Simulation of DEBORA Experiment using CUPID Code

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1. Introduction

CUPID is a three-dimensional thermal hydraulics code for the transient analysis of two-phase flows in nuclear reactor components [1]. For the safety analysis, the CUPID code has the capability to deal with fast transient problems such as Large Break LOss of Coolant Accident (LBLOCA). For this purpose, it is very important to find accurate fluid properties such as densities and viscosities even though the fluid properties are changed very rapidly. Therefore, the full-range of steam table for water was implemented at the first stage of the CUPID code development program.

Thermal hydraulic experiments using water under the high pressure condition over 150 bars corresponding to the start condition of LBLOCA analysis is very difficult to perform especially if visualization or high-precision measurements are required. So, alternative fluids were frequently used for experiments to simulate high pressure conditions by considering the similarity between water and alternative fluids. Therefore, the CUPID code should be able to calculate the fluid properties of alternative fluids to validate not only physical models but also its computing capability under high pressure conditions.

In this study, the fluid properties for various alternative fluids were implemented in the CUPID code and we make it possible to calculate fluid properties under transient calculations including phase change. For the verification and validation (V&V), DEBORA experimental data was used and it was confirmed that the CUPID code properly simulate the phase change problem with varying fluid properties.

2. Implementation of Fluid Properties

2.1 Implementation of R12 Property

The property of R12 was implemented by using the FORTRAN functions provided by NIST. The CUPID code can search various fluid properties based on the pressure and temperature at each cell. Both of liquid and gas phase properties should be searched because CUPID adopt the two fluid model. In addition, properties for subcooled and superheated conditions can be searched, too. The procedure of property calculation is described as below.

1) Find the saturated properties based on the pressure of each cell. It includes saturation temperature, density, enthalpy, specific heat and internal energy of liquid and gas phases.
2) Check the phase state of each phase whether it is a subcooled or superheated state or not by using pressure and bulk internal energy of each cell.
3) Find properties of density, enthalpy, specific heat, thermal expansion coefficient, and so on according to the phase state.
4) Calculate derivatives of densities with respect to internal energy and pressure, derivatives of temperatures with respect to internal energy and pressure.
5) Find property of non-condensable gas if it exists.

2.2 Verification of Implementation

A preliminary calculation was performed to verify the implemented property functions in the experimental condition of DEBORA1 test case. The fluid properties were compared at the 100 points where pressure and temperature were varied as shown in Fig. 1. The system pressure was varied from 2.62 MPa to 2.67 MPa along the height. REFPROP program developed by NIST was used to independently calculate the fluid properties [2].

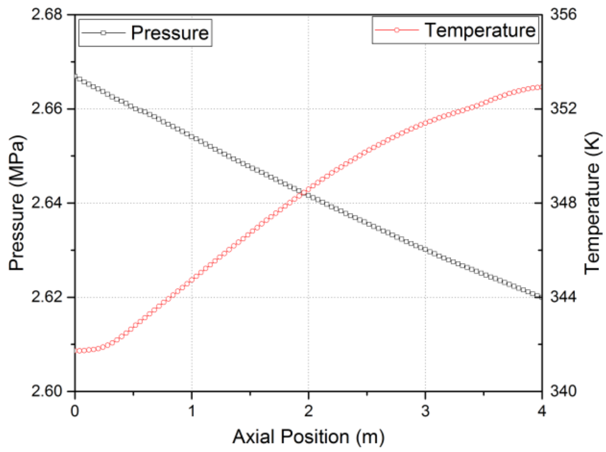


Fig. 1 Pressure and temperature variation according to axial points

Fig. 2 shows the comparison results for density and viscosity calculated by CUPID and REFPROP. The results showed the maximum error of 0.010% and 0.056% for density and viscosity, respectively. Also, it was conformed that the gas properties were properly calculated.

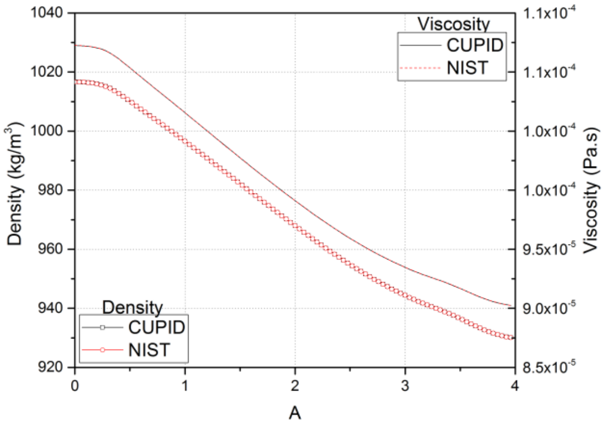


Fig. 2 Comparison result of density and viscosity

3. DEBORA Experiment and CUPID Modeling

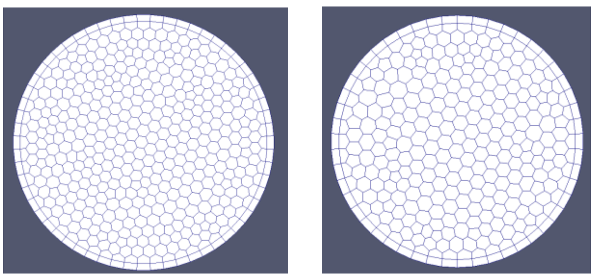
3.1 DEBORA Experiment [3]

