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Heat transfer characteristics of flow boiling in horizontal ultra-shallow microchannels

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ABSTRACT

Bubble behavior in horizontal ultra-shallow microchannels displays distinct features in flow boiling heat transfer process, which is embodied as the fast elongation and deformation. It expands the range of the microlayer region and causes effective disturbances to the main flow, and therefore contributes to the enhancement in heat transfer. However, too fast deformation of the confined bubbles also results in rapid reducing of the liquid film thickness, causing the early appearance and short span of the annular flow. The enhancement in the heat transfer capability is then limited or even weakened. These distinct features lead to unsuitable predictions of classic correlations for the experimental data. The average error of the classic correlations exceeds 50% and the largest deviation reaches 125%. On the ground of the visualization experimental results, a theoretical model based on Chen's model is proposed to calculate the flow boiling heat transfer coefficient in horizontal ultra-shallow microchannels. The presented model can be applied for both the elongation bubble flow and the annular flow as the heat transfer mechanism for these two flow patterns are specially considered respectively. Verified by the measured data, the average error of the model successfully drops to ±15%, from ±52.4% of the Chen's model whose prediction fitted experimental data the best among the classic correlations.

1. Introduction

With the wide application of the highly integrated industrial devices and the fast development of the MEMS processing technologies, the heat generated in the electronic components and devices grow rapidly while the cooling condition becomes much harsher. The related application involves kinds of high-tech fields, for instance, in space, automotive applications, nuclear engineering, and new energy utilization [1,2]. As an efficient thermal management solution for such high power density situations, flow boiling in mini/microchannels attracts a lot of attentions throughout the world. For past decades, the bubble behaviors [3,4], flow pattern development [5,6], two-phase pressure drop [7,8] and heat transfer mechanisms [9–11] during flow boiling in microchannels have been widely explored and significant process has been made in relative theories. Nevertheless, the essential relation between the heat transfer features and the bubble dynamics during flow boiling in microchannels still remains a clearer comprehending, so as to unleash the potential in practical application for more fields.

In our previous work [12], the visualization experiments on flow boiling in horizontal ultra-shallow microchannels was conducted. The cross-section of the microchannel is rectangular, and its aspect ratio equals to 0.2. The working fluid is degassed acetone. The features of the bubble dynamics in confined channels were specially explored with high speed photography. The flow patterns as well as the local heat transfer coefficients under various operating conditions were also compared. Yet, a quantified relationship between the heat transfer capability and the confined bubble behaviors requires to be further discussed and revealed. Therefore, a novel theoretical model based on Chen's model is proposed in this work, in which the effects of the deformation rate of the confined bubbles on the heat transfer are taken into account for the elongation bubble flow and the annular flow respectively. With dimensional analysis method, the influences of the inlet mass flux G and the heat flux q'' are also pondered to fully capture the flow boiling heat transfer characteristics in horizontal ultra-shallow microchannels.

2. Literature review

Bonjour and Lallemand [13] firstly observed and defined the confined bubble flow, which, however, arouse little attention

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Nomenclature

A	cross-section area of the microchannel, m
Bo	Boiling number, $q''/(Gh_{f,g})$
Co	convective number, $(1-x/x)^{0.8}/(\rho_v/\rho_l)^{0.5}$
D_h	hydraulic diameter, m
E	enhancement factor for annular flow
e	target error of linear programming
F	Reynolds number factor
Fr	Froude number, $v/(gD_h)^{0.5}$
G	inlet mass flux, kg/m^2·s^{-1}
g	gravity acceleration, m/s^2
h_{tp}	two-phase heat transfer coefficient, W/m^2·K^{-1}
k_l	heat conductivity coefficient of liquid, W/m·K^{-1}
N	total number of the variations
N_{co}	confinement number, $[\sigma/g(\rho_l-\rho_v)]^{0.5}/D_h$
P	perimeter of the microchannel, m
q''	heat flux, kW/m^2
Re	Reynolds number, $\rho v D_h/\mu$
S	suppression factor
v	superficial velocity of fluid, m/s
We	Weber number, $\rho v^2 D_h/\sigma$
x_e	thermodynamic equilibrium quality
x	quality

