REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
05-06-2009	Final	10/01/06-09/30/09

4. TITLE AND SUBTITLE	
Characterization of Convective Boiling in Branching Channel Heat Sinks	5a. CONTRACT NUMBER
	5b. GRANT NUMBER N00014-06-1-0017
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Pence, Deborah V. Liburdy, James A. Narayanan, Vinod	5d. PROJECT NUMBER 08PR00751-00
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Oregon State University 308 Kerr Administration Building Corvallis, OR 97331-8507	8. PERFORMING ORGANIZATION REPORT NUMBER N0199
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street Arlington, VA 22203-1995 Dr. Mark Spector, Program Manager	10. SPONSOR/MONITOR'S ACRONYM(S) ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 331

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Convective boiling and gas-liquid flows in branching microscale flow networks within disk-shaped heat sinks were studied experimentally. Void fraction and flow regime variations as a function of branch level were reported for gas-liquid flows and compared with existing void fraction correlations and regime maps, respectively. Two methods for assessing void fraction were used, with void fraction assessed using two-dimensional high-speed images providing the best assessment. Void fraction in convective boiling flows showed backflow that would sometimes reroute downstream through an adjacent branch and at other times flow back to the inlet plenum, depending upon the degree of upstream throttling. A technique for measuring convective wall temperatures was developed and used to qualitatively assess temperature variations between vapor and liquid phase contact. Adiabatic flow boiling data was used to validate a one-dimensional, two-phase pressure drop model for use in flow network optimization. Validation of the heat transfer portion of the model was not possible without wall temperature data.

15. SUBJECT TERMS

thermal management, convective boiling, fractal, microscale, constructal, tree net

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	SAR	17	Deborah Pence
					19b. TELEPHONE NUMBER *(Include area code)* 541-737-7018

Contract Information

Contract Number	N00014-06-1-0017
Title of Research	Characterization of Convective Boiling in Branching Channel Heat Sinks
Principal Investigator	Deborah Pence
Organization	Oregon State University
Award Period	October 1, 2006 – September 30, 2009

Technical Section

Technical Objectives

The work being performed under this work unit addressed flow boiling in a fractal-like branching heat sink. The objectives of the program were to:

(i) study local liquid and vapor velocities, wall temperatures and void fractions;
(ii) establish global pressure drop and exit quality;
(iii) validate or modify a two-phase branching flow model to predict pressure drop and heat transfer; and
(iv) study uniformity of flow distribution within the fractal-like geometry.

Technical Approach

A series of regional and local imaging data were obtained using micro-particle image velocimetry (μPIV), infrared thermography (IRT) and high-speed-high-resolution imaging (HSHR). This unique ensemble of imaging capabilities allowed for determination of phase velocities, void fraction estimates and local wall temperature distributions for comparison with those predicted from an existing branching flow model. The local void fraction estimates, based on 2-D planar images, were measured using the HSHR technique for boiling flows. For gas-liquid flows void fraction was found using (i) 2-D imaging and (ii) the measured superficial velocity and actual averaged gas velocity. Void fraction is reported on a regional basis, where regional is defined as a field of view within a single branch of the fractal-like branching heat sink. An epi-fluorescent μPIV method was used to determine time-averaged local liquid phase velocities. The gas phase velocities in gas-liquid flows were determined using a tracking method for the interface. Flow regimes of gas-liquid flows were investigated and compared with the Taitel and Dukler [1] maps. These studies employed silicon test devices with chemically etched fractal-like flow networks, which are completed with an anodically bonded Pyrex® cover. Thin-film Nichrome heaters were used to supply energy to the heat sink. Silicon-silicon test sections were designed to allow IRT of the channel wall for measuring the local temperature. Void images and global pressure drop were compared to those predicted from an existing model based on one-dimensional pressure drop and heat transfer correlations.

Accomplishments

Due to an issue with micro-PIV measurements in a convective boiling melting at the bifurcation region, liquid and gas vapor velocities were measured in lieu of liquid and vapor velocities. Accomplishments will be discussed as follows: (A) convective boiling hydrodynamics, (B) gas-liquid hydrodynamics, (C) convective boiling wall temperatures, and (D) model validation. Additional work completed under this effort include a point source void detector (not reported but referenced) and a comparison of void fraction and flow regimes in gas-liquid flows in fractal-like channel networks to existing void correlations and flow regime maps, both of which are reported. Due to problems arising during the fabrication process of the test devices for measuring wall surface temperatures, only qualitative data to demonstrate feasibility of the technique were acquired. Undetermined thermal losses prohibited evaluation of exit quality.

A. Convective Boiling Hydrodynamics

Included in these results are global pressure drop and transient pressure measurements, and void fraction and bubble dynamics.

(i) Global Pressure Drop and Pressure Transients

This past year, the remainder of the global pressure drop data was acquired. In addition, a high frequency pressure transducer at the manifold inlet was added. Due to issues of arcing with heaters at high voltages and limitations of existing power supplies, heat fluxes were restricted to relatively low values. After considering differences in flow regimes as a function of flow rates and heat fluxes, two different heat fluxes were tested at a fixed mass flow rate of 20 g/min of degassed, deionized water. These include 1.8 W/cm^2 and 2.6 W/cm^2. The inlet water temperature was fixed near 88°C. To study the influence of an upstream flow resistance on flow hydrodynamics, a control valve was located upstream of the test device and set to yield a pressure drop across the valve of 150 kPa, which was approximately 100 times larger than the pressure drop across the test device. Results show a decrease in inlet pressure oscillation frequency by roughly a factor of two, 0.28 Hz versus 0.50 Hz, compared with the inlet pressure measured without throttling. For both throttled and non-throttled cases, the frequency of inlet pressure oscillations was observed to double for a 50% increase in applied heat flux. Using high-speed imaging, the inlet plenum vapor cycling was determined. This was done by measuring the residence time for vapor and residence time for liquid phases in the inlet plenum using fourteen second long movies. The sum of the time period of the vapor residence added to the time period of the interval between cycles in each case matched the frequency of the measured pressure oscillations, to within 4%, for both the throttled and non-throttled cases. It was concluded that the pressure oscillations strongly correlate with the bubble dynamics at the inlet of the fractal-like heat sink and that throttling can be useful in reducing the oscillating frequency.

(ii) Convective Boiling Void Fraction and Bubble Dynamics

A total of 250 movies (2 μm per pixel resolution, 1024 x 1024 pixels, at 1000 fps) were acquired for several locations within a tree (a tree is defined by all branches connected to one of the channels leaving the inlet plenum) at operating conditions of 20 g/min with heat flux values of 1.8 W/cm^2 and 2.6 W/cm^2. The field of view was not sufficient to report the total void fraction per branch level in the k=3 and k=4 branch levels; hence, these data are reported as k3 and k4 upstream and k3 and k4 downstream locations. The characteristics of bubble motion, growth and collapse have been documents by Edward [2] for each branching level in the fractal-like heat sink. Because images were obtained by viewing the top of the channel the exact bubble interface shapes are not known nor is the extent of the vapor depth into the channel. Therefore, two-dimensional or apparent void fractions are reported assuming the bubble fills the entire channel depth. Using an existing one-dimensional two-phase pressure drop and heat transfer model for fractal-like flow network, void fraction was predicted as a function of position along the channel. The model predicts, for the case of 20 g/min and 1.76 W/cm^2, that vapor begins to form in the fourth or last branch level, i.e., k = 4. However, as is evident from Fig. 1, void was detected in all branch levels, presumably due to the severe backflow of bubbles that were observed. The reduction of void fraction in the k=4 level is not fully explained at this time. However, from the high-speed movies a significant number of voids were observed to collapse in this branch. An area-weighted average of the void fraction, based on the plan-form area of the channels at each branching level, was calculated for the entire test device for both the measured and model predicted void fraction results. The results for the model predicted area averaged void fraction is 0.31 for 10 g/min and 1.76 W/cm^2 versus a measured value of

0.32 for the same conditions, showing very good agreement. Results are also presented in Edward et al. [3].