DEBORA experimental data was selected for the validation of the implemented property functions as well as subcooled boiling model in the CUPID code. The test section of DEBORA was a vertical pipe with the inner diameter of 19.2 mm and the total height of 5 m. The length of heated section was 3.5 m long, and 1 m of upstream region and 0.5 m of downstream region were unheated section. The working fluid was R-12. The pressure range was 14.6 to 30 bars and this pressure range corresponds to the pressure range of water around 90 to 170 bars considering the phasic density ratio. The radial distribution of local two-phase flow parameters were measured at the outlet of the heated section. The data set (DEBORA1) was taken from open literatures [4, 5]

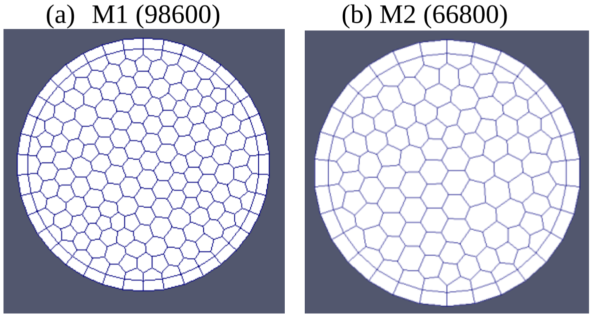
3.2 Grid Generation

Using an in-house mesh generator, CUPID-POP, polyhedral mesh was generated as shown in Fig. 3. Instead of a 2-dimensional simulation assuming a symmetric condition, a 3-dimensional simulation was performed because not only the calculation results but also the experimental results showed asymmetric behavior of vapor in the azimuthal direction. The unheated section in the upstream region was not simulated so that the total height was 4.0 m.

The number of axial grids was fixed as 200, and 4 different sizes of meshes were generated for the 2D plane. Total number of grids are 98600, 66800, 41200, and 27400 as shown in Fig. 3.



(a) M1 (98600) (b) M2 (66800)



(c) M3 (41200) (d) M4 (27400)

Fig. 3 Polyhedral grids for DEBORA simulation

3.3 Heat Flux Partitioning Model in CUPID

CUPID code adopt the heat flux partitioning model for analyzing the wall boiling including the sub-cooling boiling in computational mesh cells facing a heated wall. In the model, the heat transfer from the heated wall surface to the fluid is expressed as a sum of surface quenching heat transfer, wall boiling heat transfer and heat transfers to each phase as shown in Eq. (1) ~ Eq. (5).

$$Q_{wall} = Q_q + Q_e + Q_c \quad (1)$$

$$Q_q = h_q A_{2f} \left(T_w - T_l \right) \quad (2)$$

$$Q_e = N'' f \left(\frac{\pi}{6} D_{b,depart}^3 \right) \rho_g h_{fg} \quad (3)$$

$$Q_{c,l} = h_{c,l} \left(1 - A_{2f} \right) \left(T_w - T_l \right) \quad (4)$$

$$A_{2f} = N'' \frac{\pi D_{b,depart}^2}{4} K \quad (5)$$

Where Q_{wall}, Q_q, Q_e, Q_c, h_q, A_{2f}, T_w, T_l, N'', f, $D_{b,depart}$ and $h_{c,l}$ are total wall heat flux, quenching heat flux, evaporation heat flux, single-phase convection heat flux, quenching heat transfer coefficient, two-phase heat transfer area fraction, wall temperature, liquid temperature, nucleate site density, bubble departure frequency, departure bubble diameter, and single phase heat transfer coefficient, respectively. The default models in CUPID are Lemmert and Chwala model for nucleation site density, Cole model for bubble departure frequency, and Unal model for bubble departure diameter.

4. CUPID Calculation Results

4.1 Grid Sensitivity Calculation

The grid sensitivity calculation was performed with four different grids (M1, M2, M3, and M4). Fig. 4 shows the void fraction profile at the distance of 0.0006 m from the heated wall along the height. The peak of void fraction at the end of heated section shows some differences according to the grid sizes. However, the maximum difference is 3.38 % of void faction and it is almost negligible. Thus, M4 was selected as a reference grid.

