Validation of Wall Friction Model in SPACE-3D Module with Two-Phase Cross Flow Experiment

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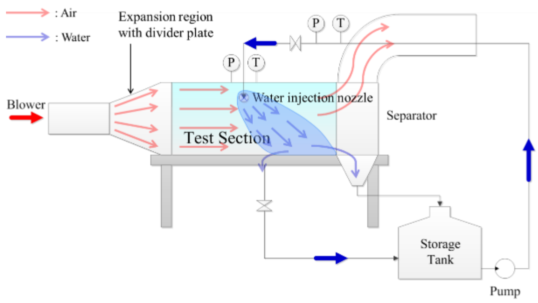
1. Introduction

The most of system analysis codes have been developed based on one-dimensional analysis and still used in the licensing of nuclear power plant. Considering the realistic phenomena in the reactor, however, recent trends in safety analysis codes have tended to adopt multi-dimensional module to simulate the complex flow more accurately. Even though the module was applied to deal the multi-dimensional phenomena, implemented models in that are one-dimensional empirical models. Therefore, prior to applying the multi-dimensional module, the constitutive models implemented in the codes need to be validated. In the downcomer of Advanced Power Reactor 1400 (APR1400) which has direct vessel injection (DVI) lines as an emergency core cooling system, multi-dimensional two-phase flow may occur due to the Loss-of-Coolant-Accident (LOCA). The accurate prediction about that is high relevance to evaluation of the integrity of the reactor core. For this reason, Yang performed an experiment that was to investigate the two-dimensional film flow which simulated the two-phase cross flow in the upper downcomer, and obtained the local liquid film velocity and thickness data [1]. From these data, it could be possible to validate the friction models in multi-dimensional module of system analysis codes. In this study, SPACE-3D was used to simulate the Yang's experiment, and obtained the local variables. Then, the wall friction model used in SPACE-3D was validated by comparing the two-phase cross flow experimental results with the calculated local variables.

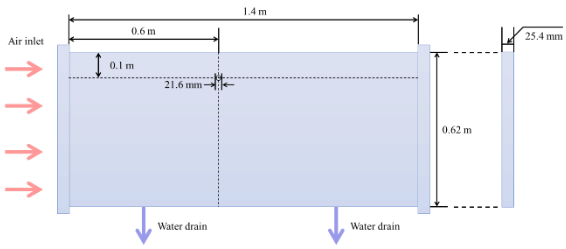
2. Two-phase cross flow experiment

2.1 Experimental facility and test conditions

An experimental facility was devised to measure the local film velocity and thickness of the two-dimensional film flow which used air and water as working fluids, as shown in Fig. 1-(a). The air was selected as a gas phase fluid instead of steam to separate condensation or heat transfer effect from the hydraulic effect. The test section was made as an unfolded-shaped upper downcomer with a 1/10 reduced scale of APR1400, as shown in Fig. 1-(b). The experimental facility includes a water supply system to simulate the falling liquid and an air supply system to provide transverse gas flow. The water which was injected through a nozzle impinged on one side of the test section and made a two-dimensional liquid film falling down the wall. The air was injected by a blower along the pipe, and uniformly distributed by a perforated plate in the expansion section. The injected air and falling water make a two-dimensional film flow. At the end of the test section, the two phases were separated by a separator. After that, the water returned to the storage tank through the drain line at the bottom of the test section and separator. The air exited through the top of the separator.



(a) Flow directions of working fluids



(b) Test section

Fig. 1. Schematics of experimental facility [1]

In order to define test conditions, the modified linear scaling method, which was developed by Yun et al. [2], was adopted. This model preserves Wallis parameter, as shown in Eq. (1), between model and proto type.

$$j_k^* = \frac{\dot{m}_k}{\rho_k A_{flow}} \left[\frac{\rho_k}{(\rho_f - \rho_g) g D_{gap}} \right]^{1/2} \quad (1)$$

According to this scaling method, the liquid and gas velocities were divided by the square root of the scaled length ratio and the reduced velocities were employed as test conditions. In the prototype reactor, it is assumed that the emergency core coolant (ECC) injected at a 2 m/s liquid velocity through the DVI lines, and the velocity of later steam varied from 15 m/s to 45 m/s [3]. Following the modified linear scaling method, 0.63 m/s of inlet liquid velocity and 5~15 m/s of later air velocity were selected as experimental conditions.