The difference in void fraction distribution between the model and measured values indicates that local models of heat transfer may need to be modified to account for the bubble flow dynamics and significant backflow. Therefore, validation of model predictions of pressure drop data over a wider range of conditions is required. However, it should be noted that even though the model does not show great agreement with experimentally observed streamwise variations in void fraction for adiabatic flow boiling, it does well predict the pressure drop, as is noted in Daniels et al. [4].

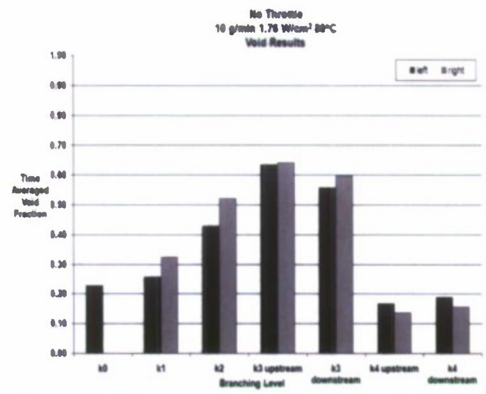


Figure 1. Time-averaged void fraction results for the non-throttled test case. The flow conditions for both cases are 10 g/min flow rate, 1.76 W/cm^2 input heat flux and 88°C inlet fluid temperature [2].

B. Gas-Liquid Hydrodynamics

Presented under this heading are flow regime maps, void fraction comparisons to existing correlations and local velocity measurements of the liquid and gas phases.

(i) Two-Phase Gas-Liquid Flow Regime Identification

Following the successful development of liquid flow field and gas interface velocity measurements during last year's reporting period, this year flow regimes were identified and void fraction assessed at each branch level. A total of 12 test conditions were investigated [5, 6]. The flow regimes were mapped as a function of superficial gas and superficial liquid velocity in each branch level. Figure 2 shows the experimentally identified flow regimes, identified in the k=0 branch level, mapped onto the Taitel and Dukler [1] map for the same hydraulic diameter of 308 μm. Results at each branch level indicate that the flow regimes are well predicted by this model. Results are also compared to the 250 μm diameter map of Chung and Kawaji [7], but with less success.

(ii) Void Fraction Assessment

The void fraction mid-way downstream in each branch level was assessed in two ways. The void fraction was assessed using the area-averaged approach previously discussed as well as using the method outlined in Revellin [8]. In this latter method, void fraction is calculated by dividing the superficial gas velocity by the velocity of the moving void. The average air/water interface velocity was used as the void velocity. In Fig. 3, plotted as hollow circles, are the experimental "apparent" void fraction data for all 12 test conditions. Gas-based void fraction data, i.e., those determined using the method reported in Revellin [8], are shown as hollow triangles. Plotted on the abscissa is the homogenous void fraction. Note that a difference in the assessed void fraction exists between these two methods. Experimental results were compared with several void fraction correlations, including Armand [9] as reported in [10], Zivi [11], Chisholm [12] and Chung et al. [13]. The image-based void fraction better correlates with the imaged-based results of Chung et al. [13] and the theoretically-based results of Zivi [11]. The gas-based void is better predicted by the homogenous model and by the Armand [9] and Chisholm [12] correlations.

(iii) Liquid and Gas Phase Velocities

Using micro-PIV techniques, the displacement of the leading and trailing edges of bubbles were measured over a fixed time interval, dependent upon the superficial liquid and gas flow rates. Statistical averages of these values were consistent with one another; however, the scatter observed was rather significant. Although considerably more uniform in the streamwise and radial distribution of bubble compared with convective boiling flows, this scatter was attributed to temporal and spatial variations in the local superficial liquid velocity. In fact, gas phase void fraction values greater than unity, as observed in Fig. 3, are attributed to this slight flow asymmetry.

C. Convective Boiling Wall Temperatures

The IRT imaging was successfully employed to obtain local wall temperature data at different regions on the Si-Si heat sink. Due to the issues encountered during fabrication, primarily a wicking of gold that resulted in a non-uniform gold layer, wall temperature measurements were only available at certain locations throughout the flow network. In addition, a number of channels were blocked in each test device making unclear the flow conditions. As such, wall temperature data cannot be correlated with global results or with void fraction results. Rather, qualitative data obtained during the course of this work unit can be considered as demonstrating the feasibility of this technique.

The calibration procedures outlined during last year's report were slightly modified, as discussed in the next paragraph, to account for the non-exact camera translation from viewing window to viewing window. Each pixel was calibration from intensity to temperature that was specific to the heat sink. Calibration curves at approximately 11 million locations spanning the entire fractal heat sink with a spatial resolution of 10 μm x 10 μm were obtained. Figures 4a and 4b illustrate typical intensity maps obtained at calibration temperatures of 45°C and 105°C, respectively, at a typical 2.54 mm x 2.36 mm area corresponding to the field of view of the camera. The intensity at all locations at a fixed calibration temperature would ideally be identical. However, the observed variations are a result of fabrication (bonding) defects whereby a non-uniform thickness of gold layer is present in different regions of the image; this highlights the importance of pixel-by-pixel location calibration.

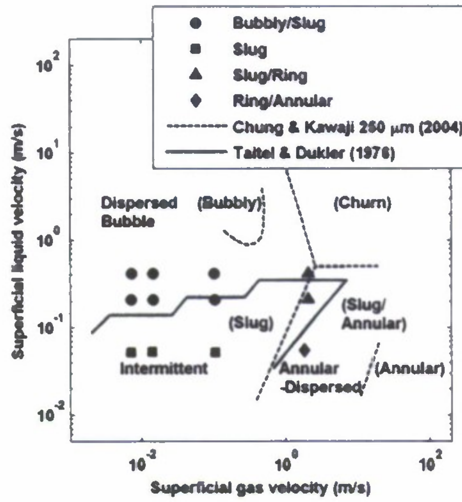


Figure 2. Flow regime map for k=0 branch level and 12 test cases [5].

