Experimental Investigation of Fluid Flow and Heat Transfer in Microchannels

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Abstract

Due to the high performance of electronic components, the heat generation is increasing dramatically. Heat dissipation becomes a significant issue in efficiency promotion and stable operation. Silicon based microchannel heat sink fabricated using semiconductor production technique plays an important role in cooling devices. Experimental tests and theoretical analyses were conducted to investigate the characteristics of fluid flow and heat transfer in microchannel heat sink in this paper, especially in the mechanism of bubble nucleation.

Methanol was used as the working fluid and flowed through microchannels with different hydraulic diameters ranging from 57–267 μm in the experiments. Experimental results of flow characteristics indicated that the flow behavior was in the laminar regime when Re = 50–850, the phenomena of early transition didn't exist. The phenomenon shows that the surface roughness, viscosity, and channel geometry have great effects on flow characteristics in microchannels.

Experimental results in heat transfer indicted that forced convection in microchannel heat sink exhibited excellent cooling performance, especially in the phase change regime. It will be applied as heat removal and temperature control devices in high power electronic components. When the critical nucleate heat flux condition appeared, flow mechanism changed into fully developed nucleate boiling and accompanied with wall temperature decreased rapidly and pressure drop increased sharply. Experimental results also indicated that the critical bubble size of methanol was between 57–83 μm.

***Key Words*:** Microchannel, Mechanism of Bubble Nucleation, Hydraulic Diameters, Critical Nucleate Heat Flux

1. Introduction

The development of micro cooling technology is mainly for solving the heat dissipation of precision and compact electronic components; such as micro miniature refrigerators, micro heat pipe spreader, micro heat exchanger, and micro channel heat sink proposed in this study. It is surely necessary to not only theoretical but also experimental the forced convection in micro channel heat sink for the arising demands for future heat removal of the electronic components.

The microchannel heat sink under the Micro-Electro-Mechanical Systems (MEMS) has first been illustrated in 1981 [1]. Their theoretical analyses and experimental tests were conducted to investigate the characteristics of heat transfer in the microchannel heat sink. Up to 790 W/cm^2 of heat flux was implemented to Very Large Scale Integration (VLSI) with high power density. Zhimin and Kok-Fah [2] have also integrated the optimum design considering the laminar and turbulent flows in the channels to construct a thermal resistance model for simulating the fluid dynamics and heat transfer characteristics in the microchannel heat sinks. Many researchers [3,4] indicated that the prediction of heat transfer in the micro devices varied from that in macro devices. Pfahler et al. [5] and Choi et al. [6] proposed the experimental results to show the different fluid and heat characteristics in the micro and macro channels as well as the tubes. Their works definitely provided the valuable conception in the heat and fluid properties of the single-phase flows.

Mohiuddin-Mala and Li [7] experimentally investigated the fluid characteristics for the silica and stainless tubes of hydraulic diameters ranging from 50 to 254 μm. Qu Weilin et al. [8] have also studied the behaviors for trapezoid silicon microchannels of a hydraulic diameter from 51 to 169 μm. Their results have contradicted the conventional macochannels with much effective heat.

Many researchers [9–15] have focused on the heat behavior during phase transformation. It has been observed that no bubbles from nucleate boiling occurred in microchannels even with the high heat flux. The evidence that the channel size is a critical parameter to the phase change is a major approach to the future research of two-phase fluid.

Peng and Wang [16–18] have then analyzed the boiling characteristics and heat phenomenon, especially the formulation and growth of the bubbles, to obtain the effects of the channel. Their results showed that it is almost impossible to have nucleate boiling in the microchannels. However, Linan Jiang et al. [19] have conducted the in-situ measurement to explore the two-phase behaviors of nitrogen in silicon microchannels of hydraulic diameter from 40 to 80 μm. It was shown that no plateau but steeply rising of the wall temperature in boiling curve when reaching the critical heat flux.

This paper not only proposes the micro-channels with anisotropic etching on the (100) silicon wafer, but also examine the process of fluid flow and heat transfer, especially the mechanism of bubble nucleation. Through the fluid behaviors and the thermal phenomenon discussed in this study, the demand for future heat removal among the electronic components is concretely solvable.

2. Fabrication and Package

This paper analyzes the fluid performance and phase change in the microchannels. The microchannels are silicon based through the bulk micro-machining and anodic bonding. The methanol is introduced as the working fluid.

