Vol. 41 No. 4 SCIENCE IN CHINA (Series E) August 1998

Bubble formation of liquid boiling in microchannels*, **

PENG Xiaofeng (彭晓峰), HU Hangying (胡杭英) and WANG Buxuan (王补宣)

(Thermal Engineering Department, Tsinghua University, Beijing 100084, China)

Received January 14, 1998

Abstract The thermodynamic aspects of phase transformation of liquids in microchannels were analyzed to further understand the boiling characteristics, and a nondimensional parameter and related criteria that determine the phase transition in microchannels were derived theoretically using classical phase stability theory. It was found that the size of the microchannels results in dramatically high heat fluxes for liquid nucleation when the microchannel is sufficiently small. This work provides theoretical substance for further investigating, especially quantitatively describing the heat and mass transfer process.

Keywords: **nucleation, boiling, microchannel, phase instability.**

Boiling of liquids in microchannels and/or microstructures, as one of the very important topics in this area, has unique significance in the development of new technologies and devices for control of energy transfer and other advanced applications requiring very compact and extremely large heat-flux heat exchangers. The investigations of microscale transport processes conducted in the last decade have shown that microscale transport processes have dramatically distinct thermal fluid flow, heat transfer, and other thermal transport phenomena as compared to conventional situations, as noted by Tien et al.[1]. As a result, a new journal entitled *International Journal of Microscale Thermophysical Engineering* was proposed by Professor C. L. Tien to focus on promoting the research work and exchanging new ideas and research information.

Experimental data in the open literature also demonstrate that the boiling characteristics of liquids in microchannels differ from those in macrochannels, although there is only a small amount of research available on the subject. Bowers and Mudawar[2] experimentally investigated flow boiling of liquid R-133 in mini-channels and microchannels. Lin et al.[3] experimentally observed bubble growth and boiling characteristics on micro-wire and micro-chip heaters in microchannels. They found that is was extremely difficult to generate bubbles in the microchannels. The liquid superheat temperature required to initiate boiling or form bubbles in these microchannels was of about the same order of magnitude as that for homogeneous nucleation in an unconstrained liquid, or even higher. The corresponding heat flux was higher than 10^8 W/m^2. Peng and his coworkers have completed a series of experimental investigations on flow boiling through microchannels with rectangular cross-sections[4—6]. The microchannel sizes ranged from 0.1×0.3 mm to 0.6×0.7 mm. The liquid velocity, subcooling, channel geometry and liquid species and concentration

* Project supported by the National Natural Science Foundation of China (Grant No. 59625612) and Tsinghua University.

** Nomenclature: A, Empirical constant; a, thermal diffusivity; $\overline{C}_v$, mole specific heat at constant volume; D_h, hydraulic diameter; H, enthalpy; h_{lv}, latent heat; N, number of moles; N_{mb}, dimensionless parameter defined by eq. (15); P, pressure; q'', heat flux; r, bubble radius; S, entropy; T, temperature; T_s, saturation temperature; t, time; V, volume; v, specific volume; v', liquid specific volume at saturation; v'', vapor specific volume at saturation; x, distance; σ, surface tension; ΔP, pressure difference; ΔT, temperature difference. Subscripts: e, equilibrium; l, liquid phase; v, vapor phase; sup, superheat.

were all found to significantly affect the boiling heat transfer coefficients. The experimentally measured boiling curves indicated that boiling was initiated at very low wall superheats of only 2—8℃ and immediately shifted to the fully developed nucleate boiling regime without evidence of partial nucleate boiling even for highly subcooled liquid flow. However, at sufficiently high wall heat fluxes or wall superheats, which should produce nucleate boiling according to the observed boiling curves, no bubbles were observed in the microchannels even with the assistance of a high-power magnifying glass. It seems that the size scale of the liquid flow geometry may strongly influence the phase-change transition and corresponding flow boiling mode. Hence, two hypothetical concepts, "evaporating space" and "fictitious boiling" were proposed to describe and explain the physical processes and fundamental phenomena[7]. If the microchannel size is smaller than the "evaporating space", then "fictitious boiling" can be induced; otherwise, normal nucleate boiling occurs. The "evaporating space" is the necessary space needed for evaporation. "Fictitious boiling" implies that the liquid has reached conventional nucleate boiling conditions but internal evaporation and bubble growth have not yet been realized or there may exist countless microbubbles within the liquid that cannot be visualized by ordinary means. However, the liquid can absorb much more heat than the usual liquid sensible heat. Therefore, "fictitious boiling" has been proposed to describe liquid convection in microchannels with very high heat transfer rates which might exceed even those of normal nucleate boiling in macrochannels.

