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Computational Two-phase Flow Analysis for Subcooled Boiling in Annulus Channel

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1. Introduction

The interfacial area concentration (IAC) is one of the most important parameters with respect to the interfacial transfer terms between two phases. In recent researches, the IAC transport equation has been developed for adiabatic bubbly flow or nucleate boiling flow. That can make it possible to analyze the two-phase flow dynamically, instead of the conventional static approach for modeling IAC.

This study is a part of the development of computational fluid dynamics (CFD) code for investigating the boiling flow with two-fluid model and IAC transport equation. Multi-dimensional approach was utilized in order to overcome the limitation in one-dimensional analysis of two-phase flow. As the step for checking the robustness of the developed code, the problem for subcooled boiling was benchmarked.

2. Code structure

2.1. Numerical scheme

Two-fluid model treats the each phase separately, so that it enables to consider phase interaction term properly. For the analysis of two-phase flow, the finite volume method was adopted in this study. It is beneficial in that the grid smoothness is not important and the coordinate transformation is not required. In order to get the numerical solution for incompressible flow, the semi-implicit method for time integration is preferred due to the smaller calculation time. Among the various semi-implicit methods, SMAC(Simplified Marker And Cell) algorithm was implemented[1], which is able to avoid the repeated iteration.

2.2. Closure relations

Before implementing the IAC transport equation, a static correlation for IAC has been included in analyzing a benchmark problem, so as to check the reasonable working of the two-fluid model. Zeitoun[2] suggested the correlation for Sauter-mean diameter in subcooled boiling flow.

$$D_s = 1.85\alpha^{0.243}\left(\frac{\sigma}{g\Delta\rho}\right)^{0.55}\left(\frac{G}{\mu}\right)^{0.1} \qquad (1)$$

, from which the IAC can be estimated by the definition, $a_i = 6\alpha / D_s$.

The mechanisms of heat transfer from wall consist of surface quenching (q_q), evaporative heat transfer (q_e), and single phase convection (q_c). Yeoh and Tu [3] modeled those terms as Eqs. (2) to (4), respectively.

$$q_q = \left(\frac{2}{\sqrt{\pi}}\sqrt{k_f\rho_f C_{pf}}\sqrt{f}\right)\cdot n\frac{\pi d_{Bw}^2}{4}\left(T_w - T_f\right) \qquad (2)$$

$$q_e = nf\left(\frac{\pi}{6}d_{Bw}^3\right)\rho_g h_{fg} \qquad (3)$$

$$q_c = St\cdot\rho_f C_{pl}u_f\left(T_w - T_f\right)\left(1 - n\frac{\pi d_{Bw}^2}{4}\right) \qquad (4)$$

As shown in the above relations, the proper models for active nucleate site density (n), bubble departure frequency (f), and bubble departure diameter (d_{Bw}) are essential. The wall temperature can be found with solving a non-linear equation. Then the term for surface quenching and convection belongs to a source term in energy equation of liquid and the amount of evaporative heat transfer is used in calculating the phase change.

3. Benchmark analysis

3.1 Problem

The benchmark for two phase flow analysis was conducted with the experimental data in Seoul National University. [4] That experiment was aimed to research the subcooled boiling for vertical upward flow in a concentric annulus, of which geometrical dimensions are listed in Table 1. Major measured parameters are the void fraction, Sauter-mean diameter and IAC. It also includes the radial distribution of measured data at 13 points so that the capability of multi-dimensional analysis of the developed code can be effectively estimated. The test condition selected for benchmark in SNU's experiment is shown in Table 2. Analysis was conducted in the grid composed of 5(radial) x 500(axial) cells.