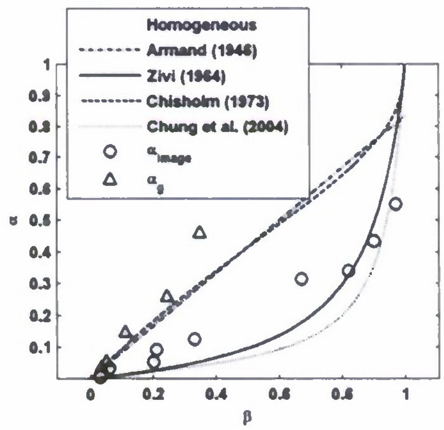
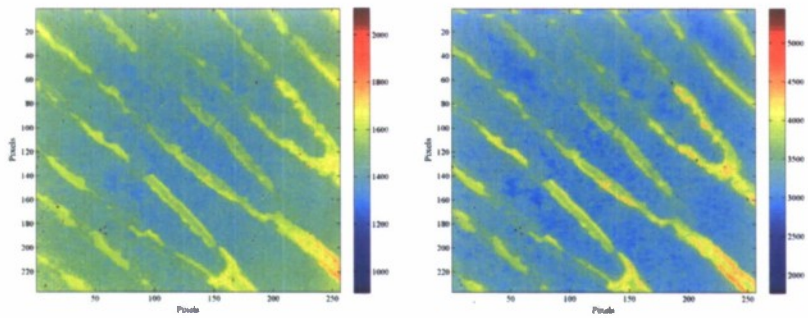


Figure 3. Void fraction in k=0 branch level and 12 cases for image-based void and 5 cases for gas velocity-based void [5].

A preliminary set of data were acquired under the following conditions: 15 g/min, inlet temperature of 88°C, and a total heat sink power input of 30 W (2.6 W/cm^2). However, recall that due to a number of blocked channels, these results will not be repeatable, and therefore, are only qualitative. With the IR detector focused on the gold layer, data were acquired. Intensity maps were recorded at 120 frames-per-second over a quadrant of the heat sink where flow boiling activity was observed. Spatial discrepancies of the order of 100 μm, attributed to the experimental procedure, were observed between the calibration and experimental intensities. To quantify and account for the existing spatial location discrepancies, a cross-correlation algorithm was developed to calculate the necessary x and y directional shift a calibration image would need to undergo relative to the flow image to result in two spatially identical images. Once



(a) Calibration temperature: 45 °C (b) Calibration temperature: 105 °C

Figure. 4. Calibration of intensity at two temperatures.

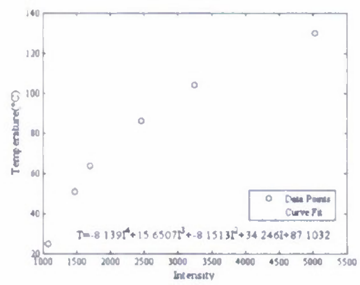


Figure. 5. A typical single point calibration curve.

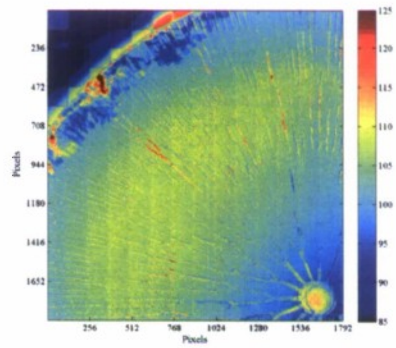


Figure. 6. Temperature map of a quadrant of the fractal heat sink top channel wall surface.

the x and y directional shift were estimated, this information was used to generate a new set of shifted calibration intensity images. These spatially shifted calibration images, generated at each flow image location, and for each of the six calibration temperatures, were utilized in the conversion of intensity at each pixel location to temperature. A typical pixel location calibration curve is shown in Fig. 5. Using such curves, the IR intensity map over a quadrant of the heat sink can be converted to temperature (Fig. 6). Uncertainty estimates indicate that temperatures can be obtained with a spatial resolution of 10 μm and a temperature uncertainty varying from 0.89°C to 1.02°C between 25°C and 125°C, respectively [14,15].

D. Model Validation

Adiabatic vapor-liquid flows were experimentally studied in the second generation flow network with a channel depth of 150 μm. Using high-speed high resolution imaging, time-averaged void fraction in each branch level was experimentally measured and compared to model predictions as a function of exit quality in Daniels et al. [4]. Although the experimental void fraction was not well-predicted by any of the previously mentioned void fraction correlations, the pressure drop was well predicted using the void fraction correlation of Zivi [11] and the phase interaction parameter of Qu and Mudawar [16]. Model results versus experimental results are shown in Fig. 7. The model used is that of Daniels et al. [17] with a null heat flux, which was also used in a previous theoretical study of adiabatic flow boiling conducted by Daniels et al. [18] in which exit quality and pressure drop were studied as a function of inlet subcooling. Results for different flow rates through fractal-like and parallel channel arrays were presented. In agreement with single-phase flows, the pressure drops through branching flow networks were much lower than those through parallel channels with the same mass flow rates.

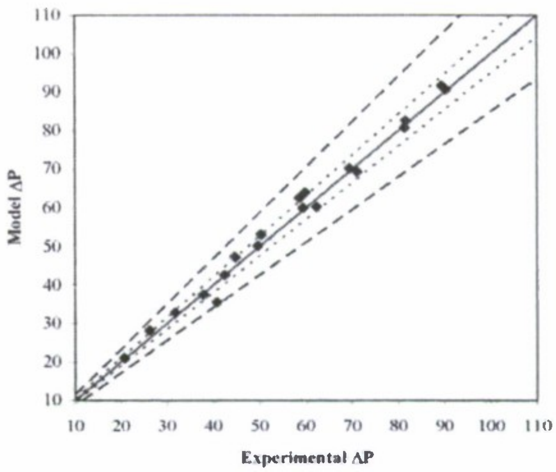


Figure 7. Comparison of model predictions and experimental pressure drop (kPa) for flow through a fractal-like branching flow network with $\gamma = 0.7$, $\beta = 0.7$ and 150 μm deep channels [4].

References

1. Y. Taitel and A.E. Dukler, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," *AIChE Journal*, vol. 22, no. 1, pp. 47-55, 1976.
2. Edward, L. *Characterization of Flow Boiling in a Fractal-Like Branching Microchannel Network*, M.S. Thesis, Oregon State University, Corvallis, OR, 2008.
3. L. Edward, J.A. Liburdy, D.V. Pence and V. Narayanan, "Flow Boiling Characteristics in a Fractal-Like Branching Microchannel Network," Paper #IMECE2008-69239, *Proceedings of the 2008 ASME International Mechanical Engineering Congress and Exposition*, November 2-6, 2008, Boston, MA.
4. B.J. Daniels, J.A. Liburdy and D.V. Pence, Experimental Studies of Adiabatic Flow Boiling in Fractal-Like Branching Micro-Channels, Paper #IMECE2008-69240 *Proceedings of the 2008 ASME International Mechanical Engineering Congress and Exposition,* Boston, MA, November 2-6, 2008.
5. Y. Kwak, *Experimental Study of Two-Phase Gas-Liquid Flow in a Microscale Fractal-Like Branching Flow Network*, Ph.D. Dissertation, Oregon State University, Corvallis, OR, 2008.
6. Y. Kwak, D.V. Pence, J.A. Liburdy and V. Narayanan, "Gas-Liquid Flows in Fractal-like Branching Flow Networks," *Proceedings of Heat Transfer and Fluid Flow in Microscale-III*, Engineering Conferences International, September 21-26, 2008, Whistler, BC, Canada.
7. P.M.Y. Chung and M. Kawaji, "The Effect of Channel Diameter on Adiabatic Two-Phase Flow Characteristics in Microchannels," *International Journal of Multiphase Flow,* vol. 30, pp. 735-761, 2004.
8. R. Revellin, D. Vincent, T. Ursenbacher, J.R. Thome and I. Zun, "Characterization of Diabatic Two-Phase Flows in Microchannels: Flow Parameter Results for R-134a in A 0.5 mm Channel," *International Journal of Multiphase Flow*, vol. 32, no. 7, pp. 755-774, 2006.
9. A.A. Armand, "The Resistance During The Movement of A Two-Phase System in Horizontal Pipes," *Izvestiya Vsesoyuznogo Teplotekhnicheskogo Instituta*, vol.1, pp. 16-23, 1946. In Russian, see translation by V. Beak in 1959.
10. V. Beak, "The Resistance During The Movement of A Two-Phase System in Horizontal Pipes," *Atomic Energy Research Establishment Transactions 828*, 1959.
11. S.M. Zivi, "Estimation of Steady-State Steam Void-Fraction by Means of The Principle of Minimum Entropy Production," *Journal of Heat Transfer*, vol. 86, pp. 247-252, 1964.
12. D. Chisholm, Void Fraction During Two-Phase Flow, *Journal Mechanical Engineering Science*, vol. 13, no. 3, pp. 235-236, 1973.
13. P.M.Y. Chung, M. Kawaji, A. Kawahara and Y. Shibata, "Two-Phase Flow through Square and Circular Microchannels-Effects of Channel Geometry," *Journal of Fluids Engineering,* vol. 126, pp. 546-552, 2004.

