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Developing correlation of bubble departure diameter in upward subcooled flow boiling based on force balance model

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1. Introduction

In simulation and calculation on subcooled flow boiling phenomena, the bubble departure diameter is among the most important boiling source terms, beside bubble nucleation density and bubble release frequency. Namely, in the wall boiling models [1-3], the bubble departure diameter was used to estimate the evaporation heat flux component. Generally, the evaporation in the models is given as:

$$q_e = \frac{\pi}{6} D_d^3 \rho_g h_{fg} f N_a \qquad (1)$$

where: $D_d$is departure bubble diameter, ρ_g is vapor density, h_{fg} is latent heat and N_a is nucleation density.

Secondly, in computational fluid dynamic, the two fluid model [4] treats the interaction between two phases through interfacial transfer terms (interfacial drag force, interfacial shear, interfacial heat transfer, interfacial mass transfer, etc.). The wall nucleation term is among important source terms in the total IAC transport equation. The nucleation source term(Φ_{NB}), or boiling term, is defined as a function of nucleation density (N_a), bubble departure diameter (D_d) and bubble departure frequency (f_d) as given in following equation:

$$\Phi_{NB} = \frac{\pi N_a f_d D_d^2 \xi_h}{A_c} \qquad (2)$$

where the remaining terms, A_c and ξ_h are the flow cross sectional area and heated perimeter respectively.

It can be seen that the bubble departure diameter appears as crucial source term in these models, which have been applied to study two-phase flow boiling. The predictive capability of the models is partly dependent on the accuracy level of input values of departure bubble diameter. So far, there have several correlations proposed for bubble departure diameter[5-7]. However, these correlations seem not to provide satisfied predictions for wide range experimental data, and properly bring out effects of thermal and mechanical factors.

This study was dedicated to develop a correlation of departure bubble diameters through analyzing force balance model. Through the analysis, it prevailed an effect of Weber number rather than only Reynolds number, which has been not considered in other correlations of departure bubble diameter. The newly developed correlation could predict well for wide range of experimental data.

2. Analyzing and deriving forms of correlations

Based on the force balance model proposed by Klausner [8], a correlation form of bubble departure diameter was obtained. According to the Klausner's model, the forces acting on a single bubble can be divided into two groups: 1) force components acting in parallel to heated surface can initiate bubble departure; 2) force components acting in normal to heated surface can cause bubble detachment. In this study, the equation of forces acting on parallel direction (subsequently called parallel forces) was analyzed to derive a correlation form of departure bubble diameter. The schematic of forces acting in parallel direction (Y-axis) is demonstrated in Fig.1, and the expression of forces is presented in Table I. The moment of bubble departure occurs when the force balance condition is violated.

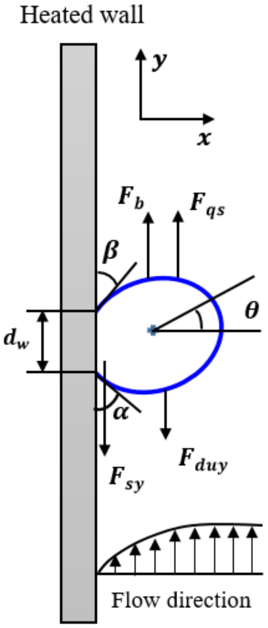

Fig.1. Schematic of parallel forces acting on a single bubble

Additionally, the performance of force balance model is strongly adhered to bubble growth model. In the analysis, the bubble growth model proposed by Zuber [9] was applied. The bubble shape was assumed to be spherical. Then, the bubble radius is given as:

$$R_b(t) = \frac{2b}{\sqrt{\pi}} \frac{\rho_f C_{fg} dT_w}{\rho_g h_{fg}} \sqrt{\alpha_f t}(1-Z) - \frac{b h_{cd} dT_{sub}}{\rho_g h_{fg}} Zt \quad (5)$$

where: ρ_f and ρ_g are respectively liquid and vapor density, h_{fg} is latent heat, b is bubble growth factor, α_f and k_f are thermal diffusivity and conductivity of liquid respectively, C_{fg} is specific heat of liquid, dT_w and dT_{sub} are the superheated and subcooled degree, Z is area fraction of bubble contacting to subcooled liquid and h_{cd} is condensation heat transfer coefficient.

Table I. Expression of forces

Forces	Expression
Surface tension force	$F_{sy} = 1.25 d_w \sigma \dfrac{\pi(\alpha-\beta)}{\pi^2-(\alpha-\beta)^2} \times (\sin\alpha + \sin\beta)$
Quasi-steady state force	$F_{qs} = \frac{1}{2} C_D \rho_f U_f^2 \pi R_b^2$
Bubble growth force	$F_{duy} = \rho_f \pi R_b^2 \left(\frac{3}{2}\dot{R}_b^2 + R_b \ddot{R}_b\right) \sin\theta$
Buoyancy force	$F_b = \frac{4}{3}\pi R_b^3 (\rho_f - \rho_g) g$

For convenience, the definition of non-dimensional numbers is provided in advance. The expressions of superheated and subcooled Jacob number, Prandtl number, density ratio, Capillary number and channel Reynold number are respectively given as: $Ja_{sup} = C_{pf} dT_w / h_{fg}$, $Ja_{sub} = C_{pf} dT_{sub} / h_{fg}$, $Pr = \mu_f C_{pf} / k_f$, $\rho^* = \rho_g / \rho_f$, $Ca = U_f \mu_f / \sigma$ and $Re_{ch} = \rho_f U_f D_{ch} / \mu_f$.

