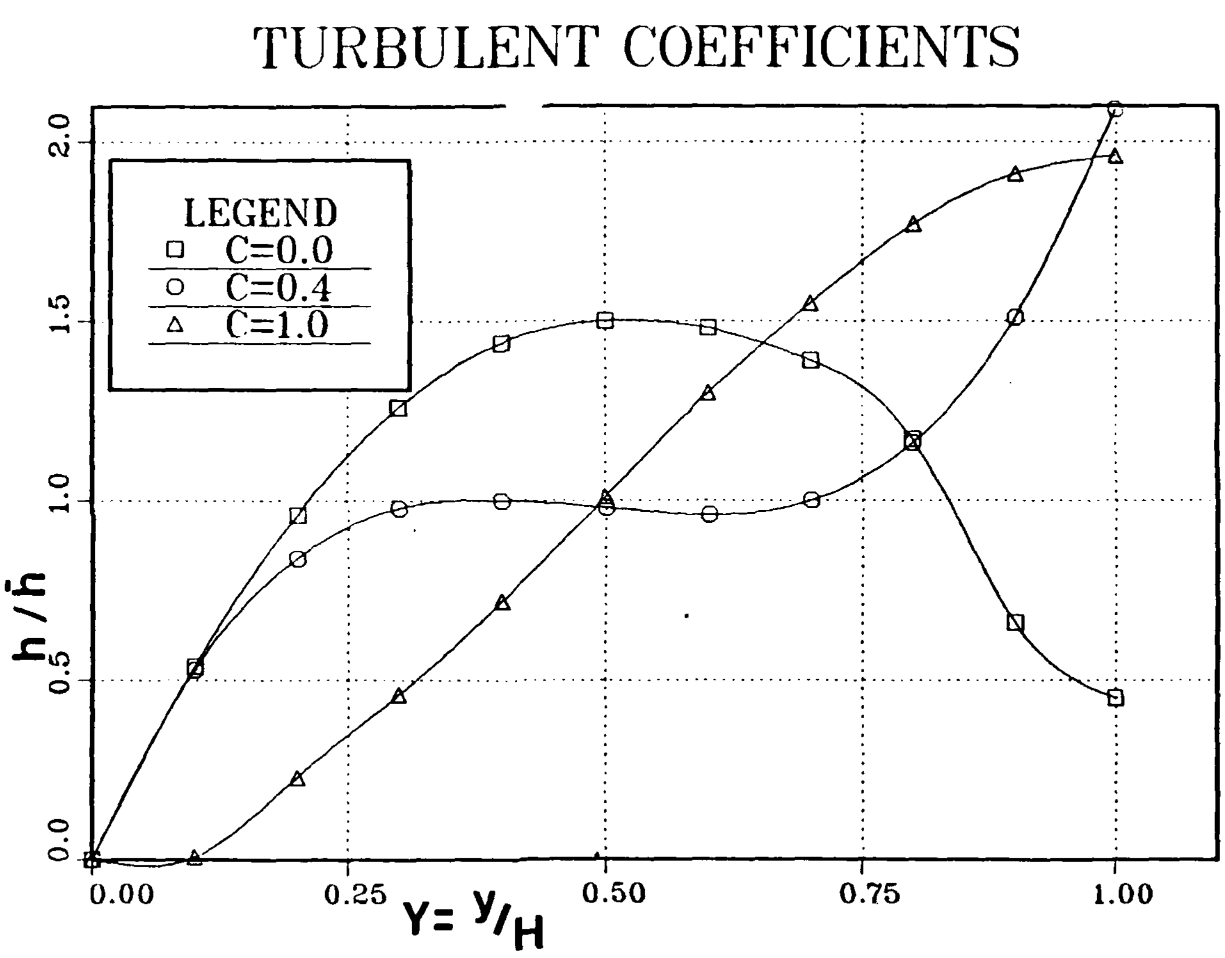


Figure 6.5 Test Results -- Convection Heat Transfer Coefficient Results for Turbulent Flow.

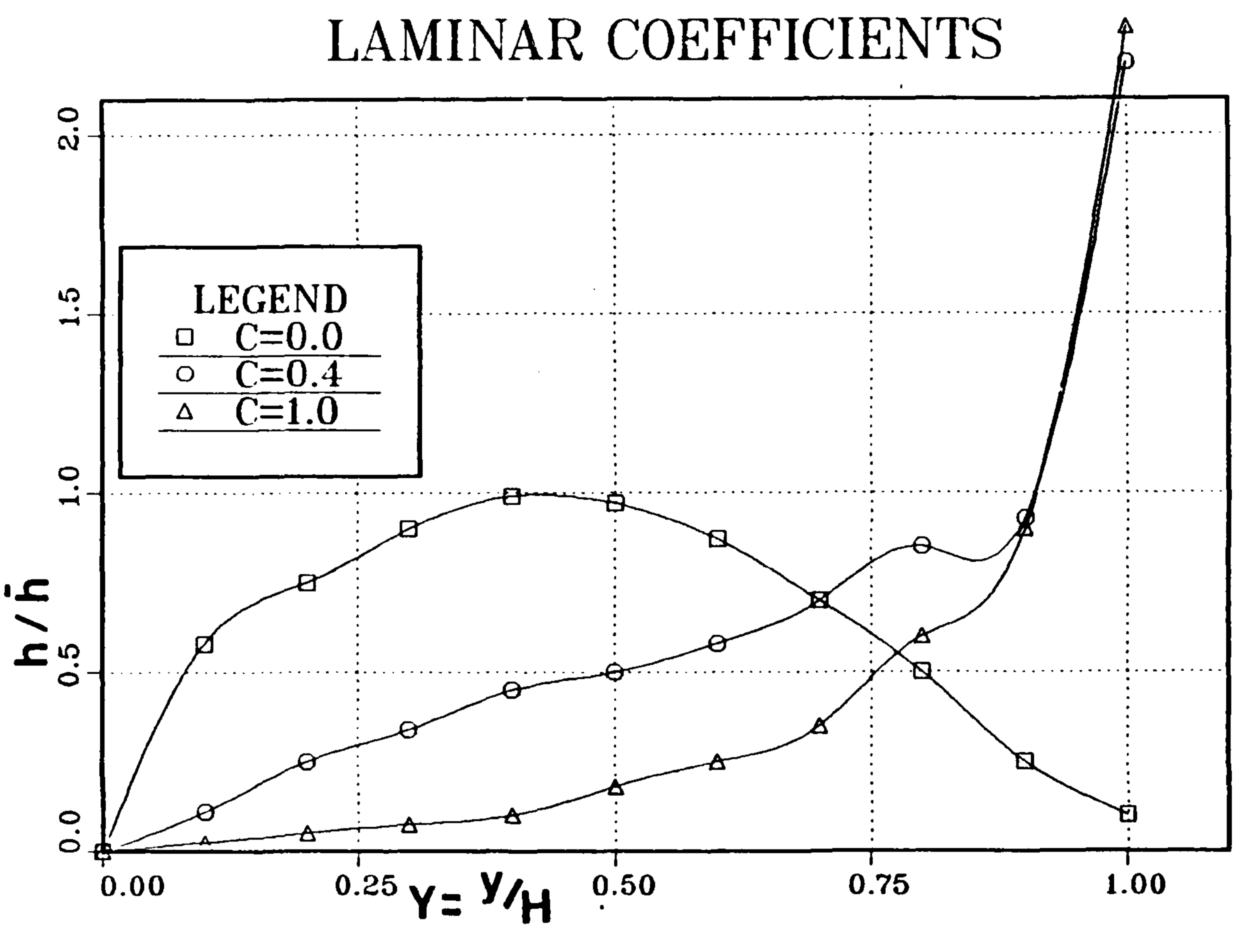


Figure 6.4 Test Results -- Convection Heat Transfer Coefficient Results for Laminar Flow.

VII. CONCLUSIONS

Findings for laminar flow are consistent with the analytical results of Acharya and Patankar. The relatively large plenum area between the fin tip and the outer channel boundary allows a preponderance of flow through the larger area. There is also a corresponding increase in velocity. Viscous effects transfer these greater velocities down into the fin channels. In these regions of heightened velocities there is an increase in the local convection heat transfer coefficient.

Unfortunately, for identical mass flow rates, there must be an attendant decrease in velocity in the portions of the channel adjacent to the fin base. Velocity profiles substantiate this decreased velocity. Subsequently, the convection coefficients also decline. Increases in the coefficient at or near the fin tip do not compensate for decreases near the base. Thus, the overall effectiveness of the fin as a heat transfer surface is strikingly reduced. Because the same heat flux was used for all tests, the fin temperature must go up as the fin dissipates less heat. The general increase in the fin temperature as clearance increases verifies this relationship.

The results for turbulent flow are very similar to the laminar findings, i.e., high velocity areas produce higher local heat transfer coefficients. However, for C=0.4 there is an area covering approximately one-half of the vertical surface where the coefficient is largely constant, even decreasing slightly. Nevertheless, the overall effectiveness of the fin is once again reduced. The temperatures within the fin for different clearance ratios support this finding.

VIII. RECOMMENDATIONS

This testing project was extensive and ambitious--it is also incomplete. As observed previously, there were inadequacies and limitations in the test equipment. Some of these problems may be easily corrected; others will require enormous investments of time and effort.

The hot wire anemometer must have an automatic data aquisition system. Recording the data manually rapidly becomes monotonous and, subsequently, error prone. This is especially true as the clearance ratio increases. Errors are likely in both the probe position and in the output voltage. Because the output values are voltages, there are many automatic systems which could record not only the voltage, but could also process the data for direct velocity outputs once the anemometer was calibrated, and the appropriate data were entered into the system.

The traversing mechanism is extremely accurate for vertical positioning, with a possible accuracy of ± 0.0002 inches. The horizontal position, however, is an entirely different matter. There was no method for horizontally positioning the wire that was used for these tests. This lack of an accurate horizontal location was especially prominent in the streamline profiles, which were not symmetric about the centerline. For further work in this area, accurate horizontal placement must be a stringent requirement.

Horizontal accuracy, which is at least as good as the vertical accuracy, should be sufficient, and could be accomplished by placing the current traversing mechanism on a horizontal slide. A standard micrometer could be used to determine the appropriate position. Because the distance necessary for horizontal movement is very small, an oval plate supporting the existing mechanism would be satisfactory. This modification would allow sufficient horizontal movement, yet not introduce air leakage problems at the surface interfaces.

Accurate horizontal positioning would allow the probe tip to be placed slightly forward of the exit plane of the finned array (Figure 8.1). This placement offers at least two advantages over the current position: (1) the wake effects discussed previously would be nullified, and (2) secondary velocities could be more accurately measured. In addition, with very precise positioning, secondary velocities could be determined in several locations. To attempt this suggested placement without the recommended horizontal accuracy, would surely mean loss of the hot wire probe.

Temperatures were measured at only two locations in the fin, and at four longitudunal positions. Therefore, of the eighty thermocouples installed, only eight were actually

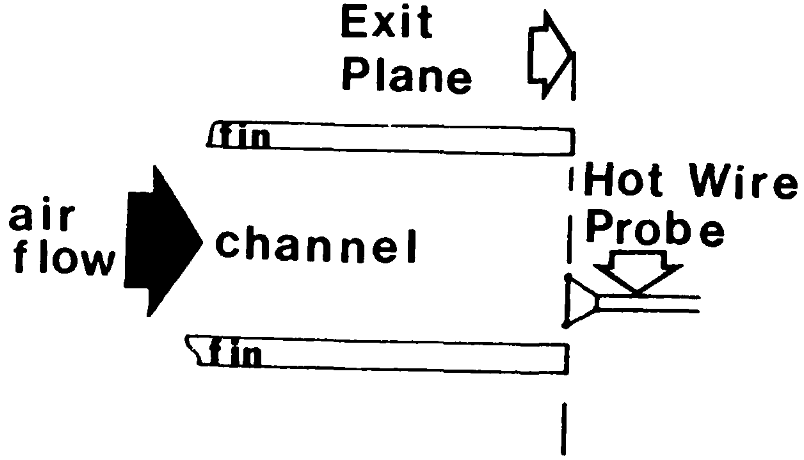


Figure 8.1 Recommended Hot Wire Probe Position.

used to produce the results for a single fin. The ability to install the thermocouples in the array has been demonstrated, but more thermocouples in a single fin would be a far better arrangement. The current locations at 3/8-inch and 3/4-inch are satisfactory, but a third thermocouple at a 1-inch depth, with a fourth at the depth of the base thickness, would produce a more accurate vertical temperature profile.

The thermocouples mounted on the base were of no use. Also, accuracy to within at least $0.01^{\circ}F$ is necessary. It is essential to know whether the fin is or is not isothermal, because the method of calculating the heat transfer coefficients depends on an accurate determination. In turn, only very accurate thermocouples will determine which conclusion is correct. With the current horizontal arrangement, and with more thermocouples installed in the vertical direction on the single fin, 16 thermocouples will be available to develop an accurate temperature profile.

In order to ascertain the vertical temperature profile of the exiting flow, an array of thermocouples in the exit air stream is essential. This change will help to determine the amount of mixing actually taking place from the secondary flow effects. An automatic data aquisition system would help here, but is probably not critical.

Essentially this project has dealt with the convection coefficient as a one-dimensional problem in the vertical direction, but the data clearly indicate a two-dimensional problem which is both vertical and horizontal. Development of the convection coefficient curves horizontally as well as vertically would give a more complete description of what is happening along the fin. There is a temperature distribution in the axial direction, and this may enhance the heat transfer characteristics.

The turbulent flow was not fully developed. A longer set of fins is necessary for fully-developed turbulent profiles. Nevertheless, it is possible to study the heat transfer coefficients prior to these ideal conditions. This specific problem was not investigated here.

APPENDIX A

LONGITUDINAL FIN ARRAY DIMENSIONS

The following pages contain pertinent information on the dimensions of the array of longitudinal fins of rectangular profile. The array is extruded commercial aluminum and nominally 15 inches by 6.5 inches with 15 fins at a spacing of 0.3 inches. Mean values were simply the sum of the measurements divided by the number of measurements. The plus-minus values were determined using the standard root-mean-square deviation. Readings were taken with the array positioned with fins up, front of the array to the right.

FIN SPACING

Channel #	Left Width (in)	Right Width (in)
1	0.310	0.312
2	0.309	0.307
3	0.308	0.306
4	0.310	0.307
5	0.308	0.308
6	0.311	0.307
7	0.306	0.308
8	0.308	0.304
9	0.305	0.308
10	0.306	0.305
11	0.304	0.309
12	0.306	0.305
13	0.303	0.307
14	0.304	0.309
15	0.309	0.308
16	0.305	0.307

mean value = 0.307 ± 0.002

Fin Thickness

Fin #	Left (in)	Right (in)
1	0.074	0.081
2	0.091	0.097
3	0.074	0.069
4	0.091	0.096
5	0.074	0.074
6	0.096	0.099
7	0.075	0.078
8	0.095	0.094
9	0.076	0.071
10	0.094	0.096
11	0.071	0.074
12	0.096	0.090
13	0.071	0.074
14	0.096	0.097
15	0.076	0.074

mean value = 0.084 ± 0.002

Fin and Base Height

Fin #	Left (in)	Right (in)
1	1.129	1.130
2	1.130	1.128
3	1.120	1.124
4	1.119	1.126
5	1.118	1.119
6	1.118	1.120
7	1.117	1.119
8	1.119	1.124
9	1.124	1.124
10	1.122	1.125
11	1.122	1.126
12	1.123	1.133
13	1.124	1.125
14	1.125	1.124
15	1.123	1.131

mean value = 1.124 $\pm$0.004

Base Plate Thickness

Channel #	Left (in)	Right (in)
1	0.210	0.196
2	0.200	0.197
3	0.199	0.201
4	0.202	0.201
5	0.205	0.204
6	0.207	0.207
7	0.210	0.212
8	0.214	0.213
9	0.215	0.212
10	0.212	0.212
11	0.207	0.208
12	0.206	0.207
13	0.204	0.205
14	0.213	0.206
15	0.205	0.204
16	0.204	0.204

mean value = 0.206 $\pm$0.005

Array Length

Fin #	Length (in)
1	15.016
2	15.000
3	15.000
4	15.016
5	14.984
6	14.984
7	15.000
8	14.984
9	14.969
10	14.953
11	14.969
12	14.977
13	14.969
14	14.953
15	14.953

mean value =15.982 $\pm$0.021

VIII. APPENDIX B

AUTODATA NINE AND THERMOCOUPLE CALIBRATION

The Autodata Nine data recorder and all thermocouples were calibrated as a system in the Measurements and Calibration Lab at Naval Postgraduate School. Standard calibration techniques were used to calibrate the thermocouples at seven points to a maximum of approximately 200^{o}F. Three points were approached with increasing temperature, three points were approached with decreasing temperature, and the maximum temperature is the seventh point.

The following thermocouple data were produced from the calibration run:

Actual Temperatures (^{o}F)

195.84	183.56	163.48	160.03	100.50	99.82	67.70

Thermocouple Readings
Temperature (^{o}F)

#							
20	197.2	185.0	164.9	161.3	101.4	100.8	68.4
21	196.9	184.7	164.6	161.1	101.3	100.7	68.4
22	197.2	185.0	164.9	161.3	101.4	100.7	68.4
23	196.8	184.6	164.5	161.0	101.3	100.6	68.4
24	196.9	184.8	164.6	161.1	101.3	100.6	68.3
25	196.7	184.4	164.3	160.8	101.2	100.6	68.4
26	196.7	184.6	164.4	160.9	101.2	100.6	68.4
27	196.4	184.2	164.1	160.6	101.2	100.5	68.3
28	196.6	184.4	164.3	160.8	101.1	100.4	68.1
29	196.3	184.1	164.0	160.6	101.1	100.4	68.2
30	197.0	184.9	164.8	161.3	101.3	100.7	68.4

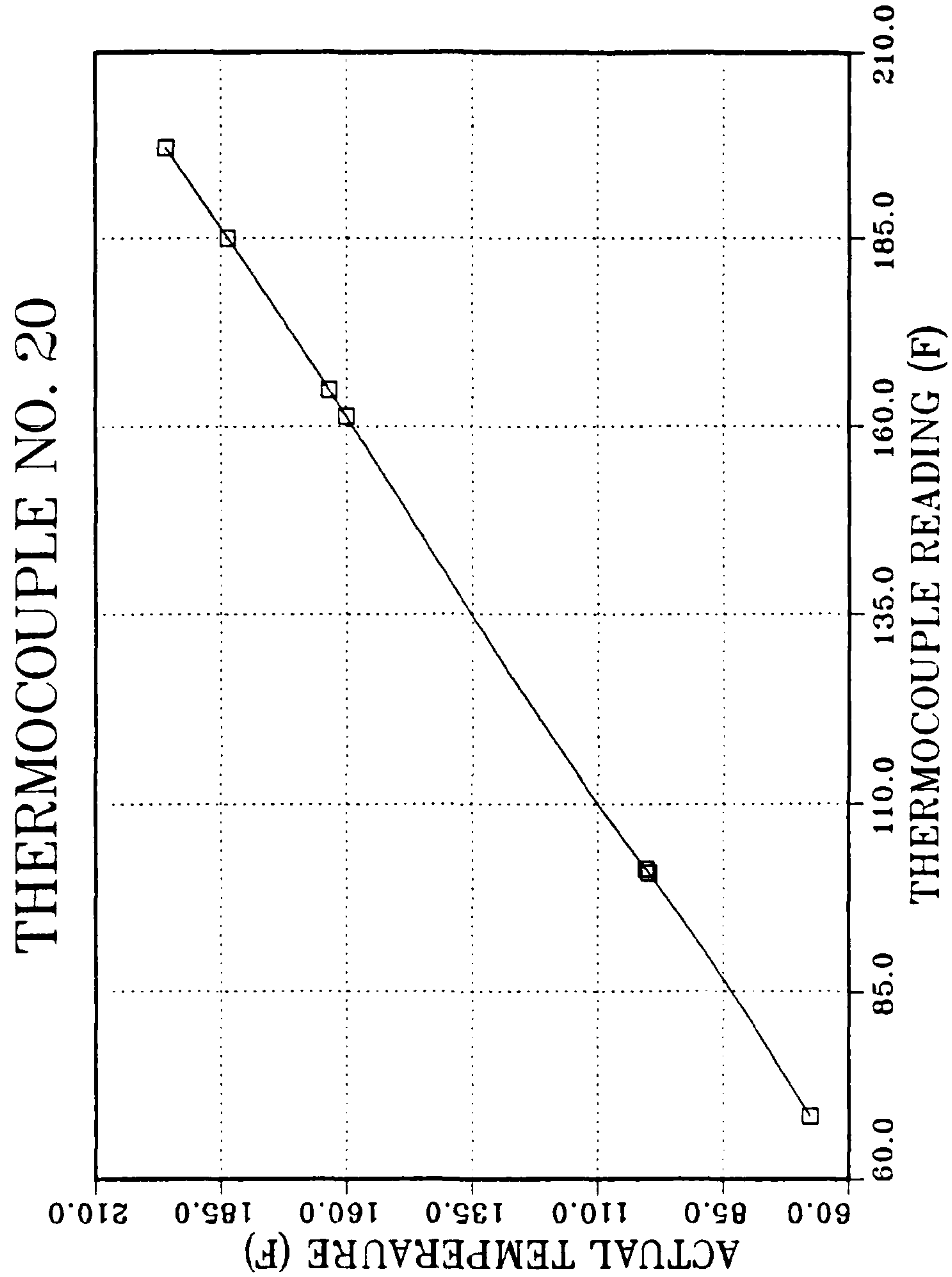
31	196.8	184.5	164.5	161.0	101.2	100.6	68.3
32	196.9	184.7	164.6	161.2	101.2	100.6	68.3
33	196.5	184.3	164.2	160.8	101.2	100.6	68.3
34	196.8	184.6	164.5	161.0	101.2	100.6	68.2
35	196.4	184.2	164.1	160.7	101.2	100.5	68.2
36	196.5	184.4	164.2	160.8	101.0	100.3	68.0
37	196.2	184.0	164.0	160.5	101.0	100.3	68.1
38	196.4	184.2	164.1	160.7	100.3	100.2	67.9
39	196.2	183.9	163.9	160.4	100.9	100.3	68.0
40	197.5	185.4	165.3	161.8	101.8	101.2	69.0
41	197.1	185.0	164.9	161.5	101.8	101.2	68.9
42	197.4	185.3	165.1	161.7	101.8	101.2	68.8
43	197.2	185.0	164.9	161.4	101.8	101.1	68.8
44	197.2	185.0	164.9	161.5	101.7	101.0	68.8
45	196.9	184.8	164.6	161.2	101.7	101.0	68.7
46	197.0	184.9	164.7	161.3	101.6	100.9	68.7
47	196.9	184.7	164.6	161.2	101.6	100.9	68.7
48	196.9	184.6	164.5	161.2	101.5	100.8	68.5
49	196.7	184.6	164.5	161.1	101.5	100.8	68.6
50	196.2	184.0	163.8	160.4	100.8	100.1	67.9
51	196.0	183.9	163.7	160.2	100.5	99.7	67.5
52	196.3	184.1	163.9	160.7	100.9	100.3	68.0
53	196.2	183.9	163.9	160.3	100.5	99.7	67.5
54	196.4	184.2	164.0	160.7	100.9	100.3	68.0
55	196.2	184.0	163.8	160.4	100.6	99.8	67.5
56	196.5	183.9	164.1	160.7	100.9	100.3	67.9
57	196.1	183.9	163.8	160.3	100.5	99.7	67.5
58	196.4	184.4	164.0	160.6	100.8	100.2	67.8
59	196.1	183.9	163.8	160.2	100.4	99.8	67.5
60	196.2	184.0	163.9	160.5	100.7	100.0	67.8
61	195.9	183.7	163.6	160.2	100.4	99.7	67.5
62	196.2	184.0	163.9	160.5	100.8	100.1	67.9
63	196.2	184.0	163.9	160.5	100.8	100.1	67.9
64	196.3	184.1	164.0	160.6	100.9	100.2	67.9
65	196.1	184.0	163.8	160.4	100.6	99.8	67.6
66	196.2	184.1	163.9	160.6	100.8	100.2	67.9
67	196.2	184.1	164.0	160.4	100.5	99.8	67.5
68	196.4	184.2	164.1	160.7	100.9	100.2	67.9
69	196.1	183.9	163.8	160.3	100.5	99.8	67.5
70	197.2	185.0	164.8	161.4	101.7	101.1	68.8
71	196.8	184.7	164.6	161.1	101.5	100.8	68.7
72	197.2	185.0	164.9	161.6	101.8	101.2	68.9
73	197.0	184.9	164.8	161.3	101.6	100.9	68.7
74	197.2	185.1	165.0	161.5	101.8	101.2	69.0
75	197.0	184.8	164.8	161.3	101.6	100.9	68.8
76	197.3	185.1	165.0	161.6	101.9	101.2	69.0
77	197.0	184.8	164.7	161.2	101.6	100.9	68.7
78	197.2	185.0	165.0	161.5	101.8	101.2	69.0
79	197.0	184.9	164.9	161.4	101.7	101.0	68.7
80	198.6	186.4	166.3	162.9	103.4	102.7	70.5
81	198.5	186.3	166.1	162.8	103.2	102.5	70.3

