Simulation of the Downward Liquid Flow DOBO Test Using CUPID

H.K. Cho[a*], B.J. Yun[a], I.K. Park[a], J.J. Jeong[a]
[a]Korea Atomic Energy Research Institute,1045 Daeduk-daero, Daejeon, Korea, 305-353
*Corresponding author: hkcho@kaeri.re.kr

1. Introduction

For the analysis of transient two-phase flows in nuclear reactor components such as a reactor vessel, steam generator, containment, etc., KAERI has developed a three-dimensional thermal hydraulics code, CUPID [1]. 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. In our previous study [2], the CUPID code and its two-phase flow models were assessed against the DOBO (DOwncomer BOiling) experiment, in particular, the upward liquid flow test. In the present paper, the downward liquid flow case of the DOBO test was simulated with the CUPID code, which is closer to the real downcomer boiling phenomena. The following sections present the experimental data and the calculation results.

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 [3, 4]. 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 in the reactor vessel downcomer. The liquid inlet was located at the upper region of the test section as indicated in Fig. 1. The injected liquid impinges on the test section wall and flows downward forming a liquid film. Due to the heat released from the heated wall, boiling occurs in the test section. The generated steam flows out the test section through the outlet, where the pressure was maintained at 1.6 bars. The accumulated liquid formed a free surface inside the channel and the water level was maintained at 5.4 m by controlling the liquid outlet flow rate located at the bottom of the test section.

3. DOBO Test Result

Fig. 2 shows the measurement results of the local void fraction. The void fraction distributions at the elevations, 1.53 m and 2.53 m, indicate typical wall peaking profiles that the maxima of the void fraction appeared at the corner made by the heated wall and a side wall. Then, the void fraction decreases gradually as the distance from the heated wall increases. Above the elevation 3.53 m, however, bubbles began to move to the center region of the channel and the void fraction profiles of a core peaking were obtained. The area averaged void fractions along the axial elevation were 0.16 and 0.22 at the elevations of 3.53 m and 4.53 m, respectively. The liquid subcooling at the bottom of the channel was 5 ^oC.

4. Calculation Results

The downcomer boiling phenomena were simulated using the CUPID code with the two-dimensional computational mesh as shown in Fig. 3. The following bubble diameter model was applied for the analysis, which was proposed in our previous study [1] in order to predict the core peaking of the void fraction profile in the upward flow DOBO test;

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

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

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

The experimental data and the numerical calculation at the elevations of 3.53 m and 4.53 m were compared in Fig 4. At the elevation of 4.53 m, the overall void fraction profile of the test was reasonably captured by the CUPID code and in particular, the core peaking profile was well reproduced. However, at 3.53 m, the present solver highly underpredicted the measured value of the void fraction. The area averaged void fraction of the test was about 0.14, whereas that of the calculation 0.02. The reason of this discrepancy has not been addressed yet and the sensitivity study to find it is ongoing with the CUPID code. Fig. 5 shows the axial profile of the area averaged void fraction and it indicates that the present code can capture overall trend of axial bubble distribution except the elevation of 3.53 m where the core peaking started.

The same test was simulated with a three-dimensional computational domain as shown in Fig. 6. The location and the value of the maximum void fraction were well predicted by the CUPID code at the elevation of 4.53 m. As same with the 2D calculation result, however, it underpredicted the measured void fraction at 3.53 m significantly. Different from the measurement that showed core peaking void fraction profile with the maximum value of 0.3 at the channel center, slight subcooled boiling nearby the heated wall appeared in the calculation.

5. Conclusion

The downward liquid DOBO test was simulated using the CUPID code with two- and three-dimensional computational meshes. Both results showed that the overall trend of the phase change can be reproduced by the CUPID calculation. However, the void fraction profile transition from a wall peaking to a core peaking was predicted to occur at a higher elevation with the CUPID code so that the axial trend of the area averaged void fraction cannot be captured at 3.53 m. Further improvement for the phase change is required to predict the downcomer boiling phenomena more precisely.

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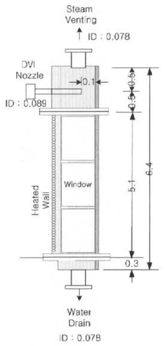

Fig. 1 DOBO Test Section

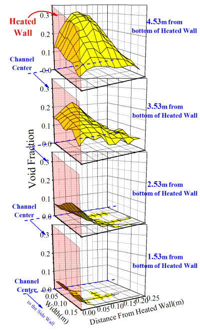

Fig. 2 Void Fraction Measurement Result

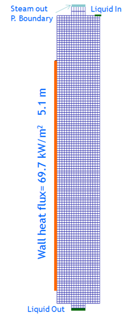

Fig. 3 2D Mesh

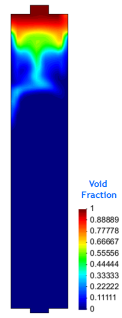

Fig. 4 Void Fraction Calculation Result: 2D

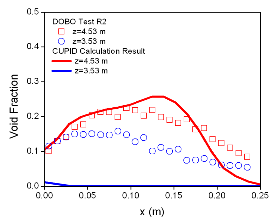

Fig. 4 Void Fraction Distribution

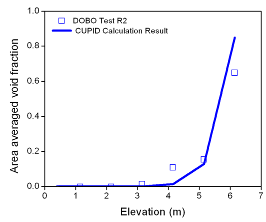

Fig. 5 Axial Void Fraction Profile

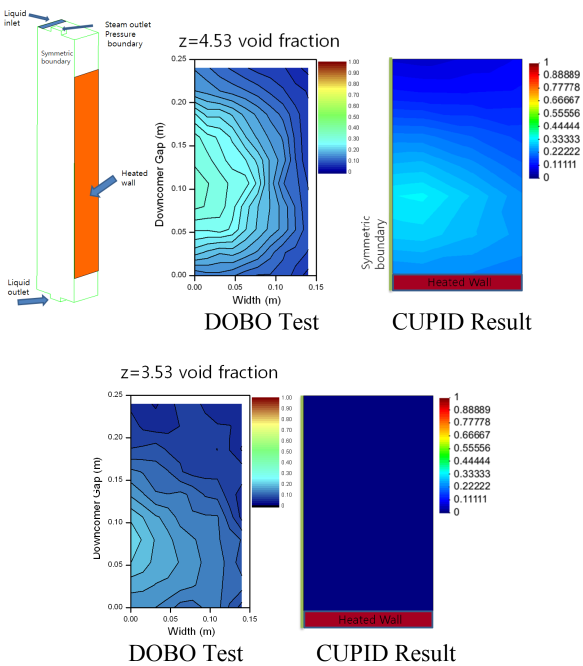

Fig. 6 Void Fraction Calculation Result: 3D