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Boiling nucleation during liquid flow in microchannels

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Abstract—The boiling of liquids in microchannels/microstructures is currently of great interest due to its very unusual phenomena and its many potential applications in a wide variety of advanced technologies. The thermodynamic aspects of phase transformations of liquids in microchannels was analyzed to further understand the boiling characteristics and to determine the conditions under which a portion of such liquids is likely to undergo phase change. A nondimensional parameter and related criteria, that determine the phase transition in microchannels, were derived theoretically. The size of the microchannels results in dramatically high heat fluxes and superheats for liquid nucleation when the microchannel is sufficiently small. The effect that the liquid thermophysical properties have on the nucleation is also described by the analysis © 1997 Elsevier Science Ltd.

INTRODUCTION

The rapid development of practical engineering applications for micro-devices, micro-systems, advanced material designs, and micro-manufacturing is creating a strong demand for better understanding of microscale transport phenomena and is causing a notable shift of thermal science and heat transfer research from macroscale to microscale. The 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 distinct thermal fluid flow, heat transfer, and other thermal transport phenomena as compared to conventional situations, as noted by Yang and Zhang [1], and Tien *et al.* [2]. Experimental data in the open literature also demonstrate that the boiling characteristics of liquids in microchannels differs from that in macro-channels, although there is still only a small amount of research available on the subject.

Bowers and Mudawar [3] experimentally investigated flow boiling of liquid R113 in mini-channels and micro-channels. They demonstrated heat transfer rates as high as 2×10^6 W m^{-2} in these channels and noted that the heat transfer and flow friction or pressure drop behavior is different from that observed in macro-channels. Lin *et al.* [4] experimentally observed bubble growth and boiling characteristics on micro-wire and micro-chip heaters in microchannels. They found that it was extremely difficult to generate bubbles in the microchannels. The liquid superheat temperature required to initiate boiling or form bubbles in these microchannels was about the same order of magnitude as that for homogeneous nucleation in an unconstrained liquid. 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 [5–10]. 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 were all found to significantly affect both the single-phase heat transfer and the boiling heat transfer coefficients [8–10]. The experimentally measured boiling curves indicated that boiling was initiated at very low wall superheats of only 2–8°C 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 [11]. If the microchannel size is smaller than the 'evaporating space', then 'fictitious boiling' and 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

NOMENCLATURE

A	empirical constant
a	thermal diffusivity
$\bar{C}_c$	mole specific heat at constant volume
D_h	hydraulic diameter
h_{lv}	latent heat
N	number of moles
N_{mb}	dimensionless parameter defined by equation (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.

Subscripts

e	equilibrium
l	liquid phase
v	vapor phase
sup	superheat.

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 macro-channels.

More recently, Wang *et al.* [12] 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. The liquid properties also have an important influence.

PHYSICAL ASPECTS OF BUBBLE GENERATION AND GROWTH

Various investigators [3–11] have demonstrated recently that the flow passage geometry has a significant impact on liquid boiling, bubble generation and bubble growth in microchannels. 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 is 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. For microchannels that are the same size as the bubble embryos, bubble initiation is physically restricted by the surrounding walls and the inertia of the liquid on both ends of the bubble, as shown in Fig. 1, since the vapor bubble occupies most of the cross-section of the microchannel once nucleation occurs. The constrained growth in microchannels 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.

Hsu [13] 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 0.016–0.288 mm and the average bubble diameters were about 0.15 mm. Therefore, the geometry of the microchannels that are also of the order of 0.1 mm in size will significantly impact the bubble generation and growth dynamics. The fluid thermal properties are also expected to have a significant influence on the active cavity and bubble sizes.

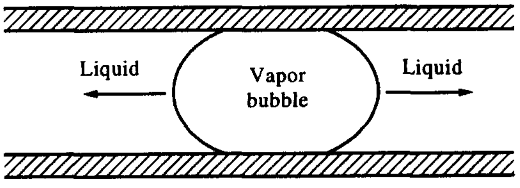

Fig. 1. Bubble model.

THERMODYNAMIC ANALYSIS OF NUCLEATION CONDITIONS

Nucleate boiling results from phase instability in the liquid. From classical thermodynamics, the phase stability conditions for a pure substance [14] include both

$$\bar{C}_v > 0 \tag{1}$$

and

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

Because $\bar{C}_v$ is greater than zero for virtually all substances, the thermal stability criterion is satisfied and equation (2) is a necessary and sufficient condition for phase stability. Obviously, equations (1) and (2) must also be satisfied for phase change in microchannels. Using the chain rule,

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

$(\partial P/\partial V)_S$ can be expressed as

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

The following thermodynamic relation can be introduced for $(\partial P/\partial S)_V$,

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

Substituting equations (4) and (5) into equation (3) and combining with equation (2) yields,

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

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

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

Since $(\partial P/\partial T)_V > 0$, equation (7) is always less than zero, so $(\partial T/\partial V)_S < 0$. Dividing equation (6) by $(\partial T/\partial V)_S$ gives

$$\left(\frac{\partial P}{\partial T}\right)_S - \left(\frac{\partial S}{\partial V}\right)_T > 0 \quad \text{or} \quad \left(\frac{\partial P}{\partial T}\right)_S > \left(\frac{\partial S}{\partial V}\right)_T. \tag{8}$$

