Assessment of Boiling Model in a Computational Analysis of the Subcooled Boiling Flow

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1. Introduction

Two-phase flow phenomena are known to be crucial for a nuclear reactor safety, such as a subcooled boiling at the downcomer during a Large-Break Loss-of-Coolant Accident (LBLOCA) [1]. For the analysis of a two-phase flow, the two-fluid model is considered as a state-of-the-art model which deals with the mass, momentum and energy of each phase. The interfacial area concentration (IAC), which is defined as the area of interface per unit mixture volume, is one of the most significant parameters in the two-fluid model. In order to resolve the problems of the conventional models for an IAC, an interfacial area transport equation has been developed for an adiabatic bubbly flow or nucleate boiling flow. [2]

For the investigation of a boiling flow with a dynamic modeling of the interfacial structure, this study focuses on the development of a computational fluid dynamics (CFD) code with implementing an interfacial area transport equation. A benchmark problem for the subcooled boiling flow is analyzed with the developed code so that the sensitivity on the boiling model can be analyzed.

2. Code Structure and Constitutive Models

2.1 Governing equations

This study adopts the two-fluid model, which is beneficial to treat the behavior of each phase separately and to consider a phase interaction term properly. The finite volume method was utilized, where a grid smoothness is not important and a coordinate transformation is not required. In order to obtain a numerical solution for an incompressible flow, the SMAC (Simplified Marker And Cell) algorithm was extended to the two-phase flow. The algorithm is known to be advantageous in avoiding repeated iterations.

For a multi-dimensional calculation of the IAC, the developed code adopted an interfacial area transport equation available for boiling phenomena as suggested by Ishii [2].

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

2.2 Boiling model

In the subcooled boiling flow, the amount of vapor generation can be computed by a wall heat flux partitioning model. The mechanisms of a heat transfer from a wall consist of the surface quenching, evaporative heat transfer, and single phase convection. Mechanistic models in the CFX-4 code, Yeoh & Tu, and CFX-5 code are compared in this study. The heat partitioning model utilized by Yeoh and Tu excluded the effect of a bubble influence factor in the quenching heat flux and adopted a nucleate site density model with a larger coefficient. Therefore, it is expected that the model would predict a larger amount of vapor generation at the same heat flux condition than the CFX-4 or CFX-5 models. The heat partitioning model of CFX-5 adopts a characteristic temperature, instead of the temperature at the near-wall cell to obtain a grid independent solution for the quenching heat flux.

One of the most significant factors governing the heat partition is the bubble departure diameter. CFX-4 and CFX-5 use a model from a high-pressure water boiling experiment by Tolubinsky.

$$d_{Bw}=\min\left(0.6\exp\left(-\frac{\Delta T_{sub}}{45[K]}\right)[mm],1.4[mm]\right) \quad (2)$$

On the other hand, Kocamustafaogullari and Ishii derived a model by considering a static equilibrium between buoyant and adhesive forces.

$$d_{Bw}=2.64\times10^{-5}\theta\left(\frac{\rho_l-\rho_g}{\rho_g}\right)^{0.9}\left(\frac{\sigma}{g\Delta\rho}\right)^{0.5} \quad (3)$$

Unal suggested a model for the departure diameter applicable to the flow condition in a wide range as,

$$d_{Bw}=\frac{2.42\times10^{-5}p^{0.709}a}{\sqrt{b\Phi}} \quad (4)$$

3. Benchmark Analysis

3.1 Experiment of the subcooled boiling

The benchmark problem selected for the two phase flow analysis was a subcooled boiling experiment at Seoul National University (SNU) [3]. That experiment focused on a boiling and condensation for a vertical upward flow in a concentric annulus, whose geometrical dimensions are listed in Table 1. The test condition selected for the benchmark in the SNU experiment is shown in Table 2. Analysis was conducted in a grid composed of 10(radial) x 120(axial) cells.

Table 1. Geometry of SNU experiment

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 2
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 Analysis results

Figure 1 represents the analysis results of the void fraction at the exit of the heated section. It compares the results with various models for a bubble departure diameter, where the analyses adopted the heat partitioning model of CFX-4. The results of the Kocamustafaogullari & Ishii model with a contact angle of 45° showed a largest void fraction and overestimated the amount of a void more than the experimental data. Since the departure diameter was proportional to the contact angle as presented in Eq. (3), a reduced contact angle in the bubble departure model induced a much smaller void fraction. Unal's model estimated a lower void fraction than Kocamustafaogullari & Ishii's model with a contact angle of 45° and the result of Tolubinsky's model revealed the best fit value of the void fraction among the tested models. From a comparison between the bubble departure diameter and the radial distribution of a void fraction, it can be inferred that the selection of the bubble departure diameter model has induced a significant difference in predicting the amount of a void generation.

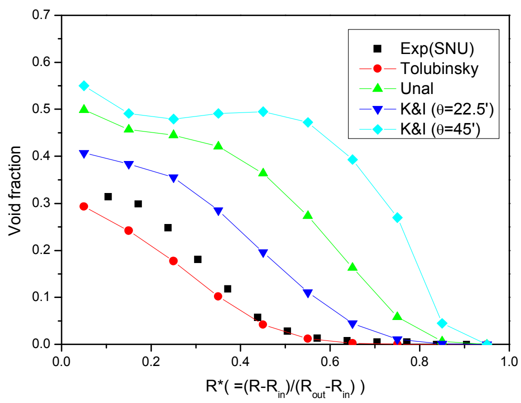

Figure 1. Comparison of Void fraction (L/Dh=90.5)

Figure 2 represents the effect of the heat partitioning models on the void fraction at the exit. Yeoh and Tu's heat partitioning model predicted a higher void fraction than the CFX-4 model or experimental data, since a lower estimation of the quenching area without the bubble influence factor effectively increased the evaporative heat flux. CFX-5 heat partitioning model did not present a significant difference with the results of the CFX-4 model. Also, when the characteristic distance from the wall was set to 100 instead of 250, it was observed that the void generation rate increased due to the higher value in assuming the characteristic temperature.

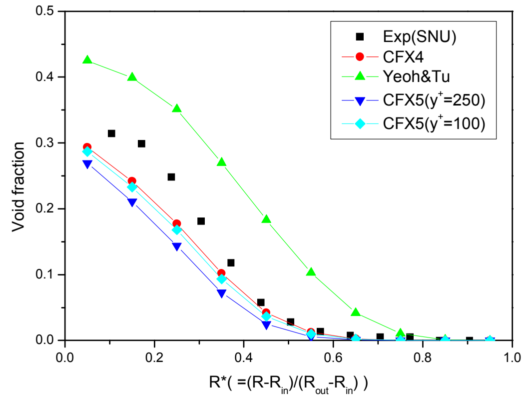

Figure 2. Comparison of IAC (L/Dh=90.5)

4. Conclusion

This study focused on the development of a multi-dimensional CFD code for a two-phase flow analysis. Benchmark problem for a subcooled boiling flow was analyzed to check the robustness of the developed code. As for the results, the code was confirmed to have the capability of predicting a reasonable behavior of a void generation and propagation, which was affected by the boiling models. Particularly, the bubble departure diameter on the heated wall had the most significant influence on the subcooled boiling phenomena especially for the void fraction in a low-pressure condition. Therefore, as a further work for an improvement of the interfacial area transport equation, an accurate modeling of the boiling source terms such as the bubble departure diameter is essential with more databases for subcooled boiling experiments.

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