

Bubble Dynamics and Boiling Heat Transfer in Microscale

J.L. Xu, W. ZHANG, C.X. ZHAO, Y.H. GAN, Q.C. SU
Guangzhou Institute of Energy Conversion
Chinese Academy of Sciences
Nengyuan Road, Wushan, Guangzhou, 510640
P.R. CHINA

Abstract:-Bubble dynamics and boiling heat transfer are received great attention in recent years, due to the wide applications in micro devices or systems. The literature is becoming rich in conventional microchannels. One should be careful to apply these results in silicon microchannels, which have much smoother wall surface and smaller channel size. The fundamental issues related to non-dimensional parameters, bubble nucleation, flow patterns, flow instabilities and heat transfer mechanisms are reviewed in this paper. Besides, future studies on the bubble dynamics and boiling heat transfer are suggested.

Key-Words:- Microchannel, boiling, bubble nucleation, flow pattern, heat transfer

1 Introduction

Microelectronics with the integrated circuits and the progress in information technology has changed the way of life, working, discovering and inventing. Moving to the limit of photolithography, the development pace is expected to slow down to double of the density every 24 months [1].

The development of miniaturized non-electrical devices or systems started much later than microelectronics. In the later seventies, silicon technologies were used to fabricate the mechanical microdevices, which were later called as the micro-electro-mechanical systems (MEMS). Among all of the MEMS devices or systems, an important classification is the microfluidics, relevant to flow and heat transfer using fluids in micro devices. The mass or volume of the working fluid in such miniature device is so small that we call it as microfluidic.

As commonly recognized, bubble dynamics and boiling heat transfer in microscale can fulfill the energy conversion with high efficiency, or mass transportation at nearly constant fluid temperatures. The following are the examples for its applications.

Micro evaporators can be used for the high heat flux electronic cooling. The recent development of the integrated circuits may have the heat flux in the order of $100W/cm^2$. Cooling of the IC chip becomes a challenge issue at such high heat fluxes [2]. Maurya and Lahiri [3]

developed a silicon MEMS vaporizing microthruster (VLM) with an internal p-diffused microheater. The device uses two micromachined, bonded silicon chips, producing thrusts in the range of $5\mu N$ to $120\mu N$ with a heating power of 1W to 2.4W at a water flow rate of $1.6\mu l/s$. In such a micro device, the bubble dynamics in microscale is a key factor affecting its operation. Yin and Prosperetti [4] reported a simple micropump, which is suitable for electrolytes, in terms of the periodic growth and collapse of a single vapor bubble in a microchannel. The size of the microchannel is in the order of $100\mu m$. The pump is noted to be simplicity, effectiveness, and absence of mechanical moving parts. A micro-thermal bubble, which is generated by a micro-heater under pulse heating, can be acted as an actuator for application in micro-bio-analytical-system (Deng et al.[5]). A specific designed non-uniform width micro-heater ($10\times 3\mu m^2$) can induce highly localized near-homogeneous bubble nucleation and results in periodic generation of stable single bubbles in deionized water. The voltage pulse applied on the internal micro-heater is in milliseconds.

Microfluidic devices or systems are being developed with fast pace in recent years, due to the great application potentials in biology and information technologies. Fresh ideas are being proposed. Some of them are entering the industry

market. A well known example of the bubble dynamics applications is the ink-printer device.

Most studies in this area are focused on the bubble dynamics and boiling heat transfer in microchannels. Some results are cited using copper or other metal heat sinks.

2 How big is the “microchannels”

If the channel characteristic size is in the range of $1 \mu m$ to $1 mm$, it is called as “micro” [6]. Because this definition has so wide range, different subranges yield different microscale effects. The typical microscale effects for single-phase flow and heat transfer are: slip flow on the solid/fluid interface, viscous dissipation effect, electronic-double-layer effect etc. [6,7,8]. Size effects are also different for gas and liquid. Rarefaction effects are important for gas flow. Pressure gradient along the flow direction may be nonlinear for gas flowing in microchannels at high flow rates. However, liquids have densities that may be one thousand times of gas. Liquid molecules are closely packaged with each other. Slip flow may not occur for liquids flowing in microchannels in micron scale.

