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Assessment of CUPID1.7 Code with PWR Sub-channel and Bundle Test (PSBT) Benchmark

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1. Introduction

The CUPID1.7 (Component Unstructured Program for Interfacial Dynamics1.7) code has been developed at KAERI for a high-resolution analysis of transient two-phase flows in nuclear components [1]. As CUPID1.7 was recently redistributed in an upgraded version from CUPID1.6, a parallel calculation based on the Message Passing Interface (MPI) is supported. After the upgrade, various verification and validation calculations have been performed to confirm not only the numerical stability and accuracy, but also the adequacy of T/H models in CUPID1.7. A PWR Sub-channel and Bundle Test (PSBT) is the international benchmark problem and is proper to validate the boiling models near a wall, especially under conditions of high system pressure and high heat flux.

2. PSBT Subchannel Test

2.1 Test Geometry

The PSBT subchannel test simulates one of the subchannels of a PWR fuel assembly, as shown in Fig. 1. The channel length is 1.555 m and the void measuring section is set at the top end at 1.400 m from the bottom. The width of the flow channel is 0.0126 m corresponding to the pitch length between two fuel rods [2].

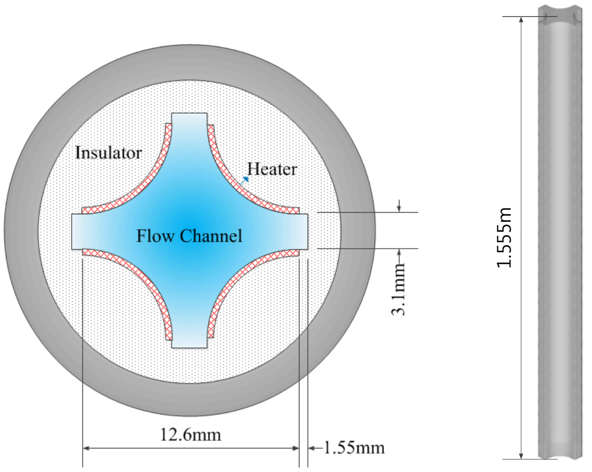

Fig. 1. Geometry of PSBT single subchannel test

2.2. Test Condition

The subchannel tests were performed by varying four control parameters: the system pressure, mass flux, induced power, and inlet temperature. Among the more than 40 test data sets opened as an international benchmark problem, in this study, the Run No.1.1223 case with the highest pressure condition was simulated. The system pressure, mass flux, induced power, and inlet temperature are 169.1bar, $10.95kg/m^2hr$, 49.9kW, and 339.7^{o}C, respectively.

3. CUPID1.7 Simulation

3.1 Computational Grid

The computational grid was generated using an in-house grid generation program, which uses Delaunay triangle and Voronoi polygon for the orthogonality of the grids. The order of the grid size is about 0.0005 m in the x and y directions and 0.00 6m in the z-direction as shown in Fig. 2. The total number of grids for the flow channel is 104,118. The heaters were not simulated with a solid material. Instead, the heat flux condition was applied to the wall where the interface between the heaters and the flow channel is defined.

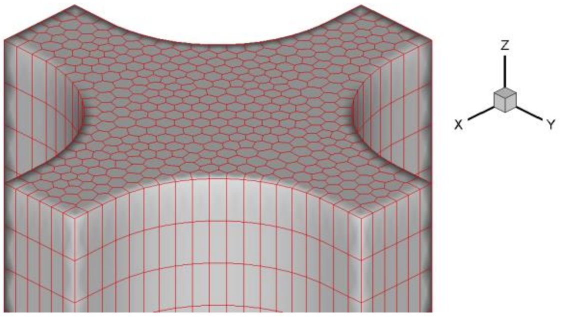

Fig. 2. Computational grid

3.2 Boiling Heat Transfer Models

CUPID1.7 uses a wall heat partitioning model to simulate the sub-cooled boiling near walls. The heat flux at the wall is distributed to mainly three components: the surface quenching (q_q), the evaporation (q_e), and the single phase convection (q_{wlc} and q_{wg}) [3]. (1) shows the heat flux conservation, which it turns into a non-linear equation for the wall temperature. In (1), α and q are the volume fraction and heat flux. Subscripts l, g, cm, bc, wlc, wg, and sat are liquid, gas, Churn-mist transition, bubble-churn transition, wall-to-liquid continuous phase, wall-to-gas, and saturation, respectively.

