Experimental investigation on bubble confinement and elongation in microchannel flow boiling

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Bubble confinement and elongation in flow boiling were investigated experimentally in a rectangular microchannel with 0.5 mm in width and 1.0 mm in height using DI water as the working fluid. Bubble growth under various mass flux, heat flux and inlet subcooling conditions was visualized using a high-speed CCD camera, and the recorded images were analyzed to provide quantitative information of the bubble confinement and elongation in the microchannel. The flow conditions and the underlying mechanisms for bubble confinement to occur were discussed. In addition, the bubble growth characteristics, such as the bubble length and growth rate, in both free and confined growth periods were compared. It was found that the bubble growth rate in free growth period is far less than that in confined growth period, and the bubble growth rate before confinement decreases with the increase of bubble size, while the elongation rate increases with the increase of confined bubble size. What is more, it was noted that the initial shape of nucleated bubble in channel corner had significant influences on bubble confinement and elongation.

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1. Introduction

With the rapid advance in modern electronics industry, there is a critical need for novel cooling and thermal management techniques to ensure the performance and reliability of various devices and systems in personal computing, electric vehicles and military avionics, etc. Microchannel flow boiling has emerged as a promising candidate due to its excellent heat dissipation capability [1,2] as well as the convenience of utilizing microscale bubbles for fluidic actuation and control [3,4]. Hence, significant research efforts have been devoted to understand the fundamental transport mechanisms in microchannel flow boiling. There are several comprehensive reviews summarizing the experimental studies of flow boiling in microchannels [5–10], where a few transport phenomena unexpected in conventional large channels were reported. A particularly interesting one is the formation of confined bubbles in microchannels [11–16]. When the growth of a bubble is constrained by channel cross-section, the bubble can only expand in the longitudinal direction of the channel where its growth is unconstrained. Hence, the bubble shape deforms and a confined bubble generates. If there has proper heat flux, the confined bubble can grow into an elongated bubble [17], which is characterized by a bullet-shaped vapor slug with nearly hemispherical nose and tail.

Thome [6] even suggested that the appearance of confined bubble flow should be taken as the threshold for transition from macro- to microscale flow boiling phenomena.

Confined bubble flow as a unique flow phenomenon in microchannel flow boiling has attracted extensive investigations. Chen et al. [18] studied the two-phase flow regimes in small tubes with inner diameters (I Ds) of 1.10, 2.01, 2.88 and 4.26 mm, respectively, using R134a as the working fluid. They found that when the tube diameter decreased to 1.10 mm, the flow characteristics were represented by the appearance of confined bubble flow and elongated bubble flow, observing the slimmer vapor slug, the thinner liquid film around the vapor slug, and the less chaotic vapor–liquid interface. Kenning et al. [19] investigated the axial growth of a confined bubble in a capillary tube at uniform superheat conditions, they proposed a one-dimensional model to describe the bubble growth from nucleation to confinement, and found that the initial growth rate of the bubble exerts a lasting influence on its subsequent growth. Barber et al. [20] studied the bubble confinement of FC-72 flow in a rectangular microchannel of hydraulic diameter 727 μm with a cross-sectional aspect ratio of 10, and concluded that there are three primary bubble growth stages in microchannels of high aspect ratios, namely, unconfined bubble growth, partial bubble confinement and full bubble confinement. They also found the correlation of the bubble confinement and elongation to the pressure fluctuations over time. The bubble confinement and elongation in subcooled flow boiling of DI water in microchannel...
was visualized by Yin et al. [21]. Two formation modes of the confined and elongated bubbles were identified, respectively the isolated bubble growing mode and the several bubbles merging mode, in addition, they found that a large boiling number can induce faster elongation of the confined bubble, and the high-speed growth and elongation of the downstream bubble partly suppresses the growth of the upstream one. Agostini et al. [22] examined the influence of bubble length on the bubble velocity in elongated bubble flow of R-134a in microchannel flow. It was found that the bubble velocity is initially proportional to the bubble length till a plateau was reached, and it also increases with channel diameter and mass flux. Revellin et al. [23] performed a similar study on the length and velocity of elongated bubbles in R-134a flow in a 0.5 mm microchannel. Their experimental measurements were obtained by an optical measurement technique and compared with the homogeneous, drift flux and Agostini et al. [22] models. They found that the trends in data were well captured by the model of Agostini et al., and the elongated bubble velocity and length increase with vapor quality. In a recent study of quasi-diabatic two-phase flow of R134a and R245fa through a glass window, a microchannel test piece, a ceramic heating glass window, a microchannel test piece, a ceramic heating crystal lens was used to magnify the image. The temperatures and pressures of the working fluid at the inlet and outlet of the microchannel were measured using K-type thermocouples and ±0.2\% respectively.