After anisotropic wet etching, {111} and {100} bottoms are received on the (100) silicon wafer. The average roughness (R_a) of less than 0.1 μm is achieved on the bevels. The fabrication process of the microchannels; which includes thin film deposition, photolithography and dopant diffusion, is shown in Figure 1. Therefore, the grooved microchannels are (see Figure 2), and then packaged with Pyrex # 7740 glass through anodic bonding.

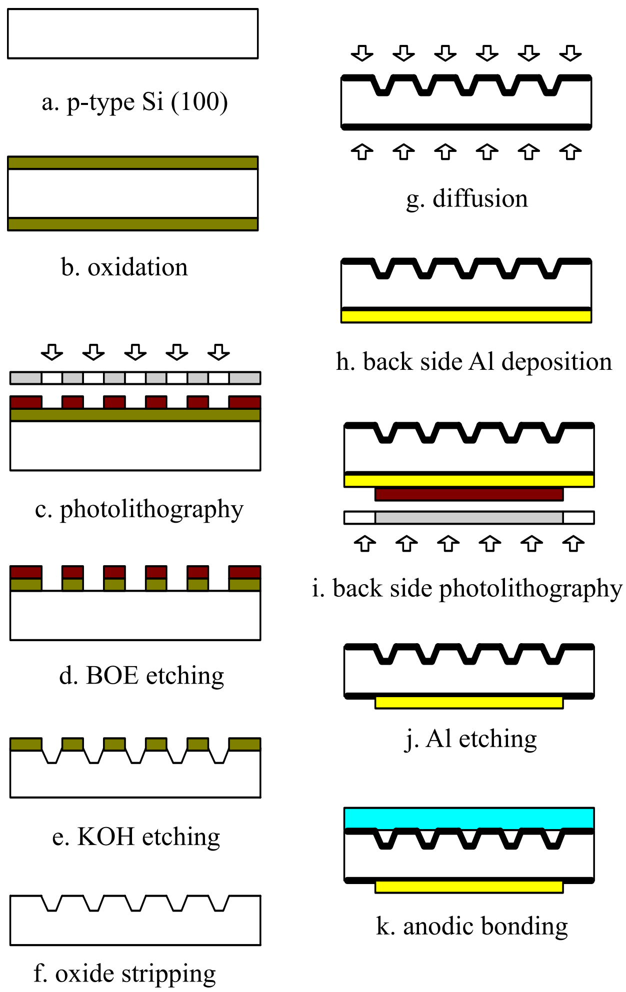

Figure 1. The fabrication process of silicon microchannels.

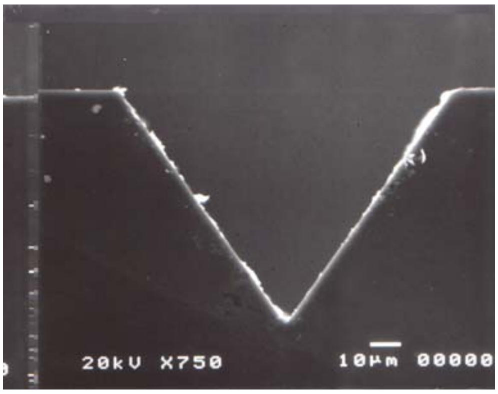

Figure 2. The micrograph of the triangular channel.

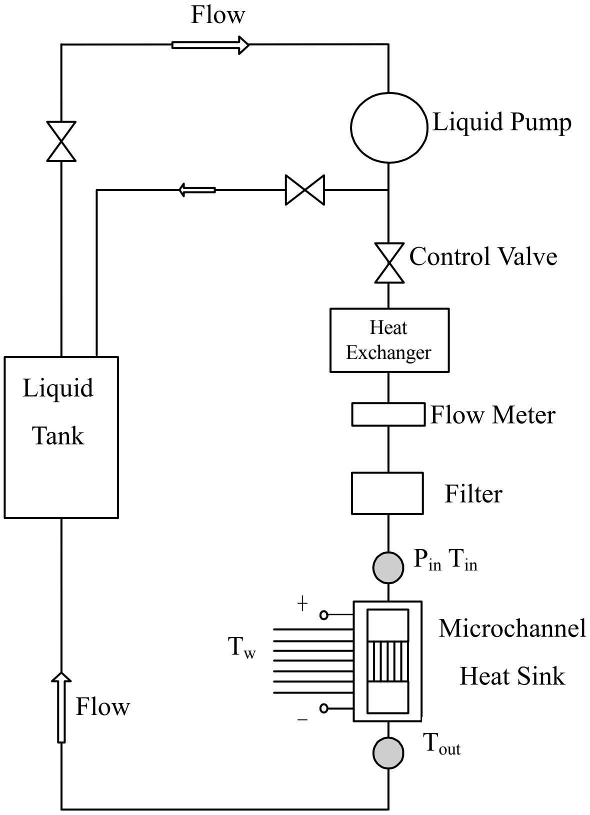

Figure 3. The experimental layout.

