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Simulation of the Downcomer Boiling Test with the Component Thermal Hydraulic Analysis Code CUPID

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1. Introduction

A component scale thermal hydraulic analysis code, CUPID (Component Unstructured Program for Interfacial Dynamics), is being developed for the analyses of components of a nuclear reactor, such as reactor vessel, steam generator, containment, etc. It adopts three-dimensional, transient, two-phase and three-field model, and includes various physical models and correlations of the interfacial mass, momentum and energy transfer for the closure relations of the two-fluid model. In the present paper, the two-phase models were assessed against the DOBO (DOwncomer BOiling) experiment, which was constructed to simulate the downcomer boiling phenomenon and the validation results against the experiment were reported.

2. DOBO Test Facility

The DOBO test facility was designed to simulate the downcomer boiling phenomena that may occur in the lower downcomer region below a cold leg during the reflood phase of a postulated LBLOCA [1]. It consists of a test section, a steam–water separator, a condenser, a heat exchanger, a drain pump, a storage tank, an air injection and ventilation system, a pre-heater and an injection pump. Among these components, the test section was simulated solely by the CUPID code for the present calculation. It has rectangular duct geometry and its dimensions are 6.4 m high, 0.25 m deep and 0.30 m wide.

During the reflood phase of a LBLOCA, the emergency core cooling water flows down in the downcomer from the elevation of the ECC injection nozzle to the lower plenum. Thus, the downcomer boiling happens with the downward liquid flow, and then the counter-current flow appears between the liquid and upward bubbles on the reactor vessel. The DOBO facility is, however, capable of reproducing the boiling phenomena not only with the downward liquid flow but also with the upward liquid flow. Since imposing boundary conditions can be simplified with the co-current upward flow, the upward liquid flow test [2] was selected for the assessment of the CUPID code in the present study as shown in Fig. 1.

3. DOBO Test Result

Fig. 2 shows the measurement results of the local void fraction. The void fraction increases gradually along the elevation up to 3.5 m due to the boiling on the heated wall. Most of the bubbles appeared nearby the heated wall according to the results. Contrary to this, the void fraction distribution measured at 4.5 m shows that bubbles resided in the whole cross sectional area and the highest void fraction appeared around the center region, i.e. a core peaking of the void fraction profile was observed. The bubbles generated on the heated wall become bigger due to the coalescence and the expansion induced by the gravitational head loss and then, they move to the center region of the channel by the lift force.

Figs. 3 and 4 present the local measurement results of the gas and liquid velocities which are averaged in width. Up to 3.5 m, the vapor generated on the heated wall is accelerated along the elevation due to the buoyancy, and therefore, the vapor velocity is the highest nearby the heated wall. On the other hand, a downward liquid flow appeared outside of the bubbly flow region for the mass conservation at a cross-sectional area. Above 3.5 m where the core peaking of the bubbles was observed, the gas and liquid velocity profiles altered significantly. The peaks of the gas and liquid velocities were placed around the center region as same with the void fraction profile. The gas velocity near the walls was almost zero and the downward liquid flow does not appear at this elevation.

4. Calculation Result

The experimental data and the numerical calculation at the elevations of 3.5 m and 4.5 m are compared in Fig 5. The result shows that the CUPID code overpredicted the void fraction of the DOBO experiment with the default two-phase models. To investigate which models caused this discrepancy, a series of sensitivity studies were performed with various models for the bubble diameter, interfacial drag coefficient and heat transfer models, and it was found that the computational results were highly sensitive with the bubble size model. The major driving force of the flow is not the forced convection but the natural convection, and thus, the fluid motion is likely to be dominated significantly by the interfacial forces and the interfacial area.