Surface tension force is important for two-phase flow and heat transfer. When the characteristic size satisfies the criterion of $\sqrt{\sigma / g(\rho_f - \rho_g)}$, the microscale effects become evident [9]. Because this criterion relates to the physical properties of the working fluids, the critical size that the surface tension force becomes dominant, which is somehow different for different working fluids. Kandlikar [9] summarized the following definitions of hydraulic diameters attributed to different channels: conventional channels larger than $3 mm$, minichannels in the range of $200 \mu m$ to $3 mm$, microchannels in the range of 10 to $200 \mu m$.

In summary, “micro” has different size ranges, for different working fluids and single or multiphase flow, physically.

3 Parameters relevant to two-phase flow and heat transfer in microchannels

The parameters that are used for the

characterization of two-phase flow and heat transfer in macroscale are well established. The definitions of these parameters can be found in some textbooks.

One should be careful when using the well established parameters in microchannels. This is because microchannels have some special characteristics. For instance, because the microchannel characteristic size is so small that bubbles have large possibilities to coalescence, a specific cross section of a microchannel is either occupied by the vapor-phase or the liquid phase, the local void fraction for such specific location is either approaching unity, or approaching zero. Kawahara et al. [10] uses the time statistic technique to compute the time averaged void fractions for specific axial locations.

Considering the magnitude of the buoyancy force, inertia force, viscous force, etc., relative to the surface tension force, one may deduce some non-dimensional parameters that govern the two-phase flow and heat transfer in microchannels. These parameters are summarized as follows [2,9].

Liquid Reynolds number, $Re = Ud / \nu$, represents the inertia force relative to viscous force. Low Re number exists in microchannels, displaying the laminar flow under most circumstances. The laminar flow makes the micro-mixing process becomes more difficult.

Boiling number, $Bo = q / Gh_{fg}$, the non-dimensional heat flux, widely applied in macro or micro scale boiling heat transfer analysis, especially for the heat transfer coefficient correlations.

Bond number, $\tilde{Bo} = g(\rho_f - \rho_g)d^2 / \sigma$, represents the buoyancy force relative to the gravity force. As commonly recognized, gravity force is not important in microchannels, Bond number is not important in microchannels. However, in some passive micro devices such as micro heat pipes, Bond number still have effects on the performance because most of micro heat pipes are still affected by the positions, i.e., horizontally or vertically positioned.

Capillary number, $Ca = \mu U / \sigma$, represents the viscous force relative to the surface tension force. It is useful in the analysis of the bubble removal process. Xu et al. [11] used the Capillary number to analyze the liquid film movement when the

vapor slug is in stationary state for a closed loop pulsating heat pipe.

We number, $We = G^2 d / \rho \sigma$, represents the inertia force relative to the surface tension force. It is useful for the analysis of flow patterns in microchannels.

Ja number, $Ja = C_{pf} \Delta T_{sat} \rho_f / \rho_g h_{fg}$, represents the ratio of the sensible heat relative to the latent heat for evaporating the same amount of vapor. It is useful for the analysis of the bubble nucleation phenomenon in microchannels.

It is recognized that bubble nucleation becomes more difficult in microscale than that in macroscale. Thus it needs a higher liquid superheat to initiate the bubble nucleation. The required liquid superheat is increased with continuous decreasing of the channel size. Once bubbles are nucleated, the superheated liquid may release its energy into the vapor phase quickly, resulting in the vapor explosive phenomenon (Xu et al. [12], Kandlikar [13], Hestroni et al.[14]), pushing the fluid out of the microchannel both downstream and upstream quickly, sometimes in the timescale of milliseconds for a typical chip length of a couple of centimeter. Kandlikar [13] analyzed the force actions during the vapor bubble explosive stage and stated that there is a large velocity difference on the vapor/liquid interface. An important parameter, the K_1 number was proposed to account for the interfacial momentum force exchange on such vapor/liquid interface, $K_1 = Bo^2 \rho_f / \rho_g$.

As one considers, Froude number, defined as $Fr = U^2 / gd$, is not important in microscale. However, Xu et al. [15] performed experiments in intercrossed microchannel array of silicon chip, which has ten triangular microchannels along the flow direction. The five transverse trapezoid microchannels arranged along the flow direction, separates the whole straight microchannels into six independent zones. The experiments were performed under the conditions of high heat fluxes and low mass fluxes, to identify the transient flow patterns and heat transfer behaviors under the worse operation conditions. The authors did find the stratified flow, with the liquid films settled down to the bottom of the triangular microchannels, wetting the two side walls of the triangular microchannels.