3. Experimental Layout and Measurement

3.1 Experimental Setup

This paper applies the heating resistance as the thermal source in the electronics device and methanol as the working fluid to evaluate the heat transfer in microchannels. The detailed experimental drawing, including liquid tank, liquid pump, 5 μm filter, flow meter, heat exchanger, is shown as Figure 3. The arrangement of thermal-couples for the measurement and the geometry explanation of the microchannel heat sink are shown in Figure 4.

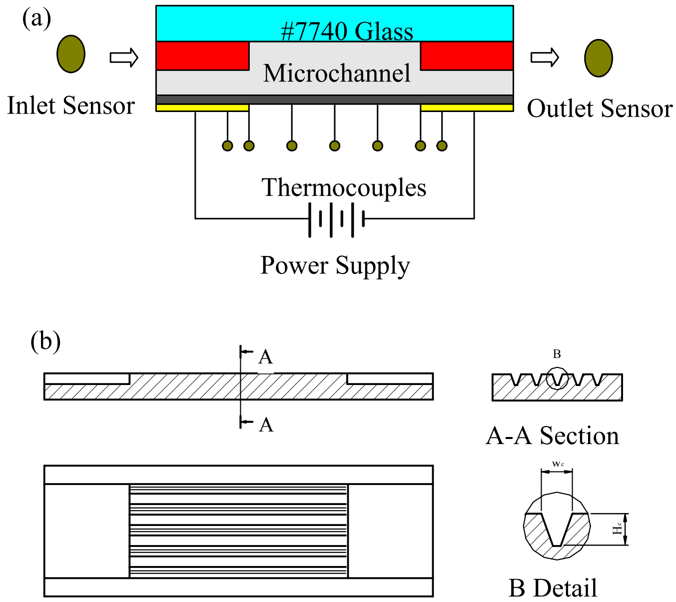

Figure 4. The thermocouple arrangement (a) and geometry explanation, (b) of microchannel heat sink.

3.2 The Measurement

The working fluid remains at a constant temperature by the liquid tank and heat exchanger, and then pumped through the filter that prevents the extraneous particles and air to the flow meter and micochannels. The thermo-couples and the pressure sensors are settled into both the inlet and outlet of the microchannel heat sink to the temperature as well as the pressure drop. The thermo-couples are also attached to the back of the micro channel heat sink for the measurement of the wall temperature. Under steady state, all data in each experiment can be obtained through the data acquisition system, and then transferred to the computer for computation.

4. Theoretical Preparation

There are two parts of theoretical analysis in this paper. They are presented as follows.

4.1 Analysis of Fluid Flow

The theoretical and the experimental friction factor are expressed as

$$f_{thy} = \frac{64}{Re} \tag{1}$$

$$f_{exp} = \frac{2 g_c \Delta P D_h}{L \rho_f V_f^2} \tag{2}$$

Table 1
Specification of the sink

Chip name	Width (μm) W_c	Depth (μm) H_c	Hydraulic diameter (μm)	Number of channel
Chip 1	400	260	221	10
Chip 2	300	130	150	13
Chip 3	250	184	134	15
Chip 4	200	148	109	19
Chip 5	150	113	83	25
Chip 6	100	78	57	38

*length of microchannels L = 15000 μm

and, the pressure drop between inlet and outlet of a channel is described as

$$\Delta P_{loss} = K\frac{\rho_f V_f^{\ 2}}{2g_c} \tag{3}$$

The theoretical friction factor is computed for the macrochannels by Eq. (1). The experimental friction factor is build from the experimental measurement by Eq. (2), and then compared to the theoretical. On the measurement of pressure drop, the pressure cannot be in-situ measured by the sensor because of the micro scale of the channels. Therefore, the pressure measured should subtract the pressure loss (ΔP_{loss}) shown in Eq. (3), where K is the pressure loss coefficient. Thus, K = 1.0 for the inlet and K = 0.5 for the outlet [8] are also suggested in this study.