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

$$\left(\frac{\partial P}{\partial T}\right)_S = \frac{\mathrm{d}P}{\mathrm{d}T} = \frac{h_{lv}}{T_s(v''-v')}. \tag{9}$$

For a system in equilibrium, the temperature is constant and equal to the saturation temperature, T_s. Considering only constant heat flux heating for the liquid in the microchannel, the entropy variation in equation (8) can be approximated as

$$\Delta S = \frac{q''\pi D_h \Delta x}{T_s} \Delta t. \tag{10}$$

The volume change in equation (8) was represented by

$$\Delta V = \frac{\pi}{4} D_h^2 \Delta x \tag{11}$$

since, as noted previously, the bubble embryo in the microchannel can only grow in the longitudinal directions (Fig. 1).

The heating time, Δt, in equation (10) 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 microchannel once nucleation occurs, the heat diffusion is assumed to occur only in the vapor, therefore,

$$\Delta t = c\frac{\frac{\pi}{4}D_h^2}{a_v}. \tag{12}$$

where c is an empirical constant determined from experiment. Combining equations (10)–(12), $(\partial S/\partial V)_T$ can be approximated as

$$\left(\frac{\partial S}{\partial V}\right)_T = \frac{cq''\pi D_h \Delta x \frac{\pi}{4} D_h^2}{T_s \frac{\pi}{4} D_h^2 \Delta x a_v} = \frac{q''\pi D_h}{T_s a_v}. \tag{13}$$

Substituting equations (9) and (13) into equation (8) and rearranging them gives the phase stability condition as

$$\frac{h_{lv} a_v}{c\pi(v''-v')q'' D_h} > 1. \tag{14}$$

Defining the dimensionless parameter

$$N_{mb} = \frac{h_{lv} a_v}{c\pi(v''-v')q'' D_h} \tag{15}$$

the condition for liquid nucleation in microchannels can be expressed as

$$N_{mb} \leqslant 1. \tag{16}$$

Equations (14) and (16) imply that nucleation is related to the applied heat flux, the thermal fluid properties and the microchannel hydraulic diameter.

The dimensionless parameter, 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.

SUPERHEAT OF NUCLEATION

The wall superheat of nucleation is also a critical parameter in the characterization of boiling initiation. The wall superheat can be related to the microchannel geometry using thermodynamic relations. Maxwell's relation

$$\left(\frac{\partial S}{\partial V}\right)_{\mathrm{T}} = \left(\frac{\partial P}{\partial T}\right)_{\mathrm{V}} \tag{17}$$

can be combined with equation (8) to give the nucleation condition as

$$\left(\frac{\partial P}{\partial T}\right)_{\mathrm{S}} \leqslant \left(\frac{\partial P}{\partial T}\right)_{\mathrm{V}}. \tag{18}$$

For saturated liquid in equilibrium, the Clausius–Clapeyron equation can be substituted into equation (18) to give the approximate relationship

$$\frac{h_{\mathrm{lv}}}{T_{\mathrm{s}}(v''-v')} \geqslant \frac{\Delta P}{\Delta T_{\mathrm{sup}}}. \tag{19}$$

Since ΔT_{sup} increases with increasing ΔP, then increasing the pressure difference would intensity the non-equilibrium effects during nucleation. For stable bubble embryo in equilibrium, the pressure difference across the bubble interface, ΔP_{e}, is given by the Young–Laplace equation

$$\Delta P_{\mathrm{e}} = \frac{2\sigma}{r}. \tag{20}$$

For nucleation in microchannels, since the bubble embryo growth is greatly restricted by the surrounding walls, the pressure difference across the interface would increase to values much greater than ΔP_{e}. This effect is related to the ratio of $2r/D_{\mathrm{h}}$ and becomes most significant as the value of $2r/D_{\mathrm{h}}$ approaches one. Using an empirical function, $f(2r/D_{\mathrm{h}})$, to account for this effect, the pressure difference ΔP can be expressed as

$$\Delta P = \Delta P_{\mathrm{e}} f(2r/D_{\mathrm{h}}). \tag{21}$$

The result in equation (16) shows that the critical nucleation heat flux is inversely proportional to D_{h}. Assuming that the superheat is also inversely proportional to D_{h}, the proposed function is assumed to take the form

$$f(2r/D_{\mathrm{h}}) = A\frac{2r}{D_{\mathrm{h}}}. \tag{22}$$

Combining and rearranging equations (19)–(22) yields

$$\Delta T_{\mathrm{sup}} \geqslant \frac{4AT_{\mathrm{s}}(v''-v')\sigma}{h_{\mathrm{lv}}D_{\mathrm{h}}} \tag{23}$$

where A is an empirical constant. Previous experiments [10] and comparison with the results of Lin *et al.* [4] have shown that $A \approx 280$.