In the consideration of the low pressure and low velocity conditions of the DOBO test, the minimum and maximum bubble diameter criteria of the default model (Yoneda model [3]) were modified for the present numerical test. The minimum bubble diameter was subject to the constraint of another bubble diameter model proposed by Ishii [4], as follows:

$D_b = \max(D_{b,Yoneda,\text{modified}}, D_1)$,

where $D_1 = 2\sqrt{\sigma / g(\rho_l - \rho_g)}$,

$$D_{b,Yoneda} = 10.06\left(\frac{10^5}{P}\right)^{0.098}\sqrt{\frac{\sigma}{9.8(\rho_l - \rho_g)}}\cdot[\min(\alpha_g, 0.118)]^{0.35},$$

$$D_{b,Yoneda,\text{modified}} = 10.06\left(\frac{10^5}{P}\right)^{0.098}\sqrt{\frac{\sigma}{9.8(\rho_l - \rho_g)}}\cdot[\min(\alpha_g, 0.25)]^{0.35}.$$

The constraint of the Yoneda et al's bubble diameter correlation, which resulted in the constant value of the bubble diameter when the void fraction was larger than 0.118, was modified since a number of large bubbles (or cap bubbles) were observed in the churn-flow region. The criterion, 0.118, was changed to 0.25; with this modification, the bubble size was increased gradually with the void fraction up to $\alpha_g = 0.25$.

Fig. 6 shows the calculation results with the modified bubble diameter model. The void fraction at 3.5 m was reasonable well predicted by the CUPID code, and in particular, the prediction of the void fraction peak was enhanced. The calculation result at 4.5 m was also enhanced remarkably with the modification and the predicted void fraction profile was well correspondent with the experimental data.

In the churn flow region (above 3.5 m), however, there are still considerable discrepancies of the velocity profile as shown in Fig. 7; in particular, the downward liquid of the calculation result nearby the wall region were not observed in the test results. This assessment result showed that a further improvement of the physical models of the two-fluid model is required for the churn-flow region. In a future study, this issue will be investigated to improve the performance of the CUPID code for the multi-dimensional two-phase flow analysis.

5. Conclusion

In the present paper, the two-phase models of the CUPID code were assessed against the DOBO (DOwncomer BOiling) experiment, which was constructed to simulate the downcomer boiling phenomenon. The benchmark calculation results showed that the CUPID code can appropriately predict the downcomer boiling phenomena under a low void fraction condition with the modification of the bubble size correlation. However, further improvement of the two-phase models for the churn flow is required to enhance the performance of the CUPID code under a high void fraction condition.

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Acknowledgments

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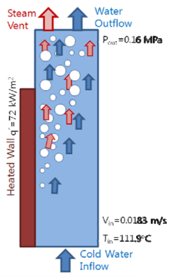

Fig. 1 Boundary conditions

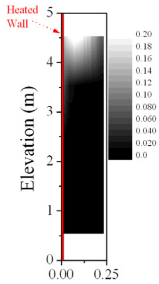

Fig. 2 Void Fraction Distribution

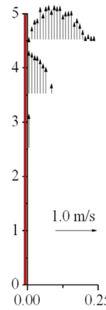

Fig. 3 Gas velocity

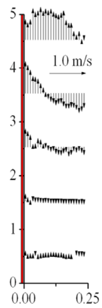

Fig. 4 Liquid velocity

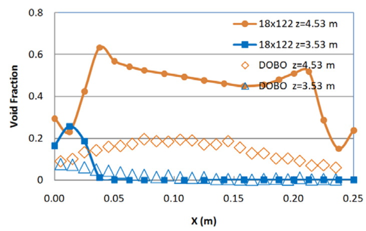

Fig. 5 Void fraction calculation results with the default bubble size model

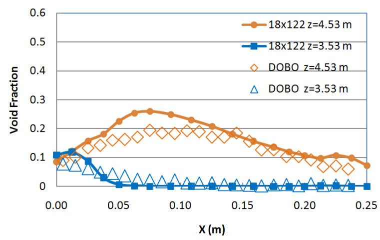

Fig. 6 Void fraction calculation results with the modified bubble size model

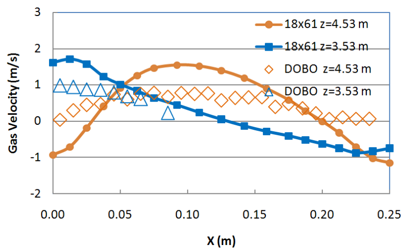

Fig. 7 Gas velocity calculation results with the modified bubble size model