2.2 Local measurement methods for two-dimensional film flow

2.2.1 Ultrasonic thickness gauge for local liquid film thickness measurement

The pulse-echo type ultrasonic thickness gauge was used to measure the liquid film thickness using the round-trip time of an ultrasonic wave. It is following as Eq. (2).

$$\delta_f = \frac{c_f(T)\Delta t}{2} \qquad (2)$$

where δ_f is the liquid film thickness, c_f is sound speed in water, T is the temperature of water, and Δt is the round trip time of an ultrasonic wave.

2.2.2 Depth-averaged PIV method for local liquid film velocity measurement

As shown in Fig. 2, two lasers excited the fluorescent particles in the liquid film and high speed camera took pictures of particles' movement in front of the test section. With the depth-averaged PIV method, it was possible to maintain the light intensity since it is not disturbed by the oscillation on the boundary nor attenuation of laser source because the light does not travel along the liquid film.

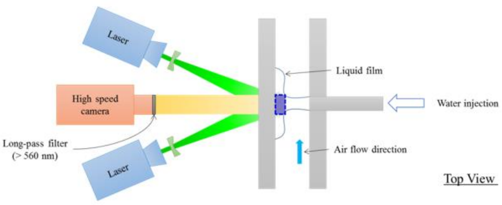
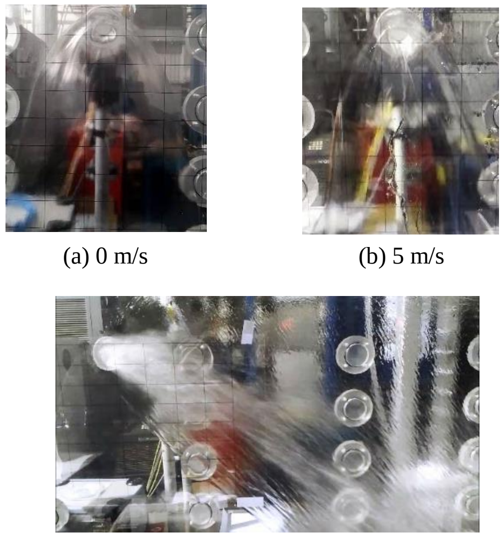


Fig. 2. Depth-averaged PIV method for measurement of liquid film velocity

2.3 Experimental results

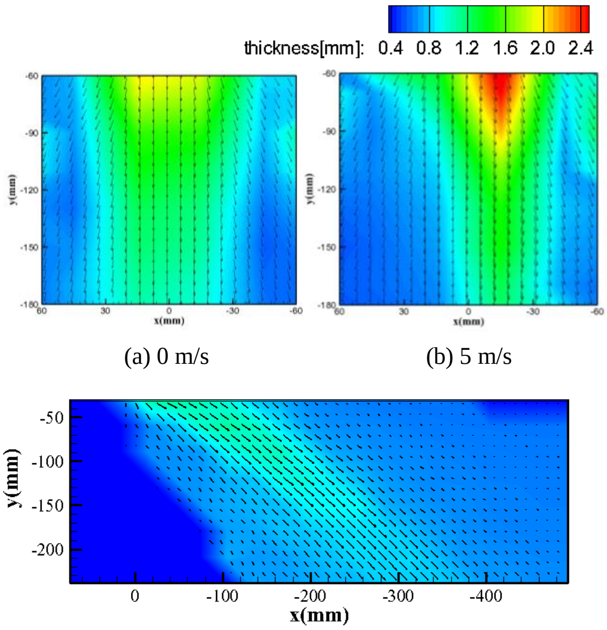
Figure 3 shows the change of the liquid film shape with increase of lateral air velocity. The experiment without air injection was considered as a reference case. The interaction between the falling liquid film and the lateral air induces momentum transfer through the interface. Fig. 4 shows the liquid film velocity and thickness according to the increase of lateral air velocity. The water inlet nozzle was positioned at (0 mm, 0 mm).