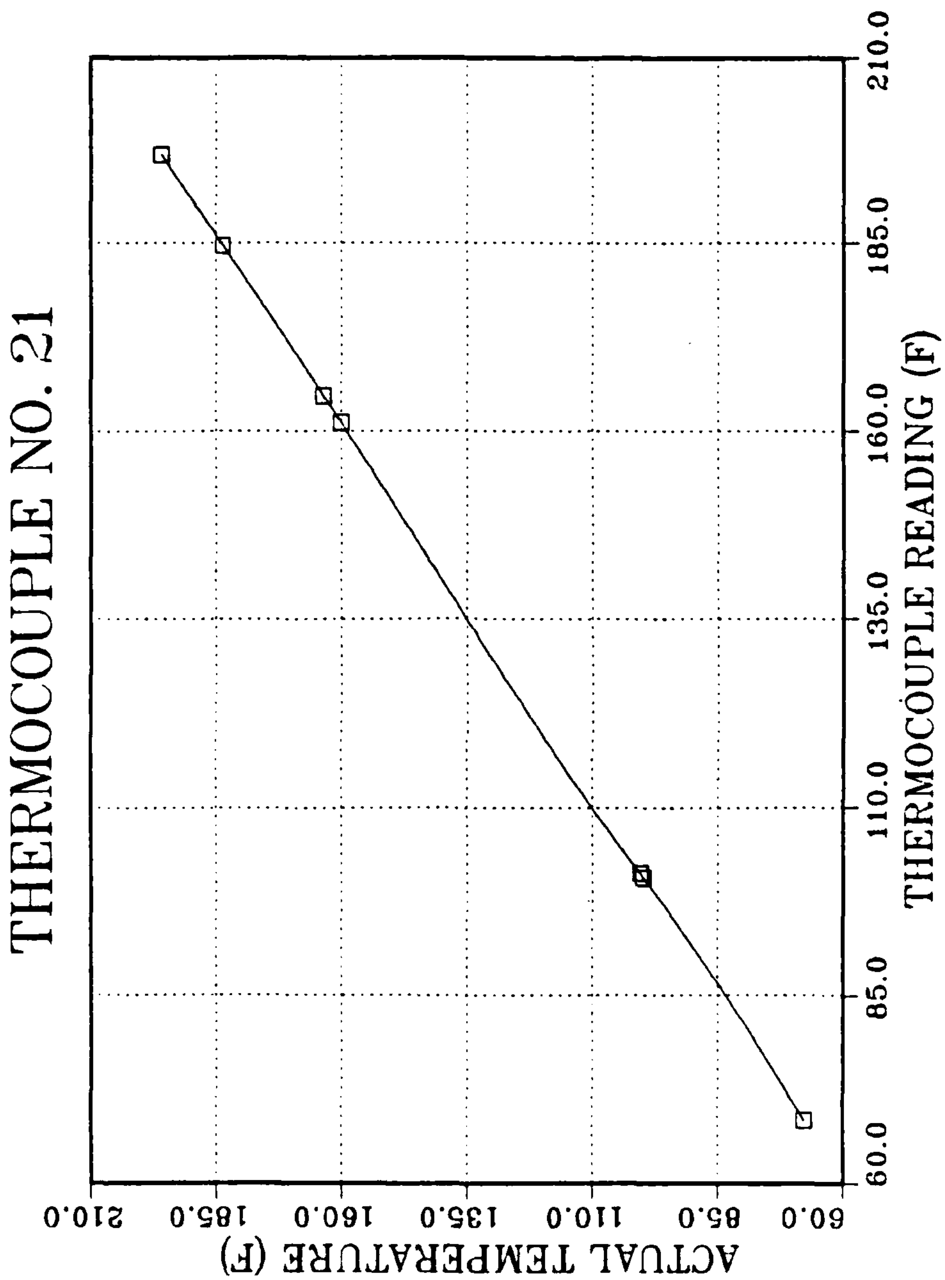
82	198.5	186.4	166.2	162.9	103.3	102.7	70.5
83	198.5	186.3	166.2	162.8	103.3	102.7	70.4
84	198.7	186.5	166.4	163.0	103.4	102.8	70.6
85	198.5	186.3	166.3	162.7	103.2	102.5	70.4
86	198.8	186.6	166.6	163.1	103.4	102.8	70.5
87	198.3	186.2	166.1	162.6	103.2	102.5	70.4
88	198.7	186.5	166.3	162.6	103.4	102.8	70.6
89	198.5	186.3	166.3	162.8	103.3	102.5	70.4
90	196.1	183.9	163.8	160.4	100.6	99.9	67.7
91	196.1	183.9	163.6	160.3	100.5	99.8	67.6
92	196.2	184.0	163.8	160.4	100.6	99.9	67.6
93	196.0	183.9	163.6	160.2	100.5	99.9	67.6
94	196.2	184.0	163.9	160.4	100.6	99.9	67.6
95	196.0	183.9	163.7	160.2	100.5	99.7	67.5
96	196.1	183.9	163.8	160.4	100.5	99.9	67.7
97	195.9	183.7	163.6	160.2	100.4	99.7	67.5
98	196.2	184.0	163.9	160.5	100.6	100.0	67.5
99	196.1	183.9	163.7	160.3	100.5	99.8	67.6

With this information, ten data files were produced. The data files were processed by the "EASYPLOT" program to produce a calibration curve similar to the graphs on pages 122 and 123. All files and calibration curves are not included because of the number of pages involved. However, the files are easily reproduced from the original data. Using the files, the curves are easily produced.

Using the original data, the following short fortran program was used to develop linear regression curve fits for each thermocouple:

```
      DIMENSION TACT(7),NUM(80),TMEA(80,7)
      READ (25,11) (TACT(I),I=1,7)
   11 FORMAT (1X,7F9.3)
      WRITE (6,11) (TACT(I),I=1,7)
      DO 100 I=1,80
      READ (25,20) NUM(I),(TMEA(I,J),J=1,7)
   20 FORMAT (1X,I4,7F9.3)
  100 WRITE (6,20) NUM(I),(TMEA(I,J),J=1,7)
      DO 200 J=1,80
      C1=0.0
```


THERMOCOUPLE NO. 20
THERMOCOUPLE READING (F)
ACTUAL TEMPERAURE (F)
60.0
85.0
110.0
135.0
160.0
185.0
210.0


THERMOCOUPLE NO. 21
THERMOCOUPLE READING (F)
ACTUAL TEMPERATURE (F)
60.0
85.0
110.0
135.0
160.0
185.0
210.0
60.0
85.0
110.0
135.0
160.0
185.0
210.0

```
      C2=0.0
      C3=0.0
      C4=0.0
      DO 300 I=1,7
      C1=TACT(I)*TMEA(J,I)+C1
      C2=TMEA(J,I)+C2
      C3=TACT(I)+C3
  300 C4=TMEA(J,I)*TMEA(J,I)+C4
      B1=((7.0*C1)-(C2*C3))/((7.0*C4)-(C2*C2))
      B2=(C3-(B1*C2))/7.0
  200 WRITE (6,30) NUM(J),B1,B2
   30 FORMAT (1X,I4,'  TACT =',F7.4,'* TMEA',F7.4)
      END
```

The following equations were produced for the actual temperature as a function of thermocouple reading:

```
20  TACT = 0.9943 * TMEA -0.3541
21  TACT = 0.9967 * TMEA -0.5030
22  TACT = 0.9940 * TMEA -0.3024
23  TACT = 0.9974 * TMEA -0.5379
24  TACT = 0.9956 * TMEA -0.3388
25  TACT = 0.9988 * TMEA -0.6189
26  TACT = 0.9979 * TMEA -0.5436
27  TACT = 1.0005 * TMEA -0.6979
28  TACT = 0.9969 * TMEA -0.2562
29  TACT = 1.0004 * TMEA -0.5924
30  TACT = 0.9950 * TMEA -0.3709
31  TACT = 0.9970 * TMEA -0.4320
32  TACT = 0.9955 * TMEA -0.3093
33  TACT = 0.9996 * TMEA -0.6571
34  TACT = 0.9962 * TMEA -0.3214
35  TACT = 0.9999 * TMEA -0.6091
36  TACT = 0.9965 * TMEA -0.1206
37  TACT = 1.0002 * TMEA -0.4811
38  TACT = 0.9952 * TMEA +0.2566
39  TACT = 1.0001 * TMEA -0.3914
40  TACT = 0.9955 * TMEA -0.9513
41  TACT = 0.9990 * TMEA -1.2087
42  TACT = 0.9957 * TMEA -0.8811
43  TACT = 0.9980 * TMEA -1.0401
44  TACT = 0.9973 * TMEA -0.9299
45  TACT = 0.9996 * TMEA -1.0774
46  TACT = 0.9980 * TMEA -0.8874
47  TACT = 0.9993 * TMEA -1.0037
48  TACT = 0.9983 * TMEA -0.7742
49  TACT = 0.9997 * TMEA -0.9458
50  TACT = 0.9986 * TMEA -0.1335
51  TACT = 0.9964 * TMEA +0.4239
```

52	TACT = 0.9986 * TMEA -0.2742
53	TACT = 0.9951 * TMEA +0.5311
54	TACT = 0.9977 * TMEA -0.1955
55	TACT = 0.9953 * TMEA +0.4540
56	TACT = 0.9976 * TMEA -0.1492
57	TACT = 0.9956 * TMEA +0.4803
58	TACT = 0.9957 * TMEA +0.1264
59	TACT = 0.9958 * TMEA +0.4729
60	TACT = 0.9973 * TMEA +0.0673
61	TACT = 0.9973 * TMEA +0.3663
62	TACT = 0.9983 * TMEA -0.1178
63	TACT = 0.9983 * TMEA -0.1178
64	TACT = 0.9978 * TMEA -0.1371
65	TACT = 0.9962 * TMEA +0.3307
66	TACT = 0.9981 * TMEA -0.1364
67	TACT = 0.9944 * TMEA +0.5519
68	TACT = 0.9968 * TMEA -0.0517
69	TACT = 0.9959 * TMEA +0.4287
70	TACT = 0.9979 * TMEA -0.9981
71	TACT = 0.9993 * TMEA -0.9477
72	TACT = 0.9984 * TMEA -1.1623
73	TACT = 0.9978 * TMEA -0.8775
74	TACT = 0.9986 * TMEA -1.2134
75	TACT = 0.9986 * TMEA -0.9906
76	TACT = 0.9983 * TMEA -1.2166
77	TACT = 0.9985 * TMEA -0.9233
78	TACT = 0.9989 * TMEA -1.2423
79	TACT = 0.9980 * TMEA -0.9644
80	TACT = 1.0004 * TMEA -2.8926
81	TACT = 0.9995 * TMEA -2.6117
82	TACT = 1.0007 * TMEA -2.8916
83	TACT = 1.0006 * TMEA -2.8428
84	TACT = 1.0001 * TMEA -2.9395
85	TACT = 0.9998 * TMEA -2.6824
86	TACT = 0.9984 * TMEA -2.7576
87	TACT = 1.0014 * TMEA -2.8251
88	TACT = 1.0009 * TMEA -2.9740
89	TACT = 0.9999 * TMEA -2.7285
90	TACT = 0.9973 * TMEA +0.1670
91	TACT = 0.9968 * TMEA +0.3266
92	TACT = 0.9961 * TMEA +0.3196
93	TACT = 0.9976 * TMEA +0.2278
94	TACT = 0.9959 * TMEA +0.3293
95	TACT = 0.9964 * TMEA +0.4239
96	TACT = 0.9970 * TMEA +0.2179
97	TACT = 0.9973 * TMEA +0.3663
98	TACT = 0.9955 * TMEA +0.3665
99	TACT = 0.9966 * TMEA +0.3364

APPENDIX C

HOT WIRE SYSTEM CALIBRATION

The hot wire system is calibrated in the following manner: (1) a series of voltage and pressure readings are taken at various flow rates, (2) the data are read into the hot wire calibration program, and (3) the program provides the appropriate values necessary to calculate velocity as a function of voltage. A sample input file is:

```
Output Label - Heading . . . .: Hot Wire Calibration
                                Saturday 14 June 86
Wire size (mm) . . . . . . . .: 5
Ambient Temperaure (C) . . . .: 19
Pressure (mmHg). . . . . . . .: 760
Number of Points . . . . . . .: 8
Static Voltage, Marker . . . .: 2.3998,1
```

Note: the marker, 1, tells the program that pressure readings are in inH_2O

```
First Point- Voltage, Pressure: .070,3.6106
Secend Point . . . . . . . . .: .066,3.5769
Third Point  . . . . . . . . .: .065,3.5721
Fourth Point . . . . . . . . .: .06,3.5378
Fifth Point  . . . . . . . . .: .05,3.4698
Sixth Point  . . . . . . . . .: .04,3.4057
Seventh Point  . . . . . . . .: .0325,3.2740
Eighth Point . . . . . . . . .: .024,3.1846
```

Only the information after the colons is put into the data file, the comments are to ensure that the correct information goes into the file.

Once the data file has been constructed, the hot wire calibration program reads the file and calculates the constants necessary for:

$$U\ (\text{m/sec}) = \left(\frac{EOC^2 - EOM^2}{B} \right)^{1/N}$$

The program listing is as follows:

```
C      PROGRAM HWCAL
C   THIS PROGRAM IS USED FOR CALCULATION OF HOT WIRE
C   CALIBRATION PARAMETERS% N,B,EO   FOR USE IN THE
C   RELATION  U=((E**2-EO**2)/B)**(1/N)
       DIMENSION U(50),E(50),G(50),F(50)
       DIMENSION TITLE(20),X(50),Y(50),XX(10),YY(10)
       READ(50,10)TITLE
    10 FORMAT(20A4)
       READ(50,*)DIA
       READ(50,*)TA
       READ(50,*)AP
       READ(50,*)N
       READ(50,*)EOM,NKKK
       READ(50,*) (G(I),E(I),I=1,N)
       PO=760.0
       TO=273.15
       TA=TO+TA
       DO=1.292
       DA=(DO*TO*AP)/(TA*PO)
       DW=998.2
       GC=9.81
       C=(((2.*DW*GC)/(1000.*DA))**0.5)
       ZNUU=13.30+(16.00-13.30)*((TA-273.)/(303.-273.))
       ZNUU=ZNUU/1000000.
       ULIM=0.068*ZNUU/(DIA*0.000001)
       DO 16 I=1,N
       IF(NKKK.EQ.1) G(I)=G(I)*25.4
       U(I)=C*(G(I)**0.5)
    16 CONTINUE
       DO 100 I=1,N
       IF(U(I).GE.ULIM)M=N
       IF(U(I).LT.ULIM)M=I-1
       IF(U(I).LT.ULIM)GO TO 101
   100 CONTINUE
   101 CONTINUE
       DO 60 I=1,M
```

```
      G(I)=ALOG(U(I))
      F(I)=ALOG((E(I)**2.)-(EOM**2.))
   60 CONTINUE
      CALL CORREL(G,F,M,SLO,ORD,RCC)
      RCC1=RCC
      EX=SLO
      EXI=1./SLO
      DO 18 I=1,M
      G(I)=U(I)**EX
      F(I)=E(I)**2.
   18 CONTINUE
      CALL CORREL(G,F,M,SLO,ORD,RCC)
      RCC2=RCC
      B=SLO
      EOC=(ORD)**0.5
C  PRINT OUT THE FINAL RESULTS
      WRITE(6,20)
   20 FORMAT(//,5X,'HOT-WIRE CALIBRATION RESULTS',/)
      KKK=0
   30 WRITE(6,21)TITLE
   21 FORMAT(5X,20A4,/)
      WRITE(6,22) EX,EXI,RCC1,EOM
      WRITE(6,23) B,EOC,RCC2,ULIM

  22 FORMAT(5X,'N=',F10.6,3X,'OR 1/N=',F10.6,3X,'CORR.COEF.
=',F10.6,
     1  3X,'EOM=',F10.6)

  23 FORMAT(5X,'B=',F10.6,6X,'EOC=',F10.6,3X,'CORR.COEFF.='
,F10.6,
     1 3X,'ULIM=',F10.6,/)
      WRITE (6,40)

  40 FORMAT(/,6X,'I',6X,'U(I)',12X,'E(I)',8X,'E(I)2-EOC2',5
X,
     1 'LN U(I)',4X,'LN(E(I)2-EOC2)',2X,'U(I)**N',/)
      DO 24 I=1,N
      AAA=(E(I)**2.)-(EOC**2.)
      BBB=ALOG(AAA)
      CCC=ALOG(U(I))
      DDD=(U(I))**EX
      Y(I)=DDD
      X(I)=AAA
      WRITE(6,25)I,U(I),E(I),AAA,CCC,BBB,DDD

  25 FORMAT(5X,I2,3X,F10.5,4X,F10.5,4X,F10.5,4X,F10.5,2(4X,
F10.5))
   24 CONTINUE
      ACHK=EOM**2.-EOC**2.
      WRITE(6,172) ACHK
  172 FORMAT (30X,'EOM**2-EOC**2=',2X,F10.5)
```

```
      IF(KKK.EQ.0)GO TO 70
      NL=N-M+2
      JJJ=0
      IF(NL.LT.4)M=N-2
      IF(NL.LT.4)NL=4
      DO 170 I=M,N
      JJJ=JJJ+1
      Y(JJJ)=Y(I)
      X(JJJ)=X(I)
  170 CONTINUE
      Y(NL)=0.0
      X(NL)=(EOM**2.)-(EOC**2.)
C REORDER DATA AND FIT THIRD ORDER POLYNOMIAL TO DATA
      X1=0.0
      X2=X1
      X3=X2
      X4=X3
      X5=X4
      X6=X5
      Y1=X6
      Y2=Y1
      Y3=Y2
      Y4=Y3
      DO 190 I=1,NL
      YY(I)=Y(I)
      XX(I)=X(I)
  190 CONTINUE
      DO 171 I=1,NL
      Y(NL-I+1)=YY(I)
      X(NL-I+1)=XX(I)
  171 CONTINUE
C FIX DATA POINT ON LINE CALIBRATION AT Y=ULIM**0.45
      XCAT=B*(ULIM**0.45)
      YCAT=ULIM**0.45
      J=NL
  301 IF(Y(J).LT.YCAT) GO TO 300
      X(J+1)=X(J)
      Y(J+1)=Y(J)
      J=J-1
      GO TO 301
  300 CONTINUE
      X(J+1)=XCAT
      Y(J+1)=YCAT
      NL=NL+1
      DO 303 I=1,NL
      WRITE (6,302) X(I),Y(I)
  302 FORMAT (///,5X,'X(I)=',2X,F10.5,5X,'Y(I)=',2X,F10.5)
  303 CONTINUE
      DO 102 I=1,NL
      X1=X1+X(I)
      X2=X2+X(I)**2.
```

```
      X3=X3+X(I)**3.
      X4=X4+X(I)**4.
      X5=X5+X(I)**5.
      X6=X6+X(I)**6.
      Y1=Y1+Y(I)
      Y2=Y2+X(I)*Y(I)
      Y3=Y3+X(I)*X(I)*Y(I)
      Y4=Y4+X(I)*X(I)*X(I)*Y(I)
  102 CONTINUE
      X0=FLOAT(NL)
C SOLVE MATRIX GAUSS/JORDAN ELIMINATION
      A12=X1/X0
      A13=X2/X0
      A14=X3/X0
      A22=X2/X1
      A23=X3/X1
      A24=X4/X1
      A32=X3/X2
      A33=X4/X2
      A34=X5/X2
      A42=X4/X3
      A43=X5/X3
      A44=X6/X3
      YA1=Y1/X0
      YA2=Y2/X1
      YA3=Y3/X2
      YA4=Y4/X3
      Y1=YA1
      Y2=YA2
      Y3=YA3
      Y4=YA4
      B22=A22-A12
      B23=A23-A13
      B24=A24-A14
      B32=A32-A12
      B33=A33-A13
      B34=A34-A14
      B42=A42-A12
      B43=A43-A13
      B44=A44-A14
      YY2=Y2-Y1
      YY3=Y3-Y1
      YY4=Y4-Y1
      C23=B23/B22
      C24=B24/B22
      C33=B33/B32
      C34=B34/B32
      C43=B43/B42
      C44=B44/B42
      Y2=YY2/B22
      Y3=YY3/B32
```

```
      Y4=YY4/B42
      D33=C33-C23
      D34=C34-C24
      D43=C43-C23
      D44=C44-C24
      W3=Y3-Y2
      W4=Y4-Y2
      E34=D34/D33
      E44=D44/D43
      Y3=W3/D33
      Y4=W4/D43
      D44=E44-E34
      YY4=(Y4-Y3)/D44
      Y4=YY4
      A3=Y4
      A2=Y3-E34*A3
      A1=Y2-C23*A2-C24*A3
      A0=Y1-A12*A1-A13*A2-A14*A3
      WRITE(6,200)

  200 FORMAT(//,5X,'HOT WIRE CALIBRATION RESULTS LOW VELOCIT
Y')
      WRITE(6,201)

  201 FORMAT(5X,'FORM OF CURVE% Y=A0+A1*X+A2*X**2+A3*X**3',/
)
      WRITE(6,202) A0,A1,A2,A3

  202 FORMAT(5X,' A0=',E15.5,2X,' A1=',E15.5,2X,' A2=',E15.5
,2X,
     1  ' A3=',E15.5,//////////////)
   70 IF(KKK.EQ.1) GO TO 31
      DO 27 I=1,M
      G(I)=U(I)**0.45
      F(I)=E(I)**2.
   27 CONTINUE
      CALL CORREL(G,F,M,SLO,ORD,RCC)
      EX=0.45
      EXI=1./EX
      RCC1=1.000
      RCC2=RCC
      B=SLO
      EOC=(ORD)**0.5
      WRITE(6,33)

   33 FORMAT(///,5X,'HOT-WIRE CALIBRATION RESULTS WITH N=0.4
5',/)
      KKK=1
      GO TO 30
   31 CONTINUE
      STOP
```

```
      END
      SUBROUTINE CORREL(G,F,M,SLO,ORD,RCC)
      DIMENSION G(50),F(50)
      X=0.
      Y=0.
      Z=0.
      X2=0.
      Y2=0.
      DO 50 I=1,M
      X=X+G(I)
      Y=Y+F(I)
      X2=X2+(G(I)**2)
      Y2=Y2+(F(I)**2)
      Z=Z+(G(I)*F(I))
   50 CONTINUE
      SLO=(Z-((X*Y)/FLOAT(M)))/(X2-((X**2)/FLOAT(M)))
      ORD=(Y-(SLO*X))/FLOAT(M)
      R=((FLOAT(M)*X2)-(X**2))/((FLOAT(M)*Y2)-(Y**2))
      RCC=SLO*SQRT(R)
      RETURN
      END
```

The program has the following output:

```
HOT-WIRE CALIBRATION RESULTS

HOT WIRE CALIBRATION  SATURDAY 14 JUNE 86

N=  0.941391    OR 1/N=  1.062257   CORR.COEF.=  0.994688   EOM=  2.399800
B=  1.483775       EOC=  2.412914   CORR.COEFF.=  0.994873   ULIM=  0.204319

I      U(I)          E(I)        E(I)2-EOC2    LN U(I)    LN(E(I)2-EOC2)  U(I)**N

1      5.36902       3.61060     7.21428       1.68064      1.97606       4.86538
2      5.21336       3.57690     6.97206       1.65123      1.94191       4.73248
3      5.17372       3.57210     6.93774       1.64359      1.93698       4.69859
4      4.97075       3.53780     6.69387       1.60357      1.90119       4.52486
5      4.53765       3.46980     6.21736       1.51241      1.82734       4.15274
6      4.05860       3.40570     5.77664       1.40084      1.75382       3.73869
7      3.65837       3.27400     4.89692       1.29702      1.58861       3.39058
8      3.14378       3.18460     4.31952       1.14542      1.46314       2.93966
                         EOM**2-EOC**2=    -0.06311


HOT-WIRE CALIBRATION RESULTS WITH N=0.45

HOT WIRE CALIBRATION  SATURDAY 14 JUNE 86
```

N= 0.450000 OR 1/N= 2.222221 CORR.COEF.= 1.000000 EOM= 2.399800
B= 6.319242 EOC= 0.674877 CORR.COEFF.= 0.996123 ULIM= 0.204319

I	U(I)	E(I)	E(I)2-EOC2	LN U(I)	LN(E(I)2-EOC2)	U(I)**N
1	5.36902	3.61060	12.58098	1.68064	2.53219	2.13036
2	5.21336	3.57690	12.33875	1.65123	2.51274	2.10234
3	5.17372	3.57210	12.30444	1.64359	2.50996	2.09513
4	4.97075	3.53780	12.06057	1.60357	2.48994	2.05774
5	4.53765	3.46980	11.58405	1.51241	2.44963	1.97503
6	4.05860	3.40570	11.14333	1.40084	2.41084	1.87832
7	3.65837	3.27400	10.26362	1.29702	2.32860	1.79258
8	3.14378	3.18460	9.68622	1.14542	2.27070	1.67438