2.1. Deriving form of departure bubble diameter

The bubble starts to depart and slide downstream along the heated surface when the force balance condition in Y-axis is violated. The total force equation in Y-axis is given as:

$$\sum F_y = F_{qs} + F_b - F_{sy} - F_{duy} \qquad (6)$$

In the later phase of bubble growth process, the effect of inertia force or growth force (F_{duy}) has been supposed to be less significant than thermal diffusivity. Therefore, the effect of growth force was ignored in this analysis. Then, the force condition for bubble departure is presented as:

$$F_{qs} + F_b - F_{sy} = 0 \qquad (7)$$

By substituting formulas of forces into Eq. (7), we yield:

$$\frac{4}{3}\pi R_b^3 (\rho_f - \rho_v) g + \frac{1}{2} C_D \rho_f U_f^2 \pi R_b^2 \\ -1.25 d_w \sigma \frac{\pi(\alpha-\beta)}{\pi^2-(\alpha-\beta)^2} (\sin\alpha + \sin\beta) = 0 \qquad (8)$$

Assumed that the bubble contact diameter, d_w, can be linear relationship with bubble diameter (D_b) as $d_w = mD_b$, and adopting the characteristics length $L_c = \sqrt{\sigma / \{g(\rho_f - \rho_g)\}}$, the Eq.(8) can be rewritten as:

$$\left(\frac{D_b}{L_c}\right)^2 = \frac{3}{\pi} 2.5m \frac{\pi(\alpha-\beta)}{\pi^2-(\alpha-\beta)^2} (\sin\alpha + \sin\beta) \\ - \frac{3}{2\pi} C_D \frac{\rho_f U_f^2}{\sigma} R_b \qquad (9)$$

Through analyzing Eq. (5) and Eq. (9), it revealed that the non-dimensional bubble departure diameter $D_d^* = D_b / L_c$ can be defined a function of dimensionless parameters including superheated and subcooled Jacob number, Prandtl number, ratio density between vapor and liquid, and Weber number which was replaced by product of Capillary and Reynolds number. The general form of correlation of dimensionless bubble departure diameter can be expressed as:

$$D_d^* = A\left(Ja_{sup}^{a1}\right)\left(Ja_{sup}^{a2}\right)\left(Pr^{a3}\right)\left(\rho^{*a4}\right)\{(CaRe_{ch})^{a5}\} \qquad (10)$$

where: the value of A, a1, a2, a3, a4, a5 can be empirically determined.

3. Correlation and validation

3.1. Departure bubble diameter

A set of experimental database of departure bubble diameters provided by Sugrue [10], Ahmadi et al. [11], Brooks et al. [12] and Basu [13] were utilized to obtain the correlated form of dimensionless departure bubble diameter. Finally, the formula of dimensionless bubble departure diameter was proposed as:

$$D_d^* = 0.01 Ja_{sup}^{0.13} Ja_{sub}^{-0.2} Pr^{2.7} (Ca \times Re_{ch})^{-0.17} \rho^{*-0.22} \qquad (11)$$

The predictive capability of the newly developed correlation was validated by based on the above-mentioned dataset. The predicted results are presented in Fig. 2. It can be seen that the newly correlation can predict well for a wide range of experimental conditions with the average mean absolute error of 20.26 %. The applicable range of the proposed correlation is: mass flux of 200 – 1170 kg/m^{2}s; subcooled level of 4 – 46.5^{o}C; superheated level of 3 – 18.8^{o}C; pressure of 101 – 860 kPa.

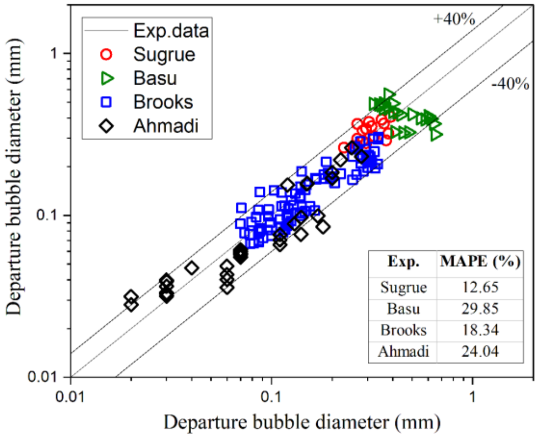

Fig.2. Comparison on predicted departure diameter and experimental data

4. Conclusion

In this paper, a non-dimensional correlation of bubble departure diameter was obtained by analysis the force equation of forces acting on a single bubble in parallel to heated surface. Some conclusions were provided: 1) through analysis, the effect of Weber number should be included in correlation of departure bubble diameter; 2) the newly developed correlation showed its predictions were good agreement with a wide range of experimental data, and they could be good input parameters for simulating and calculating subcooled flow boiling.

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