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Investigation of bubble departure diameter in horizontal and vertical subcooled flow boiling

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ABSTRACT

According to the force balance analysis on a bubble, the bubble departure diameter in horizontal subcooled flow boiling is mainly influenced by quasi-steady drag force, surface tension force and bubble growth force while an additional force, buoyancy force, plays an important role in vertical flow boiling. In this paper, the effects of these forces can be concluded by a series of dimensionless parameters including density ratio of vapor and liquid, Prandtl number, Jacob number and bubble Reynolds number. Based on the different forces, two different characteristic lengths are adopted to non-dimensionlize bubble departure diameters in horizontal flow boiling and vertical flow boiling, respectively. Finally, the semi-empirical correlations for bubble departure diameters in both horizontal and vertical subcooled flow boiling are proposed in this paper based on the force balance analysis and available experimental data from literature. The predicted results using the present correlations agree fairly well with the experimentally measured values with a mean relative error of 19.72%.

1. Introduction

Due to its efficiency and safety, subcooled flow boiling has been widely applied in the design of thermal-hydraulic systems in nuclear reactors [1–5]. The two-fluid model combined with the interfacial area transport equation [6] has been extensively used in the CFD simulation of two-phase flow, which requires closure relations for wall-to-flow and phase-to-phase heat and mass transfer. The bubble nucleation on the wall is significant in nucleate boiling system since it has provided the source of void to the bulk liquid as a boundary condition [7]. In order to gain the wall-to-flow heat transfecr in subcooled flow boiling, various wall heat flux partitioning models have been proposed in the past [8]. Kurul and Podowski [9] assumed that wall heat flux consisted of three parts: the latent heat of evaporation (q_e), the liquid-phase convection (q_c) and sensible heat due to quenching (q_q):

$$q_w = q_e + q_c + q_q \tag{1}$$

The latent heat of evaporation can be defined as follows:

$$q_e = \frac{\pi}{6} D_d^3 \rho_v h_{fg} f_d N_a \tag{2}$$

where D_d, f_d, N_a stand for bubble departure diameter, bubble departure frequency and active nucleation site density, respectively. The three sub-models are significant in wall heat flux partitioning model to predict heat transfer in subcooled flow boiling. Due to the complexity of boiling, many empirical or semi-empirical correlations are proposed to formulate these boiling parameters. However, Li et al. [10,11] has pointed out that although these correlations are available in the two-fluid model, their physical basis are rather weak and require to be evaluated under different working conditions. In order to gain a better understanding of the mechanisms of heat transfer, one of the nucleation parameters, the bubble departure diameter is studied in this paper.

The bubble departure diameter is defined as the diameter at the point of bubble leaving the nucleation site. In general, there are three different approaches to predict bubble departure diameter in subcooled flow boiling: the force balance approach, correlation approach and energy balance approach [12].

First of all, the force balance approach is based on the force balance analysis acting on the bubble attached to the heating surface. The forces acting on a bubble can be divided into two groups, forces parallel and normal to the heating surface, respectively. The break of force balance parallel to the heating surface is regarded as the criterion of bubble departure in flow boiling. Fritz [13] applied this method to predict bubble departure diameter in pool boiling by considering the balance of buoyancy and surface tension for a bubble. A detailed force-balance model was proposed

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Nomenclature

q_w	wall heat flux (kW/m^2)
q_c	liquid-phase convection
D	bubble diameter(m)
N_a	nucleation site density (/m^2)
ρ^*	density ratio
Ja	Jacob number
F_{qs}	quasi-steady drag force (N)
F_{sl}	shear lift force (N)
F_h	hydrodynamic pressure force (N)
R	bubble radius (m)
V	volume (m^3)
U	velocity (m/s)
C_D	drag coefficient
P	system pressure (MPa)
c_p	heat capacity (J/(kg·K))
λ	thermal conductivity (W/(m·K))
T	temperature (K)
G	mass flow rate (kg/(m^2·s))
q_e	latent heat of evaporation
q_q	quenching heat flux
f	frequency (Hz)
h_{fg}	latent heat (J/kg)
Pr	Prandtl number
Re	Reynolds number
F_s	surface tension (N)
F_{du}	growth force (N)
F_b	buoyancy force (N)
F_{cp}	contact pressure force (N)
σ	surface tension (N/m)
α	advancing contact angle
β	receding contact angle
θ	inclined angle
a	thermal diffusivity (m2/s)
μ	kinetic viscosity (Pa·s)
L_c	characteristic length (m)
Lo	Laplace length (m)

Subscripts

w	wall
sat	saturated
l	liquid
v	vapor
g	gas
b	bubble
d	departure
x	x-direction
y	y-direction
c	center

by Klausner and Zeng [14–16] to predicted bubble departure diameter for the working fluid of R113 in both pool boiling and horizontal flow boiling. In their work, the forces acting on the bubble contained surface tension force, bubble growth force, quasi-steady drag force, buoyancy force, shear lift force, contact pressure force and hydrodynamic pressure force. Subsequently, many researchers had extended the force balance model to different working conditions and modified the model by adjusting the expressions of forces [17–20]. The force-balance analysis reveals the mechanism of bubble departure process and gives a rather accurate prediction of bubble departure diameter. However, the calculation process of force balance model is quite complex and there are several uncertain terms in the expressions of forces remaining to be settled, such as the bubble growth rate and bubble contact diameter.