2.2. Test section

The microchannel test section is depicted in Fig. 2. It was assembled from six parts: a polycarbonate cover plate, a Pyrex glass window, a microchannel test piece, a ceramic heating peristaltic pump, a micro-filter (7 µm), a pre-heater, a microchannel test piece and a high-speed CCD camera with a microlens. The working fluid was degassed deionized water. Before water entered the test section, it was first heated in the pre-heater to reach the desired inlet subcooling. In the microchannel test section, the water was heated to saturated state and bubbles were generated. Then the vapor–liquid two-phase mixture exiting the microchannel flowed into a liquid-cooled condenser. The condensate was discharged directly into a container, which was placed on a precision electronic balance, and thus the average mass flow rate can be determined by calculating the mass increment per unit time. Flow visualization was started after the bubble appearance, and it was conducted with a high-speed CCD camera. The resolution of the camera was 640 (H) × 478 (V) pixels, and the frame rate was 250 frame per second (fps). A LED illuminator was used to provide the high intensity lighting, and an adjustable microscopic magnification lens was used to magnify the image. The temperatures and pressures of the working fluid at the inlet and outlet of the microchannel were measured using K-type thermocouples and pressure sensors with the accuracy of ±0.2 °C and ±0.1%, respectively.

2.1. Experimental apparatus

Fig. 1 shows the schematic of the experimental apparatus used to investigate the bubble confinement and elongation behaviors in microchannel flow boiling. It includes a liquid reservoir, a
element, multi layer glass fiber insulation, and a Bakelite base plate. Pyrex glass was used as the observation window due to its high transmittance and high temperature resistance, and was sandwiched between the polycarbonate cover plate and the microchannel test piece. The rectangular microchannel was fabricated in a copper plate with the dimensions of 120 mm (length) × 30 mm (width) × 2 mm (thickness) by conventional milling technique. The cross section of the channel was 0.5 mm in width and 1 mm in depth. The channel length was 100 mm. The hydraulic diameter of the channel was 667 μm and the corresponding confinement number is Co = 3.9. It is a microchannel for flow boiling according to the literature [11]. The heat flux was adjusted by controlling the electric power to the ceramic heating element. To reduce heat loss to the ambient, several layers of glass fiber were filled between the heating element and the Bakelite base plate.

2.3. Experimental procedure and data reduction

The DI water was vigorously boiled for about 1 h to remove dissolved gas before filling into the water reservoir. When the flow became stable under a certain mass flow rate, the pre-heater was electrically powered to regulate the liquid subcooling degree. After the subcooled liquid flowed into the test section, the electricity was provided to the ceramic heating slice to generate the heat flux needed for boiling. Increasing the heat flux very gradually until bubbles could steadily nucleate, grow, and deform due to channel confinement, at this moment, a stable operating condition for bubble behavior investigation was established, and the visualization image could be recorded by the high-speed CCD camera.

For visualization, the upper surface of the test section was not covered by thermal insulation material and exposed directly to the air, which induced the heat loss of the test section to the ambient. A series of single-phase heat transfer experiments of the working fluid in test section had been conducted to estimate the heat loss prior to flow boiling tests. Based on the energy conservation, the heating power must be balanced with the sensible heat gained by the fluid through the channel and the heat losses via different ways such as convection and thermal radiation to the ambient, \( Q_{\text{input}} = Q_{\text{eff}} + Q_{\text{loss}} \), where \( Q_{\text{input}} = V \times I \) is the total heating power supplied by the ceramic heating slice; \( Q_{\text{eff}} \) is the effective heat flow rate obtained by the single-phase liquid flowing through the channel; and \( Q_{\text{loss}} \) is the heat loss of the test section. The effective heat transferred to the liquid can be calculated from the inlet and outlet temperature measurements, \( Q_{\text{eff}} = \dot{m} C_p \Delta T_{\text{sub}} \) where \( \dot{m} \) is the mass flow rate; \( C_p \) is the specific heat capacity at constant pressure, \( T_{\text{fin}} \) and \( T_{\text{fout}} \) are the inlet and outlet temperatures of the liquid, respectively. The heat loss ratio for single-phase tests was determined as \( \eta_{\text{loss}} = Q_{\text{loss}} / Q_{\text{input}} \) which was in the range of 0.16–0.19 for a heat input range similar with that in flow boiling experiments. Therefore, an average value of 0.175 was chosen as the heat loss ratio of the test section and was used to calculate the heat flux. Due to the high thermal conductivity of copper material and the small channel dimensions, it is reasonable to assume that the heat flux at each side of the rectangular channel is approximately uniform. Thus the heat flux was calculated as \( q_w = Q_{\text{eff}} / A \), where \( A = (W_c + 2H_c) \times L_c \) is the heated area of the microchannel; \( W_c, H_c, \) and \( L_c \) are the width, height and length of the channel, respectively. It was worth noting that the method of determining the heat loss was similar to that used by Hetsroni et al. [25], Liu et al. [26] and Bogojevic et al. [16].