14. D. Krebs, *A Technique for Spatially Resolved Wall Temperature Measurements in Microchannel Heat Sinks Using Infrared Thermography*, M.S. Thesis, Oregon State University, Corvallis, OR, 2008.
15. D. Krebs, V. Narayanan, J. Liburdy and D. Pence, "Local Wall Temperature Measurements in Microchannel Flow Boiling Using Infrared Thermography," ASME paper number HT2008-56253, *ASME Heat Transfer Summer Conference*, August 10-14, 2008, Jacksonville, FL.
16. W. Qu, I. Mudawar, Measurement and Prediction of Pressure Drop in Two-Phase Micro-Channel Heat Sinks, International Journal of Heat and Mass Transfer (46) (2003) 2737-2753.
17. B.J. Daniels, D.V. Pence, J.A. Liburdy, Predictions of Flow Boiling in Fractal-Like Branching Microchannels, Proceedings of the ASME International Mechanical Engineering Conference and Exposition, vol. FED 261, 2005, pp. 359-368.
18. B.J. Daniels, J.A. Liburdy, D.V. Pence Adiabatic Flow Boiling in Fractal-Like Microchannels, Heat Transfer Engineering (20) (2007) 817-825.

Conclusion

Two-phase boiling in fractal-like flow networks has been demonstrated, using a predictive model validated under adiabatic flow conditions, to yield significant advantages in low pressure drop. In the symmetric inlet condition of these particular flow networks is such that incoming bubbles can be distributed uniformly through the initial channels; however, vapor formed inside the flow network can flow upstream. In many cases, the flow is redirected downstream, but depending upon the upstream flow resistance, can flow back into the inlet plenum. Therefore, upstream flow throttling is recommended.

The Taitel and Dukler [1] model well predicts the flow regimes throughout the flow network for gas-liquid flows and the Zivi [11] correlation well predicts the void fraction variations as a function of branch level. The Zivi [11] correlation is also recommended, with the two-phase interaction parameter of Qu and Mudawar [16] for use in the one-dimensional predictive model.

Several issues arose with fabrication of test devices for wall temperature measurements. It is recommended that a different technique be used such that the gold interface layers does not wick into the channels during the bonding process.

Significance

Based on results of this work, a one-dimensional two-phase predictive model has been validated and can be used for optimizing fractal-like flow networks for boiling applications. The utility of the Taitel and Dukler [1] flow regime map and the Zivi [11] void fraction correlation have been validated for a range channel dimensions under identical upstream gas-liquid flow conditions. The apparent void fraction, measured using high-speed-high-resolution imaging has been demonstrated to be a more reliable technique for measuring void fraction determined using gas phase and superficial gas velocities. Flow instabilities still exist in branching flow networks, but the adjacent channel allows for an alternate downstream flow path. Upstream throttling reduces the amplitude of oscillations and the degree of backflow. Finally, the thermal imaging technique was validated and is recommended for future studies of wall surface temperatures.

Patents

None

Awards/Honors/Theses Information

Theses are listed first by their titles, followed by a repeat of the title accompanied by the abstract.

Theses Titles

Daniels, B., 2008, "A Study of Adiabatic and Diabatic Flow Boiling in Parallel Microchannels and Fractal-like Branching Microchannels", PhD Dissertation, Oregon State University, Corvallis, OR.

Edwards, L.M., 2008, "Characterization of Flow Boiling in a Fractal-Like Branching Microchannel Network", M.S. Thesis, Oregon State University, Corvallis, OR.

Krebs, D., 2008, "A technique for spatially resolved wall temperature measurements in microchannel heat sinks using infrared thermography", MS Thesis, Oregon State University, Corvallis, OR.

Kwak, Y., 2008, "Experimental Study of Two-Phase Gas-Liquid Flow in a Microscale Fractal-Like Branching Flow Network, Ph.D. Dissertation, Oregon State University, Corvallis, OR.

Theses Information with Abstracts

Daniels, B., 2008, "A Study of Adiabatic and Diabatic Flow Boiling in Parallel Microchannels and Fractal-like Branching Microchannels", PhD Dissertation, Oregon State University, Corvallis, OR.

A one-dimensional numerical model has been developed to study diabatic and adiabatic flow boiling in microchannels. This model accounts for developing flow effects and variable property effects. The model uses correlations for void fraction and two-phase multipliers found in the literature. The model has been used to study the performance differences between diabatic flow in single-phase and two-phase flow in fractal-like branching channels. It has also been used to examine the performance differences between diabatic two-phase flow boiling in these same fractal-like branching channels and straight parallel channels with identical wall surface areas. The model also was used to study pressure drop and exit quality differences for adiabatic two-phase flow boiling between fractal-like branching channels, with different geometries than the diabatic cases, and parallel channels again with identical wall surface areas. Results from experiments examining flow boiling in fractal-like branching channels are also reported. These results include channel pressure drop and void fraction for mass flow rates ranging from 100 to 225 g/min and inlet subcooling levels of 0 to 5 °C. The fractal-like branching network studied had four branching levels, a length ratio of 0.7071, a channel width ratio of 0.7071, a channel height of 150 um, a total channel length of 18 mm and a terminal channel width of 100 μm. The channel pressure drops varied from 20 kPa to 90 kPa. These results were also compared to results from the 1-D model, and the model showed good agreement with the pressure drop results. The agreement with the void fraction results was not as good driven primarily by noise in the experimental measurement.