(a) 0 m/s (b) 5 m/s

(c) 15 m/s

Fig. 3. Change of liquid film shape with increase of air velocity



(a) 0 m/s (b) 5 m/s

(c) 15 m/s

Fig. 4. Local liquid film velocity and thickness with increase of air velocity

3. Correlation of wall friction

In system analysis codes, the wall friction is determined based on the flow regime. In this study, the flow regime was limited to the annular flow that was formed in the two-phase cross flow experiment. The wall friction model of MARS is based on a two-phase multiplier approach in which the two-phase multiplier is calculated from the Heat Transfer and Fluid Flow Service (H.T.F.S.). This correlation was chosen because it is correlated to empirical data over very broad ranges of phasic volume fractions, phasic flow rates and flow regimes [4]. As shown in Eq. (3), the two-phase pressure drop is defined using two-phase multiplier.

$$\left(\frac{dp}{dx}\right)_{2\phi} = \phi_f^2 \left(\frac{dp}{dx}\right)_f = \phi_g^2 \left(\frac{dp}{dx}\right)_g \tag{3}$$

Yao and Ghiaasiaan (1996) stated that H.T.F.S. correlation underpredicts the film thickness and Wallis correlation predicts the film thickness well in case of annular flow. SPACE accepted their study and chose the Wallis correlation as a wall friction model in annular flow. Equation (4) shows that the form of Wallis correlation using two-phase pressure drop.

$$\left(\frac{dp}{dx}\right)_{2\phi} = \frac{1}{(\alpha_l+\alpha_d)^2} \left(\frac{dp}{dx}\right)_f \tag{4}$$

4. SPACE-3D calculation

4.1 SPACE-3D modeling

The nodalization of the two-dimensional test section and specific geometrical data for SPACE-3D are presented in Fig. 5. The numbers of the volumes consist of the test section are 189 with 21 along the x-direction, and 9 along the y-direction. The water is injected into the volume at (10, 8) which is simulated as an impinging spot. The air is injected into the test section laterally with three different velocities (0 m/s, 5 m/s, 15 m/s).

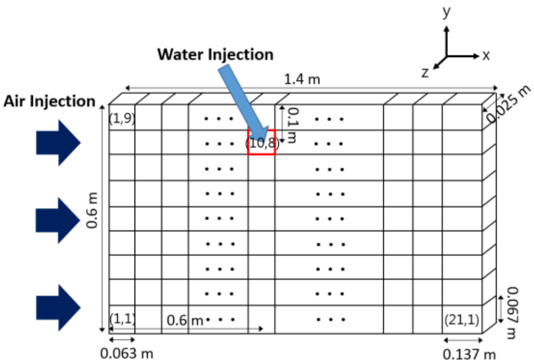
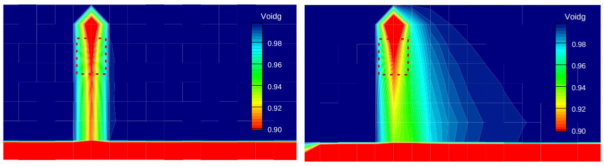


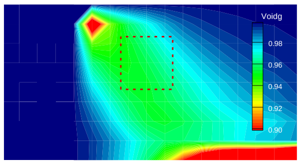
Fig. 5. Nodalization of the test section for SPACE-3D

4.2 Calculation results and analysis

The local variables such as the liquid film velocity and thickness could be obtained from SPACE-3D calculation. The contour graph of the void fraction which represents the liquid film thickness is shown in Fig. 6 (Case-1). When there was no lateral air injection, injected water impinged on the wall and fell down in the form of liquid film. According to the increase of air velocity, the amount of liquid film moving toward the outlet side of the test section increased due to the two-phase interfacial effect.