The video images recorded by the CCD camera were processed using a commercial software package (MiDas Player, Xcite, Inc.) The bubble length was determined by converting the pixels occupied by the bubble along the flow direction with a known pixel-to-size ratio, and the measurement accuracy was ±10 μm. The bubble growth rate was defined as the change rate of the bubble length.

3. Results and discussion

The bubble growth is constrained by the channel wall if the hydraulic diameter of the channel is smaller than the bubble departure diameter, resulting in the appearance of confined and elongated bubbles, which greatly impact on the heat transfer performance. Therefore, it is of interest to investigate the bubble behaviors and the formation conditions of confined bubble flow in microchannel flow boiling.

3.1. Formation of the confined bubble flow

A series of experiments were conducted under different operating conditions by adjusting the mass flux, heat flux and inlet subcooling of the liquid. The operating conditions are displayed in Fig. 3 under which confined bubbles and elongated bubbles can be observed. There exists certain heat flux range for bubble confinement and elongation to occur at specific mass flux and inlet subcooling condition, which can be recognized by the two groups of boundary lines in Fig. 3. If heat flux is less than the lower limit, bubbles depart before being confined, resulting in bubbly flow. If the heat flux exceeds the upper limit, annular flow forms due to vigorous bubble coalescence caused by the increased nucleation site density and the enhanced bubble growth rate. Bubble growth is the comprehensive result of interactions between evaporation and condensation at bubble interface in subcooled flow boiling. With the increase of inlet subcooling at a certain mass flux condition, the nucleation and growth of the bubble are delayed due to the enhanced condensation effect, resulting in the increased heat flux requirement for confined bubble occurring, and the corresponding heat flux range for confined bubble flow is expanded. Hence, it can be found in Fig. 3 that the increase of inlet subcooling at certain mass flux postpones the occurrence of confined bubble, but widens the heat flux range occurring confined bubble flow.

![Fig. 3. The operating condition for the confined and elongated bubbles occurring.](image-url)
Similarly, it also can be noted that with the increase of mass flux at given inlet subcooling, the minimum heat flux needed for confined bubble occurrence raises. However, with the increase of mass flux at a certain inlet subcooling condition, the heat flux range occurring confined bubble flow narrows. Increased mass flux generally leads to reduced bubble departure diameter and enhanced bubble departure frequency, increasing the difficulty in forming confined bubbles at moderate heat flux condition, yet easily resulting in the annular flow at high heat flux. Therefore, the lower limit of heat flux forming confined bubble increases and the heat flux range for confined bubble flow narrows when the mass flux increases at a given inlet subcooling condition.

3.2. The characteristics of bubble confinement and elongation

A complete bubble growth process in the horizontally oriented microchannel, including the bubble nucleation, confinement and elongation, is shown in Fig. 4. In the microchannel, working fluid flowed from right to left and the bubble nucleated in the channel corner. It is noted that after nucleation the bubble remains its spherical shape until \( t = 40 \text{ ms} \). Bubble growth is constrained by the channel cross-section once the top of bubble approaches the channel wall, then its shape elongates along the channel flow direction (from \( t = 48 \text{ ms} \) to \( t = 96 \text{ ms} \)).

The bubble size and its growth rate are the two most important characteristics in studying the effect of spatial confinement on flow boiling in microchannels. Fig. 5 shows the effect of mass flux on the bubble growth and elongation process at certain heat flux and inlet subcooling conditions. Fig. 5(a) and (b) respectively display the variation of bubble length and bubble growth rate during bubble growth process. The dot dash line represents the minimum dimension of the channel, indicating the transition threshold from free/unconfined growth bubble to confined growth bubble. It can be found that for both conditions, the bubble growth rates before confinement are much slower than those after being confined. This is caused by the fact that the dominant heat transfer mechanism of confined bubble flow is the evaporation of thin liquid film surrounding the elongated bubble. It can generate more vapors entering into the bubble compared with the unconfined free growth bubble, leading to large bubble growth rate in confined growth period. In addition, the growth rate of unconfined bubble decreases with the increase of bubble size, which is caused by the increased growth resistance when the bubble interface approaches the channel wall [27]. But the bubble elongation rate increases with the increase of confined bubble size due to the continual expansion of the evaporating liquid film around the bubble, until the bubble is discharged from the channel outlet.