COMPARISON WITH EXPERIMENTAL OBSERVATIONS

Previous experimental investigations by Lin *et al.* [4], and by Peng and his coworkers [5–11] indicated that the microchannel size had a significant effect on the boiling characteristics in microchannels. The nucleation criterion given by equation (16) provides theoretical evidence for these experimental observations, even though it may not give an exact limit. The critical nucleation heat flux predicted by equation (16) with $c = 1$ is depicted in Fig. 2 for water, methanol, acetone and R-12. The minimum heat flux necessary to induce 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. Generally speaking, boiling nucleation in microchannels becomes sensitive to the geometric size for microchannels that are several millimeters in size, for example, $D_{\mathrm{h}} \approx 3 \sim 4$ mm for water and methanol and $D_{\mathrm{h}} < 2$ mm for R-12 and acetone. The results show that boiling nucleation in microchannels is much more difficult to achieve than in conventional size channels and that initiation of nucleation in microchannels needs extraordinarily high heat fluxes. In addition, the theoretical evidence demonstrates that a single-phase liquid flowing in microchannels can absorb extraordinarily high heat fluxes which are even much higher than those for normal nucleate boiling. This implies that the liquid is in a highly non-equilibrium state with an exceptional capability to absorb, transfer and transport thermal energy.

Theoretical predictions using equation (16) agree well with experimental observations. The authors and their co-workers, in a series of experiments reported earlier [5–10] investigating flow boiling of water and methanol through rectangular microchannels with cross-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},

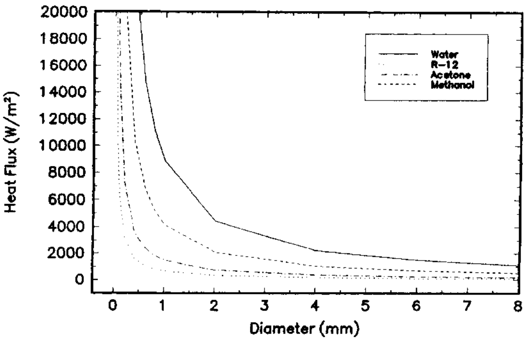

Fig. 2. Minimum heat flux for nucleation.

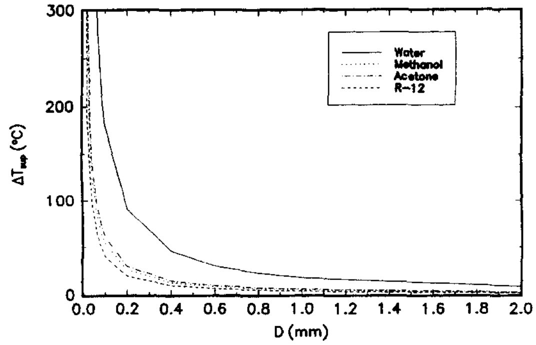

Fig. 3. Wall superheat for nucleation.

which would normally result in nucleating in conventional size channels. As shown in Fig. 2, the minimum heat flux for the nucleation of water boiling in microchannels is much greater than 10^4 W m^{-2} if the hydraulic diameter, D_h is less than 1 mm. For methanol, the minimum heat flux increases to a very high value when D_h is smaller than 0.7 mm. Apparently, if D_h is less than 0.7 mm, it is impossible to achieve nucleation for water or methanol with normal heat fluxes. Lin *et al.* [4] also found that very high heat fluxes were required to initial nucleation for water in microchannels. In another recent investigation, Ding *et al.* [15] 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 equation (16). Figure 2 shows that nucleation will readily occur for R-12 flowing in microchannels until the hydraulic diameter is much less than 0.5 mm.

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 even though there are no visible bubbles [5–10]. This transport process, termed 'fictitious boiling', was shown to be closely related to the microchannel size [10, 11]. The phase transition analysis presented in this paper and the theoretical predictions of equation (16) give strong evidence for the hypothetical concepts of 'evaporating space' and 'fictitious boiling'. The size of the evaporating space can be evaluated theoretically from Fig. 2 for different liquids. If the microchannel size is smaller than the 'evaporating space', then 'fictitious boiling' will be induced before nucleation is initiated. Otherwise, normal nucleate boiling occurs. 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 heat than the normal liquid sensible heat, resulting in very high heat transfer rates which might even exceed that of nucleate boiling in macro-channels. The present analytical investigation provides the theoretical basis for the previously observed experimental data and the proposed hypotheses. The superheats required for nucleation in microchannels as predicted by equation (23) are shown in Fig. 3 for various liquids. Clearly, nucleation in smaller channels requires higher superheats, which may indicate that such boiling is a highly non-equilibrium process.

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 nucleating criterion and a dimensionless parameter that describes the boiling conditions for liquids in microchannels. The predictions are in very good agreement with experimental observations of various investigators, such as Lin *et al.* [4], the authors and their co-workers [5–11] and Ding *et al.* [15], providing a theoretical basis for their observations. The results also provide a theoretical and quantitative basis for the 'evaporating space' hypothesis [10–12] and for nucleating in microchannels. However, more experiments are still necessary to understand the nature of the physical processes and to substantiate the theoretical conclusions.

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