4.2 Analysis of Heat Transfer

The heat flux is commonly stated as

$$q'' = \frac{rIV}{LW} \tag{4}$$

Here, V and I denote the voltage and current delivered from the power supply,respectively. And, L and W present the overall channel length and channel width, respectively. The mended factor, r, in Eq. (4) is applied to describe the sensible heat held in between the inlet and outlet.

5. Experimental Results

The experiments are conducted for various channel geometries under different flows. Additionally, the flow visualization is used to describe the experimental results. Further, the uncertainties involved in the measurements were analyzed and evaluated [21] which are given in Table 2.

Table 2
Experimental uncertainties

Parameter	Uncertainty (%)
Flow rate	5.0
Pressure drop	2.0
Temperatures	1.0
Reynolds number	5.4
Friction factor	10.5

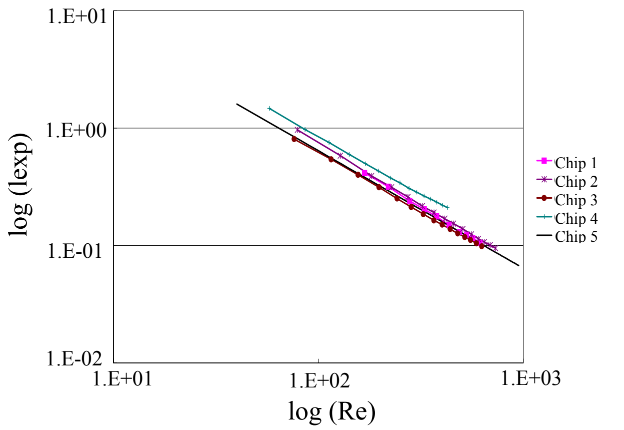

Figure 5. Exponential relations between the friction factor and the Reynolds number.

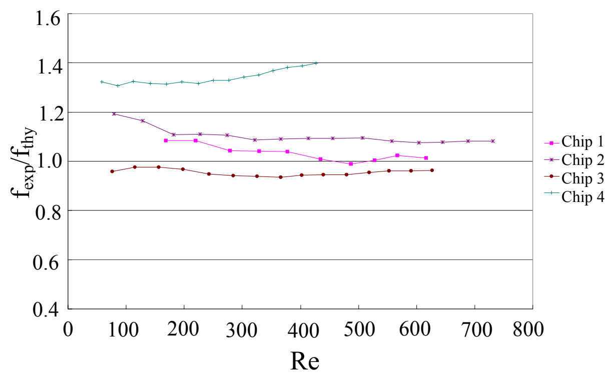

Figure 6. f_{exp}/f_{thy} and the Reynolds number.

5.1 The Fluid Flow Experiment

To analyze the friction factor, the specifications of the sink are listed in Table 1. Chip 1–4 are prepared for fluid flow experiment. Figure 5 shows the exponential relations between the friction factor and the Reynolds number. This denotes to be the laminar flow and the friction factor is decreasing with the power of Reynolds number. The computed value of f_{exp}/f_{thy} ranged from 0.9 to 1.4 is shown in Figure 6, which matches the range of 1.0–1.6 by Mohiuddin-Mala [7].

5.2 The Heat Transfer Experiment

Six different microchannel geometries in Table

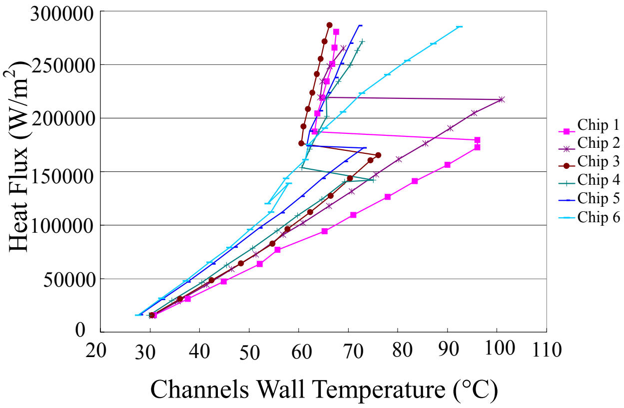

Figure 7. The heat flux and channel wall temperature.