More recently, Wang et al.[8] attempted to differentiate fictitious boiling from conventional nucleate boiling by quantifying the evaporating space. An experimentally determined nondimensional relationship accounting for the effect of channel diameter and flow rate was proposed to describe the conditions for phase-change transition or nucleation in microchannels. The present work theoretically analyzes the liquid phase change transition in microchannels using thermodynamic phase stability theory. A bubble formation/nucleation criterion is obtained analytically. The channel size is shown to have a significant impact for sufficiently small hydraulic diameters, resulting in dramatically higher heat fluxes for nucleation.

1 Bubble generation and growth in microchannels

As generally noted, bubble behavior, including size and growing process, is of critical importance for investigating nucleate boiling. The concept of "evaporating space" suggests that there exists a minimum amount of space necessary to generate a vapor bubble in a confined microchannel. In fact, bubble size has long been considered as a critical parameter in understanding nucleate boiling characteristics and the dynamic bubble process. The bubble generation and growth process are altered as the microchannel size is decreased to the same order of magnitude as the size of the bubble embryos. "Fictitious boiling" may then result due to the extremely small amount of available space. Hsu[9] investigated pool boiling characteristics of liquids and theoretically predicted a range of active cavity sizes on heated surfaces and the corresponding equilibrium bubble embryo radii. For water at atmospheric pressure and active cavity mouth diameters ranging from about 0.01 to 0.18 mm, the corresponding bubble embryo sizes were around 0.016 to 0.288 mm and the average bubble diameters were about 0.15 mm. For those microchannels that have the same size as the bubble embryos, bubble initiation is physically restricted by the surrounding walls and inertia of the liquid on both ends of the bubble, as shown in fig. 1, since the vapor bubble occupies most of the cross-sections of the microchannel once nucleation occurs, and the bubble can only grow in downward and upward direction of the flow passage. Therefore, the geometry of the microchannels that are also of the order of 1 mm in size will significantly impact the bubble generation and growth dynamics.

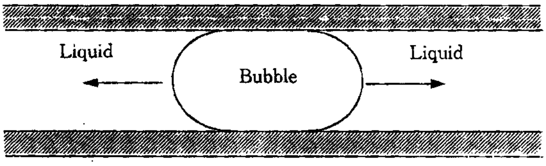

Fig. 1. Bubble model.

The liquid becomes unstable and is in transition to vapor, and bubbles form at active sites when the liquid is heated to T_s with its corresponding working pressure, P. And then, bubbles grow, and depart from the heated wall into the bulk liquid. This is a full process of nucleate boiling. Due to the great difference in density between liquid and its vapor, liquid must be removed by embryo bubble, and bubble initiation, growth and departure will be quite dissimilar to the normal situation. Perhaps, there does not exist the departure process of bubble. The constrained growth in microchannels, as shown in fig. 1, is an important concept in the following theoretical analysis of the boiling characteristics in microchannels. The relationships between the initial bubble embryo size and the microchannel size must be understood to accurately analyze boiling in microchannels. In addition to these, pressure and thermodynamic state at the interface of vapor bubble are expected to vary with microchannel geometry, and have important effect on the nucleation, and bubble dynamical characteristics.

2 Thermodynamic analysis of nucleation

From classical thermodynamics, boiling results from phase instability in the liquid. Liquid boiling or nucleation goes on under the condition of constant pressure and temperature. Actually, the temperature (or pressure) is a function of pressure (or temperature). For a specified system pressure, P, the temperature or saturated temperature $T_s = f(p)$. Introducing Gibbs function or free enthalpy,

$$G = U + PV - TS = H - TS, \tag{1}$$

the condition for thermodynamic equilibrium is

$$\mathrm{d}G \leqslant 0.$$

The phase stability condition was derived for a pure substance[10] as

$$\left(\frac{\partial P}{\partial V}\right)_T < 0. \tag{2}$$

From classical thermodynamics, we have the chain rule,

$$\left(\frac{\partial P}{\partial V}\right)_T = \left(\frac{\partial P}{\partial V}\right)_S + \left(\frac{\partial P}{\partial S}\right)_V \left(\frac{\partial S}{\partial V}\right)_T, \tag{3}$$

