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Coherent Calculation for Air-Water Flow and Boiling Flow by Using CUPID Code

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1. Introduction

The Korea Atomic Energy Research Institute has been developing a three-dimensional thermal-hydraulic code, called CUPID, which was motivated from practical needs for the realistic simulation of two-phase flows in nuclear reactor components [1]. This paper presents coherent simulation of an air-water flow test and a sub-cooled boiling flow test, and the model implementation of related to them. The closure relations for the air-water flow and sub-cooled boiling flow are turbulence model, interfacial non-drag force, interfacial condensation, wall evaporation model, interfacial area transport equation, and so on.

2. Mathematical Model

2.1 Governing Equations

The governing equations of the two-fluid, three-field model are similar to those of the time-averaged two-fluid model derived by Ishii and Hibiki [2]. The continuity, momentum, and energy equations for the k-phase are given by

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k) = \Gamma_k , \tag{1}$$

$$\begin{aligned}\frac{\partial}{\partial t}(\alpha_k \rho_k \underline{u}_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k \underline{u}_k) &= -\alpha_k \nabla P + \nabla \cdot [\alpha_k \tau_k] + \alpha_k \rho_k \underline{g} \\ &+ P \nabla \alpha_k + M_k^{mass} + M_k^{drag} + M_k^{VM} + M_k^{non-drag}\end{aligned} , \tag{2}$$

$$\begin{aligned}\frac{\partial}{\partial t}[\alpha_k \rho_k e_k] + \nabla \cdot (\alpha_k \rho_k e_k \underline{u}_k) &= -\nabla \cdot (\alpha_k q_k) + \nabla \alpha_k \tau_k : \nabla \underline{u}_k \\ &- P \frac{\partial}{\partial t}\alpha_k - P \nabla \cdot (\alpha_k \underline{u}_k) + I_k + Q'''_k\end{aligned} . \tag{3}$$

where, α_k, ρ_k, u_k, P_k, Γ_k, I_k are the k-phase volume fraction, density, velocity, pressure, and an interface mass transfer rate, and energy transfer rate, respectively. M_k represents the interfacial momentum transfer due to a mass exchange, a drag force, a virtual mass, and non-drag forces. The non-drag forces are composed of lift force, wall lubrication force[3], turbulence dispersion force[4] as follows.

$$F_{lift,l} = \alpha_g \rho_l C_L (\vec{u}_g - \vec{u}_l) \otimes (\vec{\nabla} \otimes \vec{u}_l), \tag{4}$$

$$\underline{F}_{WL,g} = \frac{\alpha_g \rho_l C_{WL} \left|\underline{u}_g - \underline{u}_l\right|^2}{D_b} \max\left(0, C_{WL1} + C_{WL2}\frac{D_b}{y_w}\right)\vec{n}_w , \tag{5}$$

$$\underline{F}_{td,g} = C_{TD} \rho_l k_l \nabla \alpha_l \ . \tag{6}$$

To consider a turbulence effect, the standard k-ε turbulence model was also implemented. For a multi-dimensional calculation of the IAC (interfacial area concentration), an IAT equation for a boiling flow was derived as follows [5].

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i \underline{u}_g) = \frac{2}{3}\frac{a_i}{\alpha_g \rho_g}\left[\Gamma_{i,g} - \alpha_g \frac{d\rho_g}{dt}\right] + \phi_{CO} + \phi_{BK} + \phi_{PH} . \tag{7}$$

In the sub-cooled boiling flow, the amount of vapor generation can be computed by a wall heat flux partitioning model. The mechanism of a heat transfer from the wall consist of the surface quenching q_q, evaporative heat transfer q_e, and single phase convection q_c which are basically included in the CFX-4 code[6] as follows.

$$q_q = \left(\frac{2}{\sqrt{\pi}}\sqrt{t_w k_f \rho_f C_{pf}}\, f\right) A_{2f} (T_w - T_f), \tag{8}$$

$$q_e = N'' f \left(\frac{\pi}{6} D_d^3\right) \rho_g h_{fg} , \tag{9}$$

$$q_c = h_c A_{1f} (T_w - T_f) . \tag{10}$$

3. Validation

3.1 Simulation of Air-Water Flow

The test section of Bankoff's test[7] is a 2.8-m tube with a diameter of 0.04 m. The only single mesh of 15^o was used for the theta direction, and the symmetric boundary condition was used for the rest part as shown in Fig. 1(a). 24x1x100 grids were used for r, θ , z coordinates as shown in Fig. 1(b). The air-water mixture with a void fraction of 0.1 was injected into the bottom and the mixture flew out from the upper part. The system pressure is 1.0 bar.