1 are selected for the heat transfer experiment. The results are shown in Figure 7 and 8. In Figure 7, it is observed that the phenomenon of decreasing wall temperature during phase change is the same as Peng and Wang [12].

Figure 8 shows the relation between the inlet/outlet pressure drop and the wall temperature. It is observed to have two sections, the single-phase section and the phase transformation section. In the single-phase section, the pressure drop between the inlet and outlet is obviously reduced with the wall temperature rises as the hydraulic diameter gets smaller. This is because of the viscosity coefficient of working fluid decreases with the temperature. When the channel wall temperature reaches the critical point for phase change, the fluid rapidly absorbs the accumulated energy on the channel for the violent nucleate boiling. Therefore, the tiny bubbles are formulated to sharply increase the pressure drop. After the severe nucleate boiling, the wall temperature greatly decreases and boiling phenomenon decelerates and the inlet/outlet pressure drop diminishes. Finally, the wall temperature grows again and much severe nucleate boiling follows to continuously boost the pressure drop. It is also observed with flow visualization that there exists the nucleate boiling at the channel inlet. This retards the fluid flow and the pressure drop is thus suddenly enlarged. From Figure 8, it is noted that the result for Chip 6 is different from others. The channel temperature hardly decreased from the phase change, the heat transfer coefficient barely reduced from the high channel wall temperature, and the inlet/outlet pressure drop did not rapidly diminish from the severe nucleate boiling. Therefore, it is found that the nucleate boiling occurs between Chip 5 and Chip 6. With this viewpoint, the critical bubble size of methanol is recognized to be in between 57–83 μm.

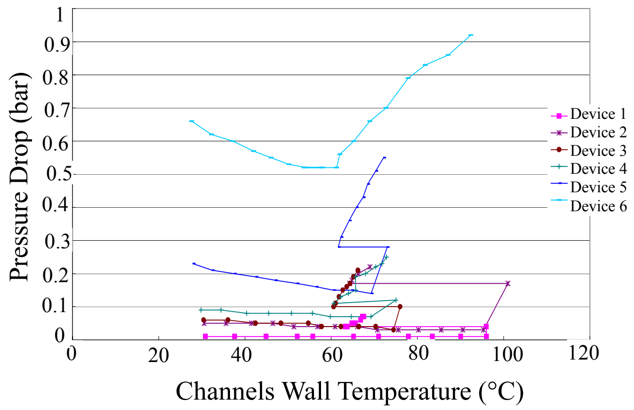

Figure 8. The pressure drop and channel wall temperature.

6. Conclusions

This paper experimentally studies the characteristics on both fluid flow and heat transfer of methanol in the (100) silicon microchannel heat sink. This paper applies methanol as working fluid in the hydraulic diameter of 57–267 μm to examine the friction characters of the fluid flow in the microchannels, the heat convection capabilities in the phase change as well as in a single-phase flow, and the mechanism of bubble nucleation.

On the aspect of fluid characteristics, the friction factor with respect to the Reynolds number is experimentally studied in this paper. It is shown that the effects of the friction and viscosity coefficient for the fluid in the microchannels are much significant than the macros.

In the heat transfer characteristics, the experimental results show that the phase changing process in the microchannels absorbs the heat and reduces the working temperature of the environment. Additionally, the hydraulic diameter of the microchannels larger than 83μm is possible for bubble nucleation is obtained and the critical bubble nucleation for methanol between 57–83 μm is also found.

This study surely contributes a valuable approach to the micro cooling technology for solving the heat dissipation of precision and compact electronic components. Future researches with the in-situ temperature measurement in the microchannels to elaborate the results of this study are fully encouraged.

Parameters and Notations

f_{thy}: theoretical friction factor

f_{exp}: experimental friction factor

g_c: unit change factor (1.0 kg m/N s^2)

L: overall channel length (m)

D_h: hydraulic diameter of the microchannel (m)

ΔP: pressure drop between inlet and outlet (pa)

ρ_f: density of working fluid (kg/m^3)

V_f: velocity of working fluid (m/s)

ΔP_{loss}: pressure loss between inlet and outlet (pa)

K: pressure loss coefficient

q'': heat flux (W/m^2)

γ: mended factor

I: current delivered from the power supply (Amp)

V: voltage delivered from the power supply (volt)

W: channel width (m)

References

[1] Tuckerman, D. B. and Pease, R. F. W., "High-Performance Heat Sinking for VLSI," *IEEE Electronic Device Letters*, Vol. EDL-2, pp. 126–129 (1981).