where S denotes the thermodynamic parameter termed "entropy", and subscripts, T, V, S, express constant temperature, volume and entropy, respectively. Using thermodynamic relation, we also have

$$\left(\frac{\partial P}{\partial V}\right)_S = \left(\frac{\partial P}{\partial T}\right)_S \left(\frac{\partial T}{\partial V}\right)_S \tag{4}$$

and

$$\left(\frac{\partial P}{\partial S}\right)_V = -\left(\frac{\partial T}{\partial V}\right)_S. \tag{5}$$

Substituting eqs. (4) and (5) into eq. (3) and combining it with eq. (2) yields

$$\left(\frac{\partial P}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_S\left(\frac{\partial T}{\partial V}\right)_S - \left(\frac{\partial T}{\partial V}\right)_S\left(\frac{\partial S}{\partial V}\right)_T < 0. \tag{6}$$

From thermodynamic relations, $(\partial T/\partial V)_S$ can be written as

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial S}{\partial V}\right)_T\left(\frac{\partial T}{\partial S}\right)_V = -\left(\frac{\partial P}{\partial T}\right)_V\frac{T}{N\bar{C}_V}. \tag{7}$$

Since $(\partial P/\partial T)_V > 0$, eq.(7) is always less than zero, so

$$\left(\frac{\partial T}{\partial V}\right)_S < 0. \tag{8}$$

Dividing eq.(6) by $(\partial T/\partial V)_S$ gives

$$\left(\frac{\partial P}{\partial T}\right)_S - \left(\frac{\partial S}{\partial V}\right)_T > 0 \quad \text{or} \quad \left(\frac{\partial P}{\partial T}\right)_S > \left(\frac{\partial S}{\partial V}\right)_T. \tag{9}$$

For a thermodynamic system in equilibrium at its saturation temperature, the pressure is only a function of temperature. Therefore, for a phase change system, the Clausius-Clapeyron equation can be used to give

$$\left(\frac{\partial P}{\partial T}\right)_S = \frac{\mathrm{d}P}{\mathrm{d}T} = \frac{h_{\mathrm{lv}}}{T_{\mathrm{s}}(\nu'' - \nu')}. \tag{10}$$

For a system in equilibrium, the boiling temperature of saturated liquid is constant and equal to T_s. Considering only constant heat flux heating for the liquid in the microchannel, the entropy variation in eq.(9) can be approximated as

$$\Delta S = \frac{q'' \cdot \pi D_{\mathrm{h}} \cdot \Delta x}{T_{\mathrm{s}}} \cdot \Delta \tau. \tag{11}$$

The heating time, $\Delta\tau$, can be determined by considering the heat transfer in the vapor. For bubble growth in a microchannel, the time should be sufficiently long for heat to diffuse throughout the cross-section. Because the bubble embryo occupies most of the microchannels once nucleation occurs, the heat diffusion is assumed to occur only in the vapor; therefore,

$$\Delta\tau = C\frac{\frac{\pi}{4}D_{\mathrm{h}}^2}{\alpha_{\mathrm{v}}}, \tag{12}$$

where C is an empirical coefficient determined from experiments. Since, as noted previously, the bubble embryo in the microchannel can only grow in the longitudinal directions (fig. 1), the volume change in eq.(9) was represented by

$$\Delta V = \frac{\pi}{4}D_{\mathrm{h}}^2\Delta x. \tag{13}$$

Combining eqs. (11)—(13) yields

$$\left(\frac{\partial S}{\partial V}\right)_T = \frac{q''\pi D_{\mathrm{h}}\Delta x C\frac{\pi}{4}D_{\mathrm{h}}^2}{T_{\mathrm{s}}\frac{\pi}{4}D_{\mathrm{h}}^2\Delta x\alpha_{\mathrm{v}}} = C\frac{q''\pi D_{\mathrm{h}}}{T_{\mathrm{s}}\alpha_{\mathrm{v}}}. \tag{14}$$