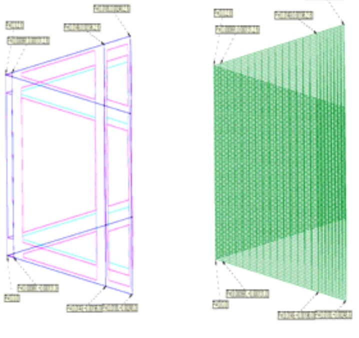

Fig.1 Geometrical and mesh condition for Bankoff's test

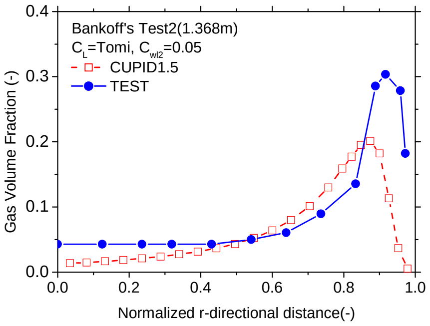

Fig.2 Gas volume fraction at Bankoff's test

The null transient calculation was done and the steady solution could be obtained at 10 seconds. The calculated gas volume fractions are compared to the measured ones in Fig. 2. The x-direction of those figures is the distance from tube center to the wall. The calculated gas volume fractions are very similar in the overall shape. The calculated void fraction is lower at center than the measured one.

3.2 Simulation of Subcooled Boiling Flow

The inner diameter of the SUBO test section[8] is 35.5mm, and the outer diameter of the heater rod is 9.98 mm as shown in Fig. 2(1). The calculation domain is a pillar with a fan-shape base area as shown in Fig. 2(b) and symmetric boundary condition was used for considering the tube. 12x1x100 grids were used for r,θ,z coordinates as shown in Fig. 2(c). BASE-RB of SUBO test was selected for the base calculation set. The 374.65 K, 1.939 bar, 943.9 kg/m^3 water is injected into the inlet. The outlet was set to constant pressure boundary of 1.573 bar. The heat flux from the heated wall is 473.7 kW/m^2.

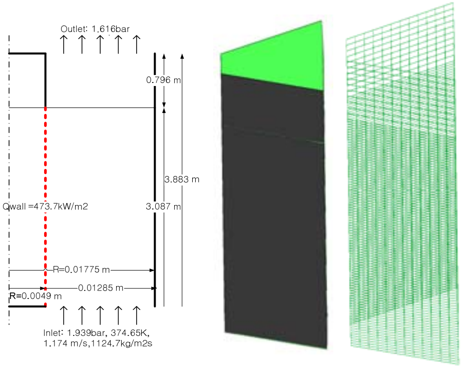

Fig. 3 Calculation domain for SUBO test: (a)schematic diagram (b)geometry (c) mesh.

The null transient calculation was done and the steady solution could be obtained at 10 seconds. The calculated gas volume fractions are compared to the measured ones in Fig. 4. The x-direction of those figures is the distance from the heated wall. The calculated gas volume fractions are similar to measured ones except first level and sixth level. This means that the evaporation is faster and the condensation is bigger in the calculation than in the experiment. The void peak near wall is much higher in the calculation mainly due to too smaller bubbles.

3. Conclusions

This paper presents coherent simulation of an air-water flow and a sub-cooled boiling flow tests and the model implementation of related to them. The results are not bad, but some improvement should be done in the area of the interfacial area transport equation and the lift force coefficient model.

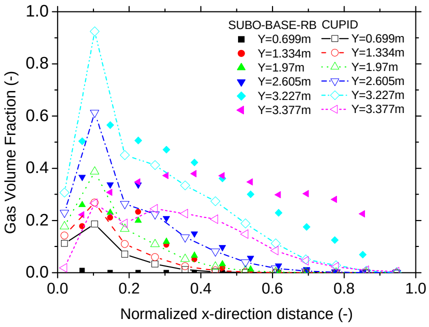

Fig. 4 Gas volume fraction at SUBO-BASE-RB.

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