4 Bubble nucleation in microscale

There are a lot of factors affecting the bubble nucleation in microchannels: roughness and cleanness of the channel wall surface, the liquid purity, mass fluxes and heat fluxes, pressures etc. At this stage it is not clear which mechanism domains the bubble nucleation in microscale, homogeneous or heterogeneous nucleation?

Peng and Wang [16] conducted a series of experiments with water, ethanol, and their mixtures flowing in different shaped microchannels. They did not observe the bubble activities in the rectangular or triangular microchannels, and proposed the fictitious boiling phenomenon. Later studies by Kandlikar and Stumm [17] with a channel height of 1mm indicate bubbles as small as $10 \mu m$ departed from the nucleation sites.

Assuming that cavities of all sizes are present on the heater surface, the wall superheat required for the bubble nucleation is developed by Hsu & Graham [18], Sato & Matsumura [19]. A simple case provided by Kandlikar [13] for the hydraulic diameter larger than 1mm shows that the wall superheat is quite small. However, the liquid superheat is increased with decreasing the hydraulic diameter of the microchannels. With water flowing in $200 \mu m$ diameter of microchannels, $\Delta T_{sat,ONB}$ is around $2^\circ C$ for the initial bubble nucleation. For the channel diameter less than $10 \mu m$, bubble nucleation becomes quite difficult. On the other hand, the liquid superheat may be decreased due to the dissolved gas, fine particles and channel corners.

For the silicon microchannel, the wall surface is quite smooth and the roughness may be one order less than that in copper microchannels. Bubble nucleation becomes more difficult. The direct measurements by Xu et al. [12] indicate that the paired or triplet bubbles are always initiated in or very close to the triangular microchannel corners at the same cross-section, indicating the heterogeneous bubble nucleation. The triangular microchannel corners become the bubble nucleation sites, followed by the bubble growth and coalescence at the same cross section of the microchannel. The bubble explosion causes higher internal pressure of the merged bubble, pushing the liquid plugs out of the microchannel both

downstream and upstream, in less than 1 millisecond. The bubble explosion and the flow reversal phenomena were also reported by Kandlikar [13] and Hetsroni et al. [14].

Li and Cheng [20] theoretically studied the bubble cavitation in a microchannel. It is shown that the existence of dissolved gas, randomly residual vapor (gas)-trapped, and corners can effectively lower the nucleation temperature in a microchannel, which may account for the experimental observation that the nucleation temperature in a microchannel is lower than that calculated in terms of the traditional homogeneous nucleation theory even though the silicon channel wall surface is very smooth. The effects of the microchannel size, mass flow rate and heat flux on boiling incipience or bubble cavitation are studied. The higher flow rate may suppress the bubble nucleation.

5 Gas-liquid two-phase flow patterns in microchannels

Xu et al. [21] performed the flow pattern studies in rectangular channels with mini/micro gaps using air-water as the working fluids. Three test sections were made with the width of 12mm. However, the gaps are 0.3, 0.6 and 1.0 mm respectively. Bubbly flow, slug flow, churn flow and annular flow were identified in the channel with the gaps of 1.0mm and 0.6mm. However, flow patterns in 0.3mm gap microchannel are quite different from the other ones. Bubbly flow was not observed. Instead, cap-bubbly flow, slug-droplet flow, churn flow and annular-droplet flow were observed in the microchannel with the gap of 0.3mm.

Zhao and Bi [22] conducted the gas-water flow patterns in triangular channels with the hydraulic diameters of 2.886mm, 1.443mm and 0.866mm. Dispersed bubbly flow, slug flow, churn flow and annular flow, which take place in macrochannels, were also observed in the two test sections with the hydraulic diameters of 2.886mm and 1.443mm. In the smallest channels with the hydraulic diameter of 0.866mm, dispersed bubbles were not observed. Instead, capillary-bubbly flow, slug flow, churn flow, and annular flow exist in the triangular channel.

Air-water flow patterns were studied by Serizawa et al. [23] in circular microtubes with

the inside diameters of 20, 25 and 100 μm and steam-water two-phase flow in a 50 μm i.d. circular tube, covering a wide range of liquid superficial velocities up to 18m/s and gas superficial velocities up to 300m/s. Several distinct flow patterns were observed. It is also shown that the surface features have strong effect on the flow patterns.