$$q_{wall} = \frac{\alpha_{g,cm} - \alpha_g}{\alpha_{g,cm} - \alpha_{g,bc}} \left(q_q + q_e + q_{wlc} \right) + \frac{\alpha_g - \alpha_{g,bc}}{\alpha_{g,cm} - \alpha_{g,bc}} q_{wg} \quad (1)$$

The wall vapor generation rate (Γ) is calculated by (2) and (3). h, N, f, and D_d are the enthalpy, nucleate site density, departure frequency, and departure diameter, respectively.

$$\Gamma_{wall} = \frac{q_e}{\left(h_{g,sat} - h_l\right)} \tag{2}$$

$$q_e = Nf\left(\frac{\pi}{6} D_d^3\right)\rho_g h_{lg} \tag{3}$$

3.3 Simulation Result

Because the PSBT subchannel benchmark provides the area-averaged void fraction at a 1.4 m height as the test results with the test conditions such as pressure, mass flux, power and inlet temperature, the area-averaged void fraction is the sole parameter that can be used to quantitatively compare between the benchmark data and the simulation results. Fig. 3 shows the simulation result for the void fraction along the test channel. The aspect ratio of the channel is reduced to 1/50 in the figure for visibility. Three planes sliced in the z-axis are generated at 0.3 m, 1.0 m, and 1.5 m heights from the bottom of the channel. Sub-cooled boiling begins to occur near the heated wall from a 0.3 m height of the test channel.

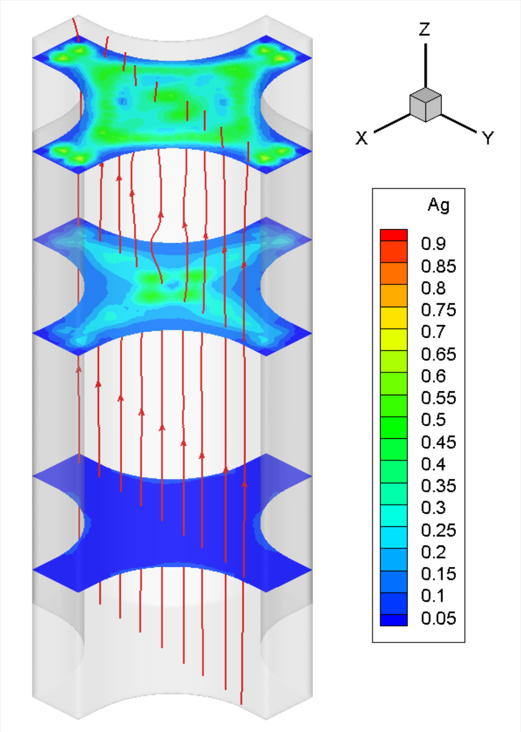

Fig. 3. Void fraction calculation result

The averaged void fraction at a 1.4 m height is 0.265 in the simulation results while the test data show 0.332. This discrepancy may be caused by the heat flux calculation, in particular the heat flux by evaporation in (3). CUPID1.7 uses the Lemmert and Chwala model, Cole model, and Cole and Rosenhow model for nucleate site density, departure frequency, and departure diameter, respectively. Thus, it is necessary to determine proper sub-models applicable to the test conditions such as the system pressure, temperature, flow velocity, etc. Details on each sub-model used in CUPID1.7 can be found in Bae’s thesis [4].

4. Conclusions

As the preliminary work for the assessment of wall boiling models in CUPID1.7, the PSBT subchannel test was simulated. CUPID1.7 properly predicts the sub-cooled boiling near a wall and behavior of the void fraction distribution. However, CUPID1.7 underestimated the area-averaged void fraction compared to the test data, and this result indicates that an improvement and validation of the boiling models are required. In addition, the turbulence model should be validated simultaneously with the boiling model since the turbulence behavior affects the temperature and velocity profile near a wall.

ACKNOWLEDGEMENT

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