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Implementation of Wall Film Condensation Model for Large System Analysis in CUPID

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1. Introduction

This study has purpose to simulate wall condensation in the presence of non-condensable using CUPID, which is developed by Korea Atomic Energy Research Institute (KAERI) for the analysis of transient two-phase flows in nuclear reactor components [1]. In the containment building of a nuclear reactor, the wall condensation occurs in the presence of non-condensable gas and it accumulates near the condensate film. The buildup of the gas inhibits the diffusion of vapor from the bulk mixture to the liquid film and leads to significant reduction in heat transfer during the condensation. In the present study, the wall condensation model with a non-condensable gas was implemented into the CUPID code and a conceptual problem for condensation in a large system was analyzed. This paper introduces the implemented wall film condensation model and then, presents the simulation result using CUPID with the model for a conceptual condensation problem of Dehbi [2]. The simulation result was compared with the STAR-CCM+ [3] calculation result.

2. Wall condensation Model

When calculating two-phase flow situation, CUPID code uses two-fluid model. It requires a proper wall condensation model applicable to the analysis of the large scale system like the containment. It means that resolution of very thin liquid film is not desired in order to save the computational cost and a wall modelling which can consider the effect of non-condensable near the liquid film. For this purpose, the wall film condensation model which combines the models proposed by Guiassian [4] and Naylor et al. [5] applied in CUPID.

The followings are the equations for the condensation model.

– **The interphase temperature equation**

$$T_{\mathrm{I}} = T_{\mathrm{sat}}\left(X_{\mathrm{v,s}}P\right), \tag{1}$$

where T_{I} represents interphase temperature, $X_{v,s}$ is mole fraction in the interphase. As shown in Fig. 1, mole fraction of steam decreases relatively at the interface because of non-condensable gas accumulation near the condensation wall. Since that, mole fraction of interface should be calculated iteratively in the model.

– **Mass fraction at the interface**

$$\mathrm{m_{v,s}} = \frac{\mathrm{X_{v,s}M_v}}{\mathrm{X_{v,s}M_v} + (1 - \mathrm{X_{v,s}})\mathrm{M_n}}, \tag{2}$$

where M_v and M_n represent molecular weight of vapor and non-condensable gas respectively.

– **Condensation mass flux equation**

$$m'' = -K_{GI}\ln\left(\frac{1 - m_{v,G}}{1 - m_{v,s}}\right), \tag{3}$$

where K_{GI} is the mass transfer coefficient. The mass transfer coefficient is obtained from Rose [7] correlation as shown in Eqn. (4)

$$\begin{aligned} Sh_x \mathrm{Re}^{-1/2} &= \frac{K_{GI}x}{\rho \mathrm{D}} \mathrm{Re}^{-1/2} \\ &= \xi(Sc)(1 + 0.941\beta_x^{1.14} Sc^{0.93})^{-1} + \beta_x Sc \end{aligned} \tag{4}$$

where, $(Sc) = Sc^{1/2}(27.8 + 75.9Sc^{0.306} + 657Sc)^{-1/6}$, $\beta_x = -\left(\frac{v_i}{U}\right)\mathrm{Re}_x^{1/2}$ and v_i represents interface velocity.

– **Heat balance equation**

$$\dot{H}_{GI}(\bar{T}_G - T_I) - \frac{k_F}{\delta}(T_I - T_W) + m'' h_{fg} = 0 \tag{5}$$

where $\dot{H}_{GI}$ is gas-side heat transfer coefficient obtained from Eq. (4) by the analogy between heat and mass transfer and δ is film thickness which can be obtained from the liquid film model [6].

A solution procedure is shown in Fig. 2. For the calculation, the mole fraction is assumed first, and interphase temperature and mass fraction of vapor are calculated using the mole fraction. Thereafter, the condensation mass flux at the gas/liquid interface was calculated using mass fraction, then total mass flow rate of a liquid film could be obtained from the condensation mass flux and the convective mass flow rate from the upstream cell. When the mass flow rate is determined, the film thickness could be calculated from liquid film model. With the calculated film thickness, the interfacial heat transfer coefficient, and the condensation mass flux, the satisfaction of the heat balance equation at the interface, Eq (5), is evaluated. By an iterative solution methods, the solutions of Eqs. (1)~(5) can be obtained and the calculation proceeds to next cell.

