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Bubble growth, departure and the following flow pattern evolution during flow boiling in a mini-tube

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ABSTRACT

In the present study, the bubble growth, departure and the following flow pattern evolution during flow boiling in the mini-tube were visualized and quantitatively investigated, along with the simultaneous measurement of the local heat transfer coefficient around a specified nucleation site. Liquid nitrogen was employed as the working fluid and the test section was a segment of vertically upward quartz glass tube with the inner diameter range of 1.3–1.5 mm, which was coated by a layer of transparent ITO film as the heater on the outer surface. The growth rates of bubbles had similar and constant growth rate in two periods of time, i.e., before and after the bubbles departing from the nucleation site, which indicated the bubble growth was primarily governed by the inertial force. The bubble departure diameter and bubble period were investigated and the corresponding correlation was obtained based on the experimental data, which showed that the tube size of the mini-tube had no notable effect on the bubble departure and the trend of the bubble departure was similar to that in macro-tubes. Whereas the following flow pattern evolution was apparently confined due to the size effect, which presented desirable heat transfer performance in mini-tubes. The heat transfer coefficients for different flow patterns along the mini-tube were obtained in terms of bubbly, slug, annular flow and the flow regimes of flow reversal and post dryout. It was found that the dominant heat transfer mechanism was the liquid film evaporation which offered desirable heat transfer capability. The heat transfer performance would be deteriorated in the post dryout regime, while flow reversal could somewhat enhance the heat transfer upstream of the nucleation site. Boiling curves around the specified nucleation site were recorded and analyzed based on the recorded flow patterns.

1. Introduction

Boiling heat transfer in mini/micro-channels has become the hotspot of research in the past decade due to the possibility of dissipating increasingly high heat fluxes for electronic, power, and laser devices. At cryogenic temperature range, micro-scale flow boiling also owns many applications in micro-cryogenic surgery apparatus (MCSA), the cooling of high temperature superconductivity (HTS) devices and so on. For example, the inlet tube of the MCSA used to cure tumors is very small, only about 0.8 mm in diameter; and some channels with the sizes in the range of millimeter or less usually form in the cooling passages of HTS cable-in-conduit conductors (CICCs). Moreover, cryogenic fluids like liquid nitrogen (LN_2) have some particular thermal properties (e.g., small surface tension, small latent heat, near zero wetting angle and large ratio of vapor density to liquid density), which will apparently have the effects on the heat transfer performance of liquid nitrogen in mini-tubes. A brief review is made on the aspects of macro- to micro-scale transition criterion, flow regime and bubble dynamics of two-phase flow in mini/micro-channels with the working fluids of water, refrigerants and liquid nitrogen in the following paragraphs.

1.1. Macro- to micro-scale transition criterion in two-phase flow

A recognized transition threshold criterion from macro- to micro-scale has not been well-established yet. Kandlikar [1] recommended the following classification and size ranges: micro-channels (10–200 μm), mini-channels (200 μm–3 mm) and conventional channels (>3 mm) based on the engineering practice and applications. Harirchian and Garimella [2] tested seven different silicon test pieces containing parallel micro-channels of widths ranging from 100 to 5850 μm with the depth of 400 μm and concluded that the micro-channel width, depth, or aspect ratio individually did not determine boiling mechanisms in micro-channels; instead, it was the cross-sectional area of the micro-channels that played a determining role. Many researchers, however, argued that the transition criteria should reflect the influence of channel size on the physical mechanisms. The confinement

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Nomenclature

A	cross-section area of the tube (m^2)
U	electric voltage through the heater (V)
Bo^*	modified Boiling number $\left(\frac{q}{h_{fg}G}\frac{\rho_L}{\rho_V}\right)$
Co	confinement number $\left(\left(\frac{\sigma}{(\rho_L-\rho_V)gD^2}\right)^{1/2}\right)$
c_p	specific heat (J/kg K)
D	diameter (mm)
D_{ini}	initial bubble diameter (mm)
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of vaporization (J/kg)
I	electric current through the heater (A)
Ja	Jakob number $\left(\frac{c_p\rho_f(T_f-T_{\text{sat}})}{h_{fg}\rho_V}\right)$
k	thermal conductivity (W/m K)
L	heating length (m)
L^*	dimensionless heating length (L/D)
p	pressure (kPa)
q	heat flux (W/m^2)
Pr	Prandtl number $\left(\frac{\eta c_p}{k}\right)$
R_a	mean roughness (μm)
Re	Reynolds number $\left(\frac{GD}{\eta}\right)$
S	surface area of the tube (m^2)
t	time (ms)
T	temperature (K)
U	electric voltage through the heater (V)