EOM**2-EOC**2= 5.30358

X(I)= 5.30358 Y(I)= 0.00000

X(I)= 3.09246 Y(I)= 0.48937

X(I)= 9.68622 Y(I)= 1.67438

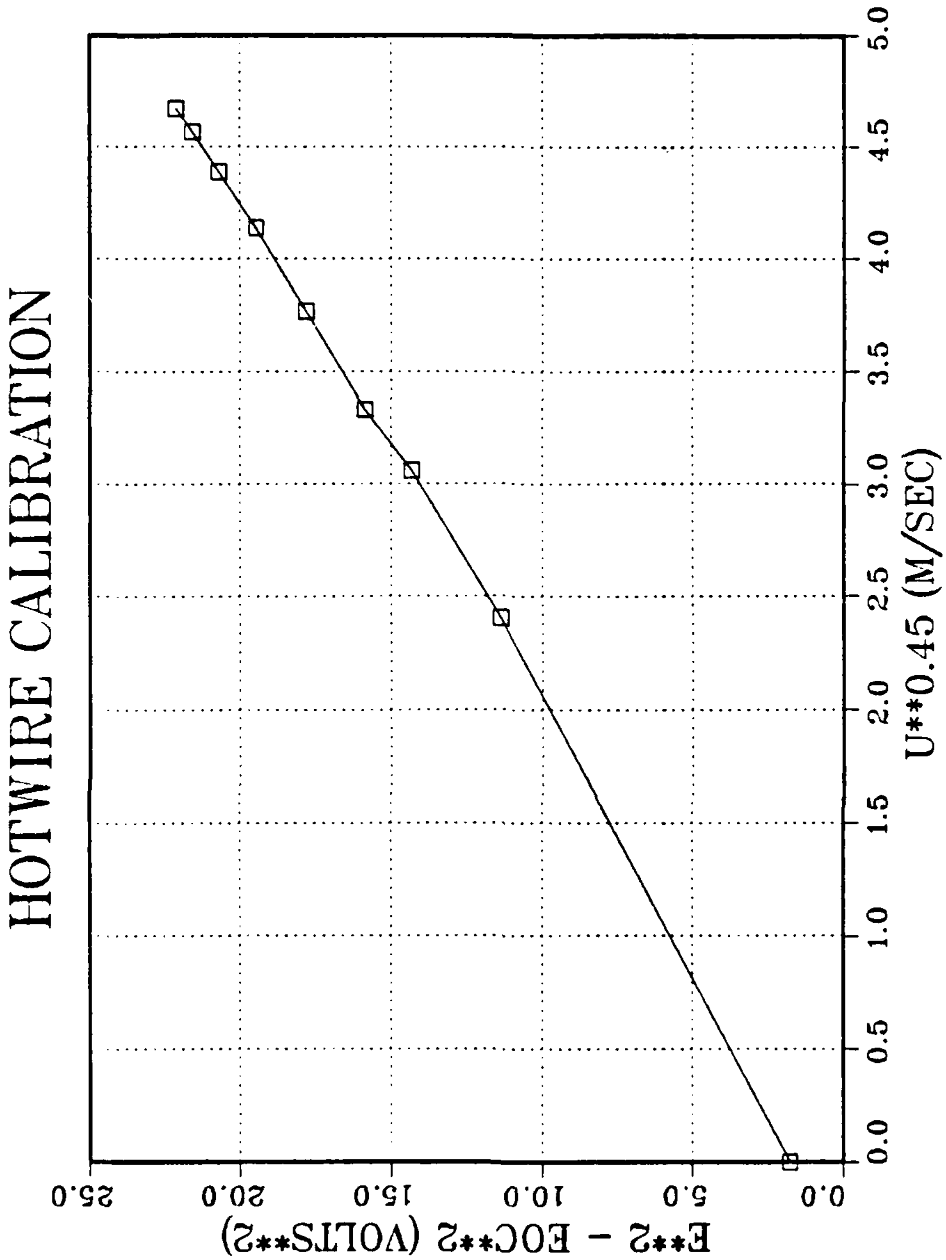
X(I)= 10.26362 Y(I)= 1.79258

X(I)= 11.14333 Y(I)= 1.87832

HOT WIRE CALIBRATION RESULTS LOW VELOCITY
FORM OF CURVE% Y=A0+A1*X+A2*X**2+A3*X**3

A0= 0.52919E+01 A1= -0.25975E+01 A2= 0.38874E+00 A3=
-0.16439E-01

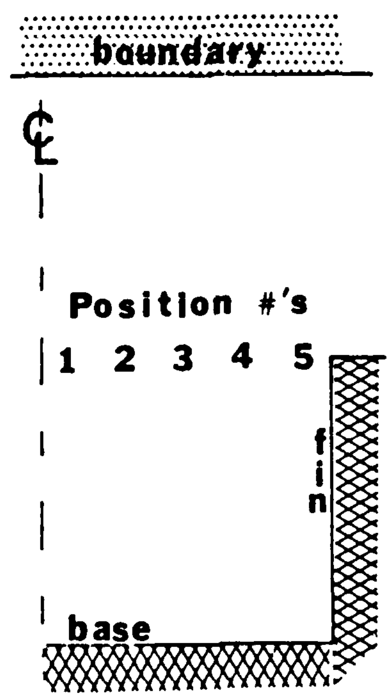
A hotwire calibration curve (p. 134) is then drawn to determine if the data is linear. If it is not, the hot wire must be recalibrated.


HOTWIRE CALIBRATION
U**0.45 (M/SEC)
E**2 − EOC**2 (VOLTS**2)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
5.0
10.0
15.0
20.0
25.0

APPENDIX D

LAMINAR HOT WIRE DATA FOR $Gr^{+}=10^{4}$ WITH C=0.0, C=0.4, AND C=1.0, INCLUDING THE UNHEATED TEST CASE

The following pages contain the data as listed above in the following format: (1) the original voltage readings, (2) the streamline patterns, and (3) the calculated velocities. The readings were taken in accordance with the diagram below. The second position, #5, is taken with the hot wire rotated 90 degrees, as shown in Figure 3.4, Page 49.



Unheated Test Case

Original Voltage Readings

#1	#2	#3	#4	#5	#5
2.3741	2.3775	2.3778	2.3811	2.3785	2.3789
2.3857	2.3875	2.3810	2.3869	2.3848	2.3870
2.4133	2.4099	2.3895	2.3950	2.3891	2.3888
2.4619	2.4538	2.4087	2.4029	2.4014	2.4044
2.5474	2.5268	2.4537	2.4166	2.4122	2.4096
2.6061	2.5872	2.5124	2.4327	2.4216	2.4220
2.6610	2.6328	2.5559	2.4520	2.4316	2.4300
2.6955	2.6649	2.5903	2.4682	2.4391	2.4405
2.7242	2.6874	2.6155	2.4792	2.4485	2.4485
2.7443	2.7032	2.6371	2.4883	2.4527	2.4530
2.7571	2.7168	2.6495	2.4908	2.4552	2.4550
2.7684	2.7259	2.6623	2.4945	2.4533	2.4543
2.7753	2.7304	2.6660	2.4894	2.4531	2.4534
2.7808	2.7373	2.6745	2.4917	2.4477	2.4481
2.7835	2.7381	2.6720	2.4860	2.4439	2.4425
2.7852	2.7425	2.6787	2.4868	2.4380	2.4365
2.7882	2.7423	2.6762	2.4794	2.4330	2.4331
2.7893	2.7456	2.6801	2.4824	2.4291	2.4319
2.7875	2.7409	2.6780	2.4734	2.4228	2.4230
2.7881	2.7449	2.6792	2.4754	2.4187	2.4295
2.7882	2.7397	2.6743	2.4686	2.4150	2.4125
2.7872	2.7398	2.6773	2.4713	2.4101	2.4096
2.7845	2.7375	2.6694	2.4637	2.4086	2.4091
2.7832	2.7370	2.6728	2.4672	2.4058	2.4045
2.7799	2.7305	2.6657	2.4618	2.4057	2.4057
2.7742	2.7284	2.6674	2.4660	2.4042	2.4038
2.7680	2.7200	2.6578	2.4601	2.4059	2.4055
2.7482	2.7029	2.6420	2.4601	2.4091	2.4099
2.7347	2.6921	2.6354	2.4617	2.4098	2.4095
2.7153	2.6689	2.6152	2.4553	2.4096	2.4093
2.6907	2.6425	2.5958	2.4469	2.4056	2.4075
2.6499	2.5985	2.5572	2.4271	2.3997	2.4005
2.5964	2.5423	2.5118	2.4123	2.3950	2.3945
2.5190	2.4669	2.4535	2.3974	2.3920	2.3920
2.4570	2.4220	2.4195	2.3939	2.3923	2.3930

Unheated Test Case

Streamlines

#1	#2	#3	#4	#5	
0.46	0.47	0.47	0.47	0.47	-0.0008
0.47	0.48	0.47	0.48	0.47	-0.0045
0.50	0.50	0.48	0.48	0.48	0.0006
0.55	0.54	0.50	0.49	0.49	-0.0060
0.65	0.63	0.54	0.50	0.50	0.0052
0.72	0.70	0.61	0.52	0.51	-0.0008
0.80	0.76	0.66	0.54	0.52	0.0032
0.85	0.81	0.70	0.56	0.53	-0.0028
0.89	0.84	0.74	0.57	0.54	0.0000
0.93	0.86	0.77	0.58	0.54	-0.0006
0.95	0.88	0.78	0.58	0.54	0.0004
0.97	0.90	0.80	0.59	0.54	-0.0020
0.98	0.90	0.81	0.58	0.54	-0.0006
0.99	0.91	0.82	0.58	0.54	-0.0008
0.99	0.92	0.82	0.58	0.53	0.0028
0.99	0.92	0.83	0.58	0.53	0.0030
1.00	0.92	0.82	0.57	0.52	-0.0002
1.00	0.93	0.83	0.57	0.52	-0.0056
1.00	0.92	0.82	0.56	0.51	-0.0004
1.00	0.93	0.83	0.57	0.51	-0.0217
1.00	0.92	0.82	0.56	0.50	0.0050
1.00	0.92	0.82	0.56	0.50	0.0010
0.99	0.92	0.81	0.55	0.50	-0.0010
0.99	0.91	0.82	0.56	0.49	0.0026
0.98	0.90	0.81	0.55	0.49	0.0000
0.97	0.90	0.81	0.56	0.49	0.0008
0.96	0.89	0.80	0.55	0.49	0.0008
0.93	0.86	0.77	0.55	0.50	-0.0016
0.91	0.85	0.76	0.55	0.50	0.0006
0.88	0.81	0.74	0.54	0.50	0.0006
0.84	0.77	0.71	0.54	0.49	-0.0038
0.78	0.71	0.66	0.52	0.49	-0.0016
0.71	0.64	0.61	0.50	0.48	0.0010
0.62	0.56	0.54	0.49	0.48	0.0000
0.55	0.51	0.51	0.48	0.48	-0.0014

MINIMUM PSI = -0.0217
AVERAGE PSI = -0.0008
MAXIMUM PSI = 0.0052

Unheated Test Case

Velocities

#1	#2	#3	#4	#5	
2.1100	2.1247	2.1260	2.1403	2.1290	2.1307
2.1603	2.1682	2.1398	2.1656	2.1564	2.1660
2.2837	2.2682	2.1770	2.2013	2.1752	2.1739
2.5137	2.4742	2.2627	2.2366	2.2298	2.2433
2.9605	2.8478	2.4737	2.2987	2.2786	2.2668
3.3005	3.1880	2.7709	2.3735	2.3218	2.3236
3.6446	3.4646	3.0080	2.4655	2.3683	2.3608
3.8743	3.6700	3.2062	2.5447	2.4037	2.4103
4.0737	3.8194	3.3576	2.5997	2.4486	2.4486
4.2180	3.9271	3.4916	2.6458	2.4688	2.4703
4.3118	4.0216	3.5704	2.6585	2.4810	2.4800
4.3960	4.0858	3.6531	2.6775	2.4718	2.4766
4.4480	4.1178	3.6772	2.6514	2.4708	2.4722
4.4898	4.1673	3.7332	2.6632	2.4447	2.4467
4.5104	4.1731	3.7167	2.6341	2.4265	2.4198
4.5234	4.2049	3.7611	2.6381	2.3985	2.3914
4.5465	4.2034	3.7445	2.6007	2.3749	2.3754
4.5549	4.2274	3.7705	2.6158	2.3566	2.3697
4.5411	4.1933	3.7565	2.5706	2.3273	2.3282
4.5457	4.2223	3.7645	2.5806	2.3084	2.3585
4.5465	4.1846	3.7319	2.5467	2.2914	2.2800
4.5388	4.1854	3.7518	2.5601	2.2691	2.2668
4.5181	4.1687	3.6996	2.5225	2.2623	2.2645
4.5081	4.1651	3.7220	2.5398	2.2496	2.2438
4.4829	4.1185	3.6753	2.5132	2.2492	2.2492
4.4397	4.1036	3.6864	2.5339	2.2424	2.2406
4.3930	4.0441	3.6238	2.5049	2.2501	2.2483
4.2464	3.9250	3.5226	2.5049	2.2645	2.2682
4.1486	3.8512	3.4809	2.5127	2.2677	2.2664
4.0111	3.6963	3.3558	2.4815	2.2668	2.2655
3.8417	3.5257	3.2388	2.4409	2.2487	2.2573
3.5729	3.2549	3.0153	2.3473	2.2222	2.2258
3.2424	2.9323	2.7677	2.2791	2.2013	2.1991
2.8059	2.5383	2.4727	2.2120	2.1880	2.1880
2.4897	2.3236	2.3121	2.1964	2.1893	2.1924

MINIMUM VELOCITY = 2.1100
AVERAGE VELOCITY = 3.1083
MAXIMUM VELOCITY = 4.5549

Heated Test Case $Gr^{+}=10^{4}$, C=0.0

Original Voltage Readings

#1	#2	#3	#4	#5	#5
2.3828	2.3700	2.3716	2.3762	2.3822	2.3822
2.3865	2.3726	2.3792	2.3799	2.3893	2.3849
2.4021	2.3803	2.3897	2.3870	2.3946	2.3858
2.4198	2.4021	2.4154	2.3906	2.4038	2.3905
2.4502	2.4398	2.4714	2.4102	2.4148	2.3969
2.4873	2.5206	2.5498	2.4470	2.4248	2.4022
2.5095	2.5822	2.6161	2.4848	2.4340	2.4067
2.5367	2.6380	2.6614	2.5320	2.4419	2.4098
2.5455	2.6778	2.6959	2.5688	2.4500	2.4131
2.5603	2.7036	2.7203	2.5900	2.4530	2.4113
2.5592	2.7197	2.7411	2.6131	2.4550	2.4084
2.5686	2.7387	2.7499	2.6206	2.4537	2.4023
2.5663	2.7435	2.7616	2.6333	2.4513	2.3951
2.5732	2.7541	2.7673	2.6339	2.4473	2.3863
2.5666	2.7587	2.7721	2.6426	2.4426	2.3768
2.5728	2.7640	2.7741	2.6389	2.4364	2.3659
2.5650	2.7643	2.7779	2.6456	2.3137	2.2332
2.5701	2.7675	2.7775	2.6410	2.4267	2.3465
2.5624	2.7670	2.7799	2.6468	2.4227	2.3477
2.5668	2.7689	2.7801	2.6405	2.4174	2.3475
2.5569	2.7664	2.7794	2.6436	2.4137	2.3488
2.5600	2.7672	2.7808	2.6374	2.4098	2.3499
2.5518	2.7655	2.7755	2.6419	2.4084	2.3533
2.5587	2.7643	2.7749	2.6350	2.4053	2.3551
2.5497	2.7609	2.7742	2.6380	2.4052	2.3597
2.5528	2.7568	2.7711	2.6292	2.4040	2.3632
2.5434	2.7517	2.7642	2.6333	2.4059	2.3698
2.5442	2.7481	2.7578	2.6233	2.4065	2.3750
2.5291	2.7397	2.7531	2.6220	2.4093	2.3823
2.5165	2.7322	2.7417	2.6103	2.4091	2.3867
2.4942	2.7123	2.7229	2.6065	2.4081	2.3903
2.4695	2.6968	2.7025	2.5865	2.4024	2.3891
2.4308	2.6707	2.6656	2.5679	2.3973	2.3885
2.4041	2.6305	2.6216	2.5276	2.3919	2.3875
2.3970	2.5740	2.5789	2.4898	2.3892	2.3892

Heated Test Case $Gr^{+}=10^{4}$, C=0.0

Streamlines

#1	#2	#3	#4	#5	
0.48	0.47	0.47	0.47	0.48	0.0000
0.48	0.47	0.47	0.48	0.48	0.0089
0.50	0.48	0.49	0.48	0.49	0.0176
0.52	0.50	0.51	0.49	0.50	0.0264
0.55	0.54	0.57	0.51	0.51	0.0353
0.59	0.63	0.66	0.54	0.52	0.0441
0.61	0.70	0.75	0.59	0.53	0.0529
0.65	0.78	0.81	0.64	0.54	0.0618
0.66	0.84	0.86	0.69	0.55	0.0705
0.68	0.88	0.90	0.71	0.55	0.0792
0.67	0.90	0.93	0.74	0.55	0.0882
0.69	0.93	0.95	0.75	0.55	0.0969
0.68	0.94	0.97	0.77	0.55	0.1057
0.69	0.96	0.98	0.77	0.54	0.1146
0.68	0.96	0.99	0.79	0.54	0.1234
0.69	0.97	0.99	0.78	0.53	0.1321
0.68	0.97	1.00	0.79	0.41	0.1585
0.69	0.98	0.99	0.78	0.52	0.1499
0.68	0.98	1.00	0.79	0.52	0.1410
0.68	0.98	1.00	0.78	0.51	0.1322
0.67	0.98	1.00	0.79	0.51	0.1234
0.68	0.98	1.00	0.78	0.51	0.1145
0.66	0.97	0.99	0.78	0.50	0.1058
0.67	0.97	0.99	0.77	0.50	0.0969
0.66	0.97	0.99	0.78	0.50	0.0882
0.67	0.96	0.98	0.77	0.50	0.0794
0.65	0.95	0.97	0.77	0.50	0.0704
0.66	0.95	0.96	0.76	0.50	0.0616
0.64	0.93	0.95	0.76	0.50	0.0530
0.62	0.92	0.94	0.74	0.50	0.0441
0.60	0.89	0.91	0.74	0.50	0.0352
0.57	0.86	0.87	0.71	0.50	0.0264
0.53	0.83	0.82	0.69	0.49	0.0176
0.50	0.77	0.76	0.64	0.49	0.0089
0.49	0.69	0.70	0.59	0.48	0.0000

MINIMUM PSI = 0.0000
AVERAGE PSI = 0.0733
MAXIMUM PSI = 0.1585

Heated Test Case $Gr^{+}=10^{4}$, C=0.0

Velocities

#1	#2	#3	#4	#5	
2.1477	2.0925	2.0993	2.1191	2.1451	2.1451
2.1638	2.1036	2.1320	2.1351	2.1761	2.1568
2.2330	2.1368	2.1779	2.1660	2.1995	2.1608
2.3135	2.2330	2.2932	2.1818	2.2406	2.1814
2.4568	2.4070	2.5606	2.2695	2.2905	2.2098
2.6407	2.8145	2.9739	2.4414	2.3366	2.2334
2.7556	3.1587	3.3613	2.6280	2.3796	2.2537
2.9015	3.4973	3.6472	2.8759	2.4170	2.2677
2.9500	3.7551	3.8771	3.0812	2.4558	2.2827
3.0328	3.9299	4.0462	3.2045	2.4703	2.2745
3.0266	4.0420	4.1948	3.3429	2.4800	2.2614
3.0801	4.1774	4.2588	3.3889	2.4737	2.2339
3.0669	4.2122	4.3452	3.4677	2.4621	2.2017
3.1065	4.2897	4.3877	3.4715	2.4428	2.1630
3.0686	4.3237	4.4238	3.5264	2.4203	2.1217
3.1042	4.3631	4.4389	3.5030	2.3909	2.0750
3.0595	4.3653	4.4677	3.5454	1.8623	1.5671
3.0887	4.3892	4.4647	3.5162	2.3454	1.9939
3.0447	4.3855	4.4829	3.5531	2.3268	1.9989
3.0698	4.3997	4.4844	3.5131	2.3024	1.9980
3.0137	4.3810	4.4791	3.5327	2.2855	2.0034
3.0312	4.3870	4.4898	3.4935	2.2677	2.0080
2.9850	4.3743	4.4495	3.5219	2.2614	2.0221
3.0238	4.3653	4.4450	3.4784	2.2474	2.0296
2.9733	4.3400	4.4397	3.4973	2.2469	2.0488
2.9906	4.3096	4.4163	3.4421	2.2415	2.0636
2.9384	4.2720	4.3646	3.4677	2.2501	2.0916
2.9428	4.2457	4.3170	3.4055	2.2528	2.1139
2.8602	4.1846	4.2823	3.3975	2.2655	2.1455
2.7926	4.1307	4.1991	3.3259	2.2645	2.1647
2.6760	3.9901	4.0645	3.3029	2.2600	2.1805
2.5512	3.8832	3.9223	3.1839	2.2343	2.1752
2.3646	3.7081	3.6746	3.0761	2.2115	2.1726
2.2420	3.4502	3.3950	2.8521	2.1876	2.1682
2.2102	3.1111	3.1395	2.6534	2.1757	2.1757

MINIMUM VELOCITY = 1.8623
AVERAGE VELOCITY = 3.1722
MAXIMUM VELOCITY = 4.4898

Heated Test Case $Gr^{+}=10^{4}$, C=0.4

Original Voltage Readings

#1	#2	#3	#4	#5	#5
2.3834	2.3867	2.3848	2.4267	2.4036	2.4034
2.4020	2.4150	2.3926	2.4522	2.4283	2.4239
2.4584	2.4798	2.4476	2.5158	2.5207	2.5122
2.5339	2.5251	2.5272	2.5903	2.6046	2.5887
2.6033	2.6190	2.5853	2.6355	2.6386	2.6189
2.6454	2.6549	2.6421	2.6718	2.6680	2.6421
2.6791	2.6839	2.6760	2.6970	2.6925	2.6618
2.6986	2.7057	2.6981	2.7137	2.7124	2.6724
2.7169	2.7174	2.7165	2.7227	2.7208	2.6788
2.7253	2.7279	2.7228	2.7262	2.7238	2.6717
2.7283	2.7325	2.7303	2.7289	2.7223	2.6637
2.7260	2.7259	2.7310	2.7209	2.7145	2.6555
2.7190	2.7238	2.7250	2.7081	2.7000	2.6328
2.7080	2.7120	2.7217	2.6941	2.6751	2.6068
2.6876	2.7006	2.7058	2.6701	2.6463	2.5775
2.6653	2.6807	2.6934	2.6423	2.6028	2.5246
2.6286	2.6588	2.6754	2.6114	2.5474	2.4611
2.5890	2.6335	2.6584	2.5769	2.4732	2.3891
2.5458	2.6123	2.6371	2.5436	2.4240	2.3320
2.5047	2.5955	2.6257	2.5224	2.3985	2.3036
2.4816	2.5801	2.6081	2.5032	2.3899	2.3043
2.4702	2.5649	2.5984	2.4947	2.3867	2.3052
2.4583	2.5589	2.5886	2.4872	2.3859	2.3054
2.4506	2.5510	2.5883	2.4840	2.3858	2.3099
2.4515	2.5479	2.5751	2.4802	2.3860	2.3113
2.4462	2.5398	2.5733	2.4784	2.3869	2.3160
2.4487	2.5415	2.5686	2.4756	2.3872	2.3132
2.4443	2.5360	2.5677	2.4740	2.3882	2.3230
2.4471	2.5378	2.5641	2.4732	2.3885	2.3222
2.4420	2.5335	2.5650	2.4739	2.3896	2.3301
2.4460	2.5329	2.5608	2.4725	2.3899	2.3352
2.4420	2.5295	2.5621	2.4723	2.3908	2.3369
2.4441	2.5310	2.5580	2.4702	2.3913	2.3442
2.4414	2.5290	2.5566	2.4718	2.3924	2.3441
2.4425	2.5271	2.5552	2.4679	2.3929	2.3473
2.4393	2.5251	2.5520	2.4679	2.3938	2.3560
2.4409	2.5238	2.5498	2.4664	2.3942	2.3541
2.4381	2.5189	2.5471	2.4657	2.3953	2.3570
2.4389	2.5172	2.5448	2.4120	2.3954	2.3609
2.4336	2.5122	2.5423	2.4589	2.3960	2.3641
2.4346	2.5074	2.5363	2.4540	2.3954	2.3661
2.4304	2.5005	2.5319	2.4510	2.3951	2.3687
2.4266	2.4932	2.5230	2.4444	2.3936	2.3699

2.4193	2.4821	2.5122	2.4358	2.3917	2.3708
2.4144	2.4717	2.4980	2.4251	2.3893	2.3710
2.4057	2.4538	2.4853	2.4154	2.3866	2.3709
2.3979	2.4336	2.4640	2.4028	2.3839	2.3779
2.3903	2.4168	2.4409	2.3924	2.3811	2.3707
2.3849	2.4002	2.4172	2.3849	2.3790	2.3712
2.3804	2.3879	2.3984	2.3802	2.3774	2.3722
2.3784	2.3820	2.3875	2.3822	2.3806	2.3760
2.3805	2.3834	2.3857	2.3873	2.3973	2.3973

