Mechanistic Modeling of Interfacial Area Transport Equation for the Analysis of Subcooled Boiling Two-phase Flow

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1. Introduction

Subcooled boiling is one of the crucial phenomena in nuclear reactor safety, such as the downcomer boiling in the reflood phase of Large-Break Loss-of-Coolant Accident (LBLOCA). Among various models to analyze a subcooled boiling two-phase flow, the two-fluid model is the most appropriate model which is beneficial to treat the transient of each phase separately. The analysis with the two-fluid model requires an accurate prediction for the interfacial area concentration. To estimate the dynamic and multi-dimensional behavior of the interfacial area concentration, an interfacial area transport equation has been derived in previous researchers [1]. In this study, the interfacial area transport equation available for the subcooled boiling flow was developed with a mechanistic model for the wall boiling source term. To evaluate the model, a two-phase flow CFD code was developed and the experimental data from the subcooled boiling test was utilized for its validation.

2. Bubble Lift-off Model

2.1 Bubble lift-off diameter model

At the moment of a bubble lift-off, the force balance on the bubble is violated and the contact diameter at the wall becomes zero. Therefore, considering the unsteady drag force and shear lift force, the force balance on the lifting bubble is given as follows.

$$-\rho_f \pi r^2 \left(\frac{3}{2} C_s \dot{r}^2 + r\ddot{r}\right)\cos\theta_i + \frac{1}{2} C_{sl} \rho_f \pi r^2 u_r^2 = 0 \qquad (1)$$

To resolve Eq. (1), the function for a bubble growth with respect to time is required. A sliding and lift-off of the bubble can occur after the departure from a nucleate site on the wall. Regarding that a bubble departure occurs at t=0, the bubble growth function can be derived as follows.

$$r(t) = r_d + \frac{2b}{\sqrt{\pi}} Ja \sqrt{\eta t} \qquad (2)$$

Hence, the explicit formulation for the bubble lift-off diameter (D_{lo}) is derived as,

$$D_{lo} = D_d \left(1 + 8.34 \left[\frac{C_{sl}}{\cos\theta_i} \cdot \left(\frac{D_d u_r}{A^2}\right)^2\right]^{-0.7}\right) \qquad (3)$$

For the bubble departure diameter (D_d), this study adopts Unal's model for the departure diameter, which is applicable to a flow condition for a wide range as given byn the following.

$$D_d = \frac{2.42 \times 10^{-5} p^{0.709} a}{\sqrt{b\Phi}} \qquad (4)$$

2.2 Interfacial area transport equation

During the sliding of a departed bubble, coalescences can occur with another bubble at a nucleate site. It reduces the number of actual bubble lift-offs from the wall, with respect to the nucleate site density for the bubble departure, so that it affects an evaporative heat flux and a nucleation source term in the interfacial area transport equation. Therefore a lift-off frequency reduction factor is considered for the boiling source term in interfacial area transport equation as follows.

$$\phi_{ph} = \pi D_{lo}^2 \cdot R_a N'' f \cdot \frac{A_H}{Vol} \qquad (5)$$

where R_a is a reduction factor for the interfacial area concentration.

Considering Eq. (5) as the boiling source term, a one-group interfacial area transport equation is derived as Eq. (6).

$$\begin{aligned} &\frac{\partial a_i}{\partial t} + \nabla \cdot \left(a_i V_g\right) \\ &= \frac{2}{3}\frac{a_i}{\alpha \rho_g}\left[\Gamma_{ig} - \alpha \frac{d\rho_g}{dt}\right] + \phi_{co} + \phi_{bk} + \phi_{ph} \end{aligned} \qquad (6)$$

where ϕ_{co} and ϕ_{bk} mean the variance of interfacial area by a coalescence and a breakup, respectively. The first term on the right-hand side of Eq. (6) is the term for a bubble size variance due to a condensation heat transfer or a pressure drop. Eq. (6) is implemented in EAGLE (Elaborated Analysis of Gas-Liquid Evolution) code for a multi-dimensional analysis of the subcooled boiling two-phase flow.

3. Analysis Results

3.1 SUBO experiment

To validate the EAGLE code with the bubble lift-off model, the experimental data of SUBO tests were utilized [2]. In this study, the results of the Base case were compared with the analysis results. The test condition is summarized in Table I.