Greek symbols

η	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	period (s, ms)

Subscripts

b	bubble
CHF	critical heat flux
d	departure bubble
exp	experimental data
f	fluid
gt	glass tube
i	inner surface of the tube
in	inlet of tube
L	liquid phase
pre	predicated data by the model
o	outer surface of the tube
out	outlet of the tube
sat	saturation state
V	vapor phase
w	wall of the tube
x	at location x along the tube

number $Co = \left[\frac{\sigma}{(\rho_L-\rho_V)gD^2}\right]^{1/2} = 0.5$, which was recommended by Kew and Cornwell [3] representing the channel size effect on the heat transfer, might be a proper candidate to serve as a criterion to differentiate between macro-scale and micro-scale two-phase flow and heat transfer. According to $Co = 0.5$, the critical hydraulic diameter to distinguish between macro-scale and micro-scale in most applications is in the range of 1.0–2.0 mm, and the confined bubble flow which characterized the confinement of channel were reported in the literature [4,5]. Thome [6] also suggested the confined bubble flow as the best interim criterion for the threshold from macro- to micro-scale. Actually, in some cases for the confined bubble flow (hydraulic diameter in the order of about 1 mm), the channel does not confine the bubble departure but the flow pattern evolution following the bubble departure. Thus, regarding whether the channel size affects the bubble departure or not, it is recommended that the micro-scale should be further subdivided into two groups. One is with relatively large hydraulic diameter somewhat analogous to the region of the mini-channel proposed by Kandlikar [1], in which channel does not restrict the bubble departure but the flow pattern evolution following the bubble departure, and most studies of two-phase flow in the name of mini- or small size passages belong to this group; the other is with relatively smaller hydraulic diameter in the order of the bubble departure diameter, in which bubble departure is confined by the channel size and the bubbly flow may not exist. The dimensions of the tubes employed in the present study belong to the first group of micro-scale and are named as "mini-tube" for the sake of convenience.

1.2. Flow regimes of two-phase flow in mini/micro-channels

Visualization of flow patterns could provide insight to the heat transfer mechanism in mini/micro-channels. A number of investigators focus on the study of flow patters appearing in mini/micro-channels, based on which flow regime maps corresponding to different flow regimes are obtained, some of which are concerned with adiabatic flow patterns by injecting air to water in small transparent glass tubes [7–10]. Some other researchers [11–14] obtained the flow boiling patterns by the similar visualization technique using R-134a, CO_2 as the working fluid. Fu et al. [15] and Zhang and Fu [16] performed visualization studies on the flow boiling of liquid nitrogen in vertically upward tubes with the inner diameter ranged from 0.5 mm to 2.0 mm, in which the typical flow patterns were bubbly, slug, churn and annular flow. Confined bubble flow was observed in 1.0 mm and 0.5 mm tubes. Flow boiling in micro-channels etched in silicon wafer by MEMS technique is expected to be the promising solution to heat management of electronic chips. With respect to this research topic, many visualization work are performed to link the heat transfer performance to the flow patterns, among which the influential studies include those of Qu and Maduwa [17], Hestronic et al. [18], Xu et al. [19] and Jiang et al. [20], etc.

The discussion about the controlling heat transfer mechanism in mini/micro-channels is usually based on whether the heat transfer coefficient is more relevant to heat flux or mass flux. The controlling mechanism is regarded to be nucleate boiling when the heat transfer coefficient is heat flux dependent. Otherwise, the mechanism is thought to be convective evaporation. Owhaib et al. [21] experimentally investigated the boiling heat transfer in vertical circular tubes with internal diameter of 1.7, 1.224 and 0.826 mm and concluded that the heat transfer mechanism was strongly related to nucleate boiling. Kandlikar [22] presented a mechanistic description of flow boiling phenomenon in flow passages with small hydraulic dimensions and concluded that nucleate boiling systematically emerged as the dominant mode of heat transfer in low Reynolds number flows (range of 100–1000). While, Thome [6] alleged that the transient evaporation of the thin liquid film surrounding elongated bubbles was the dominant heat transfer mechanism as opposed to nucleate boiling. Furthermore, a three-zone flow boiling model was developed by them to describe evaporation of elongated bubbles in micro-channels. There are many different arguments on controlling heat transfer mechanism