Edwards, L.M., 2008, "Characterization of Flow Boiling in a Fractal-Like Branching Microchannel Network", M.S. Thesis, Oregon State University, Corvallis, OR

Based on experimental investigations the present study evaluates flow instability and void fraction in a fractal-like branching microchannel network with rectangular cross-section. The hydraulic diameter of the channels ranged from 308 microns at the inlet to 143 microns at the outlet. The flow network used is characterized by set branching ratios for channel length and width of $L/2^{1/2}$ and $L2^{1/2}$, respectively, and features five branching levels. Tests were performed using DI degassed water heated to an 88°C inlet temperature with a mass flow rate of 10 g/min. Heat fluxes of 1.76 W/cm^2 and 2.64 W/cm^2 were applied to the test device for the given flow rate. Finally, a control valve directly upstream of the test device was throttled until the pressure drop across the valve was roughly 100 times larger than the pressure drop across the test device. For the cases with and without throttling at the inlet, results for inlet pressure oscillation and vapor activity at the inlet and exit of the test device are compared. Frequency of inlet pressure oscillations and the upstream flow of vapor are correlated. In addition, time average void fraction is presented for each branching level for the 10 g/min, 1.76 W/cm^2 case with and without throttling and is compared to predictions form a 1-D model.

Krebs, D., 2008, "A technique for spatially resolved wall temperature measurements in microchannel heat sinks using infrared thermography", MS Thesis, Oregon State University, Corvallis, OR.

A non-intrusive measurement technique for direct quantitative thermal visualization of channel wall temperatures in two-phase microchannel flows using infrared thermography (IRT) is presented. Specifically, the measurement of top channel wall temperatures in a fractal-like branching microchannel silicon heat sink during flow boiling is demonstrated and thoroughly documented. Obtaining quantitative local temperature measurements involving IRT poses significant challenges and requires careful consideration with regard to heat sink design, fabrication and calibration as well as data acquisition, reduction and analysis procedures -- all of which are addressed and discussed in detail. Also discussed and rigorously quantified are the potentially significant measurement uncertainties associated with obtaining non-intrusive, local data of this nature. Results indicate that temperature maps of the microchannel top wall during flow boiling can be obtained with a spatial resolution of 10 μm and an uncertainty varying from 0.82°C-1.67°C at 25 °C and 0.96°C-2.80°C.

Kwak, Y., 2008, "Experimental Study of Two-Phase Gas-Liquid Flow in a Microscale Fractal-Like Branching Flow Network, Ph.D. Dissertation, Oregon State University, Corvallis, OR.

Two-phase gas-liquid flows in microscale fractal-like branching channel flow networks were experimentally studied to assess the validity of existing void fraction correlations and flow regimes based on superficial gas and liquid velocities. Void fractions were assessed using two different methods. First, void fraction data were acquired using a high-speed-high-resolution (HSHR) camera and computed using a slip ratio, defined as gas velocity over liquid velocity. Liquid velocity represents the bulk-averaged liquid velocity as determined by microscale particle image velocimetry (micro-PIV). Gas velocity was determined by averaging gas-liquid velocities made at the channel centerline.

The fractal-like branching channel flow network has five bifurcation levels of different channel widths varying from 400 μm to 100 μm with a fixed channel depth of 250 μm. Each downstream width decreases by 30% whereas the downstream lengths increase by 40%. The total flow length through a single path is approximately 18 mm. Filtered air and Dionized water were used as the gas and liquid working fluids, respectively. Mass flow rates of air and water into each k=0 branch were varied from 0.3 g/min to 2.5 g/min and from 5.2×10^{-5} g/min to 1.2×10^{-2} g/min, respectively. These flow rates yielded superficial air and water velocities through the same branch level between 0.07 m/s and 1.8 m/s and between 0.05 m/s and 0.42 m/s, respectively.

For each branching level, due to an increase in flow area, the superficial liquid and gas flow rates change. A two-phase flow regime map was generated for each level of the fractal-like branching flow network and compared to maps developed using the Taitel and Dukler (1976) model and to maps presented in Chung and Kawaji (2004). Flow regime transitions are well predicted with the Taitel and Dukler (1976) model for each branching level.

Void fraction assessed using the slip ratio shows very good agreement with the homogenous void fraction model for all branching levels. On the other hand, void fraction determined by area-based two-dimensional image analysis shows better agreement with the void fraction correlation of Zivi (1964).

Publications and Abstracts

Publications are listed first by their titles, categorized as either journal and conference papers. The reference information is repeated in the following section along with the abstract of the article.

Publication Titles (Journals and Conferences)

Journal articles

Cullion, R.N., D.V. Pence, J.A. Liburdy and V. Narayanan, 2007, "Void Fraction Variations in a Fractal-Like Branching Microchannel Network," *Heat Transfer Engineering*, Vol. 20, No. 10, pp. 806-816.

Daniels, B.J., J.A. Liburdy and D.V. Pence, 2007, "Adiabatic Flow Boiling in Fractal-Like Microchannels," *Heat Transfer Engineering*, Vol. 20, No. 10, pp. 817-825.

Kwak, Y., D. Pence, J. Liburdy, and V. Narayanan, 2009, "Gas-Liquid Flows in a Fractal-Like Branching Flow Network," *International Journal of Heat and Fluid Flow*, accepted (invited submission).

Krebs, D., Narayanan, V., Liburdy, J., and Pence, D.V., "Spatially Resolved Wall Temperature Measurements During Flow Boiling in Microchannels," *Experimental Thermal and Fluid Science*, in review, (invited submission).

Pence, D., 2009, "The Simplicity of Fractal-Like Flow Networks for Effective Heat and Mass Transfer," *Experimental Thermal and Fluid Science*, accepted (invited submission).

Conference papers

Daniels, B.J., D.V. Pence and J.A. Liburdy, "Predictions of Flow Boiling in Fractal-Like Branching Microchannels," *Proceedings of the ASME International Mechanical Engineering Conference and Exposition*, ASME-FED, v 261, 2005, p 359-368.

Daniels, B., J.A. Liburdy, and Pence, D.V., "Experimental Studies of Adiabatic Flow Boiling in Fractal-like Branching Micro-Channels," Paper # IMECE2008-692340, *Proceedings of the ASME IMECE*, Boston, MA, 2008.

Edward, L., J.A. Liburdy, D.V. Pence, and V. Narayanan, " Flow Boiling Characteristics in a Fractal-like Branching Microchannel Network" Paper # IMECE2008-69239, *Proceedings of the ASME IMECE*, Boston, MA, 2008.

Heymann, D., K. Enfield, D. Pence, and V. Narayanan, "Gradient-Based Optimization of Single-Phase Microscale Fractal-like Branching Channel Heat Sinks," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26, 2008.

Heymann, D., Y. Kwak, L. Edward, V. Narayanan, J. Liburdy, and D. Pence, "Area-Averaged Void Fraction Analysis of Flow Boiling in a Microscale Branching Channel Network," Paper # IPACK2007-33517, *Proceedings of the ASME-JSME Thermal Engineering Summer Heat Transfer Conference*, Vancouver, BC, July 8-12, 2007.

Krebs, D., V. Narayanan, J. Liburdy, and D. Pence, "Local Wall Temperature Measurements in Microchannel Flows using Infrared Thermography," Paper #HT2008-56253, *Proceedings of the ASME Heat Transfer Summer Conference*, Jacksonville, FL, August 10-14, 2008.

Krebs, D., V. Narayanan, J.A. Liburdy, and D.V. Pence, "Transient Surface Temperature Measurements during Flow Boiling in Microchannels," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26, 2008.