Substituting eqs.(10) and (14) into eq.(9) and rearranging it gives the phase stability condition as

$$\frac{h_{\mathrm{lv}}\alpha_{\mathrm{v}}}{C\pi(\nu'' - \nu')q''D_{\mathrm{h}}} > 1$$

or the condition at which nucleation phase-change occurs can be expressed as

$$\frac{h_{lv}\alpha_v}{C\pi(\nu''-\nu')q''D_h} \leqslant 1. \tag{15}$$

Equality implies the system in thermodynamical equilibrium. Eq. (15) indicates that the nucleation is related to the applied heat flux, the thermal fluid properties and the microchannel hydraulic diameter. From eq. (15), phase change is more difficult to occur if liquid has great latent heat and thermal diffusivity, and hydraulic diameter becomes smaller. Phase transition has higher possibility as the specific volume difference between saturated vapor and liquid, and applied heat flux increase. Obviously, the heat flux at which the nucleation will be initiated goes significantly higher for very small microchannels.

Defining the dimensionless parameter,

$$N_{mb} = \frac{h_{lv}\alpha_v}{C\pi(\nu''-\nu')q''D_h} \leqslant 1. \tag{16}$$

N_{mb}, introduced to describe the nucleation characteristics of liquid boiling in microchannels, facilitates understanding of the nature of the boiling phase change and heat transfer processes.

3 Discussion

Previous experimental investigations by Peng and his coworkers[7,8] indicated that the microchannel size had a significant effect on the boiling characteristics in microchannels. The nucleation criterion given by eq. (16) provides theoretical evidence for these experimental observations and gives a limit to initiate nucleation. The critical nucleation heat flux predicted by eq. (16) with $C=1$ and $N_{mb}=1$ is depicted in fig. 2 for water, methanol, acetone and R-12. The minimum heat flux necessary for inducing phase transition or nucleation increases rapidly as the microchannel hydraulic diameter decreases for a specified liquid, and the heat flux can reach dramatically high values for extremely small channels. The fluid thermophysical properties also significantly affect the nucleation heat flux. Liquids with greater liquid/vapor density differences, higher latent heats and larger thermal diffusion coefficients need larger heat fluxes to initiate nucleation. From the results in fig. 2, some features can be found as follows.

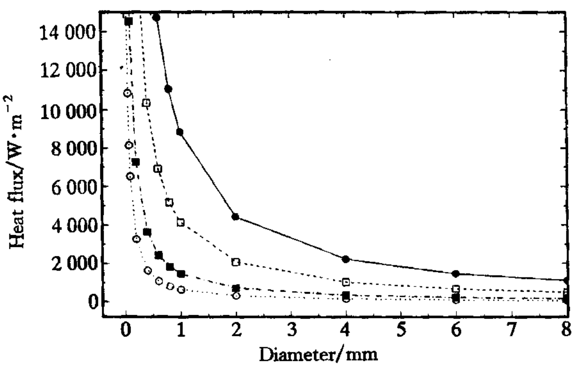

Fig. 2. Minimum heat flux for nucleation. ●, Water; ○, R-12; ■, acetone; □, methanol.

1) Generally speaking, boiling nucleation in microchannels becomes sensitive to the geometric size for microchannels with hydraulic diameter of 1 mm or smaller. Very high heat flux, which exceeds that for normal situation, is required for extremely small size microchannels. For thermodynamic nonequilibrium state, $N_{mb}<1$, the heat flux is even much higher.

2) The influence of size on the nucleation is distinct for different liquids. The critical nucleation heat flux becomes sensitive to microchannel size as $D_h \approx 3$—4 mm for water and methanol, and $D_h < 2$ mm for R-12 and acetone.

3) For water the critical nucleation heat flux is higher than the order of 10^4—10^5 [$W \cdot m^2$] as D_h becomes smaller than 1 mm. For acetone the required heat flux rapidly increases if $D_h <$ 0.8 mm. This implies that nucleation is impossible under the condition for conventional boiling, and heat transfer is still very high or even higher than the normal boiling situation. Theoretical predictions using eq. (16) agree well with experimental observations. The authors and their coworkers, in a series of experiments reported earlier[4—6] investigating flow boiling of water and methanol through rectangular microchannels with corss-sections ranging from 0.1×0.3 mm to 0.6×0.7 mm, did not observe vapor bubbles even when the applied heat flux was much greater than 10^5 W/m^2, which would normally result in nucleation in conventionally-sized channels. In another recent investigation, Ding et al.[11] experimentally investigated flow boiling of liquid R-12 flowing through a triangular channel with a hydraulic diameter of 0.7 mm. They observed bubble generation in these microchannels which is consistent with the predictions of eq. (16). Fig. 2 shows that nucleation will readily occur for R-12 flowing in microchannels until the hydraulic diameter is much less than 0.5 mm.