Experimental studies by Kawahara et al. [10] in a 100 μm circular tube using water and nitrogen gas as the working fluids. Intermittent flow and annular flow were observed. A close study of the liquid film structure revealed gas core flows with a smooth or ring-shaped. Bubble flow was not observed even at highest superficial liquid velocity ($j_L \square 4\text{m/s}$) and lowest superficial gas velocity ($j_g \square 0.1\text{m/s}$).

Hassan et al. [24] designed a new test rig to extend the range of the existing data on the flow patterns. Flow pattern maps for the hydraulic diameter of less than 1.0mm obtained from the literature review, are tested and compared. A total of approximately 1475 data points from the authors' and previous studies with $d = 100\mu\text{m}$ were used for comparison. Two general flow pattern maps were provided.

Two-phase flow patterns in conventional microchannels at adiabatic conditions are somehow different from those in silicon microchannels using the standard MEMS fabrication technique due to the following reasons: (1) the conventional channel is much rougher than the silicon microchannels, (2) it is very difficult to fabricate the channel size below 200 μm using the conventional fabrication technique.

6 Flow instabilities and transient flow patterns in microchannels

Two-phase flow instabilities can take place in nuclear reactors, boilers, heat exchangers, etc, leading to the mechanical vibration, the disturbance of the electronic control device, the local overheating of the heat transfer surface and the high thermal stress of the solid walls (Ding et al. [25]).

The pressure drop, the density wave, and the thermal oscillations are the dynamic flow instabilities. The thermal oscillation oscillations

are not independent ones, but sometimes occur accompanying with other type of flow instabilities. Flow instabilities in macroscale are well understood. They have large oscillation amplitudes and long cycle periods in the order of seconds and even minutes.

Wu and Cheng [26] studied the flow instabilities in silicon microchannels with water as the working fluids. Various modes of boiling instabilities take place following the boiling incipience. An unsteady liquid/two-phase/vapor alternative flow (LTVAF) takes place in the microchannels. Wu and Cheng [27] performed the flow instabilities in two sets of parallel microchannels with the hydraulic diameters of $155.8\mu\text{m}$ and $82.8\mu\text{m}$ respectively. The fluid pressures, wall temperatures and flow rates are found to be oscillating with large amplitudes and long periods. Bubbly flow, slug flow, churn flow and other peculiar flow patterns were observed. These instabilities can be self-sustained if the pressure drops and the mass flow rates have phase differences. Further studies on the two-phase flow instabilities are reported by Wu and Cheng [28] with the hydraulic diameter of $186\mu\text{m}$ and the length of 30.0mm. Three types of flow instabilities and some flow patterns are observed.

Peles et al. [29] divides the whole flow length of the microchannel into the liquid part and the vapor part. Boiling two-phase flow in capillary channels is identified to be unstable for the outlet mean vapor mass qualities less than unity. Hetsroni et al. [14] found that long vapor bubbles occurring in microchannels at low liquid Reynolds number, which is not similar to the classical annular flow. This phenomenon is considered as the explosive boiling with periodic wetting and dry-out. The pressure drops are found to be oscillating which is enhanced with increasing the vapor mass qualities.

6.1 Flow instabilities in single/multi microchannels

Xu et al. [30] studied the two-phase flow instabilities in a single microtube with the inside diameter of $500\mu\text{m}$. The total length of the microtube is 90 mm with the effective heating length of 45 mm. Two types of flow instabilities are observed. One is the long period/large amplitude liquid/two-phase alternative flow,

reflecting the feedback control of the mass flux and the inlet liquid temperature. The second is the long period/small amplitude periodic subcooled flow boiling, displaying the periodic bubble emission behavior of the channel exit.

Xu et al. [31] performed the experiments to measure the onset of flow instability (OFI, static flow instability) and dynamic flow instability in a compact heat sink consisting of 26 rectangular microchannels with $300\mu\text{m}$ in width and $800\mu\text{m}$ in depth. The deionized water and methanol are used as working fluids. The microchannel exit maintains the atmosphere pressure. The onset of flow instability is observed to occur at the outlet temperature of $93\text{-}96^\circ\text{C}$, which was several degrees lower than the saturated temperature corresponding to the microchannel exit pressure. Fine bubbles are detected near the microchannel exit and are moving to the outlet plenum.