Heated Test Case $Gr^{+}=10^{4}$, C=0.4

Streamlines

#1	#2	#3	#4	#5	
0.52	0.52	0.52	0.57	0.54	0.0004
0.54	0.55	0.53	0.60	0.57	0.0087
0.60	0.63	0.59	0.67	0.68	0.0160
0.70	0.69	0.69	0.78	0.80	0.0288
0.79	0.82	0.77	0.84	0.85	0.0350
0.86	0.87	0.85	0.90	0.89	0.0453
0.91	0.92	0.91	0.94	0.93	0.0530
0.94	0.95	0.94	0.97	0.97	0.0680
0.97	0.97	0.97	0.98	0.98	0.0711
0.99	0.99	0.98	0.99	0.99	0.0875
0.99	1.00	1.00	0.99	0.98	0.0981
0.99	0.99	1.00	0.98	0.97	0.0990
0.98	0.99	0.99	0.96	0.94	0.1128
0.96	0.96	0.98	0.94	0.90	0.1157
0.92	0.95	0.95	0.90	0.86	0.1179
0.89	0.91	0.93	0.85	0.79	0.1356
0.83	0.88	0.90	0.81	0.72	0.1523
0.77	0.84	0.88	0.76	0.62	0.1535
0.71	0.81	0.84	0.71	0.56	0.1706
0.66	0.78	0.83	0.68	0.54	0.1776
0.63	0.76	0.80	0.66	0.53	0.1620
0.62	0.74	0.79	0.65	0.52	0.1549
0.60	0.73	0.77	0.64	0.52	0.1532
0.59	0.72	0.77	0.63	0.52	0.1450
0.60	0.72	0.75	0.63	0.52	0.1428
0.59	0.71	0.75	0.63	0.52	0.1359
0.59	0.71	0.75	0.62	0.52	0.1415
0.59	0.70	0.74	0.62	0.53	0.1254
0.59	0.70	0.74	0.62	0.53	0.1274
0.58	0.70	0.74	0.62	0.53	0.1149
0.59	0.70	0.73	0.62	0.53	0.1060
0.58	0.69	0.74	0.62	0.53	0.1045
0.59	0.69	0.73	0.62	0.53	0.0917
0.58	0.69	0.73	0.62	0.53	0.0939
0.59	0.69	0.73	0.62	0.53	0.0889
0.58	0.69	0.72	0.62	0.53	0.0741
0.58	0.69	0.72	0.61	0.53	0.0784
0.58	0.68	0.72	0.61	0.53	0.0750
0.58	0.68	0.71	0.55	0.53	0.0677
0.58	0.67	0.71	0.60	0.53	0.0627
0.58	0.66	0.70	0.60	0.53	0.0577
0.57	0.66	0.70	0.60	0.53	0.0522
0.57	0.65	0.68	0.59	0.53	0.0469

0.56	0.63	0.67	0.58	0.53	0.0415
0.55	0.62	0.65	0.57	0.53	0.0365
0.54	0.60	0.64	0.55	0.52	0.0314
0.54	0.58	0.61	0.54	0.52	0.0121
0.53	0.56	0.58	0.53	0.52	0.0209
0.52	0.54	0.56	0.52	0.52	0.0158
0.52	0.53	0.54	0.52	0.51	0.0105
0.52	0.52	0.52	0.52	0.52	0.0093
0.52	0.52	0.52	0.52	0.54	0.0000

MINIMUM PSI = 0.0000
AVERAGE PSI = 0.0832
cAXIMUM PSI = 0.1776

Heated Test Case $Gr^{+}=10^{4}$, C=0.4

Velocities

#1	#2	#3	#4	#5	
2.1503	2.1647	2.1564	2.3454	2.2397	2.2388
2.2325	2.2914	2.1907	2.4664	2.3529	2.3324
2.4966	2.6027	2.4443	2.7889	2.8150	2.7698
2.8862	2.8386	2.8499	3.2062	3.2915	3.1968
3.2836	3.3790	3.1768	3.4815	3.5011	3.3784
3.5442	3.6051	3.5232	3.7154	3.6903	3.5232
3.7638	3.7959	3.7432	3.8846	3.8539	3.6498
3.8955	3.9443	3.8921	3.9999	3.9908	3.7193
4.0223	4.0258	4.0195	4.0631	4.0497	3.7618
4.0815	4.1000	4.0638	4.0879	4.0709	3.7147
4.1029	4.1328	4.1171	4.1071	4.0603	3.6622
4.0865	4.0858	4.1221	4.0504	4.0055	3.6089
4.0370	4.0709	4.0794	3.9610	3.9051	3.4646
3.9603	3.9880	4.0561	3.8648	3.7372	3.3047
3.8208	3.9092	3.9450	3.7042	3.5499	3.1314
3.6726	3.7745	3.8601	3.5245	3.2806	2.8359
3.4384	3.6303	3.7392	3.3326	2.9605	2.5098
3.1986	3.4690	3.6277	3.1279	2.5696	2.1752
2.9516	3.3381	3.4916	2.9395	2.3329	1.9349
2.7304	3.2370	3.4204	2.8241	2.2169	1.8231
2.6118	3.1465	3.3126	2.7226	2.1788	1.8258
2.5547	3.0590	3.2543	2.6786	2.1647	1.8293
2.4961	3.0249	3.1962	2.6402	2.1612	1.8301
2.4587	2.9806	3.1944	2.6239	2.1608	1.8475
2.4630	2.9633	3.1175	2.6047	2.1616	1.8529
2.4375	2.9185	3.1071	2.5956	2.1656	1.8713
2.4495	2.9279	3.0801	2.5816	2.1669	1.8603
2.4284	2.8977	3.0749	2.5736	2.1713	1.8989
2.4419	2.9076	3.0544	2.5696	2.1726	1.8958
2.4175	2.8841	3.0595	2.5731	2.1774	1.9273
2.4366	2.8808	3.0357	2.5661	2.1788	1.9478
2.4175	2.8623	3.0430	2.5651	2.1827	1.9547
2.4275	2.8705	3.0199	2.5547	2.1849	1.9845
2.4146	2.8596	3.0120	2.5626	2.1898	1.9841
2.4198	2.8494	3.0041	2.5433	2.1920	1.9972
2.4046	2.8386	2.9862	2.5433	2.1960	2.0333
2.4122	2.8316	2.9739	2.5358	2.1978	2.0254
2.3989	2.8054	2.9589	2.5324	2.2026	2.0375
2.4027	2.7963	2.9461	2.2777	2.2031	2.0539
2.3777	2.7698	2.9323	2.4990	2.2057	2.0674
2.3824	2.7446	2.8993	2.4751	2.2031	2.0759
2.3627	2.7086	2.8754	2.4606	2.2017	2.0869
2.3449	2.6709	2.8273	2.4289	2.1951	2.0920
2.3112	2.6143	2.7698	2.3881	2.1867	2.0959

2.2887	2.5621	2.6956	2.3380	2.1761	2.0967
2.2492	2.4742	2.6305	2.2932	2.1643	2.0963
2.2142	2.3777	2.5240	2.2361	2.1525	2.1264
2.1805	2.2997	2.4122	2.1898	2.1403	2.0955
2.1568	2.2245	2.3015	2.1568	2.1312	2.0976
2.1372	2.1700	2.2164	2.1364	2.1243	2.1019
2.1286	2.1442	2.1682	2.1451	2.1381	2.1182
2.1377	2.1503	2.1603	2.1673	2.2115	2.2115

MINIMUM VELOCITY = 2.1243
AVERAGE VELOCITY = 2.8785
MAXIMUM VELOCITY = 4.1328

Heated Test Case $Gr^{+}=10^{4}$, C=1.0

Original Voltage Readings

#1	#2	#3	#4	#5	#5
2.3357	2.3509	2.3610	2.3903	2.3555	2.3553
2.3449	2.3649	2.3649	2.4029	2.3676	2.3525
2.3540	2.3788	2.3687	2.4154	2.3797	2.3695
2.4092	2.4426	2.4231	2.4781	2.4703	2.4532
2.4832	2.4872	2.5019	2.5514	2.5525	2.5251
2.4995	2.5192	2.5286	2.5274	2.4974	2.4442
2.5084	2.5263	2.5296	2.5506	2.5333	2.4874
2.5172	2.5335	2.5307	2.5737	2.5692	2.5307
2.5512	2.5797	2.5594	2.5960	2.5858	2.5429
2.5587	2.5778	2.5810	2.5974	2.5800	2.5255
2.5925	2.6151	2.6157	2.6317	2.6146	2.5598
2.6090	2.6294	2.6325	2.6441	2.6266	2.5666
2.6255	2.6436	2.6492	2.6565	2.6386	2.5732
2.6446	2.6651	2.6711	2.6730	2.6582	2.5807
2.6541	2.6735	2.6924	2.6559	2.6272	2.5212
2.6626	2.6766	2.6893	2.6819	2.6664	2.5810
2.6644	2.6813	2.6982	2.6699	2.6468	2.5374
2.6667	2.6818	2.6925	2.6836	2.6679	2.5717
2.6696	2.6854	2.7002	2.6792	2.6597	2.5487
2.6708	2.6870	2.6956	2.6853	2.6693	2.5623
2.6711	2.6869	2.6996	2.6846	2.6662	2.5533
2.6723	2.6893	2.6993	2.6867	2.6686	2.5525
2.6737	2.6915	2.7030	2.6880	2.6679	2.5455
2.6726	2.6883	2.7034	2.6841	2.6641	2.5386
2.6715	2.6850	2.7037	2.6801	2.6602	2.5316
2.6681	2.6840	2.7008	2.6738	2.6531	2.5176
2.6695	2.6855	2.6959	2.6851	2.6683	2.5414
2.6646	2.6829	2.6978	2.6675	2.6460	2.5005
2.6592	2.6771	2.6962	2.6606	2.6338	2.4848
2.6538	2.6713	2.6945	2.6537	2.6216	2.4692
2.6438	2.6657	2.6866	2.6419	2.6075	2.4517
2.6338	2.6601	2.6787	2.6300	2.5934	2.4345
2.6120	2.6405	2.6665	2.6027	2.5507	2.3797
2.5760	2.6189	2.6486	2.5722	2.4965	2.3146
2.5372	2.5940	2.6318	2.5382	2.4237	2.2410
2.4949	2.5731	2.6107	2.5054	2.3755	2.1881
2.4546	2.5566	2.5994	2.4846	2.3505	2.1631
2.4320	2.5414	2.5820	2.4657	2.3421	2.1668
2.4208	2.5264	2.5724	2.4573	2.3390	2.1706
2.4091	2.5205	2.5627	2.4499	2.3382	2.1738
2.4016	2.5127	2.5624	2.4467	2.3381	2.1811
2.4025	2.5097	2.5493	2.4430	2.3383	2.1855
2.3973	2.5017	2.5476	2.4412	2.3392	2.1930
2.3997	2.5034	2.5429	2.4385	2.3395	2.1932

2.3954	2.4980	2.5420	2.4369	2.3404	2.2057
2.3982	2.4997	2.5385	2.4361	2.3407	2.2080
2.3932	2.4955	2.5393	2.4368	2.3418	2.2186
2.3971	2.4949	2.5352	2.4354	2.3421	2.2266
2.3932	2.4916	2.5365	2.4352	2.3430	2.2312
2.3952	2.4930	2.5324	2.4331	2.3435	2.2413
2.3937	2.4892	2.5296	2.4309	2.3450	2.2473
2.3926	2.4911	2.5310	2.4347	2.3446	2.2471
2.3905	2.4872	2.5265	2.4309	2.3459	2.2617
2.3921	2.4859	2.5243	2.4294	2.3463	2.2628
2.3893	2.4811	2.5216	2.4287	2.3474	2.2686
2.3901	2.4794	2.5194	2.3758	2.3475	2.2754
2.3849	2.4745	2.5169	2.4220	2.3481	2.2814
2.3859	2.4698	2.5109	2.4172	2.3475	2.2864
2.3818	2.4630	2.5066	2.4142	2.3472	2.2918
2.3781	2.4558	2.4978	2.4077	2.3457	2.2960
2.3709	2.4449	2.4871	2.3993	2.3439	2.2998
2.3661	2.4346	2.4730	2.3887	2.3415	2.3030
2.3576	2.4170	2.4604	2.3792	2.3389	2.3058
2.3499	2.3971	2.4394	2.3668	2.3362	2.3156
2.3425	2.3805	2.4165	2.3565	2.3335	2.3115
2.3372	2.3642	2.3930	2.3491	2.3314	2.3150
2.3328	2.3521	2.3744	2.3445	2.3299	2.3189
2.3308	2.3463	2.3636	2.3465	2.3330	2.3256
2.3329	2.3476	2.3618	2.3515	2.3494	2.3499

Heated Test Case $Gr^{+}=10^{4}$, C=1.0

Streamlines

#1	#2	#3	#4	#5	
0.50	0.51	0.52	0.55	0.52	0.0004
0.51	0.53	0.53	0.57	0.53	0.0305
0.52	0.54	0.53	0.58	0.54	0.0206
0.58	0.62	0.59	0.66	0.65	0.0328
0.67	0.67	0.69	0.76	0.76	0.0503
0.69	0.71	0.73	0.73	0.69	0.0983
0.70	0.72	0.73	0.76	0.73	0.0839
0.71	0.73	0.73	0.79	0.78	0.0696
0.76	0.80	0.77	0.82	0.81	0.0768
0.77	0.80	0.80	0.83	0.80	0.0970
0.82	0.85	0.85	0.88	0.85	0.0961
0.84	0.88	0.88	0.90	0.87	0.1043
0.87	0.90	0.91	0.92	0.89	0.1127
0.90	0.93	0.94	0.95	0.92	0.1314
0.92	0.95	0.98	0.92	0.87	0.1784
0.93	0.95	0.97	0.96	0.94	0.1435
0.93	0.96	0.99	0.94	0.90	0.1823
0.94	0.96	0.98	0.97	0.94	0.1604
0.94	0.97	0.99	0.96	0.93	0.1838
0.94	0.97	0.99	0.97	0.94	0.1770
0.94	0.97	0.99	0.97	0.94	0.1862
0.95	0.97	0.99	0.97	0.94	0.1909
0.95	0.98	1.00	0.97	0.94	0.2005
0.95	0.97	1.00	0.97	0.93	0.2054
0.94	0.97	1.00	0.96	0.93	0.2104
0.94	0.97	0.99	0.95	0.91	0.2212
0.94	0.97	0.99	0.97	0.94	0.2072
0.93	0.96	0.99	0.94	0.90	0.2366
0.92	0.95	0.99	0.93	0.88	0.2429
0.92	0.94	0.98	0.92	0.86	0.2490
0.90	0.94	0.97	0.90	0.84	0.2554
0.88	0.93	0.96	0.88	0.82	0.2613
0.85	0.89	0.94	0.83	0.76	0.2836
0.79	0.86	0.91	0.79	0.68	0.3058
0.74	0.82	0.88	0.74	0.59	0.3163
0.68	0.79	0.85	0.70	0.54	0.3299
0.63	0.77	0.83	0.67	0.51	0.3335
0.60	0.74	0.80	0.64	0.50	0.3161
0.59	0.72	0.79	0.63	0.50	0.3057
0.58	0.72	0.78	0.62	0.50	0.2995
0.57	0.71	0.77	0.62	0.50	0.2877
0.57	0.70	0.76	0.62	0.50	0.2809
0.56	0.69	0.75	0.61	0.50	0.2701
0.57	0.69	0.75	0.61	0.50	0.2702

0.56	0.69	0.75	0.61	0.50	0.2510
0.56	0.69	0.74	0.61	0.50	0.2476
0.56	0.68	0.74	0.61	0.50	0.2315
0.56	0.68	0.74	0.61	0.50	0.2183
0.56	0.68	0.74	0.61	0.50	0.2118
0.56	0.68	0.73	0.60	0.50	0.1951
0.56	0.67	0.73	0.60	0.51	0.1870
0.56	0.68	0.73	0.61	0.51	0.1867
0.55	0.67	0.72	0.60	0.51	0.1628
0.56	0.67	0.72	0.60	0.51	0.1615
0.55	0.66	0.72	0.60	0.51	0.1529
0.55	0.66	0.71	0.54	0.51	0.1406
0.55	0.66	0.71	0.59	0.51	0.1306
0.55	0.65	0.70	0.59	0.51	0.1202
0.55	0.64	0.70	0.58	0.51	0.1095
0.54	0.63	0.69	0.57	0.51	0.0988
0.53	0.62	0.67	0.56	0.50	0.0881
0.53	0.61	0.65	0.55	0.50	0.0773
0.52	0.59	0.64	0.54	0.50	0.0668
0.51	0.56	0.61	0.53	0.50	0.0421
0.50	0.54	0.58	0.52	0.49	0.0449
0.50	0.53	0.56	0.51	0.49	0.0337
0.49	0.51	0.54	0.51	0.49	0.0227
0.49	0.51	0.53	0.51	0.49	0.0153
0.49	0.51	0.52	0.51	0.51	-0.0010

MINIMUM PSI = -0.0010
AVERAGE PSI = 0.1666
MAXIMUM PSI = 0.3335

Heated Test Case $Gr^{+}=10^{4}$, C=1.0

Velocities

#1	#2	#3	#4	#5	
1.9498	2.0121	2.0543	2.1805	2.0312	2.0304
1.9873	2.0708	2.0708	2.2366	2.0822	2.0187
2.0250	2.1303	2.0869	2.2932	2.1342	2.0903
2.2650	2.4203	2.3287	2.5941	2.5552	2.4713
2.6199	2.6402	2.7158	2.9828	2.9890	2.8386
2.7034	2.8070	2.8575	2.8510	2.6925	2.4280
2.7498	2.8451	2.8629	2.9783	2.8830	2.6412
2.7963	2.8841	2.8688	3.1094	3.0835	2.8688
2.9817	3.1441	3.0278	3.2400	3.1798	2.9356
3.0238	3.1331	3.1517	3.2483	3.1459	2.8408
3.2192	3.3551	3.3588	3.4577	3.3521	3.0300
3.3180	3.4434	3.4627	3.5359	3.4260	3.0686
3.4191	3.5327	3.5684	3.6154	3.5011	3.1065
3.5391	3.6713	3.7107	3.7233	3.6264	3.1499
3.5999	3.7266	3.8533	3.6115	3.4297	2.8177
3.6550	3.7472	3.8323	3.7825	3.6798	3.1517
3.6668	3.7785	3.8928	3.7028	3.5531	2.9054
3.6818	3.7818	3.8539	3.7939	3.6897	3.0979
3.7009	3.8060	3.9065	3.7645	3.6361	2.9678
3.7088	3.8167	3.8750	3.8053	3.6989	3.0442
3.7107	3.8161	3.9024	3.8006	3.6785	2.9934
3.7187	3.8323	3.9003	3.8147	3.6943	2.9890
3.7279	3.8472	3.9257	3.8235	3.6897	2.9500
3.7207	3.8255	3.9285	3.7972	3.6648	2.9119
3.7134	3.8033	3.9305	3.7705	3.6394	2.8737
3.6910	3.7966	3.9106	3.7286	3.5935	2.7985
3.7002	3.8066	3.8771	3.8040	3.6923	2.9273
3.6681	3.7892	3.8900	3.6871	3.5480	2.7086
3.6329	3.7505	3.8791	3.6420	3.4709	2.6280
3.5980	3.7121	3.8675	3.5973	3.3950	2.5497
3.5340	3.6753	3.8140	3.5219	3.3090	2.4640
3.4709	3.6387	3.7611	3.4471	3.2246	2.3819
3.3363	3.5131	3.6805	3.2800	2.9789	2.1342
3.1227	3.3784	3.5646	3.1007	2.6878	1.8658
2.9043	3.2281	3.4583	2.9098	2.3315	1.5940
2.6796	3.1059	3.3283	2.7341	2.1161	1.4179
2.4781	3.0120	3.2603	2.6269	2.0104	1.3400
2.3702	2.9273	3.1575	2.5324	1.9759	1.3514
2.3181	2.8456	3.1019	2.4912	1.9632	1.3631
2.2645	2.8139	3.0464	2.4553	1.9600	1.3730
2.2307	2.7725	3.0447	2.4399	1.9596	1.3958
2.2348	2.7566	2.9711	2.4222	1.9604	1.4097
2.2115	2.7148	2.9616	2.4137	1.9640	1.4336
2.2222	2.7236	2.9356	2.4008	1.9653	1.4342

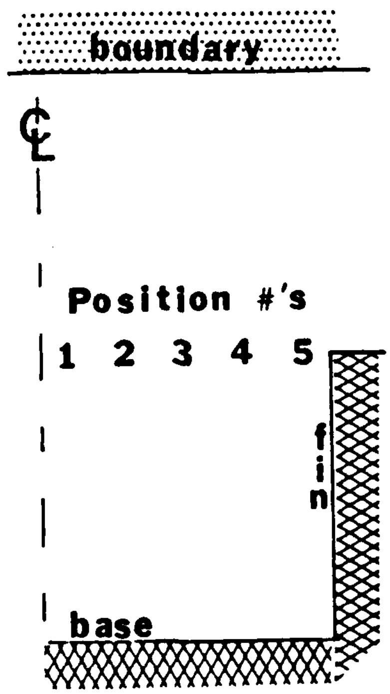
2.2031	2.6956	2.9306	2.3933	1.9689	1.4748
2.2155	2.7044	2.9114	2.3895	1.9702	1.4824
2.1933	2.6827	2.9158	2.3928	1.9746	1.5176
2.2106	2.6796	2.8933	2.3862	1.9759	1.5445
2.1933	2.6626	2.9004	2.3852	1.9796	1.5602
2.2022	2.6698	2.8781	2.3754	1.9816	1.5951
2.1955	2.6504	2.8629	2.3650	1.9878	1.6160
2.1907	2.6601	2.8705	2.3829	1.9861	1.6153
2.1814	2.6402	2.8461	2.3650	1.9915	1.6672
2.1885	2.6335	2.8343	2.3580	1.9931	1.6712
2.1761	2.6092	2.8198	2.3547	1.9976	1.6922
2.1796	2.6007	2.8081	2.1174	1.9980	1.7170
2.1568	2.5761	2.7947	2.3236	2.0005	1.7392
2.1612	2.5527	2.7630	2.3015	1.9980	1.7578
2.1433	2.5191	2.7404	2.2878	1.9968	1.7781
2.1273	2.4839	2.6946	2.2582	1.9906	1.7941
2.0963	2.4313	2.6397	2.2204	1.9832	1.8085
2.0759	2.3824	2.5686	2.1735	1.9734	1.8208
2.0400	2.3006	2.5063	2.1320	1.9628	1.8316
2.0080	2.2106	2.4051	2.0788	1.9519	1.8697
1.9775	2.1377	2.2983	2.0354	1.9409	1.8537
1.9559	2.0678	2.1924	2.0047	1.9325	1.8674
1.9381	2.0171	2.1113	1.9857	1.9265	1.8827
1.9301	1.9931	2.0653	1.9939	1.9389	1.9093
1.9385	1.9985	2.0577	2.0146	2.0059	2.0080

MINIMUM VELOCITY = 1.9265
AVERAGE VELOCITY = 2.8549
MAXIMUM VELOCITY = 3.9305

APPENDIX E

LAMINAR HOT WIRE DATA FOR $Gr^{+}=10^{6}$ WITH C=0.0, C=0.4, AND C=1.0.

The following pages contain the data as listed above in the following format: (1) the original voltage readings, (2) the streamline patterns, and (3) the calculated velocities. The readings were taken in accordance with the diagram below. The second position, #5, is taken with the hot wire rotated 90 degrees, as shown in Figure 3.4, Page 49.