[2] Zhimin, W. and Kok-Fah, C., "The Optimum Thermal Design of Microchannel Heat Sinks," *IEEE/CPMT Electronic Packaging Technology Conference*, pp. 123–129 (1997).

[3] Yang, W. J. and Zhang, N. L., "Micro- and Nano-scale Heat Transfer Phenomena Research Trends," *Transport Science and Technology*, pp. 1–15 (1992).

[4] Peterson, G. P. and Ortega, A., "Thermal Control of Electronic Equipment and Devices," *Advances in Heat Transfer*, Vol. 17, pp. 181–314 (1990).

[5] Pfahler, J., Harley, J., Bau, H. H. and Zemel, J., "Liquid Transport in Micron and Submicron Channels," *J. Sensors Actors A*, Vol. 21–23, pp. 431–434 (1990).

[6] Choi, S. B., Barron, R. F. and Warrington, R. O. "Liquid Flow and Heat Transfer in Microtubes," *ASME Micromechanical Sensors, Actuators and Systems*, Vol. 32, pp. 123–128 (1991).

[7] Mala, G. M. and Li, D., "Flow Characteristics of Water in Micro Tubes," *Int. J. Heat and Fluid Flow*, Vol. 20, pp. 142–148 (1999).

[8] Weilin, Q., Mala, G. and Li, M. D., "Pressure-driven Water Flows in Trapezoidal Silicon Microchannels," *Int. J. Heat and Mass Transfer*, Vol. 43, pp. 353–364 (1999).

[9] Peng, X. F., Peterson, G. P. and Wang, B. X., "Frictional Flow Characteristics of Water Flowing through Rectangular Microchannels," *Experimental Heat Transfer*, Vol. 7, pp. 249–264 (1994).

[10] Peng, X. F. and Wang, B. X., "Forced Convection and Flow Boiling Heat Transfer for Liquid Flowing through Microchannels," *Int. J. Heat Mass Transfer*, Vol. 36, pp. 3421–3427 (1993).

[11] Wang, B. X. and Peng, X. F., "Experimental Investigation on Liquid Forced Convection Heat Transfer through Microchannels," *Int. J. Heat Mass Transfer*, Vol. 37 Suppl. 1, pp. 73–82 (1994).

[12] Peng, X. F., Peterson, G. P. and Wang, B. X., "Heat Transfer Characteristics of Water Flowing through Microchannels," *Experimental Heat Transfer*, Vol. 7, pp. 265–283 (1994).

[13] Peng, X. F., Wang, B. X., Peterson, G. P. and Ma, H. B., "Experimental Investigation of Heat Transfer in Flat Plates with Rectangular Microchannels," *Int. J. Heat and Mass Transfer*, Vol. 38, pp. 127–137 (1995).

[14] Peng, X. F. and Peterson, G. P. "The Effect of Thermofluid and Geometrical Parameters on Convection of Liquids through Rectangular Microchannels," *Int. J. Heat and Mass Transfer*, Vol. 38, pp. 755–758 (1995).

[15] Peng, X. F. and Peterson, G. P., "Convective Heat Transfer and Flow Friction for Water Flow in Microchannel Structure," *Int. J. Heat and Mass Transfer*, Vol. 39, pp. 2599–2608 (1996).

[16] Peng, X. F., Hu, H. Y. and Wang, B. X., "Boiling Nucleation during Liquid Flow in Microchannels," *Int. J. Heat and Mass Transfer*, Vol. 41, pp. 101–106 (1998).

[17] Peng, X. F., Hu, H. Y. and Wang, B. X., "Flow Boiling through V-shape Microchannels," *Experimental Heat Transfer*, Vol. 11, pp. 87–90 (1998).

[18] Peng, X. F. and Wang, B. X., "Boiling Characteristics in Microchannels/Microstructures," *The 11th Int. Symposium on Transport Phenomena*, ISTP-11, pp. 485–491 (1998).

[19] Jiang, L., Wong, M. and Zohar, Y., "Phase Change in Microchannel Heat Sinks with Integrated Temperature Sensors," *J. of Microelectromechanical System*, Vol. 8, pp. 358–365 (1999).

[20] Holman, J. P., *Experimental Methods for Engineers*, McGraw-Hill, NY, U.S.A., pp. 37–57 (1989).

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