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Implementation of Wall Shear Stress Model for a Thin Liquid Film in CUPID

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1. Introduction

For the analysis of transient two-phase flows in nuclear reactor components, a three-dimensional thermal hydraulics code, named CUPID, has been developed at Korea Atomic Energy Research Institute [1]. It has been validated against various conceptual problems and experimental results, but mainly focused on the low void fraction flows such as a bubbly flow. In order to extend its applicability to high void fraction flows such as an annular flow and film flow, additional validation procedures are required and adequate constitutive models for those flows need to be implemented. In the present study, one of the required constitutive models of the two-phase equations, a wall shear stress model for a thin liquid film, was implemented and tested. This paper introduces the mechanistic wall shear stress model for a liquid film and then, presents the simulation result using CUPID with the model for a conceptual problem of a downward liquid film flow. The simulation result was compared with the analytical solution and the STAR-CCM+ [2] calculation result for the verification and validation.

2. Mechanistic Liquid Film Model

When a liquid film is simulated using a Eulerian-Eulerian two-fluid model, different sets of constitutive models need to be adopted depending on the relative size between the liquid film thickness and the first cell from the wall on which it flows down. If the liquid film is relatively very thin and therefore, the former is much smaller than the latter, a wall shear stress model of a thin liquid film should be applied to consider the velocity gradient across the thickness. In the present study, an approach which evaluates the wall shear stress using a force balance equation of a liquid film was implemented into CUPID.

The force balance equation is;

$$\frac{d}{dy}\left[\left(\nu_L+E\right)\frac{dU_L}{dy}\right]-\frac{1}{\rho_L}\frac{dP}{dz}+g\sin\theta=0, \tag{1}$$

where E is the eddy diffusivity in the liquid film [3]. Note that for a liquid film in a stagnant gas, $dP/dz=\rho_G g\sin\theta$. And by using no-slip boundary condition at $y=0$, and $dU_L/dy=0$ at $y=\overline{\delta_F}$, integration of equation will give

$$U_L^*\left(y^*\right)=\int_0^{y^*}\left(1-\frac{y^*}{\overline{\delta_F^*}}\right)\Big/\left(1+\frac{E}{\nu_L}\right)dy^*, \tag{2}$$

where $y^*=\frac{y}{\nu_L}\sqrt{\overline{\delta_F}\left[-\frac{1}{\rho_L}\frac{dP}{dz}+g\sin\theta\right]}$,

$$\overline{\delta_F^*}=\frac{\overline{\delta_F}}{\nu_L}\sqrt{\overline{\delta_F}\left[-\frac{1}{\rho_L}\frac{dP}{dz}+g\sin\theta\right]}, \text{ and}$$

$$U_L^*=U_L\Big/\sqrt{\overline{\delta_F}\left[-\frac{1}{\rho_L}\frac{dP}{dz}+g\sin\theta\right]}.$$

If mass flow is given, the liquid film thickness and velocity profile which satisfy $\Gamma_F/\mu_L=\int_0^{\overline{\delta^*}}U_L^*dy^*$ can be found numerically as illustrated in the flowchart, Fig. 1.

3. Validation of the Implementation

In order to validate the implemented model in CUPID, a conceptual problem for a downward liquid film as shown in Fig. 2 was simulated and the results were compared with the analytical solution obtained from Eqs. (1) and (2) and the STAR-CCM+ simulation results. In the STAR-CCM+ calculation, the fluid-film model [2], which is devoted to the thin film simulation, was applied. As shown in Fig. 3, the predicted downward liquid velocities are remarkably decreased by the implementation of the wall shear stress model. Without it, the wall shear stress is under-estimated because the velocity gradient across the thin liquid film cannot be taken into account and it results in significantly over-predicted liquid velocity. With the implemented model, the predicted liquid velocity and the film thickness are in reasonably good agreement with the analytical solution after being the fully-developed and the STAR-CCM calculation results as presented in Figs. 3 and 4. The error between the analytical solution and the simulation result is less than 2% in the thickness and it is likely to be caused by the effect of the interfacial friction forces. In the analytical solution, the interfacial friction was neglected, on the other hand in the simulations, it was included. The effect of mesh size was also investigated with four different first cell sizes from the wall, 3.3 mm~20mm, and the converged calculation results can be obtained even with large mesh size as shown in Fig. 5. Meanwhile, Fig. 6 shows the calculation results of the void fraction and velocity distributions calculated by CUPID.