Table I: Test condition of Base case

Parameter	Test condition
Heat flux (kW/m^2)	470.6
Mass flux (kg/m^{2}s)	1132.6
Inlet subcooling (K)	19.1

3.2 Results

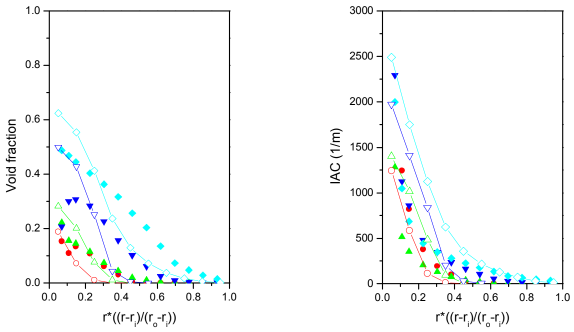
Figure 1 shows the radial and axial distribution of the void fraction, interfacial area concentration, and bubble velocity. As shown in the experimental results, the radial distribution of the void fraction indicated the existence of a bubbly boundary layer near the heated surface, which is one of the representative characteristics of the subcooled boiling. This behavior of bubbly boundary layer was simulated well with EAGLE code.

In the case of the distribution of the interfacial area concentration, as revealed in Fig. 1(b), the amount of interfacial area concentration was closely related to the void fraction. Also, the experimental results showed that the coalescences between departed bubbles from the heated surface occurred more vigorously and it affected a decrease of the interfacial area concentration at a higher elevation. In the EAGLE analysis, the interfacial area transport equation with a bubble lift-off model predicted the distribution of the IAC reasonably well. Therefore, it is concluded that the advanced modeling of a boiling source term contributed an enhancement of the calculation capability of the subcooled boiling flow.

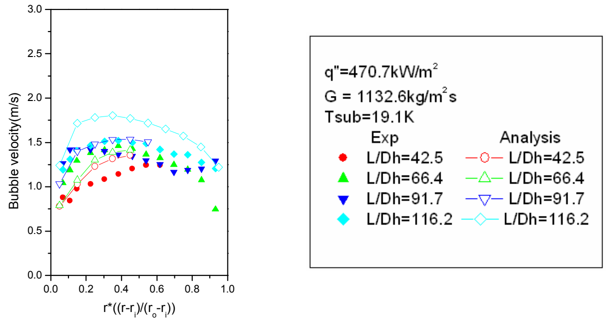
As shown in Fig. 1(c), the peak value of the bubble velocity appeared within the central region of the flow channel rather than near the wall. It was caused by the buoyancy effect, that is, the bubble with a larger diameter due to the coalescence interactions could obtain a larger buoyancy force and be accelerated faster than the small bubbles near the wall. This trend of the bubble velocity could be estimated well in EAGLE code analysis. Also, an enhancement of the turbulence near the heated wall was implemented in EAGLE code. It considered the phenomena that boiling bubbles at the surface break up the laminar sublayer near the wall and increase the turbulent viscosity or the turbulent wall shear stress [3], which are given by Eq. (7) and (8) respectively. As revealed in Fig. 1(c), the profile of the bubble velocity near the heated wall showed similar results to the experiment by the modeling of an enhanced turbulence near the wall.

$$\mu_t^{boil} = \mu_t\left(1+\frac{6q_{ev}}{\rho_g h_{fg}\alpha_p u_l^{'}}\right) \qquad (7)$$

$$\tau_w^{boil} = \tau_w\left(1+\frac{6q_{ev}}{\rho_g h_{fg}\alpha_p u_l^{'}}\right) \qquad (8)$$



(a) Void fraction (b) IAC



(c) Bubble velocity

Fig. 1 Comparison of local bubble parameter distribution

4. Conclusions

This study focused on a numerical analysis of the subcooled boiling two-phase flow by developing an advanced model for the interfacial area transport equation. A mechanistic model for a boiling source term in the interfacial area transport equation was derived by considering the bubble lift-off diameter and the frequency reduction factor at the heated surface. The developed model has been implemented in EAGLE code and the experimental data of SUBO facility was utilized for a validation of the model. Analysis results showed a reasonable similarity between the local bubble parameters of the experiment and code analysis results.

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