Computational Analysis of a Two-phase Flow with an Interfacial Area Transport Equation

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1. Introduction

For the analysis of a two-phase flow with boiling or condensation, the interaction between two phases such as the interfacial momentum or heat transfer is proportional to the interfacial area. So the interfacial area concentration (IAC), which is defined as the area of interface per unit volume, is one of the most important parameters governing the behavior of each phase. IAC transport equation has been developed for the adiabatic bubbly flow or nucleate boiling flow [1]. It describes the transport phenomena of the IAC with the source term for adiabatic interaction and phase change.

In order to implement the IAC transport equation and analyze the characteristics of a two-phase flow, this study focuses on the development of a computational fluid dynamics (CFD) code for investigating a boiling flow with a two-fluid model. As the step for checking the robustness of the developed code, the experiment of a subcooled boiling in a vertical annulus channel was analyzed to validate the capability of the IAC transport equation.

2. Code Structure

2.1 Governing equations

This study adopts the two-fluid model, which treats each phase separately and enables us to consider a phase interaction term properly. The finite volume method was utilized, which is beneficial in that grid smoothness is not important and a coordinate transformation is not required. In order to obtain a numerical solution for an incompressible flow, the semi-implicit method for a time integration is preferred due to the smaller calculation time. Among the various semi-implicit methods, the SMAC (Simplified Marker And Cell) algorithm [2], which was originally developed for a single-phase flow, was applied to the two-phase flow. The algorithm is known to be beneficial in avoiding repeated iterations.

2.2 Interfacial Area Transport Equation

For a multi-dimensional calculation of the IAC, Yao and Morel [1] suggested an IAC transport equation available for boiling phenomena as follows.

$$\frac{\partial a_i}{\partial t} + \nabla \cdot \left(a_i V_g\right) = \frac{2}{3}\frac{a_i}{\alpha \rho_g}\left[\Gamma_{ig} - \alpha \frac{d\rho_g}{dt}\right] + \frac{36\pi}{3}\left(\frac{\alpha}{a_i}\right)^2 \left(\varphi_n^{CO} + \varphi_n^{BK}\right) + \pi d_{Bw}^2 \varphi_n^{NUC} \quad (1)$$

where $\boldsymbol{\varphi}_n^{CO}$, $\boldsymbol{\varphi}_n^{BK}$ and $\boldsymbol{\varphi}_n^{NUC}$ mean the source terms about a coalescence, breakup and nucleation, respectively. The first term in the right-hand side of Eq. (1) is the shrinkage term of a bubble due to a condensation heat transfer. Noting that the subcoold boiling flow interested in this study is a bubbly flow, the coalescence by a random collision and the breakup by a turbulent impact is considered in the adiabatic source terms, which is the second term in the right-hand side of Eq. (1).

The source term relevant to a nucleation at wall, $\boldsymbol{\varphi}_n^{NUC}$, is the nucleation rate per unit volume and unit time , so that it is determined as,

$$\varphi_n^{NUC} = \frac{n \cdot f \cdot A_H}{V} \quad (2)$$

As shown in the above relations, the proper models for an active nucleate site density (n), a bubble departure frequency (f), and a bubble departure diameter (d_{bw}) are essential. Yeoh and Tu [3] have adopted the following models from literature.

$$n = \left[210\left(T_w - T_{sat}\right)\right]^{1.805} \quad (3)$$

$$d_{bw} = 2.496 \times 10^{-5}\theta \left(\frac{\rho_l - \rho_g}{\rho_g}\right)^{0.9}\left(\frac{\sigma}{g\Delta\rho}\right)^{0.5} \quad (4)$$

$$f = \sqrt{\frac{4g\left(\rho_l - \rho_g\right)}{3 d_{bw}\rho_l}} \quad (5)$$

3. Benchmark Analysis

3.1 Experiment of the subcooled boiling

The benchmark for a 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 a 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 the measured data at 13 points so that the capability of a multi-dimensional analysis of the developed code can be effectively estimated. The test conditions selected for the benchmark in SNU's experiment are shown in

Table 2. Analysis was conducted in a grid composed of 10(radial) x 120(axial) cells.

