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Experimental investigation on bubble confinement and elongation in microchannel flow boiling

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ABSTRACT

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.

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

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Nomenclature

A	surface area (mm^2)
Co	confinement number, $Co = (\sigma/g(\rho_L - \rho_V)D_h^2)^{1/2}$
C_{pl}	specific heat (J/kg K)
D_h	hydraulic diameter (mm)
g	gravity acceleration (m/s^2)
G	mass flux (kg/m^2 s)
H_c	channel height (mm)
I	current (A)
L_c	channel length (mm)
L_b	bubble length (mm)
$\dot{m}$	mass flow rate (kg/s)
q_w	wall heat flux (W/m^2)
Q_{eff}	heat transfer into the fluid (W)
Q_{input}	supplied input power (W)
Q_{loss}	heat loss from test section (W)
$T_{f,in}$	fluid inlet temperature (°C)
$T_{f,out}$	fluid outlet temperature (°C)
V	voltage (V)
W_c	channel width (mm)

Greek symbols

ΔT_{sub}	inlet subcooling (°C)
ε_{loss}	heat loss ratio
ρ_L	liquid density (kg/m^3)
ρ_V	vapor density (kg/m^3)
σ	surface tension (N/m)

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 2.32 mm I.D. tube, Arcanjo et al. [24] visualized the flow patterns and measured the velocity, frequency and length of the elongated bubbles. It was found that the velocity of elongated bubbles increases with decreasing saturation temperature and increasing vapor quality and mass flux.

In spite of the extensive studies on the confined bubble flow in microchannel flow boiling, the operating conditions resulting in bubble confinement and elongation remain elusive and the influences of operating conditions on growth characteristics of confined bubble are still not fully understood. These knowledges are necessary to explore the accurate heat transfer mechanisms on flow boiling in microchannel and to promote the utilization of confined bubble in practice.

In the present work, the confinement and elongation of single bubbles in flow boiling were investigated experimentally in a microchannel. The formation process and growth rate of confined bubble and the effects of operating conditions on the confined bubble behaviors were discussed.

2. Experimental setup

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 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.

2.2. 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

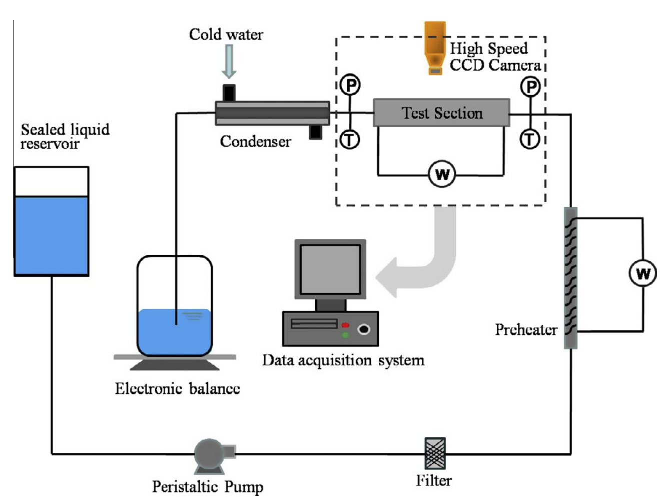

Fig. 1. The schematic of the experimental system.