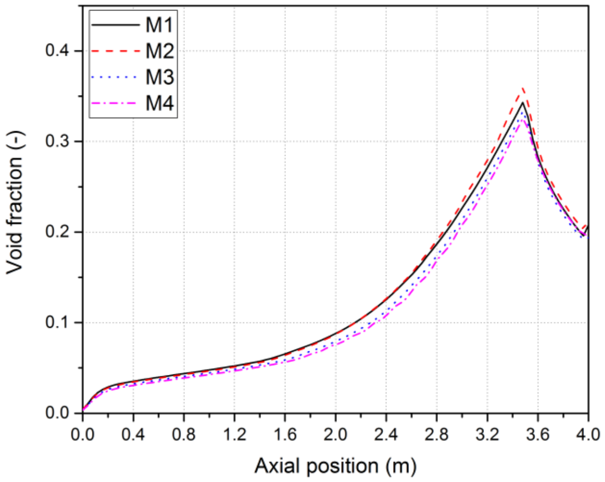


Fig. 4 Comparison result of grid sensitivity calculation

4.2 Effect of Bubble Departure Diameter Model

It is well known that the most effective parameter among sub-models in a heat partitioning model is a bubble departure diameter model. Therefore, the sensitivity test for the bubble departure diameter model was performed by using three different models: Fritz [7], Tolubinski [8], and Unal [9] model. Unal model showed the best result and Tolubinski model showed the lowest void fraction near the heated wall. However, the differences were not significant as the bubble diameter model affects the void fraction result in low pressure conditions.

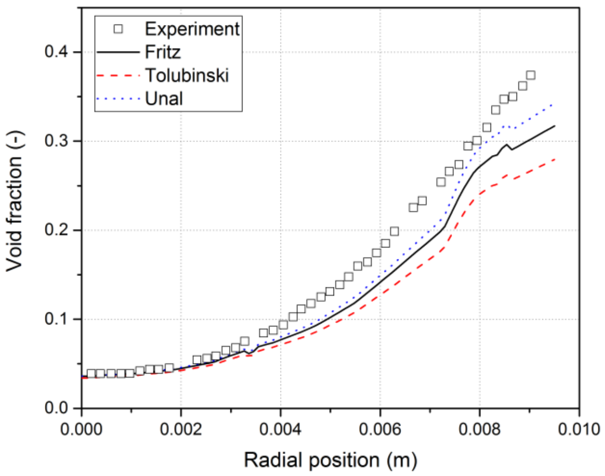


Fig. 5 Comparison result of sensitivity calculation for bubble departure diameter

4.3 Effect of Non-Drag Force Models

While the wall heat flux partitioning model determines the generation rate of vapor from heated walls, non-drag forces such as lift force and wall lubrication force governs the transportation of the generated bubbles in the perpendicular direction of perpendicular to heated wall.

The CUPID code uses Tomiyama's lift force model [10] and Antal's wall lubrication model [11]. For a sensitivity calculation, the coefficients of each model was simply multiplied by factor 2. Fig. shows the result of sensitivity calculation. When the coefficient of lift force model became double, the bubbles were pushed to the wall so that the void fraction near wall sharply increased. And, it can be noticed that the lubrication force compensates the effect of the lift force because two forces have opposite signs if the bubble is smaller than 5.6 mm [10].

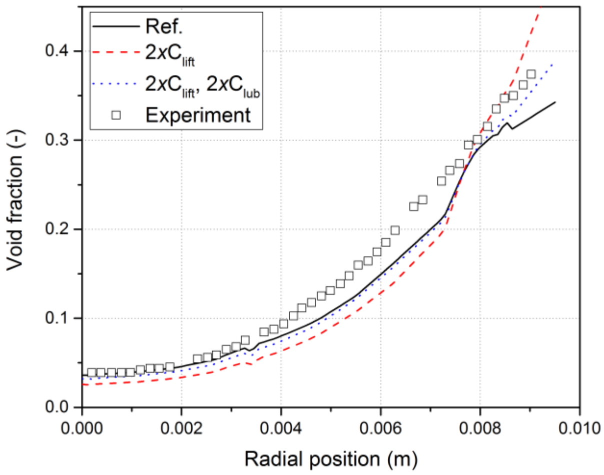


Fig. 6 Comparison result of sensitivity calculation for lift force and lubrication force model

5. Conclusions

In this study, the property of R12 was implemented and V&V was performed. DEBORA experimental data was used for the validation. The CUPID code properly calculated various properties of R12 under the transient condition including boiling phenomenon.

Unal's bubble departure diameter model showed the most proper result in the sensitivity calculation but the differences were not significant. On the other hand, the non-drag forces such as the lift force and wall lubrication force affected the calculation results, in particular, the radial distribution of void fraction. When the lift force increased, the void fraction near wall sharply increased because the bubble diameters are generally small under the high pressure condition. Therefore, it can be concluded that the effect of non-drag forces is more significant than the effect of models that determine the size of bubbles when the pressure is relatively high.

ACKNOWLEDGMENTS

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