Kwak, Y., D. Pence, J. Liburdy, and V. Narayanan, "Liquid and Gas Phase Velocity Measurements for Two Phase Flow in a Branching Microchannel Network," Paper #IMECE2007-41621, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* Seattle, WA, November 11-15, 2007.

Kwak, Y., D. Pence, J. Liburdy, and V. Narayanan, "Gas-Liquid Flows in Fractal-Like Branching Flow Networks," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26, 2008.

Pence, D., "KEYNOTE ADDRESS: The Simplicity of Fractal-Like Flow Networks for Effective Heat and Mass Transport," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26, 2008.

Publication Information with Abstracts

Journal articles with abstracts

Cullion, R.N., D.V. Pence, J.A. Liburdy and V. Narayanan, 2007, "Void Fraction Variations in a Fractal-Like Branching Microchannel Network," *Heat Transfer Engineering*, Vol. 20, No. 10, pp. 806-816.

Based on predictions of lower pressure drop penalties in fractal-like branching channels compared to parallel channels, an experimental investigation of two-phase void fraction variations was performed. The flow network, mimicking flow networks found in nature, was designed with a self-similar bifurcating channel configuration and etched 150 mm into a 38.1 mm diameter silicon disk. A Pyrex® cover was anodically bonded to the silicon disk to allow for flow visualization. The length and width scale ratios between channels on either side of a bifurcation are fixed. The channel widths range in size from 100 mm to 400 μm over a total channel length of approximately 17 mm.

Experimental results of flow boiling are presented for a heater energy input power of 66 W and an inlet water flow rate of 45 g/min at a fixed inlet fluid temperature of 88°C. High-speed, high-resolution imaging was used to visualize the flow and to quantify void fraction values in several channels within a branching structure. Both time-averaged and instantaneous two-dimensional void fraction data are presented, showing correlation between channels at the same bifurcation level and between channels at different bifurcation levels.

Daniels, B.J., J.A. Liburdy and D.V. Pence, 2007, "Adiabatic Flow Boiling in Fractal-Like Microchannels," *Heat Transfer Engineering*, Vol. 20, No. 10, pp. 817-825.

Fractal-like branching channels are proposed for a number of microscale applications, including heat sinks, heat exchangers, absorbers, desorbers, and micro-mixers. Based on model predictions, the benefit of fractal-like channel designs is a lower pressure drop than parallel straight channels for a given flow rate, when compared to an equal channel surface area basis with the terminal channel cross-section of the fractal-like network used to define the parallel channel geometry. The fractal-like flow networks are a unique geometry that follows fractal bifurcation patterns, in this case mimicking the flow patterns found in nature. Two-phase flow applications require an understanding of how the geometric constraints impact the flow characteristics during multiphase flow. One-dimensional modeling predictions are used in this study to asses the relative impact of flow network designs on pressure drop and void fraction distributions for adiabatic flow boiling. The characterization of the flow networks includes a specified branching ratio of channel length and channel width (or diameter) and also the number of branching levels, or bifurcations, in a given length. The goal of the present study is to identify the adiabatic boiling characteristics within the fractal-like flow network and compare results to straight parallel channels. The model used is a compilation of two-phase flow models presented in the literature but modified to include a local two-phase flow parameter, flow re-development, as well as variable property effects. Results are compared with straight channels based on flow boiling conditions, pressure drop, and vapor quality distributions for a range of flow rates and subcooling.

Kwak, Y., D. Pence, J. Liburdy, and V. Narayanan, 2009, "Gas-Liquid Flows in a Fractal-Like Branching Flow Network," *International Journal of Heat and Fluid Flow*, accepted (invited submission).

Two-phase air-water flows in a microscale fractal-like flow network were experimentally studied and results were compared to predictions from existing macroscale void fraction correlations and flow regime maps. Void fraction was assessed using (1) two-dimensional analysis of high-speed images (direct method) and (2) experimentally determined using gas velocities (indirect method). Fixed downstream-to-upstream length and width ratios of 1.4 and 0.71, respectively, characterize the five-level flow network. Channels were fabricated in a 38 mm diameter silicon disk, 250 μm deep disk with a terminal channel width of 100 μm. A Pyrex top allowed for flow visualization. Superficial air and water velocities through the various branch levels were varied from 0.007 m/s to 1.8 m/s and from 0.05 m/s to 0.42 m/s, respectively. Two-phase flow regime maps were generated for each level of the flow network and are well predicted by the Taitel and Dukler model. Void fraction assessed using the indirect method shows very good agreement with the homogeneous void fraction model for all branch levels for the given range of flow conditions. Void fraction determined directly varies considerably from that assessed indirectly, showing better agreement with the void fraction correlation of Zivi.

Krebs, D., Narayanan, V., Liburdy, J., and Pence, D.V., 2009, "Spatially Resolved Wall Temperature Measurements During Flow Boiling in Microchannels," *Experimental Thermal and Fluid Science*, invited submission, accepted pending revisions.

Spatial and temporal variations of channel wall temperature during flow boiling microchannel flows using infrared thermography are presented and analyzed. In particular, the top channel wall temperature in a branching microchannel silicon heat sink is directly measured non-intrusively. Using this technique, time-averaged temperature measurements, with a spatial resolution of 10 µm, are presented over an 18 mm x 18 mm area of the heat sink during flow boiling. Within a specific sub-region of the heat sink, intensity maps are recorded at a rate of 120 frames per second. Time series data at selected locations within this sub-region are analyzed for their frequency content, and dominant temperature fluctuations are extracted using proper orthogonal decomposition.

Results indicate that temperatures can be determined from recorded radiation intensity with a spatial resolution of 10 µm and a temperature uncertainty varying from 0.89 °C at 25 °C to 1.02 °C at 125 °C. The time series data indicate periodic wall temperature fluctuations of approximately 2 °C that are attributed to the passage of vapor slugs. A dominant band of frequencies around 2-4 Hz is suggested by the frequency analysis. Proper orthogonal decomposition results indicate that first six orthogonal modes account for approximately 90 percent of the variance in temperature. The first mode reconstruction accounts for temporal variations in the dataset in the sub-region analyzed; however the magnitude of fluctuations and spatial variations in temperature are not accurately captured. A reconstruction using the first twenty five modes is considered sufficient to capture both the temporal and spatial variations in the data.

Pence, D., 2009, "The Simplicity of Fractal-Like Flow Networks for Effective Heat and Mass Transfer," *Experimental Thermal and Fluid Science*, accepted (invited submission).

A variety of applications using dish-shaped fractal-like flow networks and the status of one and two-dimensional predictive models for these applications are summarized. Applications discussed include single-phase and two-phase heat sinks and heat exchangers, two-phase flow separators, desorbers, and passive micromixers. Advantages to using fractal-like flow networks versus parallel flow networks include lower pressure drop, lower maximum wall temperature, inlet plenum symmetry, alternate flow paths, and pressure recovery at the bifurcation. The compact nature of microscale fractal-like branching heat exchangers makes them ideal for modularity. Major differences between fractal-like and constructal approaches to disk-shaped heat sink designs are highlighted, and the importance of including geometric constraints, including fabrication constraints, in flow network design optimization is discussed. Finally, a simple procedure for designing single-phase heat sinks with fractal-like flow networks based solely on geometric constraints is outlined. Benefit-to-cost ratios resulting from geometric-based designs are compared with those from flow networks determined using multivariable optimization. Results from the two network designs are within 11%.