4. Conclusion

From this validation against the conceptual problem, it was found that the implemented model can reproduce the downward liquid film behavior, such as the film thickness and the velocity appropriately. However, the present work is limited to the downward liquid film merely, so that more validations for high void fraction flows are required with various flow conditions. Moreover, since the model is evaluated for the laminar liquid film, the influence of the turbulence on the film behavior needs to be tested.

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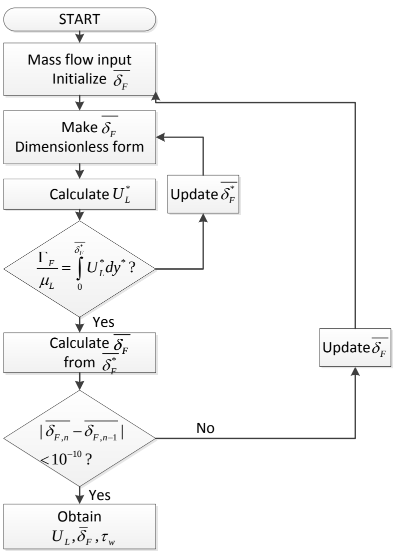

Fig. 1 Flowchart of the wall shear stress model

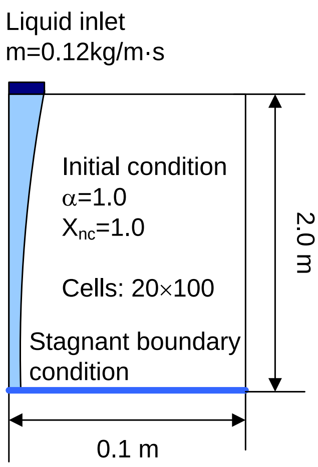

Fig. 2 Calculation condition

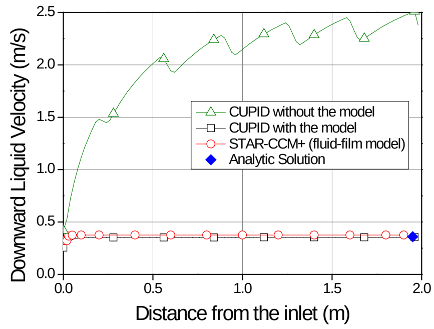

Fig. 3 Calculation Result: liquid velocity

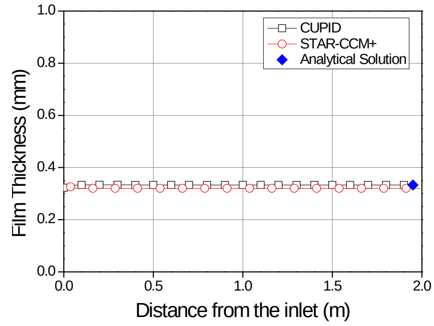

Fig. 4 Calculation Result: film thickness

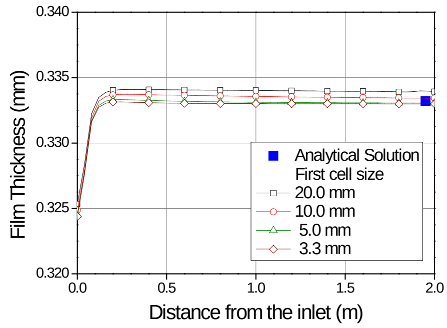

Fig. 5 First cell size effect

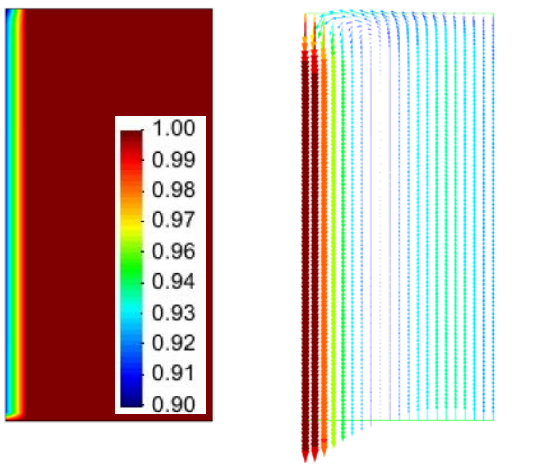

Fig. 6 Calculation Result: void fraction and velocity