Another method is to empirically correlate the bubble departure diameter. Based on the available experimental data, the bubble departure diameter is correlated with significant influence parameters. Considering the effects of pressure on bubble departure diameter, Fritz's expression was developed by Kocamustafaogullari and Ishii [21]. Prodanovic [22] carried out the experiments in a vertical annual test section and correlated maximum bubble diameter, bubble ejection diameter, bubble growth and condensation time with Boiling number, Jacob number and dimensionless subcooling based on his own experimental data. Brooks et al. [12,23] combined his experimental data with available experimental data from literature to correlate bubble departure diameter with Jacob number, Boiling number, density ratio and Prandtl number. Several existed correlations are listed in Table 1. Due to its convenience and simplicity, the correlation approach has been widely used to predict bubble departure diameter. However, most of the correlations usually agree well with their own experimental data but are difficult to extend to other working conditions.

The third approach is energy balance approach to determine the maximum bubble diameter or bubble departure diameter. The energy approach has considered the growth of vapor bubble and provided a prediction of bubble diameter based on the energy conservation. Zuber [25] developed a model by assuming that the heat transfer through the vapor-liquid interface contributed to the

Table 1
Correlations for bubble departure diameter in subcooled flow boiling.

Author	Correlation	Application
Fritz [13]	$D_d = 0.0208\theta\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$	Atmospheric pressure
Kocamustafaog-ullari & Ishii [21]	$D_d = 0.0012\left(\frac{\rho_l-\rho_v}{\rho_v}\right)^{0.9}\left[0.0208\theta\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}\right]$	$P: 0.1-19.8$ MPa
Prodanovic [22]	$D_m^+ = 236.749Ja^{-0.581}\Theta^{-0.8843}(\rho_l/\rho_v)^{1.772}Bo^{0.138}$ $D_m^+ = \frac{D_m\sigma}{\rho_l\alpha_l^2},\ \Theta = \frac{T_w-T_b}{T_w-T_{sat}},\ Bo = \frac{q_w}{Gh_{fg}}$	$P: 0.105-0.3$ MPa $G: 74-795$ kg/(m$^2\cdot$s) $Subcooling: 10-30$ K
Basu [24]	$D_d^* = 1.3(\sin\theta)^{0.4}(0.13\exp(-1.75\times10^{-4}\mathrm{Re}_l)+0.005)Ja_{\mathrm{sup}}^{0.45}\exp(-0.0065Ja_{sub})$ $D_d^* = \frac{D_d}{Lo}, Lo = \sqrt{\frac{\sigma}{(\rho_l-\rho_v)g}},\ Ja_{\mathrm{sup}} = \frac{\rho_l c_{pl}\Delta T_w}{\rho_v h_{fg}},\ Ja_{sub} = \frac{\rho_l c_{pl}\Delta T_{sub}}{\rho_v h_{fg}}$	$Ja_{\mathrm{sup}}: 14-56$ $Ja_{sub}: 1-138$ $\mathrm{Re}_l: 0-7980$ $\theta: 30^\circ-90^\circ$
Brooks [12]	$D_d^* = C_{D_d}(Ja_w N_T)^{-0.49}\rho^{*-0.78}Bo^{0.44}\mathrm{Pr}^{1.72}$ $D_d^* = \frac{D_d}{Lo},\ Bo = \frac{q_w}{Gh_{fg}},\ Ja_w = \frac{c_{pl}(T_w-T_{sat})}{h_{fg}},\ N_T = \frac{T_w-T_f}{T_w-T_{sat}}$ $C_{D_d} = \begin{cases} 2.11\times10^{-3}(\text{conventional channel}) \\ 1.36\times10^{-2}(\text{mini}-\text{channel}) \end{cases}$	$\mathrm{Pr}_{sat}: 0.98-7.76$ $Ja_w: 7.6\times10^{-4}-0.12$ $N_T: 1.0-99$ $\rho^*: 6.4\times10^{-4}-3.4\times10^{-2}$ $Bo: 7.3\times10^{-5}-1.0\times10^{-3}$