Conference papers

Daniels, B.J., D.V. Pence and J.A. Liburdy, 2005, "Predictions of Flow Boiling in Fractal-Like Branching Microchannels," *Proceedings of the ASME International Mechanical Engineering Conference and Exposition*, ASME-FED, v 261, 2005, p 359-368.

Single-phase and two-phase flows in microscale fractal-like branching flow networks are studied using a one-dimensional model that includes variable property and developing flow effects. Pressure drop, pumping power, changes in the bulk fluid temperature and a performance parameter are reported for mass flow rates ranging from 25 to 500 g/min and wall heat fluxes from 5 to 40 W/cm2. Two-phase flow through fractal-like flow networks is also compared to flow through a series of parallel channels for identical wall heat fluxes and for flow rates between 25 and 100 g/min. Channel length, height, convective surface area, heat flux and flow rate were the same between the fractal-like and parallel channel array. It was found that single-phase flows through fractal-like flow networks exhibit lower pressure drop and pumping power than do two-phase flows at the same wall heat flux and mass flow rate. The inlet temperature for the single-phase cases is 20°C, whereas the two-phase flow enters as a saturated liquid. The pressure drop and pumping power were always lowest for the fractal-like flow networks compared with the parallel channel arrays for identical heat transfer and flow rates.

Heymann, D., Y. Kwak, L. Edward, V. Narayanan, J. Liburdy, and D. Pence, 2007, "Area-Averaged Void Fraction Analysis of Flow Boiling in a Microscale Branching Channel Network," Paper # IPACK2007-33517, *Proceedings of the ASME-JSME Thermal Engineering Summer Heat Transfer Conference*, Vancouver, BC, July 8-12.

Area-averaged void fraction images of convective boiling in a branching channel heat sink were acquired with a high speed high resolution camera at a rate of 1,000 frames per second for one second. Data sets are limited by the buffer size of the camera. Test conditions include a flow rate of 30 g/min, 30 W of energy added, and a subcooling of approximately 11°C. Time-varying area-based void fraction data were estimated using an image processing algorithm designed to minimize noise. Conditions for upstream bubble growth are reported as are liquid momentum, evaporation momentum, and surface tension forces for two extreme mass fluxes through the channels. Mass fluxes vary for each branching level as well as with the amount of vapor present in the heat sink. The heat sink is 38.1 mm in diameter with a radial branching flow pattern. The ratio of daughter-to-mother branching lengths is equal to 1.4, which is in contrast to a previous investigation in which the length scale ratio was 0.70.

Kwak, Y., D. Pence, J. Liburdy, and V. Narayanan, 2007, "Liquid and Gas Phase Velocity Measurements for Two Phase Flow in a Branching Microchannel Network," Paper #IMECE2007-41621, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* Seattle, WA, November 11-15.

This is a work in progress. The objective of the present work is to develop techniques for assessing velocity deficits in branching microchannel networks. Liquid velocity distributions were acquired using μPIV in gas-liquid flows through the initial branch in a fractal-like branching microchannel flow network. Gas interface velocities were determined along the centerline of the channel. The flow rate of air and water were 0.0016 g/min and 20 g/min, respectively. The primary observed flow regime was elongated bubbles. Experimental liquid velocities well matched the 0.20 m/s superficial liquid velocity. Experimental interface velocities were approximately an order of magnitude higher than the superficial gas velocity of 0.01 m/s. Velocity deficits based on measurements are on the order of 0.065 m/s. Using interfacial velocities at the channel centerline, the trailing edge velocity was observed to be 15% percent faster, on average, than the leading edge velocity. This could be attributed to bubbles expanding into the bifurcation. Twenty percent standard deviations in average interface velocities were attributed to insufficient samples as well as projected to be a consequence of changing shape of the interface between consecutive image pairs. Changes in bubble shape may also be responsible for the observed differences between leading and trailing edge velocities.

Heymann, D., Young, J., Cardenas, R., 2007, "Non-Intrusive Unilateral Measurements of Void Incidence within a Microchannel", Proc. of IMECE 2007, Seattle, WA, USA, IMECE2007-42009.

Void fraction measurements are used to characterize two-phase flow within a microchannel. Limitations of typical void fraction measurement systems include disruption of the flow (intrusive optical probe) and non-continuous data acquisition. Using the principles of total internal reflection, a Non-Intrusive Void Incidence Sensor (NIVIS) has been developed to determine the void incidence (frequency of a vapor bubble passing a known position in the channel). Continuous data can be recorded with a typical computer. A light beam is introduced through a fiber optic to the outside of a transparent channel wall at a critical angle. This critical angle is designed such that when a vapor bubble is present at the specified location, total internal reflection will occur. An output fiber is fixed in a determined position to receive light in the case of total internal reflection. Without the presence of a vapor bubble, the light beam will be reflected past the output fiber. A substantial increase in output signal is noticed when total internal reflection occurs. Characteristics of the NIVIS, proven during non-intrusive testing, include: continuous data acquisition of bubble incidences, measurements within a 100 micron wide channel, and bubble boundary differentiation.

Daniels, B., J.A. Liburdy, and Pence, D.V., 2008 , "Experimental Studies of Adiabatic Flow Boiling in Fractal-like Branching Micro-Channels," Paper # IMECE2008-692340, *Proceedings of the ASME IMECE*, Boston, MA,.

Adiabatic flow boiling experiments in micro-scale fractal-like branching channels have been performed in fractal-like branching channels. Flow rates were varied between 100 g/min and 250 g/min, and the inlet sub-cooling was also varied between 1 and 5 degrees. The resulting exit qualities ranged between 0.01 and 0.03, and the pressure drops ranged between 20 and 100 kPa. Images were analyzed to measure the void fraction within the branching channels. The branching channels used in this are scaled similarly to the distribution systems found in nature, e.g. the veins in a leaf and the human circulatory and respiratory systems. In these branching channel networks, each channel bifurcation maintains constant width and length ratios between the upstream and downstream levels. Branching channel networks are arranged in a circular heat sink where the fluid enters the inlet plenum at the center of the disk, and exits through the terminal branching level at the periphery of the disk. The heat sink used had 16 branching channel networks feeding off the inlet plenum, four branching levels, a terminal channel with of 100 um, a channel height of 150 um, and a total channel length was 18 mm. The experimental results are compared to results from a one dimensional model which is based on existing two-phase frictional pressure drop and void fraction correlations developed for mini- and micro-scale flows. The model also includes effects due to compressibility, variable fluid properties and developing flow. It is shown that some correlation combinations result in model pressure drop predictions that agree well with experimental results with an average deviation of less than 5% and a maximum deviation of less than 15%.

Edward, L., J.A. Liburdy, D.V. Pence, and V. Narayanan, 2008, " Flow Boiling Characteristics in a Fractal-like Branching Microchannel Network" Paper # IMECE2008-69239, *Proceedings of the ASME IMECE*, Boston, MA.