From Fig. 5(b), bubble growth rate decreases evidently with the increase of mass flux in both unconfined growth period and confined growth period, which can further confirm that the increase of mass flux postpones the occurrence of confined bubble flow in microchannel flow boiling. The inertial force of the flowing fluid, as a resistance force for bubble growth, increases with the increase of mass flux, which results in the decreased bubble growth rate in unconfined growth period. In confined growth period, apart from the increased inertia force of flowing fluid, the evaporation capacity of liquid film around bubble reduces with the increased mass flux due to the accelerated moving velocity of elongated bubble. Consequently, the bubble growth rate also decreases with the increase of mass flux during bubble confined growth period.

The effect of heat flux on bubble confinement and elongation is shown in Fig. 6. The increment of heat flux leads to the increase of bubble growth rate before confinement, thus remarkably shortening the time needed to achieve the confined bubble flow in microchannel. The bubble elongation rate increases with heat flux immediately after the bubble is confined, however, this dependence becomes weak when the bubble length reaches a certain value, e.g., \( L_0 = 1.75 \text{ mm} \) in Fig. 6(b). In the subsequent process, the confined bubbles have almost the same elongation rates even for different heat flux conditions. The confined bubble growth is determined by the combined action of the evaporation of thin liquid film surrounding the bubble and the condensation at

![Fig. 4. Typical bubble confinement and elongation process.](image-url)

![Fig. 5. The effect of mass flux on the bubble confinement and elongation (\( q_w = 65.0 \text{ kW/m}^2, \Delta T_{sat} = 77 \text{ °C} \)). (a) Bubble length variation with time. (b) Variation of bubble growth rate with bubble length.](image-url)
The effect of heat flux on the bubble confinement and elongation 
($G = 33.3 \text{ kg/m}^2\text{s}$, $\Delta T_{\text{sub}} = 77 ^\circ \text{C}$). (a) Bubble length variation with time. (b) Variation of bubble growth rate with bubble length.

The effect of inlet subcooling on bubble confinement and elongation ($q_w = 28.9 \text{ kW/m}^2$, $G = 33.3 \text{ kg/m}^2\text{s}$). (a) Bubble length variation with time. (b) Variation of bubble growth rate with bubble length.
bubble certainly last through the whole bubble growth process due to the continuity of bubble growth, and generally strengthen with bubble continuous elongation due to the increased bubble size. For case (c), even if the bubble has been confined in channel width direction, the areas of microlayer between the bubble and channel sides wall is still smaller than that in case (a) or case (b) due to the inheritance of bubble growth process, the bubble elongation rate is certainly smaller than the latter two cases, and the difference of bubble growth rate increases with bubble continuous elongation, until the bubble is discharged out of the channel. Therefore, it can be known that the phenomena mentioned at the beginning of this paragraph belong to the above situation. Namely, the nucleated bubble in condition of $q_{w} = 46.0 \text{ kW/m}^2$, $G = 33.3 \text{ kg/m}^2 \text{s}$ and $\Delta T_{\text{sub}} = 77 \degree \text{C}$ in Fig. 7 is case (c), those phenomena were caused by the relatively small microlayer region between bubble and channel walls in both free and confined growth periods. Due to the complexities of initial shape of nucleated bubble and its significant influences on bubble confinement and elongation, much work needs to be conducted in the future.

4. Summary

Heat transfer mechanisms in microchannel flow boiling are still intangible due in part to the lack of a complete understanding of bubble dynamics in confined space. In this work, bubble confinement and elongation in a single rectangular microchannel flow boiling was investigated. A series of experiments were conducted to observe the confinement and elongation phenomena of bubbles at various mass flux, heat flux and inlet subcooling conditions. The main findings are as follows:

(1) For given mass flux and inlet subcooling, a heat flux range exists for the confined bubble to appear in microchannel flow boiling. The threshold heat flux increases with increasing mass flux and inlet subcooling. The heat flux range for confined bubble regime narrows with the increase of mass flux, but expands with the increase of inlet subcooling.

(2) The bubble growth rate in free growth period is far less than that in confined growth period, and both of them increase with the decrease of mass flux and inlet subcooling.

(3) The bubble growth rate before confinement decreases with the increase of bubble size, but the elongation rate increases with the increase of confined bubble size.

(4) The influence of heat flux on the bubble confinement and elongation is ascertained. In the free growth period and the earlier stage of bubble elongation, the bubble growth rate increases with the increase of heat flux. After the elongated bubble reaches a particular length, the effect of heat...
flux on bubble elongation rate vanishes, which is determined by the elongation mechanism of the confined bubble in microchannel flow boiling.

(5) The initial shape of nucleated bubble in channel corner has significant influences on bubble confinement and elongation. The original small microlayer region beneath the nucleated bubble results in the relatively small bubble growth rate, increasing the time needed for bubble confinement and leading to the relatively small bubble elongation rate in confined growth period.

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