Once the mass flux is lower than that of OFI, three types of flow instabilities are observed: large amplitude/long period oscillation superimposed with small amplitude/short period oscillation (LALPO type), small amplitude/short period oscillation (SASPO). Thermal oscillations are observed to accompany with the above two oscillations.

6.2 Transient flow patterns and instabilities

Xu et al. [12] performed the experiments in silicon microchannels using acetone as the working fluid. The silicon chip consists of ten triangular microchannels with the hydraulic diameter of $155.4\mu\text{m}$, and the length of 21.45mm. It is found that all the microchannels repeat the flow patterns in the timescale of milliseconds, with stable fluid pressures/temperatures, which is explained as that the response time of the pressure and temperature sensors is longer than the cycle periods of the transient flow patterns. A full cycle can be divided into three substages: liquid refilling stage ($0 < t < 9\text{ms}$), bubble nucleation, growth and coalescence stage ($10 < t < 21\text{ms}$), and transient liquid film evaporation stage ($22\text{ms} < t < 47\text{ms}$).

In the liquid refilling stage, liquid plug (represented by the white image) may cover the whole microchannel. The liquid front is traveling downstream with flat vapor/liquid interface,

separating the whole microchannel into liquid plug region and vapor slug region (flow pattern A). Sometimes the liquid plug may entrain the “inverse bubble slug” (flow pattern B).

In the bubble nucleation, growth, and coalescence stage, paired or triplet bubbles are nucleated in or very close to the microchannel corners in the same cross section (flow pattern C). After the bubble nucleation, they will have several milliseconds to grow up, followed by the coalescence process. The quick release of the superheated liquid energy to the vapor phase causes the vapor explosion.

The transient liquid film evaporation stage starts from the liquid plug pushed out of the microchannels. The liquid films are accumulated in the microchannel corners due to the surface tension effect.

A set of images showing the bubble nucleation, growth and coalescence is illustrated in Xu et al.[12] for a single microchannel. A set of bubble groups appeared. Each group has two or three bubbles, symmetrically located at the same cross section at $t = 3ms$. The liquid plug A is separated by the merged bubble and is pushed out of the microchannel at $t = 6ms$. Meanwhile, the liquid plugs B and C are flushed out of the flow field and totally disappeared at $t = 7ms$. From above one knows that the liquid plugs pushed out of the flow field in less than 1 millisecond.

The transient flow patterns in whole microchannels in the timescale of milliseconds are different from those with large amplitudes and cycle periods. This type flow instability reflects the fluid mechanics and heat transfer in the silicon chips, and may not be related to the other components of the forced convective loop.

7 Microscale boiling heat transfer behaviors

The literature on microscale boiling heat transfer is becoming rich in recent years [32,33,34,35,36,37,38,39,40,41,42], with d ranging from a couple of millimeters to several millimeters.

As for the microscale boiling heat transfer behaviors, three groups can be categorized. The first group identified the nucleate boiling heat transfer mechanism, with the heat transfer coefficients dependent on the heat fluxes only

[32,33, 38]. The second group concludes the convective heat transfer mechanism with the heat transfer coefficients dependent on the mass fluxes only [39, 42]. The third group is belonging to the hybrid or some special heat transfer mechanisms [34,35, 37,41,43,44]. The conflicting conclusions are resulted from different working fluids, operation parameter ranges etc.

7.1 Effect of boiling number on the microscale boiling heat transfer

Xu et al. [45] provides a strong link between the transient flow patterns and the heat transfer coefficients. Five microscale boiling heat transfer mechanisms can be deduced in terms of the transient flow pattern observations described in Xu et al.[12].

The microscale boiling heat transfer behavior is a combined of all the five heat transfer mechanisms. The boiling number is identified to be the control parameter, reflecting the balance of the heat flux and mass flux. The microscale boiling heat transfer can have different dominant heat transfer mechanisms. The boiling number strongly affects the nucleation sites.

7.1.1 Heat transfer at low boiling numbers

The single-phase liquid flow covers a larger percentage of the whole flow length. Bubble nucleations are most likely taking place at the end of the heating section. The heat transfer is much enhanced in the bubble nucleated area. Dry-out may not occur even at the end of the heating area. Heat transfer coefficients should be increased versus the equilibrium vapor mass qualities along the flow direction (region 1).