Heated Test Case $Gr^{+}=10^{6}$, C=0.0

Original Voltage Readings

#1	#2	#3	#4	#5	#5
2.3757	2.3653	2.3692	2.3714	2.3751	2.3751
2.3793	2.3679	2.3768	2.3751	2.3821	2.3748
2.3949	2.3755	2.3873	2.3822	2.3874	2.3727
2.4125	2.3973	2.4130	2.3858	2.3966	2.3745
2.4428	2.4349	2.4689	2.4054	2.4076	2.3779
2.4798	2.5156	2.5472	2.4421	2.4175	2.3803
2.5020	2.5770	2.6135	2.4798	2.4267	2.3818
2.5291	2.6327	2.6587	2.5269	2.4346	2.3820
2.5379	2.6724	2.6932	2.5637	2.4426	2.3823
2.5526	2.6982	2.7176	2.5848	2.4456	2.3776
2.5515	2.7143	2.7384	2.6079	2.4476	2.3717
2.5609	2.7332	2.7471	2.6154	2.4463	2.3627
2.5586	2.7380	2.7588	2.6280	2.4439	2.3525
2.5655	2.7486	2.7645	2.6286	2.4400	2.3408
2.5622	2.7509	2.7669	2.6330	2.4377	2.3332
2.5589	2.7532	2.7693	2.6373	2.4353	2.3255
2.5620	2.7559	2.7703	2.6355	2.4322	2.2109
2.5651	2.7585	2.7713	2.6336	2.4291	2.2084
2.5612	2.7587	2.7733	2.6370	2.3680	2.1452
2.5573	2.7588	2.7751	2.6403	2.3068	2.0820
2.5624	2.7620	2.7747	2.6357	2.4194	2.1979
2.5598	2.7604	2.7748	2.6379	2.3631	2.1543
2.5586	2.7618	2.7749	2.6386	2.4163	2.2044
2.5547	2.7615	2.7771	2.6415	2.4154	2.2080
2.5591	2.7634	2.7773	2.6352	2.4101	2.2107
2.5492	2.7609	2.7766	2.6383	2.4065	2.2150
2.5523	2.7617	2.7780	2.6321	2.4026	2.2189
2.5441	2.7600	2.7727	2.6366	2.4012	2.2253
2.5510	2.7588	2.7721	2.6297	2.3981	2.2300
2.5421	2.7554	2.7714	2.6327	2.3980	2.2376
2.5358	2.7462	2.7614	2.6280	2.3987	2.2506
2.5215	2.7342	2.7503	2.6168	2.4021	2.3661
2.4867	2.7069	2.7202	2.6013	2.4009	2.3769
2.4235	2.6654	2.6629	2.5628	2.3901	2.2899
2.3898	2.5689	2.5763	2.4848	2.3820	2.3817

Heated Test Case $Gr^{+}=10^{6}$, C=0.0

Streamlines

#1	#2	#3	#4	#5	
0.47	0.46	0.47	0.47	0.47	0.0000
0.48	0.47	0.47	0.47	0.48	0.0147
0.49	0.47	0.49	0.48	0.49	0.0294
0.51	0.49	0.51	0.48	0.49	0.0438
0.54	0.53	0.57	0.50	0.51	0.0582
0.58	0.62	0.66	0.54	0.52	0.0721
0.61	0.70	0.75	0.58	0.52	0.0862
0.64	0.78	0.81	0.64	0.53	0.1000
0.65	0.83	0.86	0.68	0.54	0.1136
0.67	0.87	0.90	0.71	0.54	0.1271
0.67	0.90	0.93	0.74	0.55	0.1409
0.68	0.93	0.95	0.75	0.55	0.1544
0.68	0.93	0.97	0.77	0.54	0.1681
0.69	0.95	0.98	0.77	0.54	0.1816
0.68	0.95	0.98	0.78	0.54	0.1908
0.68	0.96	0.99	0.78	0.53	0.1999
0.68	0.96	0.99	0.78	0.53	0.3708
0.68	0.97	0.99	0.78	0.53	0.3704
0.68	0.97	0.99	0.78	0.47	0.3828
0.67	0.97	1.00	0.79	0.41	0.3956
0.68	0.97	0.99	0.78	0.52	0.3730
0.68	0.97	0.99	0.78	0.46	0.3634
0.68	0.97	0.99	0.78	0.51	0.3599
0.67	0.97	1.00	0.79	0.51	0.3536
0.68	0.98	1.00	0.78	0.51	0.3428
0.66	0.97	1.00	0.78	0.50	0.3317
0.67	0.97	1.00	0.77	0.50	0.3206
0.66	0.97	0.99	0.78	0.50	0.3090
0.67	0.97	0.99	0.77	0.50	0.2975
0.66	0.96	0.99	0.78	0.50	0.2856
0.65	0.95	0.97	0.77	0.50	0.2661
0.63	0.93	0.95	0.75	0.50	0.0704
0.59	0.88	0.91	0.73	0.50	0.0474
0.52	0.82	0.82	0.68	0.49	0.1875
0.49	0.69	0.70	0.59	0.48	0.0006

MINIMUM PSI = 0.0000
AVERAGE PSI = 0.2031
MAXIMUM PSI = 0.3956

Heated Test Case $Gr^{+}=10^{6}$, C=0.0

Velocities

#1	#2	#3	#4	#5	
2.1169	2.0725	2.0891	2.0985	2.1143	2.1143
2.1325	2.0835	2.1217	2.1143	2.1446	2.1130
2.2009	2.1161	2.1673	2.1451	2.1678	2.1040
2.2800	2.2115	2.2823	2.1608	2.2084	2.1118
2.4213	2.3838	2.5482	2.2478	2.2578	2.1264
2.6027	2.7878	2.9594	2.4179	2.3029	2.1368
2.7164	3.1285	3.3454	2.6027	2.3454	2.1433
2.8602	3.4640	3.6296	2.8483	2.3824	2.1442
2.9081	3.7193	3.8587	3.0521	2.4203	2.1455
2.9895	3.8928	4.0272	3.1739	2.4347	2.1251
2.9834	4.0041	4.1752	3.3114	2.4443	2.0997
3.0362	4.1378	4.2384	3.3570	2.4380	2.0615
3.0232	4.1723	4.3244	3.4347	2.4265	2.0187
3.0624	4.2493	4.3668	3.4384	2.4080	1.9706
3.0436	4.2662	4.3847	3.4659	2.3970	1.9397
3.0249	4.2831	4.4027	3.4929	2.3857	1.9089
3.0425	4.3030	4.4103	3.4815	2.3711	1.4919
3.0601	4.3222	4.4178	3.4696	2.3566	1.4837
3.0379	4.3237	4.4329	3.4910	2.0839	1.2863
3.0159	4.3244	4.4465	3.5118	1.8355	1.1093
3.0447	4.3482	4.4434	3.4828	2.3116	1.4494
3.0300	4.3363	4.4442	3.4966	2.0632	1.3134
3.0232	4.3467	4.4450	3.5011	2.2974	1.4705
3.0013	4.3445	4.4616	3.5194	2.2932	1.4824
3.0261	4.3586	4.4631	3.4797	2.2691	1.4913
2.9705	4.3400	4.4578	3.4992	2.2528	1.5055
2.9878	4.3459	4.4685	3.4602	2.2352	1.5186
2.9422	4.3333	4.4283	3.4885	2.2290	1.5401
2.9806	4.3244	4.4238	3.4452	2.2151	1.5561
2.9312	4.2993	4.4185	3.4640	2.2146	1.5822
2.8966	4.2318	4.3437	3.4347	2.2178	1.6276
2.8193	4.1450	4.2618	3.3655	2.2330	2.0759
2.6376	3.9526	4.0455	3.2716	2.2276	2.1221
2.3306	3.6733	3.6570	3.0470	2.1796	1.7710
2.1783	3.0818	3.1244	2.6280	2.1442	2.1429

MINIMUM VELOCITY = 1.8355
AVERAGE VELOCITY = 3.1816
MAXIMUM VELOCITY = 4.4685

Heated Test Case $Gr^{+}=10^{6}$, C=0.4

Original Voltage Readings

#1	#2	#3	#4	#5	#5
2.3210	2.3386	2.3510	2.3780	2.3408	2.3406
2.3303	2.3526	2.3549	2.3906	2.3529	2.3368
2.3539	2.3483	2.3568	2.3544	2.3533	2.3508
2.3393	2.3665	2.3587	2.4032	2.3651	2.3520
2.3575	2.3509	2.3645	2.3580	2.3603	2.3472
2.3523	2.3604	2.3655	2.3640	2.3567	2.3485
2.3639	2.3704	2.3687	2.3698	2.3630	2.3536
2.3615	2.3696	2.3725	2.4096	2.3617	2.3671
2.3730	2.3584	2.3750	2.3651	2.3656	2.3336
2.3915	2.3928	2.3772	2.3779	2.3673	2.3467
2.3801	2.3980	2.3803	2.4351	2.4063	2.3788
2.4398	2.4367	2.3965	2.3858	2.3795	2.3565
2.3906	2.3802	2.4008	2.3687	2.3747	2.3237
2.4363	2.4627	2.4355	2.4987	2.4985	2.4581
2.4208	2.4177	2.4566	2.3883	2.3857	2.3214
2.5116	2.5079	2.5151	2.5730	2.5821	2.5285
2.4577	2.4985	2.5352	2.4249	2.3956	2.2837
2.3680	2.5517	2.5641	2.4676	2.3602	2.2841
2.5808	2.6017	2.5732	2.6181	2.6160	2.5195
2.4798	2.5597	2.6014	2.4627	2.4047	2.2120
2.6228	2.6375	2.6301	2.6545	2.6453	2.4744
2.5068	2.6153	2.6466	2.5097	2.4126	2.2180
2.4016	2.6481	2.6508	2.5456	2.3683	2.1288
2.6564	2.6664	2.6639	2.6796	2.6696	2.5027
2.5156	2.6551	2.6811	2.5465	2.4206	2.2269
2.6757	2.6883	2.6861	2.6963	2.6896	2.5191
2.6940	2.7000	2.7045	2.7053	2.6979	2.5285
2.5302	2.6807	2.7056	2.5674	2.4236	2.2309
2.4646	2.6895	2.7082	2.5840	2.3790	2.2331
2.7023	2.7104	2.7108	2.7087	2.7009	2.5300
2.7053	2.7149	2.7183	2.7114	2.6994	2.5249
2.7030	2.7084	2.7190	2.7035	2.6917	2.5196
2.6961	2.7064	2.7130	2.6907	2.6771	2.5000
2.6852	2.6946	2.7097	2.6766	2.6524	2.4769
2.6648	2.6832	2.6938	2.6528	2.6237	2.4506
2.6426	2.6632	2.6813	2.6249	2.5803	2.4008
2.6060	2.6414	2.6633	2.5941	2.5251	2.3403
2.4595	2.5627	2.5960	2.4860	2.3681	2.1928
2.4295	2.5307	2.5629	2.4630	2.3641	2.2084
2.4251	2.5205	2.5519	2.4561	2.3667	2.2281
2.4221	2.5137	2.5458	2.4531	2.3694	2.2588
2.4061	2.5142	2.5628	2.4451	2.3243	2.1301
2.3826	2.4895	2.5381	2.4290	2.3245	2.1534
2.3785	2.4833	2.5298	2.4245	2.3271	2.1800

2.3785	2.4794	2.5269	2.4229	2.3283	2.1936
2.3790	2.4770	2.5200	2.4186	2.3304	2.2107
2.3758	2.4750	2.5169	2.4186	2.3312	2.2260
2.3746	2.4689	2.5120	2.4164	2.3327	2.2339
2.3702	2.4624	2.5073	2.4098	2.3335	2.2477
2.3562	2.4327	2.4774	2.3870	2.3292	2.2670
2.3278	2.3682	2.4067	2.3442	2.3188	2.2797
2.3182	2.3353	2.3518	2.3392	2.3348	2.3190

Heated Test Case $Gr^{+}=10^{6}$, C=0.4

Streamlines

#1	#2	#3	#4	#5	
0.47	0.49	0.50	0.53	0.49	0.0004
0.48	0.50	0.50	0.54	0.50	0.0327
0.50	0.50	0.50	0.50	0.50	0.0051
0.49	0.51	0.51	0.55	0.51	0.0265
0.51	0.50	0.51	0.51	0.51	0.0266
0.50	0.51	0.51	0.51	0.50	0.0167
0.51	0.52	0.52	0.52	0.51	0.0191
0.51	0.52	0.52	0.56	0.53	0.0293
0.52	0.51	0.52	0.51	0.51	0.0638
0.54	0.54	0.53	0.53	0.52	0.0414
0.53	0.55	0.53	0.59	0.56	0.0540
0.60	0.59	0.55	0.54	0.53	0.0459
0.54	0.53	0.55	0.52	0.52	0.0998
0.59	0.62	0.59	0.67	0.67	0.0753
0.57	0.57	0.62	0.54	0.54	0.1239
0.69	0.68	0.69	0.77	0.78	0.0954
0.62	0.67	0.72	0.58	0.55	0.2070
0.52	0.74	0.76	0.63	0.51	0.1471
0.78	0.81	0.77	0.84	0.83	0.1643
0.64	0.75	0.81	0.62	0.56	0.3337
0.84	0.87	0.85	0.89	0.88	0.2732
0.68	0.83	0.88	0.68	0.56	0.3354
0.55	0.88	0.89	0.73	0.52	0.4061
0.90	0.91	0.91	0.93	0.92	0.2650
0.69	0.89	0.94	0.73	0.57	0.3330
0.93	0.95	0.94	0.96	0.95	0.2681
0.96	0.97	0.97	0.98	0.96	0.2657
0.71	0.93	0.98	0.76	0.58	0.3311
0.63	0.95	0.98	0.79	0.53	0.2649
0.97	0.99	0.99	0.98	0.97	0.2675
0.98	0.99	1.00	0.99	0.97	0.2726
0.97	0.98	1.00	0.97	0.95	0.2701
0.96	0.98	0.99	0.95	0.93	0.2785
0.94	0.96	0.98	0.93	0.89	0.2789
0.91	0.94	0.96	0.89	0.84	0.2786
0.87	0.91	0.94	0.85	0.78	0.2924
0.82	0.87	0.91	0.80	0.70	0.3065
0.62	0.75	0.80	0.65	0.52	0.3125
0.58	0.71	0.75	0.62	0.51	0.2823
0.58	0.70	0.74	0.62	0.51	0.2544
0.58	0.69	0.73	0.61	0.52	0.2072
0.56	0.69	0.75	0.60	0.47	0.3476
0.53	0.66	0.72	0.58	0.47	0.3119
0.53	0.65	0.71	0.58	0.47	0.2730

0.53	0.64	0.71	0.58	0.48	0.2523
0.53	0.64	0.70	0.57	0.48	0.2267
0.52	0.64	0.69	0.57	0.48	0.2015
0.52	0.63	0.69	0.57	0.48	0.1900
0.52	0.62	0.68	0.56	0.48	0.1667
0.50	0.59	0.64	0.54	0.48	0.1234
0.48	0.52	0.56	0.49	0.47	0.0794
0.47	0.48	0.50	0.49	0.48	0.0324

MINIMUM PSI = 0.0004
AVERAGE PSI = 0.1896
MAXIMUM PSI = 0.4061

Heated Test Case $Gr^{+}=10^{6}$, C=0.0

Velocities

#1	#2	#3	#4	#5	
1.8910	1.9616	2.0125	2.1268	1.9706	1.9697
1.9281	2.0192	2.0287	2.1818	2.0204	1.9543
2.0246	2.0013	2.0367	2.0267	2.0221	2.0117
1.9644	2.0776	2.0446	2.2379	2.0716	2.0167
2.0396	2.0121	2.0691	2.0417	2.0514	1.9968
2.0179	2.0518	2.0733	2.0670	2.0363	2.0022
2.0665	2.0942	2.0869	2.0916	2.0627	2.0233
2.0564	2.0908	2.1032	2.2668	2.1429	2.0801
2.1053	2.0434	2.1139	2.0716	2.0737	1.9413
2.1858	2.1916	2.1234	2.1264	2.0810	1.9947
2.1359	2.2146	2.1368	2.3848	2.2519	2.1303
2.4070	2.3923	2.2080	2.1608	2.1333	2.0354
2.1818	2.1364	2.2272	2.0869	2.1126	1.9017
2.3904	2.5176	2.3867	2.6992	2.6982	2.4951
2.3181	2.3038	2.4878	2.1717	2.1603	1.8926
2.7667	2.7472	2.7852	3.1053	3.1581	2.8569
2.4931	2.6982	2.8933	2.3370	2.2040	1.7478
2.0839	2.9845	3.0544	2.5418	2.0509	1.7493
3.1505	3.2740	3.1065	3.3735	3.3606	2.8086
2.6027	3.0295	3.2722	2.5176	2.2447	1.4956
3.4024	3.4941	3.4477	3.6025	3.5435	2.5756
2.7414	3.3564	3.5518	2.7566	2.2805	1.5155
2.2307	3.5614	3.5787	2.9505	2.0852	1.2385
3.6148	3.6798	3.6635	3.7671	3.7009	2.7200
2.7878	3.6064	3.7771	2.9555	2.3171	1.5456
3.7412	3.8255	3.8107	3.8798	3.8343	2.8065
3.8641	3.9051	3.9361	3.9416	3.8907	2.8569
2.8661	3.7745	3.9437	3.0732	2.3310	1.5592
2.5270	3.8336	3.9616	3.1692	2.1312	1.5667
3.9209	3.9769	3.9797	3.9651	3.9113	2.8651
3.9416	4.0083	4.0321	3.9839	3.9010	2.8375
3.9257	3.9630	4.0370	3.9292	3.8485	2.8091
3.8784	3.9492	3.9950	3.8417	3.7505	2.7060
3.8046	3.8682	3.9720	3.7472	3.5890	2.5881
3.6694	3.7912	3.8628	3.5915	3.4080	2.4587
3.5264	3.6589	3.7785	3.4154	3.1476	2.2272
3.2999	3.5188	3.6596	3.2287	2.8386	1.9685
2.5019	3.0464	3.2400	2.6341	2.0844	1.4330
2.3585	2.8688	3.0476	2.5191	2.0674	1.4837
2.3380	2.8139	2.9856	2.4853	2.0784	1.5496
2.3241	2.7778	2.9516	2.4708	2.0899	1.6568
2.2510	2.7804	3.0470	2.4323	1.9041	1.2422
2.1468	2.6519	2.9092	2.3561	1.9049	1.3107
2.1290	2.6204	2.8640	2.3352	1.9153	1.3923

2.1290	2.6007	2.8483	2.3278	1.9201	1.4355
2.1312	2.5886	2.8113	2.3079	1.9285	1.4913
2.1174	2.5786	2.7947	2.3079	1.9317	1.5425
2.1122	2.5482	2.7688	2.2978	1.9377	1.5695
2.0933	2.5161	2.7440	2.2677	1.9409	1.6174
2.0342	2.3735	2.5906	2.1660	1.9237	1.6864
1.9180	2.0848	2.2537	1.9845	1.8823	1.7329
1.8800	1.9482	2.0158	1.9640	1.9462	1.8831

MINIMUM VELOCITY = 1.8800
AVERAGE VELOCITY = 2.7256
MAXIMUM VELOCITY = 4.0370

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Original Voltage Readings

#1	#2	#3	#4	#5	#5
2.3060	2.3086	2.3115	2.3086	2.3060	2.3058
2.3424	2.3450	2.3480	2.3450	2.3424	2.3253
2.3760	2.3787	2.3817	2.3787	2.3760	2.3610
2.4034	2.4060	2.4091	2.4060	2.4034	2.3872
2.4525	2.4553	2.4584	2.4553	2.4525	2.4462
2.4531	2.4559	2.4590	2.4559	2.4531	2.4399
2.4608	2.4636	2.4667	2.4636	2.4608	2.4454
2.4608	2.4636	2.4667	2.4636	2.4608	2.4393
2.5434	2.5463	2.5495	2.5463	2.5434	2.5015
2.5545	2.5573	2.5606	2.5573	2.5545	2.5238
2.5656	2.5684	2.5717	2.5684	2.5656	2.5269
2.5864	2.5893	2.5926	2.5893	2.5864	2.5511
2.5985	2.6014	2.6047	2.6014	2.5985	2.5313
2.6031	2.6060	2.6093	2.6060	2.6031	2.5491
2.6205	2.6235	2.6268	2.6235	2.6205	2.5364
2.6272	2.6301	2.6335	2.6301	2.6272	2.5536
2.6323	2.6352	2.6386	2.6352	2.6323	2.4936
2.6377	2.6406	2.6440	2.6406	2.6377	2.5353
2.6404	2.6433	2.6467	2.6433	2.6404	2.6239
2.6452	2.6481	2.6515	2.6481	2.6452	2.4140
2.6473	2.6502	2.6536	2.6502	2.6473	2.4150
2.6481	2.6510	2.6544	2.6510	2.6481	2.4128
2.6485	2.6514	2.6548	2.6514	2.6485	2.3576
2.6493	2.6522	2.6556	2.6522	2.6493	2.4621
2.6496	2.6525	2.6559	2.6525	2.6496	2.4124
2.6514	2.6543	2.6577	2.6543	2.6514	2.4599
2.6522	2.6551	2.6585	2.6551	2.6522	2.4611
2.6537	2.6566	2.6600	2.6566	2.6537	2.4143
2.6542	2.6571	2.6605	2.6571	2.6542	2.4613
2.6570	2.6600	2.6634	2.6600	2.6570	2.4616
2.6590	2.6620	2.6654	2.6620	2.6590	2.4588
2.6567	2.6597	2.6631	2.6597	2.6567	2.4575
2.6564	2.6594	2.6628	2.6594	2.6564	2.4526
2.6559	2.6589	2.6623	2.6589	2.6559	2.4530
2.6532	2.6561	2.6595	2.6561	2.6532	2.4513
2.6537	2.6566	2.6600	2.6566	2.6537	2.4527
2.6528	2.6557	2.6591	2.6557	2.6528	2.4526
2.6517	2.6546	2.6580	2.6546	2.6517	2.4527
2.6507	2.6536	2.6570	2.6536	2.6507	2.4526
2.6507	2.6536	2.6570	2.6536	2.6507	2.4536
2.6491	2.6520	2.6554	2.6520	2.6491	2.4531
2.6473	2.6502	2.6536	2.6502	2.6473	2.4524
2.6463	2.6492	2.6526	2.6492	2.6463	2.4525
2.6452	2.6481	2.6515	2.6481	2.6452	2.4524

2.6429	2.6458	2.6492	2.6458	2.6429	2.4512
2.6460	2.6489	2.6523	2.6489	2.6460	2.4551
2.6406	2.6435	2.6469	2.6435	2.6406	2.4509
2.6352	2.6381	2.6415	2.6381	2.6352	2.4468
2.6249	2.6278	2.6312	2.6278	2.6249	2.4382
2.6242	2.6271	2.6305	2.6271	2.6242	2.4324
2.6156	2.6186	2.6219	2.6186	2.6156	2.4254
2.6037	2.6066	2.6099	2.6066	2.6037	2.4156
2.5958	2.5987	2.6020	2.5987	2.5958	2.3995
2.5871	2.5900	2.5933	2.5900	2.5871	2.3829
2.5708	2.5736	2.5769	2.5736	2.5708	2.3661
2.5397	2.5426	2.5458	2.5426	2.5397	2.3592
2.4972	2.5000	2.5032	2.5000	2.4972	2.3389
2.4871	2.4898	2.4930	2.4898	2.4871	2.3598
2.4587	2.4615	2.4646	2.4615	2.4587	2.2430
2.4330	2.4357	2.4388	2.4357	2.4330	2.2448
2.3814	2.3841	2.3871	2.3841	2.3814	2.2229
2.3583	2.3609	2.3639	2.3609	2.3583	2.2148
2.3050	2.3076	2.3105	2.3076	2.3050	2.1805
2.2804	2.2829	2.2858	2.2829	2.2804	2.1724
2.2702	2.2727	2.2756	2.2727	2.2702	2.1699
2.2602	2.2627	2.2656	2.2627	2.2602	2.1740
2.2510	2.2536	2.2564	2.2536	2.2510	2.1890

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Streamlines

#1	#2	#3	#4	#5	
0.50	0.50	0.50	0.50	0.50	0.0004
0.54	0.54	0.54	0.54	0.54	0.0349
0.58	0.58	0.58	0.58	0.58	0.0302
0.61	0.61	0.62	0.61	0.61	0.0321
0.67	0.68	0.68	0.68	0.67	0.0123
0.67	0.68	0.68	0.68	0.67	0.0256
0.68	0.69	0.69	0.69	0.68	0.0297
0.68	0.69	0.69	0.69	0.68	0.0413
0.80	0.80	0.81	0.80	0.80	0.0764
0.82	0.82	0.83	0.82	0.82	0.0562
0.83	0.84	0.84	0.84	0.83	0.0701
0.87	0.87	0.88	0.87	0.87	0.0635
0.89	0.89	0.90	0.89	0.89	0.1176
0.89	0.90	0.90	0.90	0.89	0.0952
0.92	0.93	0.93	0.93	0.92	0.1441
0.93	0.94	0.94	0.94	0.93	0.1267
0.94	0.95	0.95	0.95	0.94	0.2278
0.95	0.96	0.96	0.96	0.95	0.1721
0.96	0.96	0.97	0.96	0.96	0.0294
0.96	0.97	0.98	0.97	0.96	0.3545
0.97	0.97	0.98	0.97	0.97	0.3557
0.97	0.97	0.98	0.97	0.97	0.3594
0.97	0.98	0.98	0.98	0.97	0.4276
0.97	0.98	0.98	0.98	0.97	0.2954
0.97	0.98	0.98	0.98	0.97	0.3616
0.98	0.98	0.99	0.98	0.98	0.3011
0.98	0.98	0.99	0.98	0.98	0.3005
0.98	0.98	0.99	0.98	0.98	0.3639
0.98	0.99	0.99	0.99	0.98	0.3027
0.99	0.99	1.00	0.99	0.99	0.3058
0.99	0.99	1.00	0.99	0.99	0.3120
0.98	0.99	1.00	0.99	0.98	0.3109
0.98	0.99	1.00	0.99	0.98	0.3171
0.98	0.99	0.99	0.99	0.98	0.3160
0.98	0.98	0.99	0.98	0.98	0.3150
0.98	0.98	0.99	0.98	0.98	0.3137
0.98	0.98	0.99	0.98	0.98	0.3127
0.98	0.98	0.99	0.98	0.98	0.3112
0.97	0.98	0.99	0.98	0.97	0.3101
0.97	0.98	0.99	0.98	0.97	0.3088
0.97	0.98	0.98	0.98	0.97	0.3075
0.97	0.97	0.98	0.97	0.97	0.3062
0.97	0.97	0.98	0.97	0.97	0.3048
0.96	0.97	0.98	0.97	0.96	0.3036

0.96	0.97	0.97	0.97	0.96	0.3023
0.97	0.97	0.98	0.97	0.97	0.3009
0.96	0.96	0.97	0.96	0.96	0.2998
0.95	0.95	0.96	0.95	0.95	0.2987
0.93	0.93	0.94	0.93	0.93	0.2975
0.93	0.93	0.94	0.93	0.93	0.3046
0.91	0.92	0.92	0.92	0.91	0.3034
0.89	0.90	0.90	0.90	0.89	0.3018
0.88	0.89	0.89	0.89	0.88	0.3141
0.87	0.87	0.88	0.87	0.87	0.3261
0.84	0.85	0.85	0.85	0.84	0.3288
0.79	0.80	0.80	0.80	0.79	0.2986
0.73	0.74	0.74	0.74	0.73	0.2707
0.72	0.72	0.73	0.72	0.72	0.2237
0.68	0.68	0.69	0.68	0.68	0.3591
0.65	0.65	0.65	0.65	0.65	0.3232
0.58	0.59	0.59	0.59	0.58	0.2846
0.56	0.56	0.56	0.56	0.56	0.2634
0.50	0.50	0.50	0.50	0.50	0.2377
0.47	0.47	0.48	0.47	0.47	0.2114
0.46	0.46	0.47	0.46	0.46	0.1985
0.45	0.45	0.46	0.45	0.45	0.1734
0.44	0.45	0.45	0.45	0.44	0.1278