3. Validation of the Implementation

The wall film condensation model was implemented into CUPID and a conceptual problem of Dehbi [2] as shown in Fig. 3 was simulated and the results were compared with the STAR-CCM+ simulation results. Dehbi's conceptual problem simulates the flow over a hypothetical vertical wall condenser which is 20 m long hence being of typical NPP containment vertical dimensions. The Condensation wall length is 20 m, and the width is 1 m. A steam-air mixture with 50% steam by mass is assumed to enter the channel from the top with a low velocity of 0.3 m/s. The fluid entrance temperature was set to 405 K and the domain was held at 4 bar pressure, and accordingly the steam partial pressure is 2.47 bars yielding a saturation temperature of 400 K. The wall temperature is maintained at 360K. In the STAR-CCM+ calculation, the fluid-film model, which is devoted to the thin film simulation, and evaporation/condensation model, which is devoted to the phase transition, were applied. As shown in Fig. 4, the predicted void fraction was decreased by condensation on the wall and consequently, the film thickness was gradually increased along the wall. This result was met with STAR-CCM+ result qualitatively. The gas velocity at the end of condenser was presented in Fig. 5 and the velocity showed a similar trend with STAR-CCM+ calculation result as shown in Fig. 6.

However, the film thickness showed significant discrepancy as it flows down in Fig. 7. Since CUPID does not consider the mass diffusion of non-condensable gas by the concentration gradient, the predicted mass fraction increased drastically near the wall whereas, STAR-CCM+ result showed gradual increase of mass fraction as shown in Fig. 9. Due to the lack of the mass diffusion term, the condensation rate was under-predicted by the over-estimated buildup of the non-condensable gas near the wall.

In the future, the mass diffusion term will be added into the non-condensable gas continuity equation and the analysis of this conceptual problem will be repeated in order to validate the implemented condensation model.

4. Conclusion

From this conceptual problem analysis, it was found that CUPID with wall condensation model can predict steam condensation in the presence of the non-condensation gas mixture condensation and non-condensable gas effect near the liquid film qualitatively. However, non-condensable gas diffusivity term is needed to predict condensation mass flux and heat flux accurately. In addition to this, more improvement of the wall condensation model is desired, such as consideration of the interfacial shear stress, temperature distribution inside the liquid film, etc.

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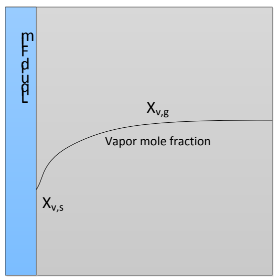