7.1.2 Heat transfer at medium boiling numbers

The bubble nucleation sites can take place anywhere in the whole microchannel. The nucleate heat transfer contributes the major part. The microscale boiling heat transfer in a full cycle is similar to a successive of bubble nucleation, growth, and departure from the cavity followed by the refilling of the fresh liquid, inside a cavity. The heat transfer coefficients should be mainly depended on the heat fluxes, less on the mass fluxes (region 2).

7.1.3 Heat transfer at high boiling numbers

High boiling numbers shift the bubble nucleation sites to the microchannel upstream. The single-phase liquid flow length is short. The temporary dry-out possibilities are increased along the flow direction. The strong vapor explosive effect domains the heat transfer mechanisms, inducing the forced convective heat transfer regions (the heat transfer coefficients are mainly depended on the mass fluxes, region 3).

7.2 Microscale boiling heat transfer measurements

The above transient flow pattern based heat transfer analysis is well consistent with the measured heat transfer performance. Totally we performed the microscale boiling heat transfer experiments for 102 runs (Xu et al. [45]). These heat transfer performances are clearly identified by dividing the boiling numbers into three subranges. The heat transfer coefficients versus the local vapor mass qualities and the transition boundaries among the three heat transfer regions can be found in Xu et al.[45].

The measured boiling heat transfer coefficients in region 1 are shown in Xu et al.[45] for five runs. The smaller parameter differences among the five runs result in the coinciding with each other. The heat transfer coefficients in the two-phase area are increased with increasing the vapor mass qualities (region 1).

Xu et al.[45] gives the perfect nucleate boiling heat transfer dominant heat transfer behaviors (region 2). The heat transfer coefficients are mainly relied on the heat fluxes. The higher the heat flux is, the higher heat transfer coefficients. Besides, the mass fluxes almost have no effects on the heat transfer coefficients.

The heat transfer coefficients with the effects of heat fluxes and mass fluxes can be found in Xu et al.[45] for the vapor explosive induced forced convective heat transfer (region 3). It is shown that the heat transfer coefficients are less dependent on the heat fluxes. Meanwhile they are mainly depended on the mass fluxes. Generally higher mass fluxes cause higher heat transfer coefficients, which are also decreased with the increase of the local vapor mass qualities.

8 Conclusions

Bubble dynamics and boiling heat transfer are received great attention in recent years, due to the wide applications in micro devices or systems. The literature is becoming rich in conventional microchannels. One should be careful to apply these results in silicon microchannels, which have much smoother wall surface and smaller channel size. The fundamental issues related to non-dimensional parameters, bubble nucleation, flow patterns, flow instabilities and heat transfer mechanisms are reviewed. Liquid requires higher superheat and has larger possibilities to be nucleated on the wall surface or channel corners. The high energy transfer rate from the superheated liquid to the vapor interface induces the vapor explosive phenomena, pushing the liquid part out of the channel quickly, leaving the liquid films accumulated in the channel corners. A full cycle of the transient flow patterns may include different substages having different heat transfer mechanisms. The time and space integrated effects account for the heat transfer performance, which is characterized by the boiling numbers. The heat transfer coefficients with the effects of heat fluxes and mass fluxes can display three distinct regions by dividing the boiling numbers into three subranges, diminishing the disagreement of the microscale boiling heat transfer. Besides, future studies on the bubble dynamics and boiling heat transfer are suggested.

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References

- [1] Nguyen N.T. and Wereley S., *Fundamentals and Applications of Microfluidics*, Boston: Artech House, 2002
- [2] Gan Y.H., Xu J.L., Zhou J.J., and Chen Y., Key issues related to microscale phase change heat transfer, *Advances in Mechanics*, Vol.34, No.3, 2004, pp.399-407 (in Chinese)
- [3] Maurya D.K., Lahiri S.K., Silicon MEMS vaporizing liquid microthruster with internal microheater, *J. of Micromechanics and*