MINIMUM PSI = 0.0004
AVERAGE PSI = 0.2360
MAXIMUM PSI = 0.4276

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Velocities

#1	#2	#3	#4	#5	
1.8324	1.8424	1.8537	1.8424	1.8324	1.8316
1.9771	1.9878	2.0001	1.9878	1.9771	1.9081
2.1182	2.1299	2.1429	2.1299	2.1182	2.0543
2.2388	2.2505	2.2645	2.2505	2.2388	2.1669
2.4679	2.4815	2.4966	2.4815	2.4679	2.4375
2.4708	2.4844	2.4995	2.4844	2.4708	2.4075
2.5083	2.5220	2.5373	2.5220	2.5083	2.4337
2.5083	2.5220	2.5373	2.5220	2.5083	2.4046
2.9384	2.9544	2.9722	2.9544	2.9384	2.7138
3.0002	3.0159	3.0345	3.0159	3.0002	2.8316
3.0629	3.0789	3.0979	3.0789	3.0629	2.8483
3.1833	3.2003	3.2198	3.2003	3.1833	2.9811
3.2549	3.2722	3.2921	3.2722	3.2549	2.8721
3.2824	3.2999	3.3199	3.2999	3.2824	2.9700
3.3883	3.4068	3.4272	3.4068	3.3883	2.8999
3.4297	3.4477	3.4690	3.4477	3.4297	2.9951
3.4615	3.4797	3.5011	3.4797	3.4615	2.6729
3.4954	3.5137	3.5353	3.5137	3.4954	2.8939
3.5124	3.5308	3.5525	3.5308	3.5124	3.4092
3.5429	3.5614	3.5832	3.5614	3.5429	2.2868
3.5563	3.5748	3.5967	3.5748	3.5563	2.2914
3.5614	3.5800	3.6018	3.5800	3.5614	2.2814
3.5640	3.5825	3.6044	3.5825	3.5640	2.0400
3.5691	3.5877	3.6096	3.5877	3.5691	2.5147
3.5710	3.5896	3.6115	3.5896	3.5710	2.2795
3.5825	3.6012	3.6232	3.6012	3.5825	2.5039
3.5877	3.6064	3.6284	3.6064	3.5877	2.5098
3.5973	3.6160	3.6381	3.6160	3.5973	2.2882
3.6006	3.6193	3.6413	3.6193	3.6006	2.5107
3.6186	3.6381	3.6602	3.6381	3.6186	2.5122
3.6316	3.6511	3.6733	3.6511	3.6316	2.4985
3.6167	3.6361	3.6583	3.6361	3.6167	2.4922
3.6148	3.6342	3.6563	3.6342	3.6148	2.4684
3.6115	3.6309	3.6531	3.6309	3.6115	2.4703
3.5941	3.6128	3.6348	3.6128	3.5941	2.4621
3.5973	3.6160	3.6381	3.6160	3.5973	2.4688
3.5915	3.6102	3.6322	3.6102	3.5915	2.4684
3.5845	3.6031	3.6251	3.6031	3.5845	2.4688
3.5780	3.5967	3.6186	3.5967	3.5780	2.4684
3.5780	3.5967	3.6186	3.5967	3.5780	2.4732
3.5678	3.5864	3.6083	3.5864	3.5678	2.4708
3.5563	3.5748	3.5967	3.5748	3.5563	2.4674
3.5499	3.5684	3.5903	3.5684	3.5499	2.4679
3.5429	3.5614	3.5832	3.5614	3.5429	2.4674

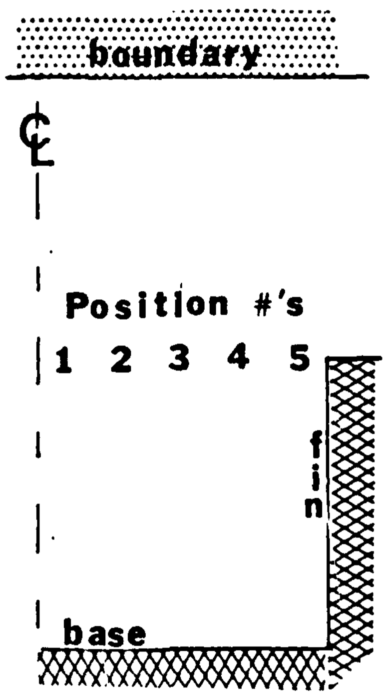
3.5283	3.5467	3.5684	3.5467	3.5283	2.4616
3.5480	3.5665	3.5883	3.5665	3.5480	2.4805
3.5137	3.5321	3.5537	3.5321	3.5137	2.4601
3.4797	3.4979	3.5194	3.4979	3.4797	2.4404
3.4154	3.4334	3.4546	3.4334	3.4154	2.3994
3.4111	3.4291	3.4502	3.4291	3.4111	2.3721
3.3582	3.3766	3.3969	3.3766	3.3582	2.3394
3.2860	3.3035	3.3235	3.3035	3.2860	2.2942
3.2388	3.2561	3.2758	3.2561	3.2388	2.2213
3.1874	3.2045	3.2240	3.2045	3.1874	2.1481
3.0927	3.1088	3.1279	3.1088	3.0927	2.0759
2.9180	2.9339	2.9516	2.9339	2.9180	2.0467
2.6915	2.7060	2.7226	2.7060	2.6915	1.9628
2.6397	2.6534	2.6698	2.6534	2.6397	2.0493
2.4980	2.5117	2.5270	2.5117	2.4980	1.6010
2.3749	2.3876	2.4023	2.3876	2.3749	1.6073
2.1416	2.1533	2.1665	2.1533	2.1416	1.5320
2.0430	2.0539	2.0665	2.0539	2.0430	1.5049
1.8285	1.8386	1.8498	1.8386	1.8285	1.3939
1.7355	1.7448	1.7556	1.7448	1.7355	1.3686
1.6980	1.7071	1.7178	1.7071	1.6980	1.3609
1.6618	1.6708	1.6813	1.6708	1.6618	1.3736
1.6291	1.6383	1.6482	1.6383	1.6291	1.4208

MINIMUM VELOCITY = 1.6291
AVERAGE VELOCITY = 3.0973
MAXIMUM VELOCITY = 3.6733

APPENDIX F

TURBULENT HOT WIRE DATA FOR $Gr^{+}=10^{4}$ WITH C=0.0, C=0.4, AND C=1.0.

The following pages contain the data as listed above in the following format: (1) the original voltage readings, (2) the streamline patterns, and (3) the calculated velocities. The readings were taken in accordance with the diagram below. The second position, #5, is taken with the hot wire rotated 90 degrees, as shown in Figure 3.4, Page 49.



Heated Test Case $Gr^{+}=10^{4}$, $C=0.0$

Original Voltage Readings

#1	#2	#3	#4	#5	#5
3.3550	3.3518	3.3686	3.3589	3.3578	3.3447
3.3590	3.3703	3.3766	3.4102	3.3790	3.3645
3.3704	3.3593	3.3791	3.3659	3.3630	3.3312
3.3774	3.3986	3.3844	3.4355	3.4035	3.3761
3.4368	3.4371	3.4005	3.3865	3.3768	3.3540
3.3879	3.3809	3.4048	3.3694	3.3721	3.3214
3.4333	3.4630	3.439[illegible]	3.4988	3.4951	3.4550
3.4179	3.4183	3.4604	3.3890	3.3830	3.3191
3.5081	3.5080	3.5187	3.5727	3.5782	3.5250
3.4546	3.4986	3.5387	3.4254	3.3928	3.2816
3.3654	3.5516	3.5675	3.4678	3.3577	3.2820
3.5769	3.6014	3.5765	3.6177	3.6119	3.5160
3.4765	3.5596	3.6047	3.4630	3.4019	3.2103
3.6187	3.6370	3.6333	3.6539	3.6410	3.4712
3.5034	3.6149	3.6496	3.5098	3.4097	3.2163
3.3988	3.6475	3.6538	3.5455	3.3657	3.1278
3.6521	3.6658	3.6669	3.6788	3.6653	3.4993
3.5121	3.6545	3.6841	3.5464	3.4177	3.2252
3.6714	3.6875	3.6890	3.6955	3.6851	3.5156
3.6895	3.6992	3.7074	3.7045	3.6934	3.5249
3.5267	3.6800	3.7085	3.5673	3.4207	3.2292
3.4614	3.6887	3.7111	3.5837	3.3763	3.2314
3.6978	3.7096	3.7137	3.7079	3.6964	3.5265
3.7008	3.7141	3.7212	3.7106	3.6949	3.5214
3.6985	3.7076	3.7219	3.7027	3.6872	3.5161
3.6916	3.7056	3.7159	3.6899	3.6727	3.4966
3.6807	3.6938	3.7126	3.6759	3.6481	3.4736
3.6605	3.6824	3.6967	3.6522	3.6196	3.4475
3.6384	3.6626	3.6843	3.6244	3.5764	3.3980
3.6020	3.6409	3.6663	3.5938	3.5216	3.3379
3.4564	3.5626	3.5993	3.4862	3.3655	3.1913
3.4265	3.5306	3.5663	3.4633	3.3616	3.2069
3.4222	3.5205	3.5553	3.4565	3.3641	3.2264
3.4192	3.5138	3.5492	3.4535	3.3668	3.2569
3.3159	3.3362	3.3560	3.3401	3.3324	3.3167

Heated Test Case $Gr^{+}=10^{4}$, C=0.0

Streamlines

#1	#2	#3	#4	#5	
0.62	0.62	0.63	0.62	0.62	0.0179
0.62	0.63	0.64	0.67	0.64	0.0197
0.63	0.62	0.64	0.63	0.63	0.0431
0.64	0.66	0.65	0.69	0.66	0.0367
0.69	0.69	0.66	0.65	0.64	0.0309
0.65	0.64	0.66	0.63	0.63	0.0678
0.69	0.72	0.70	0.75	0.75	0.0519
0.68	0.68	0.71	0.65	0.64	0.0845
0.76	0.76	0.77	0.83	0.83	0.0667
0.71	0.75	0.79	0.68	0.65	0.1431
0.63	0.81	0.82	0.72	0.62	0.1003
0.83	0.86	0.83	0.88	0.87	0.1167
0.73	0.81	0.86	0.72	0.66	0.2358
0.88	0.90	0.90	0.92	0.90	0.1976
0.76	0.87	0.91	0.76	0.67	0.2372
0.66	0.91	0.92	0.80	0.63	0.2886
0.92	0.93	0.93	0.95	0.93	0.1923
0.77	0.92	0.95	0.80	0.67	0.2357
0.94	0.96	0.96	0.97	0.96	0.1950
0.96	0.97	0.98	0.98	0.97	0.1935
0.78	0.95	0.98	0.82	0.68	0.2344
0.72	0.96	0.99	0.84	0.64	0.1841
0.97	0.98	0.99	0.98	0.97	0.1948
0.97	0.99	1.00	0.99	0.97	0.1987
0.97	0.98	1.00	0.98	0.96	0.1966
0.96	0.98	0.99	0.96	0.94	0.2026
0.95	0.97	0.99	0.94	0.91	0.2023
0.93	0.95	0.97	0.92	0.88	0.2013
0.90	0.93	0.95	0.89	0.83	0.2104
0.86	0.90	0.93	0.85	0.78	0.2194
0.71	0.82	0.86	0.74	0.63	0.2186
0.68	0.78	0.82	0.72	0.63	0.1964
0.68	0.77	0.81	0.71	0.63	0.1762
0.68	0.77	0.80	0.71	0.63	0.1426
0.59	0.60	0.62	0.61	0.60	0.0217

MINIMUM PSI = 0.0179
AVERAGE PSI = 0.1530
MAXIMUM PSI = 0.2886

Heated Test Case $Gr^{+}=10^{4}$, C=0.0

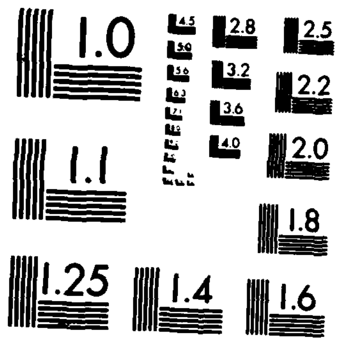
Velocities

#1	#2	#3	#4	#5	
10.7962	10.7486	11.0004	10.8545	10.8380	10.6435
10.8560	11.0261	11.1219	11.6433	11.1585	10.9385
11.0276	10.8604	11.1600	10.9596	10.9160	10.4459
11.1341	11.4612	11.2413	12.0482	11.5379	11.1142
12.0692	12.0741	11.4909	11.2736	11.1249	10.7813
11.2952	11.1876	11.5583	11.0125	11.0534	10.3042
12.0125	12.5004	12.1115	13.1084	13.0445	12.3675
11.7654	11.7718	12.4571	11.3122	11.2198	10.2712
13.2700	13.2683	13.4560	14.4351	14.5378	13.5675
12.3609	13.1049	13.8125	11.8853	11.3710	9.7439
10.9521	14.0463	14.3385	12.5806	10.8365	9.7494
14.5135	14.9772	14.5060	15.2919	15.1794	13.4085
12.7270	14.1927	15.0405	12.5004	11.5128	8.7986
15.3114	15.6711	15.5979	16.0091	15.7506	12.6377
13.1881	15.2375	15.9226	13.2997	11.6354	8.8754
11.4643	15.8804	16.0070	13.9353	10.9566	7.7943
15.9728	16.2504	16.2728	16.5171	16.2402	13.1171
13.3400	16.0212	16.6269	13.9517	11.7622	8.9901
16.3649	16.6975	16.7288	16.8648	16.6476	13.4014
16.7392	16.9425	17.1159	17.0544	16.8207	13.5658
13.5978	16.5419	17.1392	14.3348	11.8100	9.0420
12.4737	16.7225	17.1945	14.6410	11.1173	9.0707
16.9131	17.1626	17.2500	17.1265	16.8836	13.5942
16.9762	17.2585	17.4107	17.1839	16.8522	13.5038
16.9278	17.1201	17.4257	17.0163	16.6913	13.4102
16.7831	17.0777	17.2970	16.7476	16.3915	13.0704
16.5564	16.8291	17.2265	16.4574	15.8925	12.6781
16.1425	16.5916	16.8899	15.9748	15.3290	12.2439
15.6989	16.1852	16.6310	15.4228	14.5041	11.4519
14.9887	15.7486	16.2605	14.8321	13.5073	10.5436
12.3907	14.2479	14.9370	12.8919	10.9536	8.5590
11.9029	13.6673	14.3163	12.5054	10.8949	8.7554
11.8340	13.4878	14.1138	12.3923	10.9325	9.0057
11.7861	13.3698	14.0025	12.3427	10.9732	9.4080
10.2254	10.5188	10.8111	10.5759	10.4634	10.2368

MINIMUM VELOCITY = 10.2254
AVERAGE VELOCITY = 13.9405
MAXIMUM VELOCITY = 17.4257

AD-A174 138 FORCED CONVECTION HEAT TRANSFER FROM A FINNED ARRAY 3/3
WITH AN ADJUSTABLE OUTER CHANNEL BOUNDARY(U) NAVAL
POSTGRADUATE SCHOOL MONTEREY CA T L MELLON JUN 86

UNCLASSIFIED F/G 20/13 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Heated Test Case $Gr^{+}=10^{4}$, C=0.4

Original Voltage Readings

#1	#2	#3	#4	#5	#5
3.3087	3.3328	3.3518	3.3719	3.3284	3.3282
3.3179	3.3468	3.3557	3.3845	3.3403	3.3226
3.3413	3.3425	3.3576	3.3486	3.3407	3.3345
3.3269	3.3606	3.3595	3.3970	3.3524	3.3339
3.3449	3.3451	3.3652	3.3522	3.3477	3.3271
3.3398	3.3546	3.3662	3.3581	3.3441	3.3266
3.3512	3.3644	3.3694	3.3638	3.3503	3.3297
3.3489	3.3636	3.3732	3.4034	3.3689	3.3412
3.3603	3.3526	3.3757	3.3592	3.3529	3.3061
3.3785	3.3867	3.3779	3.3718	3.3546	3.3172
3.3673	3.3918	3.3810	3.4286	3.3933	3.3470
3.4265	3.4302	3.3971	3.3797	3.3667	3.3232
3.3777	3.3741	3.4014	3.3627	3.3620	3.2887
3.4230	3.4561	3.4360	3.4918	3.4846	3.4201
3.4076	3.4115	3.4569	3.3822	3.3729	3.2826
3.4976	3.5010	3.5152	3.5656	3.5675	3.4861
3.4442	3.4916	3.5352	3.4185	3.3826	3.2727
3.3553	3.5445	3.5639	3.4609	3.3476	3.1756
3.5662	3.5942	3.5729	3.6105	3.6011	3.4107
3.4661	3.5525	3.6011	3.4561	3.3917	3.2073
3.6078	3.6297	3.6297	3.6466	3.6301	3.3699
3.4929	3.6077	3.6460	3.5028	3.3995	3.2171
3.3886	3.6402	3.6501	3.5384	3.3556	3.1307
3.6411	3.6585	3.6632	3.6714	3.6543	3.4037
3.5016	3.6472	3.6804	3.5393	3.4074	3.2316
3.6604	3.6801	3.6853	3.6881	3.6740	3.4237
3.6784	3.6918	3.7037	3.6971	3.6823	3.4348
3.5161	3.6726	3.7048	3.5602	3.4104	3.2413
3.4510	3.6813	3.7074	3.5765	3.3662	3.1459
3.6867	3.7022	3.7100	3.7005	3.6853	3.4421
3.6897	3.7067	3.7175	3.7032	3.6838	3.4389
3.6874	3.7002	3.7182	3.6953	3.6761	3.4356
3.6805	3.6982	3.7122	3.6825	3.6617	3.4179
3.6697	3.6864	3.7089	3.6685	3.6372	3.3970
3.6495	3.6750	3.6930	3.6449	3.6087	3.3728
3.6275	3.6553	3.6806	3.6172	3.5657	3.3254
3.5912	3.6336	3.6626	3.5866	3.5110	3.2673
3.4460	3.5555	3.5957	3.4792	3.3554	3.1231
3.4162	3.5235	3.5627	3.4564	3.3515	3.1405
3.4119	3.5135	3.5517	3.4496	3.3540	3.1619
3.4089	3.5068	3.5457	3.4466	3.3567	3.1941
3.3931	3.5073	3.5626	3.4386	3.3120	3.0687
3.3698	3.4827	3.5381	3.4225	3.3122	3.0935
3.3657	3.4765	3.5298	3.4181	3.3148	3.1218

3.3657	3.4726	3.5270	3.4166	3.3160	3.1371
3.3662	3.4702	3.5201	3.4123	3.3180	3.1560
3.3630	3.4682	3.5170	3.4123	3.3189	3.1730
3.3619	3.4622	3.5121	3.4102	3.3204	3.1828
3.3575	3.4558	3.5074	3.4036	3.3211	3.1982
3.3436	3.4262	3.4776	3.3809	3.3169	3.2194
3.3155	3.3622	3.4073	3.3384	3.3066	3.2337
3.3060	3.3295	3.3526	3.3334	3.3224	3.2746

Heated Test Case $Gr^{+}=10^{4}$, C=0.4

Streamlines

#1	#2	#3	#4	#5	
0.58	0.60	0.62	0.64	0.60	0.0003
0.59	0.62	0.62	0.65	0.61	0.0243
0.61	0.61	0.62	0.62	0.61	0.0086
0.60	0.63	0.63	0.66	0.62	0.0253
0.61	0.61	0.63	0.62	0.62	0.0282
0.61	0.62	0.63	0.63	0.61	0.0240
0.62	0.63	0.63	0.63	0.62	0.0282
0.62	0.63	0.64	0.67	0.63	0.0375
0.63	0.62	0.64	0.63	0.62	0.0631
0.64	0.65	0.64	0.64	0.62	0.0506
0.63	0.65	0.65	0.69	0.66	0.0616
0.69	0.69	0.66	0.64	0.63	0.0585
0.64	0.64	0.66	0.63	0.63	0.0971
0.68	0.71	0.70	0.75	0.74	0.0827
0.67	0.67	0.71	0.65	0.64	0.1182
0.75	0.76	0.77	0.82	0.83	0.1010
0.70	0.75	0.79	0.68	0.65	0.1420
0.62	0.80	0.82	0.72	0.62	0.2172
0.83	0.86	0.83	0.87	0.86	0.2218
0.72	0.81	0.86	0.71	0.65	0.2284
0.87	0.90	0.90	0.91	0.90	0.2906
0.75	0.87	0.91	0.76	0.66	0.2257
0.65	0.91	0.92	0.80	0.62	0.2755
0.91	0.93	0.93	0.94	0.92	0.2795
0.76	0.92	0.95	0.80	0.67	0.2178
0.93	0.95	0.96	0.96	0.95	0.2778
0.95	0.97	0.98	0.97	0.96	0.2744
0.77	0.94	0.98	0.82	0.67	0.2100
0.71	0.96	0.99	0.84	0.63	0.2697
0.96	0.98	0.99	0.98	0.96	0.2700
0.97	0.99	1.00	0.98	0.96	0.2718
0.96	0.98	1.00	0.97	0.95	0.2680
0.95	0.98	0.99	0.96	0.93	0.2723
0.94	0.96	0.99	0.94	0.90	0.2704
0.92	0.95	0.97	0.91	0.87	0.2681
0.89	0.92	0.95	0.88	0.82	0.2757
0.85	0.90	0.93	0.85	0.77	0.2832
0.70	0.81	0.86	0.74	0.62	0.2835
0.68	0.78	0.82	0.71	0.62	0.2607
0.67	0.77	0.81	0.71	0.62	0.2396
0.67	0.76	0.80	0.71	0.62	0.2058
0.66	0.76	0.82	0.70	0.59	0.2988
0.64	0.74	0.80	0.68	0.59	0.2722
0.63	0.73	0.79	0.68	0.59	0.2434

0.63	0.73	0.78	0.68	0.59	0.2272
0.63	0.73	0.78	0.67	0.59	0.2075
0.63	0.73	0.77	0.67	0.59	0.1885
0.63	0.72	0.77	0.67	0.59	0.1785
0.62	0.71	0.76	0.67	0.59	0.1606
0.61	0.69	0.73	0.64	0.59	0.1293
0.59	0.63	0.67	0.61	0.58	0.0983
0.58	0.60	0.62	0.60	0.59	0.0650

MINIMUM PSI = 0.0003
AVERAGE PSI = 0.1765
MAXIMUM PSI = 0.2988

Heated Test Case $Gr^{+}=10^{4}$, C=0.4

Velocities

#1	#2	#3	#4	#5	
10.1228	10.4692	10.7486	11.0504	10.4053	10.4024
10.2540	10.6745	10.8067	11.2428	10.5788	10.3215
10.5935	10.6111	10.8350	10.7011	10.5847	10.4940
10.3835	10.8799	10.8634	11.4363	10.7575	10.4852
10.6465	10.6494	10.9491	10.7545	10.6878	10.3864
10.5715	10.7902	10.9641	10.8425	10.6347	10.3792
10.7397	10.9370	11.0125	10.9280	10.7263	10.4241
10.7056	10.9250	11.0701	11.5363	11.0049	10.5920
10.8754	10.7605	11.1082	10.8589	10.7649	10.0860
11.1509	11.2767	11.1417	11.0489	10.7902	10.2439
10.9807	11.3555	11.1891	11.9367	11.3788	10.6775
11.9029	11.9625	11.4378	11.1692	10.9717	10.3301
11.1386	11.0838	11.5050	10.9115	10.9009	9.8421
11.8468	12.3857	12.0563	12.9878	12.8646	11.8005
11.6023	11.6639	12.3989	11.2075	11.0656	9.7577
13.0877	13.1465	13.3944	14.3033	14.3385	12.8902
12.1898	12.9843	13.7496	11.7750	11.2136	9.6218
10.8007	13.9172	14.2719	12.4654	10.6863	8.3648
14.3144	14.8397	14.4388	15.1523	14.9714	11.6512
12.5521	14.0627	14.9714	12.3857	11.3539	8.7605
15.1001	15.5269	15.5269	15.8624	15.5347	11.0201
13.0067	15.0982	15.8504	13.1777	11.4753	8.8856
11.3060	15.7347	15.9326	13.8071	10.8052	7.8280
15.7526	16.1020	16.1974	16.3649	16.0171	11.5410
13.1569	15.8744	16.5502	13.8233	11.5992	9.0733
16.1405	16.5440	16.6518	16.7100	16.4182	11.8580
16.5089	16.7873	17.0375	16.8984	16.5895	12.0368
13.4102	16.3895	17.0608	14.2037	11.6465	9.2005
12.3015	16.5688	17.1159	14.5060	10.9641	8.0067
16.6809	17.0058	17.1711	16.9699	16.6518	12.1555
16.7434	17.1010	17.3312	17.0269	16.6206	12.1034
16.6954	16.9636	17.3462	16.8606	16.4614	12.0498
16.5523	16.9215	17.2180	16.5937	16.1669	11.7654
16.3300	16.6747	17.1477	16.3055	15.6751	11.4363
15.9205	16.4388	16.8124	15.8284	15.1175	11.0640
15.4836	16.0373	16.5543	15.2822	14.3052	10.3619
14.7828	15.6038	16.1852	14.6957	13.3207	9.5483
12.2193	14.1175	14.8683	12.7728	10.8022	7.7398
11.7384	13.5410	14.2498	12.3907	10.7441	7.9429
11.6702	13.3645	14.0481	12.2784	10.7813	8.1981
11.6228	13.2473	13.9390	12.2292	10.8216	8.5940
11.3756	13.2560	14.2479	12.0985	10.1697	7.1305
11.0185	12.8322	13.8017	11.8388	10.1726	7.4036
10.9566	12.7270	13.6530	11.7686	10.2096	7.7248