Table 1. Geometry of SNU experiment

Flow area	9.72615cm^2
Heating length	1870mm
Hydraulic diameter	21mm
Outer diameter of heater	19mm
Inner diameter of channel	40mm

Table 2. Test condition for subcooled boiling

Mass flux	342.207 kg/m^{2}s
Heat flux	212.706 kW/m^2
Inlet pressure	1.21bar
Inlet subcooling	21.695K

3.2 Results

Figure 1 represents the calculation result of void fraction, around the exit of heated section (H=1.87m). Generation of vapor near the wall increased local void fraction. In the other hand, wall lubrication force and condensation heat transfer affected the propagation of void fraction in radial direction.

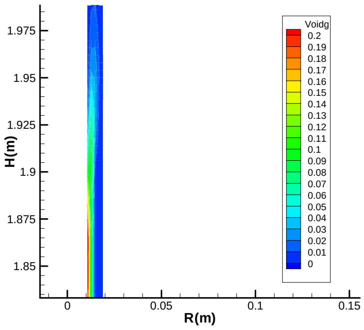

Figure 1. Void fraction near the exit

Figures 2 and 3 compare the radial distribution of void fraction and IAC, respectively, between the experiment and analysis at the position of L/D$_h$=71.4. As shown in the figures, the void fraction and IAC in analysis predicted the reasonable behavior. However, IAC result showed an underestimation near the wall. It is due to the use of one-dimensional correlation of Sauter-mean diameter given as Eq. (1), which overestimated the experimental one.

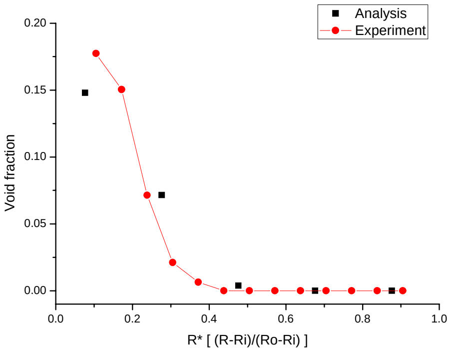

Figure 2. Void fraction at L/D$_h$=71.4

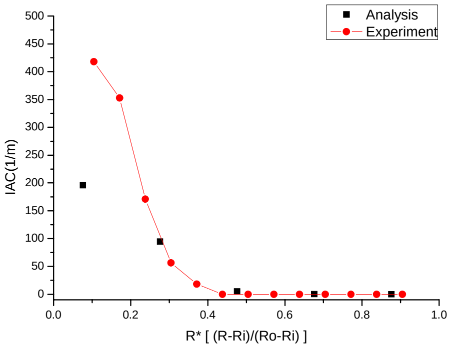

Figure 3. IAC at L/D$_h$=71.4

For a multi-dimensional calculation of IAC, the limitation of one-dimensional model should be overcome by implementation of IAC transport equation. Yao and Morel [5] suggested the equation available for boiling phenomena as follows.

$$\frac{\partial a_i}{\partial t} + \nabla\cdot\left(a_i V_g\right) = \frac{2}{3}\frac{a_i}{\alpha\rho_g}\left[\Gamma_{g,i} - \alpha\frac{d\rho_g}{dt}\right] + \frac{36\pi}{3}\left(\frac{\alpha}{a_i}\right)^2\left(\phi_n^{CO} + \phi_n^{BK}\right) + \pi d_{Bw}^2\phi_n^{NUC} \qquad (5)$$

where ϕ_n^{CO}, ϕ_n^{BK} and ϕ_n^{NUC} mean the source term about coalescence, breakup and nucleation, respectively. It is expected to dynamically model the behavior of IAC in two-phase flow.

4. Conclusion

This study focused on the development of multi-dimensional CFD code for two-phase flow analysis. It was based on the two-fluid model and one-dimensional correlations for interphase transfer were adopted as a step for checking robustness of the code. Benchmark problems of two-phase flow were analyzed. The developed code was confirmed to have the capability in predicting two-phase flow phenomena, especially the void propagation in subcooled boiling. In the future, implementation of IAC transport equation with phase change term will make it possible to analyze the interphase phenomena dynamically.

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