Fig. 1 Vapor mole fraction near the condensation wall

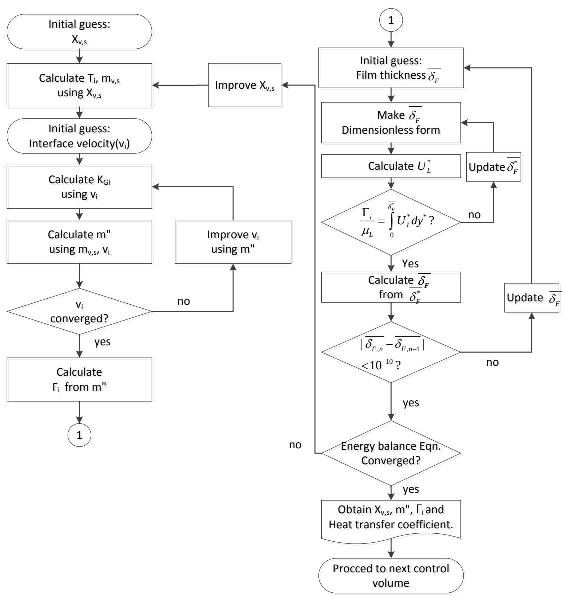

Fig. 2 Flowchart of the wall condensation model

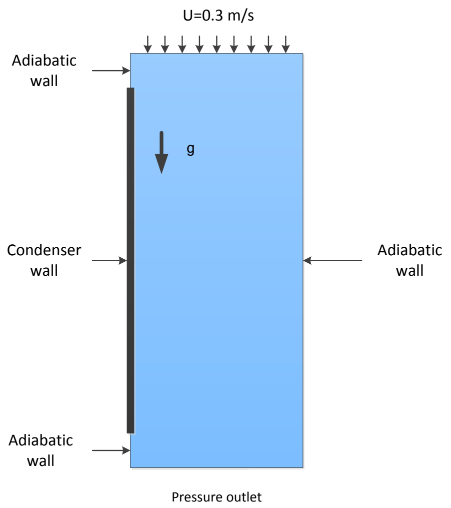

Fig. 3 Dehbi condensation problem condition

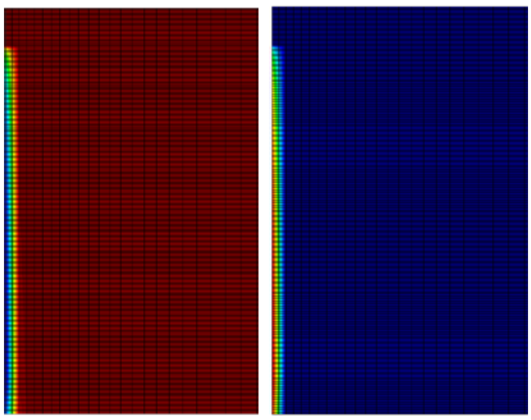

Fig. 4 Calculation Result: void fraction and film thickness

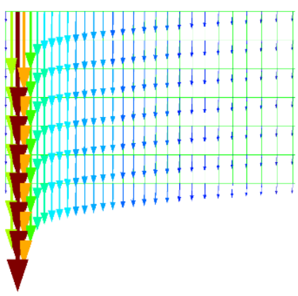

Fig. 5 Calculation Result: Gas velocity near the Outlet

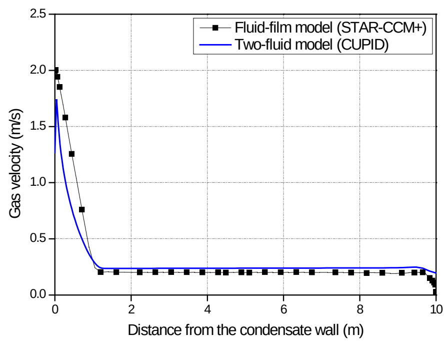

Fig. 6 Calculation Result at the End of Condenser Wall: Gas velocity comparison between CUPID and STAR-CCM+

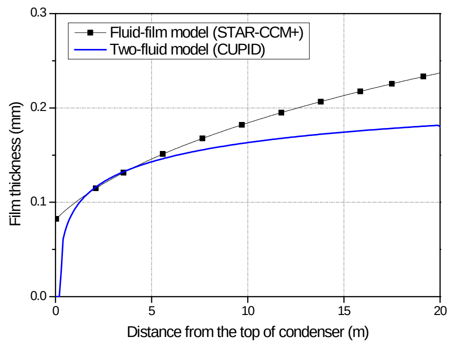

Fig. 7 Calculation Result along the Condenser Wall : Film Thickness

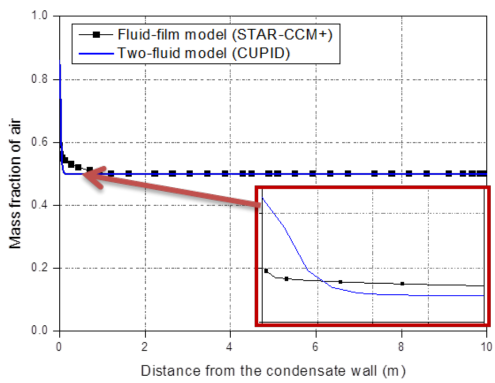

Fig. 8 Calculation Result at the End of Condenser Wall:: Vapor mole fraction at the end of the condenser wall