10.9566	12.6612	13.6031	11.7447	10.2268	7.9029
10.9641	12.6209	13.4808	11.6765	10.2554	8.1271
10.9160	12.5873	13.4261	11.6765	10.2683	8.3330
10.8994	12.4870	13.3400	11.6433	10.2899	8.4535
10.8335	12.3807	13.2578	11.5394	10.2999	8.6455
10.6273	11.8981	12.7457	11.1876	10.2397	8.9152
10.2196	10.9039	11.5976	10.5510	10.0930	9.1007
10.0845	10.4212	10.7605	10.4779	10.3186	9.6478

MINIMUM VELOCITY = 10.0845
AVERAGE VELOCITY = 12.9886
MAXIMUM VELOCITY = 17.3462

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Original Voltage Readings

#1	#2	#3	#4	#5	#5
3.3157	3.3375	3.3542	3.3767	3.3354	3.3352
3.3249	3.3515	3.3581	3.3893	3.3474	3.3306
3.3339	3.3653	3.3619	3.4018	3.3595	3.3455
3.3888	3.4288	3.4163	3.4642	3.4495	3.4269
3.4623	3.4732	3.4949	3.5372	3.5312	3.4964
3.4785	3.5052	3.5216	3.5133	3.4764	3.4142
3.4874	3.5122	3.5226	3.5364	3.5121	3.4551
3.4961	3.5193	3.5237	3.5595	3.5478	3.4963
3.5299	3.5654	3.5522	3.5816	3.5643	3.5065
3.5374	3.5635	3.5738	3.5830	3.5586	3.4874
3.5710	3.6007	3.6085	3.6172	3.5930	3.5195
3.5874	3.6149	3.6253	3.6295	3.6049	3.5244
3.6038	3.6290	3.6420	3.6419	3.6168	3.5290
3.6228	3.6505	3.6637	3.6584	3.6363	3.5347
3.6322	3.6589	3.6850	3.6413	3.6055	3.4735
3.6406	3.6619	3.6819	3.6672	3.6444	3.5312
3.6424	3.6666	3.6908	3.6553	3.6250	3.4858
3.6447	3.6671	3.6851	3.6688	3.6459	3.5181
3.6476	3.6706	3.6928	3.6645	3.6378	3.4933
3.6488	3.6722	3.6882	3.6705	3.6473	3.5049
3.6491	3.6721	3.6922	3.6698	3.6442	3.4940
3.6503	3.6745	3.6919	3.6719	3.6466	3.4914
3.6517	3.6767	3.6956	3.6732	3.6459	3.4825
3.6506	3.6735	3.6960	3.6693	3.6421	3.4738
3.6495	3.6702	3.6963	3.6654	3.6383	3.4648
3.6461	3.6692	3.6934	3.6592	3.6312	3.4491
3.6475	3.6707	3.6885	3.6703	3.6463	3.4708
3.6426	3.6681	3.6904	3.6529	3.6242	3.4283
3.6373	3.6624	3.6888	3.6460	3.6120	3.4107
3.6319	3.6567	3.6871	3.6391	3.5999	3.3934
3.6220	3.6511	3.6792	3.6273	3.5859	3.3740
3.6120	3.6455	3.6713	3.6155	3.5719	3.3551
3.5904	3.6259	3.6591	3.5883	3.5294	3.2987
3.5546	3.6045	3.6414	3.5580	3.4755	3.2284
3.5160	3.5796	3.6246	3.5240	3.4032	3.1570
3.4739	3.5589	3.6035	3.4914	3.3553	3.1064
3.4339	3.5424	3.5922	3.4706	3.3304	3.0833
3.4114	3.5272	3.5748	3.4519	3.3221	3.0890
3.4003	3.5123	3.5652	3.4435	3.3190	3.0946
3.3887	3.5065	3.5555	3.4361	3.3182	3.0998
3.3812	3.4987	3.5552	3.4329	3.3181	3.1089
3.3821	3.4957	3.5423	3.4292	3.3183	3.1152
3.3769	3.4877	3.5406	3.4274	3.3192	3.1244
3.3793	3.4894	3.5359	3.4247	3.3195	3.1266

3.3750	3.4840	3.5350	3.4231	3.3204	3.1409
3,3778	3.4857	3.5315	3.4223	3.3207	3.1452
3.3729	3.4815	3.5323	3.4230	3.3218	3.1575
3.3767	3.4809	3.5282	3.4216	3.3221	3.1674
3.3729	3.4776	3.5295	3.4214	3.3230	3.1738
3.3748	3.4790	3.5254	3.4193	3.3235	3.1859
3.3733	3.4752	3.5226	3.4172	3.3250	3.1937
3.3723	3.4771	3.5240	3.4209	3.3246	3.1955
3.3702	3.4732	3.5195	3.4172	3.3259	3.2117
3.3718	3.4719	3.5173	3.4157	3.3263	3.2148
3.3690	3.4672	3.5146	3.4150	3.3274	3.2224
3.3698	3.4655	3.5124	3.3623	3.3275	3.2312
3.3646	3.4607	3.5099	3.4084	3.3281	3.2390
3.3656	3.4560	3.5039	3.4036	3.3275	3.2459
3.3616	3.4492	3.4996	3.4006	3.3272	3.2531
3.3579	3.4420	3.4908	3.3941	3.3257	3.2592
3.3507	3.4311	3.4801	3.3857	3.3239	3.2648
3.3459	3.4208	3.4660	3.3751	3.3215	3.2700
3.3375	3.4034	3.4534	3.3657	3.3189	3.2746
3.3299	3.3835	3.4326	3.3534	3.3162	3.2864
3.3225	3.3670	3.4097	3.3431	3.3135	3.2841
3.3172	3.3508	3.3862	3.3357	3.3114	3.2896
3.3128	3.3387	3.3676	3.3311	3.3099	3.2952
3.3108	3.3329	3.3568	3.3331	3.3130	3.3039
3.3129	3.3342	3.3550	3.3381	3.3294	3.3299
3.3793	3.4894	3.5359	3.4247	3.3195	3.1266
3.3750	3.4840	3.5350	3.4231	3.3204	3.1409
3.3778	3.4857	3.5315	3.4223	3.3207	3.1452
3.3729	3.4815	3.5323	3.4230	3.3218	3.1575
3.3767	3.4809	3.5282	3.4216	3.3221	3.1674
3.3793	3.4894	3.5359	3.4247	3.3195	3.1266
3.3750	3.4840	3.5350	3.4231	3.3204	3.1409
3.3778	3.4857	3.5315	3.4223	3.3207	3.1452
3.3729	3.4815	3.5323	3.4230	3.3218	3.1575
3.3767	3.4809	3.5282	3.4216	3.3221	3.1674

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Streamlines

#1	#2	#3	#4	#5	
0.61	0.62	0.64	0.66	0.62	0.0003
0.61	0.64	0.64	0.67	0.63	0.0230
0.62	0.65	0.65	0.68	0.64	0.0192
0.67	0.71	0.70	0.74	0.73	0.0299
0.74	0.75	0.77	0.82	0.81	0.0447
0.76	0.78	0.80	0.79	0.75	0.0801
0.76	0.79	0.80	0.82	0.79	0.0728
0.77	0.80	0.80	0.84	0.83	0.0652
0.81	0.85	0.83	0.86	0.85	0.0726
0.82	0.84	0.86	0.87	0.84	0.0890
0.85	0.89	0.90	0.91	0.88	0.0909
0.87	0.90	0.91	0.92	0.89	0.0989
0.89	0.92	0.93	0.93	0.90	0.1071
0.91	0.94	0.96	0.95	0.93	0.1224
0.92	0.95	0.99	0.93	0.89	0.1580
0.93	0.96	0.98	0.96	0.94	0.1353
0.93	0.96	0.99	0.95	0.91	0.1652
0.94	0.96	0.99	0.97	0.94	0.1516
0.94	0.97	1.00	0.96	0.93	0.1704
0.94	0.97	0.99	0.97	0.94	0.1677
0.94	0.97	0.99	0.97	0.94	0.1763
0.94	0.97	0.99	0.97	0.94	0.1817
0.95	0.98	1.00	0.97	0.94	0.1905
0.94	0.97	1.00	0.97	0.93	0.1960
0.94	0.97	1.00	0.96	0.93	0.2017
0.94	0.97	1.00	0.95	0.92	0.2112
0.94	0.97	0.99	0.97	0.94	0.2034
0.93	0.97	0.99	0.95	0.91	0.2261
0.93	0.96	0.99	0.94	0.90	0.2325
0.92	0.95	0.99	0.93	0.89	0.2387
0.91	0.94	0.98	0.92	0.87	0.2452
0.90	0.94	0.97	0.90	0.85	0.2512
0.87	0.92	0.95	0.87	0.81	0.2685
0.84	0.89	0.93	0.84	0.75	0.2894
0.79	0.86	0.91	0.80	0.68	0.2943
0.75	0.84	0.89	0.77	0.64	0.3011
0.71	0.82	0.88	0.75	0.62	0.3013
0.69	0.81	0.86	0.73	0.61	0.2871
0.68	0.79	0.85	0.72	0.61	0.2779
0.67	0.78	0.84	0.71	0.61	0.2714
0.66	0.78	0.84	0.71	0.61	0.2613
0.66	0.77	0.82	0.71	0.61	0.2545
0.66	0.77	0.82	0.71	0.61	0.2451
0.66	0.77	0.82	0.70	0.61	0.2429

0.66	0.76	0.81	0.70	0.61	0.2276
0.66	0.76	0.81	0.70	0.61	0.2230
0.66	0.76	0.81	0.70	0.61	0.2100
0.66	0.76	0.81	0.70	0.61	0.1987
0.66	0.76	0.81	0.70	0.61	0.1922
0.66	0.76	0.80	0.70	0.61	0.1783
0.66	0.75	0.80	0.70	0.61	0.1706
0.65	0.75	0.80	0.70	0.61	0.1680
0.65	0.75	0.80	0.70	0.61	0.1497
0.65	0.75	0.80	0.69	0.61	0.1464
0.65	0.74	0.79	0.69	0.62	0.1383
0.65	0.74	0.79	0.65	0.62	0.1274
0.65	0.74	0.79	0.69	0.62	0.1183
0.65	0.73	0.78	0.68	0.62	0.1088
0.65	0.73	0.78	0.68	0.62	0.0992
0.64	0.72	0.77	0.67	0.61	0.0895
0.64	0.71	0.76	0.67	0.61	0.0799
0.63	0.70	0.74	0.66	0.61	0.0699
0.62	0.68	0.73	0.65	0.61	0.0604
0.62	0.67	0.71	0.64	0.61	0.0410
0.61	0.65	0.69	0.63	0.60	0.0405
0.61	0.64	0.67	0.62	0.60	0.0302
0.60	0.63	0.65	0.62	0.60	0.0204
0.60	0.62	0.64	0.62	0.60	0.0127
0.60	0.62	0.64	0.62	0.62	-0.0007

MINIMUM PSI = -0.0007
AVERAGE PSI = 0.1538
MAXIMUM PSI = 0.3013

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Velocities

#1	#2	#3	#4	#5	
10.2225	10.5378	10.7843	11.1234	10.5071	10.5042
10.3547	10.7441	10.8425	11.3168	10.6834	10.4372
10.4852	10.9506	10.8994	11.5112	10.8634	10.6553
11.3091	11.9399	11.7400	12.5204	12.2768	11.9094
12.4887	12.6714	13.0411	13.7855	13.6780	13.0669
12.7609	13.2195	13.5073	13.3610	12.7254	11.7066
12.9124	13.3417	13.5250	13.7711	13.3400	12.3691
13.0618	13.4666	13.5445	14.1909	13.9771	13.0652
13.6548	14.2996	14.0572	14.6016	14.2793	13.2421
13.7891	14.2646	14.4556	14.6279	14.1744	12.9124
14.4035	14.9638	15.1136	15.2822	14.8169	13.4702
14.7108	15.2375	15.4404	15.5229	15.0443	13.5569
15.0232	15.5131	15.7705	15.7685	15.2744	13.6387
15.3914	15.9406	16.2076	16.1000	15.6573	13.7407
15.5762	16.1101	16.6456	15.7566	15.0559	12.6764
15.7427	16.1710	16.5812	16.2789	15.8184	13.6780
15.7785	16.2667	16.7663	16.0373	15.4345	12.8850
15.8244	16.2769	16.6476	16.3116	15.8484	13.4455
15.8825	16.3485	16.8082	16.2239	15.6870	13.0136
15.9065	16.3813	16.7121	16.3464	15.8764	13.2142
15.9125	16.3792	16.7956	16.3321	15.8144	13.0256
15.9366	16.4285	16.7894	16.3751	15.8624	12.9809
15.9648	16.4738	16.8668	16.4018	15.8484	12.8288
15.9427	16.4080	16.8753	16.3219	15.7725	12.6815
15.9205	16.3403	16.8815	16.2422	15.6969	12.5304
15.8524	16.3198	16.8207	16.1162	15.5564	12.2702
15.8804	16.3505	16.7184	16.3423	15.8564	12.6310
15.7825	16.2973	16.7580	15.9889	15.4188	11.9319
15.6771	16.1811	16.7246	15.8504	15.1813	11.6512
15.5702	16.0656	16.6892	15.7128	14.9485	11.3803
15.3758	15.9527	16.5254	15.4797	14.6825	11.0823
15.1813	15.8404	16.3628	15.2491	14.4202	10.7977
14.7676	15.4522	16.1142	14.7278	13.6459	9.9817
14.1010	15.0366	15.7586	14.1633	12.7102	9.0316
13.4085	14.5640	15.4267	13.5498	11.5332	8.1391
12.6832	14.1799	15.0175	12.9809	10.8007	7.5487
12.0222	13.8793	14.8017	12.6276	10.4343	7.2903
11.6623	13.6067	14.4742	12.3163	10.3143	7.3534
11.4878	13.3435	14.2959	12.1784	10.2698	7.4158
11.3075	13.2421	14.1175	12.0579	10.2583	7.4742
11.1922	13.1067	14.1120	12.0061	10.2568	7.5771
11.2060	13.0549	13.8774	11.9464	10.2597	7.6490
11.1264	12.9175	13.8467	11.9174	10.2726	7.7549
11.1631	12.9466	13.7622	11.8740	10.2769	7.7803

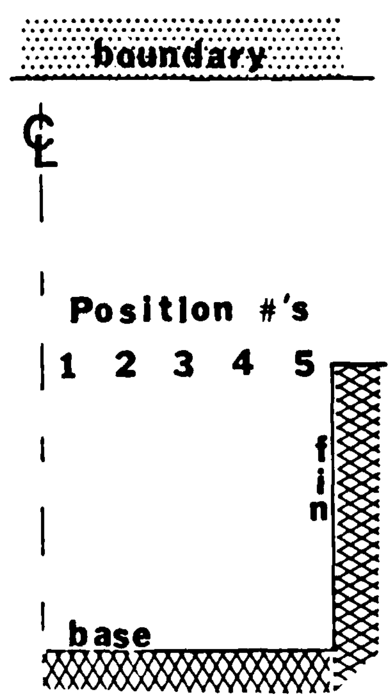
11.0975	12.8544	13.7460	11.8484	10.2899	7.9476
11.1402	12.8833	13.6834	11.8356	10.2942	7.9984
11.0656	12.8118	13.6977	11.8468	10.3100	8.1452
11.1234	12.8016	13.6245	11.8244	10.3143	8.2648
11.0656	12.7457	13.6477	11.8212	10.3273	8.3428
11.0944	12.7694	13.5747	11.7877	10.3345	8.4919
11.0716	12.7051	13.5250	11.7543	10.3561	8.5890
11.0564	12.7372	13.5498	11.8133	10.3503	8.6116
11.0246	12.6714	13.4702	11.7543	10.3691	8.8165
11.0489	12.6495	13.4314	11.7304	10.3749	8.8561
11.0064	12.5706	13.3838	11.7193	10.3908	8.9539
11.0185	12.5421	13.3452	10.9054	10.3923	9.0681
10.9400	12.4621	13.3014	11.6149	10.4009	9.1703
10.9551	12.3841	13.1968	11.5394	10.3923	9.2614
10.8949	12.2718	13.1223	11.4925	10.3879	9.3572
10.8395	12.1539	12.9706	11.3912	10.3662	9.4389
10.7323	11.9770	12.7880	11.2613	10.3402	9.5145
10.6612	11.8117	12.5505	11.0990	10.3057	9.5850
10.5378	11.5363	12.3410	10.9566	10.2683	9.6478
10.4270	11.2275	12.0012	10.7724	10.2296	9.8102
10.3201	10.9762	11.6354	10.6200	10.1911	9.7784
10.2439	10.7337	11.2690	10.5115	10.1612	9.8546
10.1811	10.5553	10.9853	10.4445	10.1398	9.9327
10.1526	10.4706	10.8231	10.4736	10.1840	10.0549
10.1825	10.4896	10.7962	10.5466	10.4198	10.4270

MINIMUM VELOCITY = 10.1398
AVERAGE VELOCITY = 13.2941
MAXIMUM VELOCITY = 16.8815

APPENDIX G

TURBULENT HOT WIRE DATA FOR $Gr^{+}=10^{6}$ WITH C=0.0, C=0.4, AND C=1.0

The following pages contain the data as listed above in the following format: (1) the original voltage readings, (2) the streamline patterns, and (3) the calculated velocities. The readings were taken in accordance with the diagram below. The second position, #5, is taken with the hot wire rotated 90 degrees, as shown in Figure 3.4, Page 49.



Heated Test Case $Gr^{+}=10^{6}$, C=0.0

Original Voltage Readings

#1	#2	#3	#4	#5	#5
3.5149	3.5188	3.5227	3.5181	3.5142	3.5003
3.5166	3.5205	3.5244	3.5198	3.5159	3.5006
3.5210	3.5249	3.5288	3.5242	3.5203	3.4865
3.5239	3.5279	3.5318	3.5272	3.5233	3.4946
3.5319	3.5359	3.5398	3.5352	3.5313	3.5071
3.5415	3.5455	3.5494	3.5448	3.5408	3.4870
3.5516	3.5555	3.5595	3.5549	3.5509	3.5097
3.5551	3.5590	3.5630	3.5584	3.5544	3.4864
3.5575	3.5614	3.5654	3.5608	3.5568	3.5033
3.5597	3.5636	3.5676	3.5630	3.5590	3.4411
3.5602	3.5641	3.5681	3.5635	3.5595	3.4785
3.5607	3.5646	3.5686	3.5640	3.5600	3.4646
3.5601	3.5640	3.5680	3.5634	3.5594	3.3570
3.5615	3.5654	3.5694	3.5648	3.5608	3.3934
3.5624	3.5663	3.5703	3.5657	3.5617	3.3580
3.5630	3.5669	3.5709	3.5663	3.5623	3.3083
3.5623	3.5662	3.5702	3.5656	3.5616	3.3991
3.5622	3.5661	3.5701	3.5655	3.5615	3.3593
3.5621	3.5660	3.5700	3.5654	3.5614	3.3965
3.5611	3.5650	3.5690	3.5644	3.5604	3.3971
3.5612	3.5651	3.5691	3.5645	3.5605	3.3596
3.5608	3.5647	3.5687	3.5641	3.5601	3.4062
3.5600	3.5639	3.5679	3.5633	3.5593	3.3948
3.5614	3.5653	3.5693	3.5647	3.5607	3.3926
3.5591	3.5630	3.5670	3.5624	3.5584	3.3924
3.5608	3.5647	3.5687	3.5641	3.5601	3.3884
3.5582	3.5621	3.5661	3.5615	3.5575	3.3863
3.5591	3.5630	3.5670	3.5624	3.5584	3.3881
3.5529	3.5568	3.5608	3.5562	3.5522	3.3739
3.5466	3.5505	3.5545	3.5499	3.5459	3.3597
3.5417	3.5457	3.5496	3.5450	3.5410	3.3560
3.5273	3.5313	3.5352	3.5306	3.5267	3.3628
3.5115	3.5154	3.5193	3.5147	3.5108	3.3656
3.5028	3.5067	3.5106	3.5060	3.5021	3.3866
3.4785	3.4824	3.4863	3.4818	3.4779	3.4613

Heated Test Case $Gr^{+}=10^{6}$, C=0.0

Streamlines

#1	#2	#3	#4	#5	
0.93	0.93	0.94	0.93	0.93	0.0181
0.93	0.94	0.94	0.94	0.93	0.0199
0.94	0.94	0.95	0.94	0.94	0.0436
0.94	0.95	0.95	0.94	0.94	0.0370
0.95	0.96	0.96	0.95	0.95	0.0312
0.96	0.97	0.97	0.97	0.96	0.0682
0.98	0.98	0.99	0.98	0.97	0.0524
0.98	0.98	0.99	0.98	0.98	0.0853
0.98	0.99	0.99	0.99	0.98	0.0675
0.99	0.99	1.00	0.99	0.98	0.1440
0.99	0.99	1.00	0.99	0.99	0.1008
0.99	0.99	1.00	0.99	0.99	0.1178
0.99	0.99	1.00	0.99	0.99	0.2370
0.99	0.99	1.00	0.99	0.99	0.1994
0.99	0.99	1.00	0.99	0.99	0.2382
0.99	0.99	1.00	0.99	0.99	0.2896
0.99	0.99	1.00	0.99	0.99	0.1940
0.99	0.99	1.00	0.99	0.99	0.2367
0.99	0.99	1.00	0.99	0.99	0.1966
0.99	0.99	1.00	0.99	0.99	0.1949
0.99	0.99	1.00	0.99	0.99	0.2354
0.99	0.99	1.00	0.99	0.99	0.1846
0.99	0.99	1.00	0.99	0.99	0.1963
0.99	0.99	1.00	0.99	0.99	0.2002
0.98	0.99	0.99	0.99	0.98	0.1980
0.99	0.99	1.00	0.99	0.99	0.2041
0.98	0.99	0.99	0.99	0.98	0.2037
0.98	0.99	0.99	0.99	0.98	0.2027
0.98	0.98	0.99	0.98	0.98	0.2117
0.97	0.97	0.98	0.97	0.97	0.2206
0.96	0.97	0.97	0.97	0.96	0.2196
0.94	0.95	0.95	0.95	0.94	0.1974
0.93	0.93	0.94	0.93	0.92	0.1774
0.92	0.92	0.92	0.92	0.91	0.1436
0.89	0.89	0.90	0.89	0.89	0.0219

MINIMUM PSI = 0.0181
AVERAGE PSI = 0.1540
MAXIMUM PSI = 0.2896

Heated Test Case $Gr^{+}=10^{6}$, C=0.0

Velocities

#1	#2	#3	#4	#5	
13.3891	13.4578	13.5268	13.4455	13.3768	13.1344
13.4190	13.4878	13.5569	13.4755	13.4067	13.1396
13.4967	13.5658	13.6352	13.5534	13.4843	12.8970
13.5480	13.6191	13.6887	13.6067	13.5374	13.0359
13.6905	13.7622	13.8323	13.7496	13.6798	13.2526
13.8630	13.9353	14.0062	13.9227	13.8504	12.9055
14.0463	14.1175	14.1909	14.1065	14.0335	13.2979
14.1102	14.1817	14.2553	14.1707	14.0974	12.8953
14.1542	14.2258	14.2996	14.2148	14.1413	13.1864
14.1946	14.2664	14.3404	14.2553	14.1817	12.1392
14.2037	14.2756	14.3496	14.2646	14.1909	12.7609
14.2130	14.2848	14.3589	14.2738	14.2001	12.5271
14.2019	14.2738	14.3478	14.2627	14.1890	10.8261
14.2277	14.2996	14.3737	14.2886	14.2148	11.3803
14.2443	14.3163	14.3905	14.3052	14.2314	10.8410
14.2553	14.3274	14.4016	14.3163	14.2424	10.1171
14.2424	14.3144	14.3886	14.3033	14.2295	11.4690
14.2406	14.3126	14.3867	14.3015	14.2277	10.8604
14.2387	14.3107	14.3849	14.2996	14.2258	11.4285
14.2203	14.2922	14.3663	14.2812	14.2074	11.4378
14.2222	14.2941	14.3682	14.2830	14.2093	10.8649
14.2148	14.2867	14.3607	14.2756	14.2019	11.5803
14.2001	14.2719	14.3459	14.2609	14.1872	11.4021
14.2258	14.2978	14.3719	14.2867	14.2130	11.3679
14.1835	14.2553	14.3293	14.2443	14.1707	11.3648
14.2148	14.2867	14.3607	14.2756	14.2019	11.3029
14.1670	14.2387	14.3126	14.2277	14.1542	11.2705
14.1835	14.2553	14.3293	14.2443	14.1707	11.2983
14.0700	14.1413	14.2148	14.1303	14.0572	11.0808
13.9553	14.0262	14.0992	14.0153	13.9426	10.8665
13.8666	13.9390	14.0098	13.9263	13.8540	10.8111
13.6084	13.6798	13.7496	13.6673	13.5978	10.9129
13.3295	13.3979	13.4666	13.3856	13.3172	10.9551
13.1777	13.2456	13.3137	13.2334	13.1656	11.2751
12.7609	12.8271	12.8936	12.8169	12.7507	12.4720