Greek alphabet

ρ_l	liquid density, kg/m^3
ρ_v	vapor density, kg/m^3
ε	void fraction
δ	liquid film thickness
τ_w	wall sheer stress, N
φ_L	two phase frictional multiplier
α	aspect ratio (ratio of width to depth)
χ	Martinelli parameter
μ	dynamic viscosity, Pa·s
σ	surface tension, N/m

Subscripts

f	fluid
l	liquid phase
v	vapor phase
tp	two-phase flow

[14]. Cornwell and Kew [15,16] identified confined bubble pattern during their flow boiling experiments of R-113 in vertical channels with the cross section of 1.2 mm × 0.9 mm and 3.25 mm × 1.1 mm. As the size and the motion of the confined bubbles were restricted by the walls, they put up forward a dimensionless number Confinement number N_{co} to describe the characteristics in the elongation bubble regime, shown as Eq. (1).

$$N_{co} = \left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{0.5} \Big/ D_h \tag{1}$$

In Cornwell and Kew's experiments, the annular flow was captured at a low vapor quality (less than 0.2), and the heat transfer coefficient in annular flow region grew with the increasing of the quality. Meanwhile, related heat transfer coefficient correlations were given according to the flow regime observed in their experiments, where dimensionless numbers (i.e. Confinement number, Boiling number, Reynolds number, Nusselt number and Prandtl number) were all introduced.

There is an ongoing controversy about the dominant heat transfer mechanism in the microchannels, not to mention considering the complicated affects of the confined bubbles on the heat transfer process. Thome [17] even proposed that the occurrence of the confined bubble flow would result in a transition in the flow boiling phenomena. Some researchers held the view the heat transfer is basically intensified by the mixing flow through bubble nucleation and bubble submersion [18–22] in microchannels. Some other insist that the two-phase forced convection dominates the region by both the conduction and the convection through the liquid film [23–26].

In particular, flow boiling heat transfer coefficient in mini/micro-channels has been studied by many researchers. Many predicting correlations based on either the analytical method or experimental data are already proposed. These correlations can be basically divided into three kinds of models. The first one is from Chen's model [27], combining the nucleate boiling with the forced convection mechanism by two dimensionless factors, the Reynolds number factor F and the suppression factor S. Chen's model is widely adopted and taken as a benchmark in the literature [28]. The second is from Shah's model [36], comparing the larger impact between the boiling number Bo and the convective number Co. The third one is Kutateladze's model [39], using two independent components by a power-type asymptotic model. Numbers of flow boiling correlations published in the last three decades are only variations of these 3 types of models [28].

There are some classic correlations for flow boiling heat transfer coefficient h_{TP} collected, and shown in Table 1.

3. Heat transfer characteristics

3.1. Heat transfer mechanism

Fig. 1 shows the variation of heat transfer coefficient h_{TP} with the thermodynamic equilibrium quality x_e. When subcooled boiling starts, the bubbles appear, heat transfer coefficient is dominated by nucleate boiling. Limited by the aspect ratio of cross-section of the microchannel, the bubbles get confinement in the depth direction, and the Onset of Turning Point (OTP) [12] occurs. In this stage, the bubbles begin to combine and further elongate. On one hand, the deformation of the confined bubbles enables the liquid-vapor (LV) interface of the microlayer region expanded. On the other hand, the fast elongation in the axial direction enlarges the absorbed film region. Meanwhile, the fast elongation of the confined bubbles towards to both ends induces the perturbations of liquid phase at both upstream and downstream, and therefore results in inevitable forced heat convection. Obvious forced convection has occurred before the nucleate boiling is completely suppressed, and the heat transfer is dominated by both heat transfer mechanisms. This stage occupies a large span of time during the whole heat transfer process, and the heat transfer capability can maintain at a stable level. This feature will possess a positive value of application in heat transfer.

The schematic diagram of the heat transfer mechanism in stage II can refer to Fig. 2. Along with the increasing of the heat flux, the vapor core is finally surrounded by the annular liquid film, and the annular flow forms. Till then, the nucleate boiling stops, and the forced heat convection is considered to be the predominant mechanism. It should be noticed that the annular flow appears at small thermodynamic equilibrium quality x_e due to the fast development of the confined bubbles in the previous stage. This is also the reason that the classic correlations poorly predict the experimental data.