- Microengineering*, Vol.15, 2005, pp.966-970
- [4] Yin Z., and Prosperetti, A microfluidic “blinking bubble” pump, *J. of Micromechanics and Microengineering*, Vol.15, 2005, pp.643-651
- [5] Deng P., Lee Y.K., and Cheng P., The growth and collapse of a micro-bubble under pulse heating, *Int. J. of Heat and Mass Transfer*, Vol.46, 2005, pp. 4041-4050
- [6] Gad-el-Hak, The fluid mechanics of microdevices—the Freeman scholar lecture, ASME, *J. of Fluids Engineering*, Vol.121, No.5, 1999, pp.5-33
- [7] Koo J. and Kleinstreuer C., Liquid flow in microchannels: experimental observations and computational analysis of microfluidics effects, *J. of Micromechanics and Microengineering*, Vol.13, 2003, pp.568-579
- [8] Guo Z.Y., and Li Z.X., Size effect on microscale single-phase flow and heat transfer, *Int. J. of Heat and Mass Transfer*, Vol.46, 2003, pp.149-159
- [9] Kandlikar S.G., Fundamental issues related to flow boiling in minichannels and microchannels, *Experimental Thermal and Fluid Science*, Vol.26, 2002, pp.389-407
- [10] Kawahara A., Chung P.M., Kawaji M., Investigation of two-phase flow pattern, void fraction, and pressure drop in a microchannel, *Int. J. of Multiphase Flow*, Vol.28, 2002, pp.1411-1435
- [11] Xu J.L., Li Y.X., and Wong T.N., High speed flow visualization of a closed loop pulsating heat pipe, *Int. J. Heat and Mass Transfer*, Vol.48, 2005, pp.3338-3351
- [12] Xu J.L., Gan Y.H., Zhang D.C., and Li X.H., Microscale boiling heat transfer in a micro-timescale at high heat fluxes, *J. of Micromechanics and Microengineering*, Vol.15, 2005, pp.362-376
- [13] Kandlikar S. G., Heat transfer mechanisms during flow boiling in microchannels, *ASME J. of Heat Transfer*, Vol.126, 2004, pp.8-16
- [14] Hetsroni G., Mosyak A., Pogrebnyak E., and Segal Z., Explosive boiling of water in parallel microchannels, *Int. J. of Multiphase Flow*, Vol.31, No.4, 2005, pp.371-392
- [15] Xu J.L., Zhang W., Wang Q.W., and Su Q.C., Transient flow patterns and heat transfer behaviors inside intercrossed microchannel array in a micro-timescale, submitted to *Int. J. Multiphase Flow* (in review)
- [16] Peng X.F., Wang B.X., Forced convection and boiling characteristics in microchannels, *Proceedings of 11th IHTC*, August 23-28, Kyongju, Korea, Vol.1, 1998, pp.371-390
- [17] Kandlikar S.G., Stumm B.S., A control volume approach to predict departure bubble diameter in flow boiling, *ASME J. of Heat Transfer*, Vol.117,1995, pp. 990-997
- [18] Hsu Y.Y., and Graham R.W., An analytical and experimental study of the thermal boundary layer and ebullition cycle in nucleate boiling, 1961, *NASA TN-D-594*
- [19] Sato T., and Matsumura H., On the conditions of incipient subcooled boiling with forced convection, *Bull JSME*, Vol.7, No.26, 1964, pp.392-398
- [20] Li J. and Cheng P., 2004, Bubble cavitation in a microchannel, *Int. J. of Heat and Mass Transfer*, Vol.47, 2004, pp.2689-2698
- [21] Xu J.L., Cheng P., Zhao T.S., Gas-liquid two-phase flow regimes in rectangular channels with mini/micro gaps, *Int. J. of Multiphase Flow*, Vol.25, 1999, pp.411-432
- [22] Zhao T.S., Bi Q.C., Co-current air-water two-phase flow patterns in vertical triangular microchannels, *Int. J. of Multiphase Flow*, Vol.27, 2001, pp.765-782
- [23] Serizawa A., Feng Z.P., Kawara Z., Two-phase flow in microchannels, *Experimental Thermal and Fluid Science*, Vol.26, 2002, pp.703-714
- [24] Hassan I., Vaillancourt M., Pehlivan K., Two-phase flow regime transitions in microchannels: a comparative experimental study, *Microscale Thermophysical Engineering*, Vol.9, No.2, 2005, pp.165-182
- [25] Ding Y., Kakac S., and Chen X.J., Dynamic instability of boiling two-phase flow in a single horizontal channel, *Experimental Thermal and Fluid Science*, Vol.11, 1995, pp.327-342
- [26] Wu H.Y. and Cheng P., Liquid/two-phase alternating flow during boiling in microchannels at high heat flux, *Int. Comm. In Heat and Mass Transfer*, Vol.30, No.3, 2003, pp.295-302
- [27] Wu H.Y. and Cheng P., Visualization and measurements of periodic boiling in silicon microchannels, *Int. J. Heat and Mass Transfer*, Vol.46, No.14, 2003, pp.2603-2614
- [28] Wu H.Y. and Cheng P., Boiling instability in parallel silicon microchannels at different