MINIMUM VELOCITY = 12.7507
AVERAGE VELOCITY = 14.0117
MAXIMUM VELOCITY = 14.4016

Heated Test Case $Gr^{+}=10^{6}$, C=0.4

Original Voltage Readings

#1	#2	#3	#4	#5	#5
3.3800	3.3837	3.4359	3.3837	3.3800	3.3314
3.3474	3.3511	3.4484	3.3511	3.3474	3.2736
3.3142	3.3178	3.4553	3.3178	3.3142	3.2167
3.3057	3.3094	3.4616	3.3094	3.3057	3.1833
3.3103	3.3139	3.4665	3.3139	3.3103	3.1731
3.3104	3.3141	3.4704	3.3141	3.3104	3.1649
3.3120	3.3157	3.4718	3.3157	3.3120	3.1503
3.3052	3.3089	3.4720	3.3089	3.3052	3.1269
3.3027	3.3064	3.4721	3.3064	3.3027	3.1104
3.2983	3.3020	3.4714	3.3020	3.2983	3.0805
3.2984	3.3020	3.4715	3.3020	3.2984	3.0561
3.3297	3.3334	3.4717	3.3334	3.3297	3.1684
3.3264	3.3301	3.4711	3.3301	3.3264	3.1359
3.3201	3.3238	3.4708	3.3238	3.3201	3.1110
3.3179	3.3216	3.4704	3.3216	3.3179	3.0882
3.3931	3.3969	3.4689	3.3969	3.3931	3.1576
3.4096	3.4134	3.4679	3.4134	3.4096	3.1799
3.4174	3.4212	3.4665	3.4212	3.4174	3.1940
3.4195	3.4233	3.4644	3.4233	3.4195	3.1937
3.4253	3.4291	3.4631	3.4291	3.4253	3.1972
3.4245	3.4283	3.4614	3.4283	3.4245	3.2004
3.4260	3.4298	3.4601	3.4298	3.4260	3.1982
3.4281	3.4319	3.4581	3.4319	3.4281	3.2019
3.2105	3.2141	3.4574	3.2141	3.2105	3.0004
3.2715	3.2751	3.4554	3.2751	3.2715	3.1093
3.4227	3.4265	3.4546	3.4265	3.4227	3.1927
3.4244	3.4282	3.4560	3.4282	3.4244	3.1911
3.2789	3.2825	3.4546	3.2825	3.2789	3.1097
3.4269	3.4307	3.4560	3.4307	3.4269	3.1919
3.1994	3.2029	3.4546	3.2029	3.1994	2.9849
3.3019	3.3056	3.4550	3.3056	3.3019	3.1248
3.4259	3.4297	3.4550	3.4297	3.4259	3.1803
3.3170	3.3207	3.4545	3.3207	3.3170	3.1366
3.4404	3.4442	3.4552	3.4442	3.4404	3.2585
3.2453	3.2489	3.4554	3.2489	3.2453	3.0786
3.3583	3.3621	3.4554	3.3621	3.3583	3.2492
3.4307	3.4345	3.4563	3.4345	3.4307	3.3524
3.3984	3.4022	3.4559	3.4022	3.3984	3.3074
3.4337	3.4376	3.4551	3.4376	3.4337	3.3702
3.4218	3.4256	3.4541	3.4256	3.4218	3.3472
3.4764	3.4803	3.4549	3.4803	3.4764	3.4315
3.4323	3.4361	3.4546	3.4361	3.4323	3.3855
3.4466	3.4504	3.4543	3.4504	3.4466	3.4082
3.4283	3.4321	3.4523	3.4321	3.4283	3.3804

3.4171	3.4209	3.4502	3.4209	3.4171	3.3890
3.4201	3.4239	3.4470	3.4239	3.4201	3.3991
3.4009	3.4047	3.4361	3.4047	3.4009	3.3831
3.3983	3.4021	3.4272	3.4021	3.3983	3.3774
3.3831	3.3869	3.4245	3.3869	3.3831	3.3644
3.3903	3.3941	3.4151	3.3941	3.3903	3.3840
3.3668	3.3706	3.4134	3.3706	3.3668	3.3490
3.3602	3.3640	3.4122	3.3640	3.3602	3.3600

Heated Test Case $Gr^{+}=10^{6}$, C=0.4

Streamlines

#1	#2	#3	#4	#5	
0.87	0.88	0.94	0.88	0.87	0.0649
0.84	0.84	0.96	0.84	0.84	0.0982
0.80	0.80	0.97	0.80	0.80	0.1295
0.79	0.79	0.98	0.79	0.79	0.1608
0.79	0.80	0.98	0.80	0.79	0.1785
0.79	0.80	0.99	0.80	0.79	0.1885
0.80	0.80	0.99	0.80	0.80	0.2075
0.79	0.79	0.99	0.79	0.79	0.2273
0.78	0.79	0.99	0.79	0.78	0.2435
0.78	0.78	0.99	0.78	0.78	0.2723
0.78	0.78	0.99	0.78	0.78	0.2989
0.81	0.82	0.99	0.82	0.81	0.2060
0.81	0.82	0.99	0.82	0.81	0.2397
0.80	0.81	0.99	0.81	0.80	0.2610
0.80	0.81	0.99	0.81	0.80	0.2837
0.89	0.89	0.98	0.89	0.89	0.2839
0.91	0.91	0.98	0.91	0.91	0.2764
0.92	0.92	0.98	0.92	0.92	0.2692
0.92	0.93	0.98	0.93	0.92	0.2716
0.93	0.93	0.98	0.93	0.93	0.2736
0.93	0.93	0.98	0.93	0.93	0.2694
0.93	0.93	0.97	0.93	0.93	0.2732
0.93	0.94	0.97	0.94	0.93	0.2713
0.69	0.69	0.97	0.69	0.69	0.2708
0.75	0.75	0.97	0.75	0.75	0.2107
0.93	0.93	0.97	0.93	0.93	0.2758
0.93	0.93	0.97	0.93	0.93	0.2791
0.76	0.76	0.97	0.76	0.76	0.2185
0.93	0.94	0.97	0.94	0.93	0.2807
0.68	0.68	0.97	0.68	0.68	0.2767
0.78	0.79	0.97	0.79	0.78	0.2261
0.93	0.93	0.97	0.93	0.93	0.2918
0.80	0.80	0.97	0.80	0.80	0.2289
0.95	0.95	0.97	0.95	0.95	0.2225
0.72	0.73	0.97	0.73	0.72	0.2177
0.85	0.85	0.97	0.85	0.85	0.1420
0.94	0.94	0.97	0.94	0.94	0.1013
0.90	0.90	0.97	0.90	0.90	0.1181
0.94	0.94	0.97	0.94	0.94	0.0827
0.92	0.93	0.97	0.93	0.92	0.0970
0.99	1.00	0.97	1.00	0.99	0.0583
0.94	0.94	0.97	0.94	0.94	0.0615
0.96	0.96	0.97	0.96	0.96	0.0505
0.93	0.94	0.96	0.94	0.93	0.0630

0.92	0.92	0.96	0.92	0.92	0.0375
0.92	0.93	0.96	0.93	0.92	0.0281
0.90	0.90	0.94	0.90	0.90	0.0240
0.90	0.90	0.93	0.90	0.90	0.0281
0.88	0.88	0.93	0.88	0.88	0.0253
0.89	0.89	0.92	0.89	0.89	0.0086
0.86	0.86	0.91	0.86	0.86	0.0243
0.85	0.85	0.91	0.85	0.85	0.0003

MINIMUM PSI = 0.0003
AVERAGE PSI = 0.1769
MAXIMUM PSI = 0.2989

Heated Test Case $Gr^{+}=10^{6}$, C=0.4

Velocities

#1	#2	#3	#4	#5	
11.1738	11.2305	12.0547	11.2305	11.1738	10.4488
10.6834	10.7382	12.2587	10.7382	10.6834	9.6341
10.2011	10.2525	12.3725	10.2525	10.2011	8.8805
10.0803	10.1327	12.4770	10.1327	10.0803	8.4597
10.1455	10.1968	12.5588	10.1968	10.1455	8.3342
10.1469	10.1997	12.6242	10.1997	10.1469	8.2344
10.1697	10.2225	12.6478	10.2225	10.1697	8.0590
10.0732	10.1256	12.6511	10.1256	10.0732	7.7838
10.0380	10.0902	12.6528	10.0902	10.0380	7.5941
9.9761	10.0281	12.6411	10.0281	9.9761	7.2595
9.9775	10.0281	12.6427	10.0281	9.9775	6.9948
10.4241	10.4779	12.6461	10.4779	10.4241	8.2769
10.3763	10.4299	12.6360	10.4299	10.3763	7.8888
10.2855	10.3388	12.6310	10.3388	10.2855	7.6010
10.2540	10.3071	12.6242	10.3071	10.2540	7.3445
11.3756	11.4347	12.5990	11.4347	11.3756	8.1464
11.6338	11.6939	12.5823	11.6939	11.6338	8.4177
11.7575	11.8180	12.5588	11.8180	11.7575	8.5928
11.7909	11.8516	12.5237	11.8516	11.7909	8.5890
11.8837	11.9447	12.5020	11.9447	11.8837	8.6329
11.8708	11.9319	12.4737	11.9319	11.8708	8.6732
11.8949	11.9560	12.4521	11.9560	11.8949	8.6455
11.9287	11.9899	12.4189	11.9899	11.9287	8.6921
8.8012	8.8472	12.4072	8.8472	8.8012	6.4182
9.6055	9.6546	12.3741	9.6546	9.6055	7.5816
11.8420	11.9029	12.3609	11.9029	11.8420	8.5765
11.8692	11.9303	12.3841	11.9303	11.8692	8.5565
9.7067	9.7563	12.3609	9.7563	9.7067	7.5862
11.9094	11.9705	12.3841	11.9705	11.9094	8.5665
8.6606	8.7047	12.3609	8.7047	8.6606	6.2644
10.0267	10.0789	12.3675	10.0789	10.0267	7.7595
11.8933	11.9544	12.3675	11.9544	11.8933	8.4226
10.2411	10.2942	12.3592	10.2942	10.2411	7.8970
12.1278	12.1898	12.3708	12.1898	12.1278	9.4295
9.2534	9.3012	12.3741	9.3012	9.2534	7.2386
10.8455	10.9024	12.3741	10.9024	10.8455	9.3052
11.9705	12.0320	12.3890	12.0320	11.9705	10.7575
11.4581	11.5175	12.3824	11.5175	11.4581	10.1044
12.0190	12.0822	12.3691	12.0822	12.0190	11.0246
11.8276	11.8885	12.3526	11.8885	11.8276	10.6804
12.7254	12.7914	12.3658	12.7914	12.7254	11.9835
11.9964	12.0579	12.3609	12.0579	11.9964	11.2582
12.2292	12.2916	12.3559	12.2916	12.2292	11.6118
11.9319	11.9931	12.3229	11.9931	11.9319	11.1799

11.7527	11.8133	12.2883	11.8133	11.7527	11.3122
11.8005	11.8612	12.2357	11.8612	11.8005	11.4690
11.4971	11.5567	12.0579	11.5567	11.4971	11.2213
11.4565	11.5159	11.9142	11.5159	11.4565	11.1341
11.2213	11.2798	11.8708	11.2798	11.2213	10.9370
11.3323	11.3912	11.7209	11.3912	11.3323	11.2351
10.9732	11.0307	11.6939	11.0307	10.9732	10.7071
10.8739	10.9310	11.6749	10.9310	10.8739	10.8709

MINIMUM VELOCITY = 8.6606
AVERAGE VELOCITY = 11.2972
MAXIMUM VELOCITY = 12.7914

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Original Voltage Readings

#1	#2	#3	#4	#5	#5
3.3911	3.3949	3.4425	3.3949	3.3911	3.3916
3.3891	3.3929	3.4445	3.3929	3.3891	3.3798
3.3819	3.3856	3.4461	3.3856	3.3819	3.3668
3.3698	3.3736	3.4482	3.3736	3.3698	3.3476
3.3548	3.3586	3.4512	3.3586	3.3548	3.3251
3.3420	3.3457	3.4534	3.3457	3.3420	3.3120
3.3313	3.3350	3.4553	3.3350	3.3313	3.2868
3.3295	3.3332	3.4573	3.3332	3.3295	3.2778
3.3198	3.3235	3.4563	3.3235	3.3198	3.2607
3.3184	3.3221	3.4581	3.3221	3.3184	3.2521
3.3143	3.3180	3.4587	3.3180	3.3143	3.2405
3.3149	3.3186	3.4595	3.3186	3.3149	3.2337
3.3100	3.3137	3.4613	3.3137	3.3100	3.2214
3.3141	3.3178	3.4627	3.3178	3.3141	3.2182
3.3121	3.3158	3.4636	3.3158	3.3121	3.2076
3.3136	3.3173	3.4649	3.3173	3.3136	3.2025
3.3093	3.3129	3.4642	3.3129	3.3093	3.1956
3.3073	3.3110	3.4644	3.3110	3.3073	3.1789
3.3098	3.3134	3.4646	3.3134	3.3098	3.1791
3.3087	3.3124	3.4647	3.3124	3.3087	3.1717
3.3029	3.3066	3.4646	3.3066	3.3029	3.1546
3.3079	3.3116	3.4647	3.3116	3.3079	3.1539
3.3004	3.3041	3.4647	3.3041	3.3004	3.1371
3.3059	3.3096	3.4647	3.3096	3.3059	3.1312
3.2998	3.3035	3.4646	3.3035	3.2998	3.1214
3.3033	3.3070	3.4647	3.3070	3.3033	3.1113
3.2966	3.3003	3.4648	3.3003	3.2966	3.1032
3.2998	3.3034	3.4644	3.3034	3.2998	3.0978
3.2872	3.2909	3.4647	3.2909	3.2872	3.0799
3.2939	3.2976	3.4644	3.2976	3.2939	3.0771
3.2962	3.2999	3.4644	3.2999	3.2962	3.0733
3.2984	3.3020	3.4647	3.3020	3.2984	3.0669
3.3036	3.3072	3.4642	3.3072	3.3036	3.0585
3.3310	3.3347	3.4636	3.3347	3.3310	3.0839
3.3510	3.3547	3.4628	3.3547	3.3510	3.1085
3.3704	3.3741	3.4610	3.3741	3.3704	3.1307
3.3873	3.3911	3.4605	3.3911	3.3873	3.1659
3.3954	3.3992	3.4595	3.3992	3.3954	3.1893
3.3961	3.3999	3.4581	3.3999	3.3961	3.1954
3.3969	3.4007	3.4569	3.4007	3.3969	3.2021
3.3991	3.4029	3.4556	3.4029	3.3991	3.2097
3.4021	3.4059	3.4551	3.4059	3.4021	3.2182
3.4076	3.4114	3.4542	3.4114	3.4076	3.2436
3.4021	3.4059	3.4546	3.4059	3.4021	3.2315

3.4014	3.4052	3.4533	3.4052	3.4014	3.2392
3.4032	3.4069	3.4538	3.4069	3.4032	3.2459
3.4034	3.4072	3.4526	3.4072	3.4034	3.2508
3.4055	3.4093	3.4526	3.4093	3.4055	3.2605
3.4037	3.4075	3.4522	3.4075	3.4037	3.2634
3.4061	3.4099	3.4512	3.4099	3.4061	3.2731
3.4012	3.4050	3.4517	3.4050	3.4012	3.2661
3.4059	3.4097	3.4520	3.4097	3.4059	3.2865
3.3984	3.4022	3.4519	3.4022	3.3984	3.2679
3.4060	3.4098	3.4530	3.4098	3.4060	3.3002
3.3951	3.3989	3.4528	3.3989	3.3951	3.2708
3.4051	3.4089	3.4519	3.4089	3.4051	3.3100
3.4070	3.4108	3.4514	3.4108	3.4070	3.3243
3.4080	3.4118	3.4523	3.4118	3.4080	3.3319
3.4081	3.4119	3.4522	3.4119	3.4081	3.3384
3.4088	3.4126	3.4522	3.4126	3.4088	3.3406
3.4204	3.4242	3.4503	3.4242	3.4204	3.3649
3.4131	3.4169	3.4484	3.4169	3.4131	3.3636
3.4029	3.4066	3.4455	3.4066	3.4029	3.3476
3.3831	3.3869	3.4333	3.3869	3.3831	3.3226
3.3847	3.3885	3.4248	3.3885	3.3847	3.3513
3.3830	3.3868	3.4187	3.3868	3.3830	3.3608
3.3747	3.3785	3.4113	3.3785	3.3747	3.3607
3.3703	3.3741	3.4122	3.3741	3.3703	3.3534
3.3640	3.3678	3.4113	3.3678	3.3640	3.3638

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Streamlines

#1	#2	#3	#4	#5	
0.91	0.91	0.97	0.91	0.91	-0.0007
0.90	0.91	0.97	0.91	0.90	0.0126
0.89	0.90	0.98	0.90	0.89	0.0205
0.88	0.88	0.98	0.88	0.88	0.0301
0.86	0.87	0.98	0.87	0.86	0.0404
0.85	0.85	0.98	0.85	0.85	0.0409
0.83	0.84	0.99	0.84	0.83	0.0605
0.83	0.84	0.99	0.84	0.83	0.0700
0.82	0.82	0.99	0.82	0.82	0.0800
0.82	0.82	0.99	0.82	0.82	0.0894
0.81	0.82	0.99	0.82	0.81	0.0992
0.81	0.82	0.99	0.82	0.81	0.1087
0.81	0.81	1.00	0.81	0.81	0.1184
0.81	0.82	1.00	0.82	0.81	0.1274
0.81	0.82	1.00	0.82	0.81	0.1383
0.81	0.82	1.00	0.82	0.81	0.1465
0.81	0.81	1.00	0.81	0.81	0.1499
0.81	0.81	1.00	0.81	0.81	0.1680
0.81	0.81	1.00	0.81	0.81	0.1707
0.81	0.81	1.00	0.81	0.81	0.1784
0.80	0.81	1.00	0.81	0.80	0.1923
0.81	0.81	1.00	0.81	0.81	0.1987
0.80	0.80	1.00	0.80	0.80	0.2102
0.80	0.81	1.00	0.81	0.80	0.2231
0.80	0.80	1.00	0.80	0.80	0.2278
0.80	0.81	1.00	0.81	0.80	0.2431
0.79	0.80	1.00	0.80	0.79	0.2451
0.80	0.80	1.00	0.80	0.80	0.2546
0.78	0.79	1.00	0.79	0.78	0.2615
0.79	0.80	1.00	0.80	0.79	0.2716
0.79	0.80	1.00	0.80	0.79	0.2781
0.80	0.80	1.00	0.80	0.80	0.2873
0.80	0.81	1.00	0.81	0.80	0.3015
0.83	0.84	1.00	0.84	0.83	0.3013
0.86	0.86	1.00	0.86	0.86	0.2947
0.88	0.88	0.99	0.88	0.88	0.2901
0.90	0.91	0.99	0.91	0.90	0.2693
0.91	0.92	0.99	0.92	0.91	0.2521
0.91	0.92	0.99	0.92	0.91	0.2462
0.91	0.92	0.99	0.92	0.91	0.2396
0.92	0.92	0.99	0.92	0.92	0.2335
0.92	0.92	0.99	0.92	0.92	0.2272
0.93	0.93	0.99	0.93	0.93	0.2044
0.92	0.92	0.99	0.92	0.92	0.2122

0.92	0.92	0.98	0.92	0.92	0.2027
0.92	0.92	0.99	0.92	0.92	0.1970
0.92	0.93	0.98	0.93	0.92	0.1916
0.92	0.93	0.98	0.93	0.92	0.1826
0.92	0.93	0.98	0.93	0.92	0.1772
0.92	0.93	0.98	0.93	0.92	0.1685
0.92	0.92	0.98	0.92	0.92	0.1713
0.92	0.93	0.98	0.93	0.92	0.1524
0.91	0.92	0.98	0.92	0.91	0.1660
0.92	0.93	0.98	0.93	0.92	0.1360
0.91	0.91	0.98	0.91	0.91	0.1587
0.92	0.93	0.98	0.93	0.92	0.1230
0.93	0.93	0.98	0.93	0.93	0.1076
0.93	0.93	0.98	0.93	0.93	0.0993
0.93	0.93	0.98	0.93	0.93	0.0912
0.93	0.93	0.98	0.93	0.93	0.0893
0.94	0.95	0.98	0.95	0.94	0.0729
0.93	0.94	0.98	0.94	0.93	0.0654
0.92	0.92	0.97	0.92	0.92	0.0730
0.90	0.90	0.96	0.90	0.90	0.0802
0.90	0.90	0.95	0.90	0.90	0.0449
0.90	0.90	0.94	0.90	0.90	0.0300
0.89	0.89	0.93	0.89	0.89	0.0191
0.88	0.88	0.93	0.88	0.88	0.0230
0.87	0.88	0.93	0.88	0.87	0.0003

MINIMUM PSI = -0.0007
AVERAGE PSI = 0.1542
MAXIMUM PSI = 0.3015

Heated Test Case $Gr^{+}=10^{6}$, C=1.0

Velocities

#1	#2	#3	#4	#5	
11.3446	11.4036	12.1621	11.4036	11.3446	11.3524
11.3137	11.3725	12.1948	11.3725	11.3137	11.1707
11.2029	11.2598	12.2210	11.2598	11.2029	10.9732
11.0185	11.0762	12.2554	11.0762	11.0185	10.6863
10.7932	10.8500	12.3048	10.8500	10.7932	10.3575
10.6038	10.6583	12.3410	10.6583	10.6038	10.1697
10.4474	10.5013	12.3725	10.5013	10.4474	9.8157
10.4212	10.4750	12.4056	10.4750	10.4212	9.6916
10.2812	10.3345	12.3890	10.3345	10.2812	9.4591
10.2612	10.3143	12.4189	10.3143	10.2612	9.3438
10.2025	10.2554	12.4288	10.2554	10.2025	9.1900
10.2111	10.2640	12.4421	10.2640	10.2111	9.1007
10.1413	10.1939	12.4720	10.1939	10.1413	8.9410
10.1997	10.2525	12.4954	10.2525	10.1997	8.8997
10.1711	10.2239	12.5104	10.2239	10.1711	8.7643
10.1925	10.2454	12.5321	10.2454	10.1925	8.6997
10.1313	10.1825	12.5204	10.1825	10.1313	8.6128
10.1030	10.1555	12.5237	10.1555	10.1030	8.4054
10.1384	10.1897	12.5271	10.1897	10.1384	8.4078
10.1228	10.1754	12.5287	10.1754	10.1228	8.3171
10.0408	10.0930	12.5271	10.0930	10.0408	8.1104
10.1115	10.1640	12.5287	10.1640	10.1115	8.1020
10.0056	10.0577	12.5287	10.0577	10.0056	7.9029
10.0831	10.1356	12.5287	10.1356	10.0831	7.8338
9.9971	10.0492	12.5271	10.0492	9.9971	7.7202
10.0464	10.0987	12.5287	10.0987	10.0464	7.6044
9.9523	10.0042	12.5304	10.0042	9.9523	7.5125
9.9971	10.0478	12.5237	10.0478	9.9971	7.4517
9.8213	9.8727	12.5287	9.8727	9.8213	7.2529
9.9145	9.9663	12.5237	9.9663	9.9145	7.2221
9.9466	9.9985	12.5237	9.9985	9.9466	7.1806
9.9775	10.0281	12.5287	10.0281	9.9775	7.1110
10.0507	10.1015	12.5204	10.1015	10.0507	7.0205
10.4430	10.4969	12.5104	10.4969	10.4430	7.2969
10.7367	10.7917	12.4970	10.7917	10.7367	7.5725
11.0276	11.0838	12.4671	11.0838	11.0276	7.8280
11.2859	11.3446	12.4587	11.3446	11.2859	8.2466
11.4114	11.4706	12.4421	11.4706	11.4114	8.5341
11.4223	11.4815	12.4189	11.4815	11.4223	8.6103
11.4347	11.4940	12.3989	11.4940	11.4347	8.6946
11.4690	11.5285	12.3774	11.5285	11.4690	8.7910
11.5159	11.5756	12.3691	11.5756	11.5159	8.8997
11.6023	11.6623	12.3543	11.6623	11.6023	9.2309
11.5159	11.5756	12.3609	11.5756	11.5159	9.0720

11.5050	11.5646	12.3394	11.5646	11.5050	9.1729
11.5332	11.5913	12.3477	11.5913	11.5332	9.2614
11.5363	11.5960	12.3278	11.5960	11.5363	9.3265
11.5693	11.6291	12.3278	11.6291	11.5693	9.4564
11.5410	11.6007	12.3212	11.6007	11.5410	9.4955
11.5787	11.6386	12.3048	11.6386	11.5787	9.6273
11.5018	11.5614	12.3130	11.5614	11.5018	9.5321
11.5756	11.6354	12.3179	11.6354	11.5756	9.8116
11.4581	11.5175	12.3163	11.5175	11.4581	9.5565
11.5771	11.6370	12.3344	11.6370	11.5771	10.0028
11.4067	11.4659	12.3311	11.4659	11.4067	9.5959
11.5630	11.6228	12.3163	11.6228	11.5630	10.1413
11.5929	11.6528	12.3081	11.6528	11.5929	10.3460
11.6086	11.6686	12.3229	11.6686	11.6086	10.4561
11.6102	11.6702	12.3212	11.6702	11.6102	10.5510
11.6212	11.6813	12.3212	11.6813	11.6212	10.5832
11.8053	11.8660	12.2900	11.8660	11.8053	10.9445
11.6892	11.7495	12.2587	11.7495	11.6892	10.9250
11.5285	11.5866	12.2111	11.5866	11.5285	10.6863
11.2213	11.2798	12.0125	11.2798	11.2213	10.3215
11.2459	11.3045	11.8756	11.3045	11.2459	10.7412
11.2198	11.2782	11.7782	11.2782	11.2198	10.8829
11.0929	11.1509	11.6607	11.1509	11.0929	10.8814
11.0261	11.0838	11.6749	11.0838	11.0261	10.7724
10.9310	10.9883	11.6607	10.9883	10.9310	10.9280

MINIMUM VELOCITY = 9.8213
AVERAGE VELOCITY = 11.1839
MAXIMUM VELOCITY = 12.5321

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