Table 1. Geometry of SNU experiment

Flow area	$9.72615cm^2$
Total length	2800mm
Heating length	1870mm
Hydraulic diameter	21mm
Outer diameter of heater	19mm
Inner diameter of channel	40mm

Table 2. Test condition for subcooled boiling

	Test Case 1	Test Case 2
Mass flux	$339.637\ kg/m^2s$	$342.207\ kg/m^2s$
Heat flux	$96.701\ kW/m^2$	$212.706\ kW/m^2$
Inlet pressure	1.30 bar	1.21bar
Inlet subcooling	12.404K	21.695K

3.2 Analysis results

Figure 1 compare the radial distribution of the void fraction and IAC at the position of L/Dh=90.5. As represented in the comparison of the void fraction for both test cases, the developed code predicted a reasonable distribution of the void fraction. It is larger near the heated wall due to the generation of a vapor at the wall, according to the wall heat flux partition model. The distribution of the void fraction is also dependent on the non-drag force in a lateral direction, that is, the lift force and the wall lubrication force.

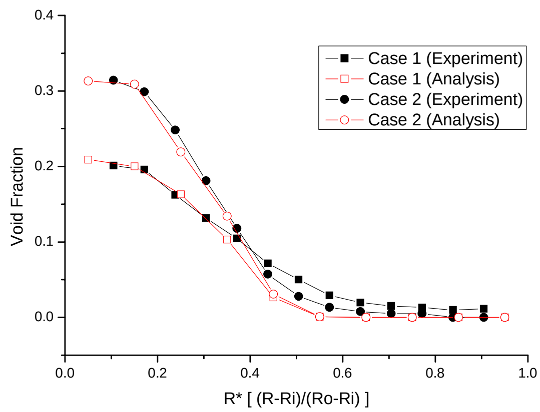

Figure 1. Comparison of Void fraction (L/Dh=90.5)

On the other hand, prediction of the IAC in the developed code estimated a similar trend with respect to the experimental results as shown in Figure 2. Overestimation of the IAC near the heated wall reveals that the wall boiling models, as listed in Eqs. (3), (4) and (5) should be improved for a more accurate analysis. The coalescence and breakup model in Eq. (1) includes the effect of an energy dissipation term. Because the code in its current status has not implemented a turbulence model yet, the one-dimensional calculation for the energy dissipation also contributed the different behavior of the IAC. Therefore, a turbulence model such as the standard k-e model is essential for predicting the correct behavior of a flow in a further study.

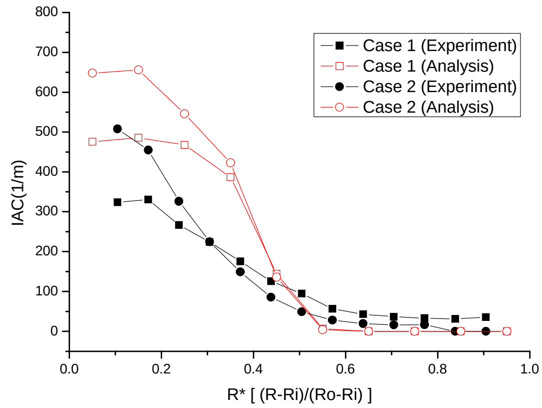

Figure 2. Comparison of IAC (L/Dh=90.5)

4. Conclusion

This study focused on the development of a multi-dimensional CFD code for a two-phase flow analysis. It was based on the two-fluid model, which can consider the behavior of each phase separately. Governing equations were integrated by the finite volume method and the one-group IAC transport equation was adopted. For satisfying a continuity, the SMAC algorithm was utilized by considering of the term for a phase change. In order to check on the robustness of the developed code, benchmark problems of a two-phase flow were analyzed. As the results, the developed code was confirmed to have the capability in predicting a vapor generation in a subcooled boiling. The limitation of wall boiling models and the lack of a turbulence modeling induced a difference of the IAC near the heated wall. In the future, it is required that the wall boiling model should be improved and an implementation of a turbulence model such as the standard k-e model is essential to analyze the multi-dimensional two-phase flow phenomena and to estimate the IAC transport equation exactly.

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