- heat flux, *Int. J. Heat and Mass Transfer*, Vol.47, No.17-18, 2004, pp.3631-3641
- [29] Pelles, Y.P., Yarin L.P., and Hetsroni G., Steady and unsteady flow in a heated capillary, *Int. J. Multiphase Flow*, Vol.27, No.4, 2001, pp.577-598
- [30] Xu J.L., Zhou J.J., Gan Y.H. and Chen Y., Unsteady flow phenomenon in a heated microchannel at high heat fluxes, *Experimental Heat Transfer*, Vol.17, 2004, pp.299-319
- [31] Xu J.L., Zhou J.J. and Gan Y.H., Static and dynamic flow instability of a parallel microchannel heat sink at high heat fluxes, *Energy Conversion and Management*, Vol.46, 2005, pp.313-334
- [32] Lazarek G.M., Black S.H., Evaporative heat transfer, pressure drop and critical heat flux in a small vertical tube with R-113, *Int. J. Heat and Mass Transfer*, Vol.25, 1982, pp.945-960
- [33] Wambsganss M.W., France D.M., Jendrzeczyk J A and Tran T.N., Boiling heat transfer in a horizontal small-diameter tube, *ASME J. Heat Transfer*, Vol.115, 1993, pp.963-972
- [34] Tran T.N., Wambsganss M.W., and France D.M., Small circular and rectangular-channel boiling with two refrigerants, *Int. J. Multiphase Flow*, Vol.22, 1996, pp.485-498
- [35] Kew P.A. and Cornwell K, Correlations for the prediction of boiling heat transfer in small-diameter channels, *Applied Thermal Engineering*, Vol.17, 1997, pp.705-715
- [36] Ravigururajan T.S., Impact of channel geometry on two-phase flow heat Transfer Characteristics of Refrigerants in microchannel heat exchangers, *ASME J. Heat Transfer*, Vol.120, 1998, pp.485-491
- [37] Yan Y and Lin T, Evaporation heat transfer and pressure drop of refrigerant R-134a in a small pipe, *Int. J. Heat Mass Transfer*, Vol. 41, 1998, pp.4183-4194
- [38] Bao Z.Y., Fletcher D.F. and Haynes B.S., Flow boiling heat transfer of Freon R11 and HCFC123 in narrow passages, *Int. J. Heat Mass Transfer*, Vol.43, 2000, pp.3347-3358
- [39] Lee H.J. and Lee S.Y., Heat transfer correlation for boiling flows in small rectangular horizontal channels with low aspect ratios, *Int. J. Multiphase Flow*, Vol.27, 2001, pp.2043-2062
- [40] Warriar G.R., Pan T and Dhir V.K., Heat transfer and pressure drop in narrow rectangular channels, *Experimental Thermal and Fluid Science*, Vol.26, 2002, pp.53-64
- [41] Yu W, France D.M., Wambsganss M.W. and Hull J.R., Two-phase pressure drop, boiling heat transfer, and critical heat flux to water in a Small-Diameter Horizontal Tube, *Int. J Multiphase Flow*, Vol.28, 2002, pp.927-941
- [42] Qu W and Mudawar I, Flow boiling heat transfer in two-phase micro-channel heat sinks —I. Experimental investigation and assessment of correlation methods, *Int. J. Heat Mass Transfer*, Vol.46, 2003, pp.2755-2771
- [43] Jiang L, Wong M, and Zohar Y, Forced convection boiling in a microchannel heat sink, *Journal of Microelectromechanical Systems*, Vol.10, 2001, pp.80-87
- [44] Hetsroni G, Mosyak A, Segal Z and Ziskind G, A uniform temperature heat sink for cooling of electronic devices, *Int. J. Heat Mass Transfer*, Vol.45, 2002, pp.3275-3286
- [45] Xu J.L., Shen S., Gan Y.H., Li Y.X., Zhang W., and Su Q.C., Transient flow pattern based microscale boiling heat transfer mechanisms, *J. of Micromechanics and Microengineering*, Vol.15, 2005, pp.1344-1361