The present study evaluates flow instability and void fraction in a fractal-like branching microchannel network with a rectangular cross-section. The hydraulic diameter of the channels ranged from 308μm at the inlet to 143μm at the outlet. The flow network is characterized by set branching ratios for channel length and width of $1/\sqrt{2}$ and $\sqrt{2}$, respectively, and features five branching levels. Test were performed using deionized, degassed water heated to an 88°C inlet temperature with a mass flow rate of 10g/min. Heat fluxes of 1.76 W/cm^2 and 2.64 W/cm^2 were applied to the test device for the given flow rate. An upstream control valve was used to throttled the flow with a pressure drop approximately 150 times larger than the pressure drop across the test device. For the cases with and without throttling results for inlet pressure oscillation frequency and vapor activity at the inlet of the test device are compared. In addition, time averaged void fraction is compared for each branching level with and without throttling and is compared to predictions from a 1-D model. Results show good agreement between model and experiments in the average void fraction although local values differ significantly.

Heymann, D., K. Enfield, D. Pence, and V. Narayanan, 2008, "Gradient-Based Optimization of Single-Phase Microscale Fractal-like Branching Channel Heat Sinks," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26.

Fractal-like branching flow networks in disk-shaped heat sinks were numerically optimized using a gradient-based search method to minimize pressure drop and flow power. A previously validated one-dimensional pressure drop and heat transfer model, with water as the working fluid, was employed. Geometric constraints based on fabrication limitations were considered, and the optimization methodology was validated using a direct numerical search.

The geometric parameters that define an optimal flow network in the present investigation include the length scale ratio, width scale ratio, and terminal channel width. Along with disk radius, these parameters influence the number of branch levels and number of channels attached to the inlet plenum. The geometric characteristics of the optimized flow networks were studied as a function of disk radius, applied heat flux, and maximum allowable wall temperature. A maximum inlet plenum radius, range of terminal channel widths, and minimum interior and periphery channel spacing were specified geometric constraints. In general, all geometric constraints and the heat flux had a significant influence on the optimal flow network design as well as on the benefit-to-cost ratio, which is defined as advected energy divided by flow power.

Krebs, D., V. Narayanan, J. Liburdy, and D. Pence, 2008, "Local Wall Temperature Measurements in Microchannel Flows using Infrared Thermography," Paper #HT2008-56253, *Proceedings of the ASME Heat Transfer Summer Conference*, Jacksonville, FL, August 10-14.

Quantitative measurement of channel wall temperature in two-phase microchannel flows using infrared thermography is discussed. In particular, the top channel wall temperature of a branching microchannel silicon heat sink is presented. Quantitative temperature measurements require several considerations in the design and fabrication of the heat sink and test facility, in calibration, and in data analysis; each of these are discussed. Temperature measurements, with a spatial resolution of 10 μm, are presented over an 18 mm x 18 mm area of the heat sink during flow boiling.

Krebs, D., V. Narayanan, J.A. Liburdy, and D.V. Pence, 2008, "Transient Surface Temperature Measurements during Flow Boiling in Microchannels," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26.

A technique to measure temporal and spatial temperature variations during flow boiling is presented. As an illustration, the top channel wall temperature in a branching microchannel silicon heat sink is determined by measurement of radiation intensities using infrared thermography. Intensity maps at a region encompassing the 0th and 1st branching levels of the heat sink were recorded at a rate of 120 frames per second. Time series data at selected locations within this imaging area is analyzed for their frequency content. Dominant temperature fluctuations are extracted using proper orthogonal decomposition (POD) within a relevant sub-section of the imaging area.

The time series data indicate periodic wall temperature fluctuations of approximately 2 oC that are attributed to the passage of vapor slugs. A dominant band of frequencies around 2-4 Hz is suggested by the frequency analysis. Six dominant orthogonal modes account for approximately 90 percent of the variance in temperature. The first mode reconstruction accounts for temporal variations in the dataset; however the magnitude of fluctuations and spatial variations in temperature are not accurately captured. A reconstruction using the first twenty five modes is considered sufficient to capture both the temporal and spatial variations in the data.

Kwak, Y., D. Pence, J. Liburdy, and V. Narayanan, 2008, "Gas-Liquid Flows in Fractal-Like Branching Flow Networks," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26.

Two-phase air-water flows in a microscale fractal-like flow network were experimentally studied and results compared to predictions from existing macroscale void fraction correlations and flow regime maps. Void fraction was assessed using (1) two-dimensional analysis of high-speed images (direct method) and (2) experimentally determined using gas velocities (indirect method).

Fixed downstream-to-upstream length and width ratios of 1.4 and 0.71, respectively, characterize the five-level flow network. Channels were fabricated in a 38 mm diameter silicon disk, 250 μm deep disk with a terminal channel width of 100 μm. A Pyrex top allowed for visualization. Superficial air and water velocities through the various branching levels were varied from 0.007 m/s to 1.8 m/s and from 0.05 m/s to 0.42 m/s, respectively.

Two-phase flow regime maps were generated for each level of the flow network and are well predicted by the Taitel and Dukler model. Void fraction assessed using the indirect method shows very good agreement with the homogeneous void fraction model for all branch levels for the given range of flow conditions. Void fraction determined directly varies considerably from that assessed indirectly, showing better agreement with the void fraction correlation of Zivi.

Pence, D., 2008, "KEYNOTE ADDRESS: The Simplicity of Fractal-Like Flow Networks for Effective Heat and Mass Transport," *Proceedings of the Engineering Conference International Heat Transfer and Fluid Flow in Microscale III*, Whistler, BC, Canada, September 21-26.

A variety of applications using dish-shaped fractal-like flow networks and the status of one and two-dimensional predictive models for these applications are summarized. Applications discussed include single-phase and two-phase heat sinks and heat exchangers, two-phase flow separators, desorbers, and passive micromixers. Advantages to using fractal-like flow networks versus parallel flow networks include lower pressure drop, lower maximum wall temperature, inlet plenum symmetry, alternate flow paths, and pressure recovery at the bifurcation. The compact nature of microscale fractal-like branching heat exchangers makes them ideal for modularity.

Major differences between fractal-like and constructal approaches to disk-shaped heat sink designs are highlighted, and the importance of including geometric constraints, Two-phase air-water flows in a microscale fractal-like flow network were experimentally studied and results compared to predictions from existing macroscale void fraction correlations and flow regime maps. Void fraction was assessed using (1) two-dimensional analysis of high-speed images (direct method) and (2) experimentally determined using gas velocities (indirect method).

Fixed downstream-to-upstream length and width ratios of 1.4 and 0.71, respectively, characterize the five-level flow network. Channels were fabricated in a 38 mm diameter silicon disk, 250 μm deep disk with a terminal channel width of 100 μm. A Pyrex top allowed for visualization. Superficial air and water velocities through the various branching levels were varied from 0.007 m/s to 1.8 m/s and from 0.05 m/s to 0.42 m/s, respectively.

Two-phase flow regime maps were generated for each level of the flow network and are well predicted by the Taitel and Dukler model. Void fraction assessed using the indirect method shows very good agreement with the homogeneous void fraction model for all branch levels for the given range of flow conditions. Void fraction determined directly varies considerably from that assessed indirectly, showing better agreement with the void fraction correlation of Zivi.including fabrication constraints, in flow network design optimization is discussed. Finally, a simple procedure for designing single-phase heat sinks with fractal-like flow networks based solely on geometric constraints is outlined. Benefit-to-cost ratios resulting from geometric-based designs are compared with those from flow networks determined using multivariable optimization. Results from the two network designs are within 11%.