4) These observations and comparison show that all results for distinct liquids with empirical coefficient $C = 1$ are in very good agreement with the experimental measurements by different investigators. This might imply that the value of empirical coefficient, C, is very close to 1. More experimental investigations are needed to demonstrate this conclusion.

Although bubbles have not been observed in very small microchannels even for very high heat fluxes, the heat transfer characteristics as indicated by the measured boiling curves are the same as for normal nucleate boiling[4—6]. This transport process, termed "fictitious boiling"[7] was shown to be closely related to the microchannel size. The phase transition regime, termed "fictitious boiling" for boiling in microchannels, is an important property which is quite different from boiling characteristics in conventional channels. The predictions shown in fig. 2 clearly demonstrate that the liquid in this regime can absorb much more sensible heat than the normal liquid does, resulting in very high heat transfer rates which might even exceed that of nucleate boiling in macrochannels. Actually, the liquid is with great nonequilibrium.

As mentioned previously, the interfacial pressure and thermodynamic state have important influence on nucleation and bubble dynamical characteristics. This is a highly complicated problem and worthy to be investigated. A special research program was actually proposed to understand this transport phenomenon. Authors will present some new development in other papers.

4 Conclusion

The boiling characteristics for liquids in microchannels were investigated by analyzing the thermodynamics of the liquid phase transition. Consideration of the fundamental thermodynamics and the interaction of the bubble growth process and the microchannel geometry led to a liquid nucleation criterion and a dimensionless parameter that describes the boiling conditions for liquids in microchannels. The results also provide a theoretical and quantitative basis for the hypothesis "evaporating space" and "fictitious boiling".

References

1 Tien, C. L., Qiu, T. Q., Norris, P. M., Microscale thermal phenomena in contemporary technology, *Thermal Science and Engineering*, 1994, 2(1): 1.

2 Bowers, M. B., Mudawar, I., High flux boiling in low flow rate, low pressure drop mini-channel and microchannel heat sinks, *Int. J. Heat and Mass Transfer*, 1994, 37(2): 321.

3 Lin, L., Udell, K. S., Pisano, A. P., Liquid-vapor phase transition and bubble formation in micro structures, *Thermal Science and Engineering*, 1994, 2(1): 52.

4 Peng, X. F., Wang, B. X., Experimental investigation on flow boiling of subcooled liquid through microchannels, *J. Engineering Thermophysics* (in Chinese), 1993, 14(3): 281.

5 Peng, X. F., Wang, B. X., Forced-convection and flow boiling heat transfer for liquid flowing through microchannels, *Int. J. Heat and Mass Transfer*, 1993, 36(14): 3421.

6 Peng, X. F., Wang, B. X., Cooling characteristics with microchanneled structures, *J. Enhanced Heat Transfer*, 1994, 1(4): 315.

7 Peng, X. F., Wang, B. X., Evaporating space and fictitious boiling for internal evaporation of liquid, *Science Foundation in China*, 1994, 2(2): 55.

8 Wang, B. X., Peng, X. F., Hu, H. Y., Study of bubble formation conditions for liquid flow boiling in microchannels, *6th National Conference on Engineering Thermophysics* (in Chinese) (ed. Wang, B.X.), Wuhan: Wuhan Science and Technology Press, 1996, 389—392.

9 Hsu, Y. Y., On the size range of active nucleation cavities on a heating surface, *J. Heat Transfer*, 1962, 84: 207.

10 Carey, V. P., *Liquid-Vapor Phase Phenomena*, Washington D. C.: Hemisphere Publishing Corporation, 1992.

11 Ding, L. S., Jiang, M. J., Sun, H., Measurement of heat transfer characteristics and friction factors for the flow boiling of CFC-12 through triangular microchannels used for the refrigerating evaporators, in *Heat Transfer Science and Technology 1996* (ed. Wang, B. X.), Beijing: Higher Education Press, 1996, 360—365.