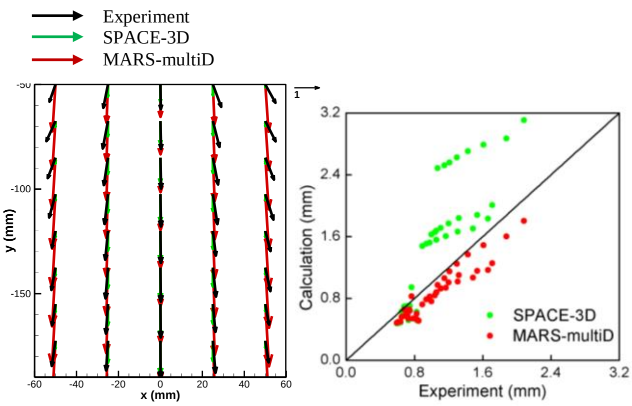
(a) 0 m/s (b) 5 m/s



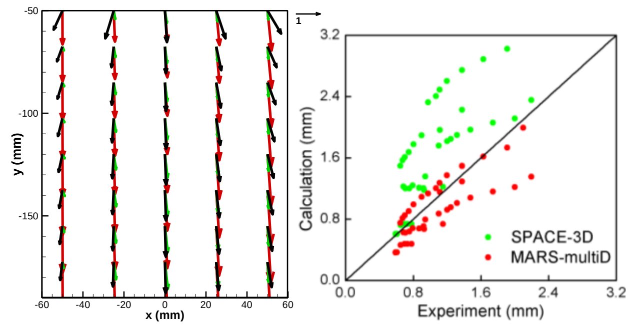
(c) 15 m/s

Fig. 6. Void fraction contour with increase of air velocity (Case-1)

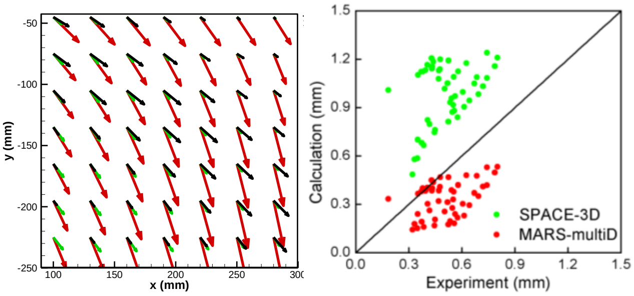
In order to validate the wall friction model of SPACE-3D, the variables such as the liquid film velocity and thickness were obtained from SPACE-3D. These calculated variables were compared with the experimental results and the data from MARS-multiD at the marked region in Fig. 6. As shown in Fig. 7 (Case-2) SPACE-3D tended to underestimate the magnitude of the liquid film velocity and overestimate the liquid film thickness. On the other hand, MARS-multiD tended to overestimate the magnitude of the liquid film velocity and underestimate the liquid film thickness. Consequently, SPACE-3D predicted larger and MARS-multiD predicted smaller wall friction than experimental value. These two different results from codes are related to the friction models they use. H.T.F.S. correlation used in MARS-multiD underestimated the wall friction, and it had already predicted by Yao and Ghiaasiaan (1996). However, Wallis correlation used in SPACE-3D overestimated the wall friction, which does not agree with Yao and Ghiaasiaan.



(a) 0 m/s



(b) 5 m/s



(c) 15 m/s

Fig. 7. Comparison of the liquid film velocity and thickness (Case-2)

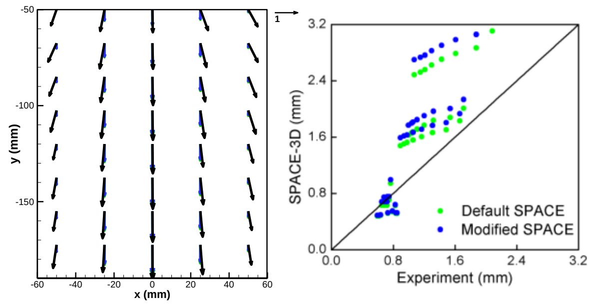
3.3 Modified SPACE-3D calculation

The general form of the equations for wall and interfacial frictions are as follows.

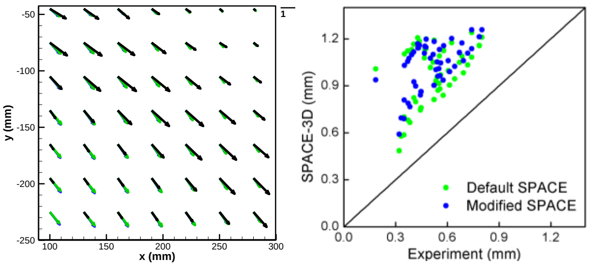
$$\tau_w = \frac{1}{2} f_w \rho_L U_L |\overrightarrow{U_L}| \quad (5)$$

$$\tau_i = \frac{1}{2} f_i \rho_G (U_G - U_L) |(\overrightarrow{U_G} - \overrightarrow{U_L})| \quad (6)$$

In case of 1-D analysis code, it is reasonable to use absolute value of a component of velocity for calculating friction. However, in case of using multi-dimensional module like SPACE-3D, absolute value of velocity vector should be used in the Eqns. (5) and (6). The problem is that the existing SPACE-3D have not considered the velocity vector and calculated the friction as 1-D analysis. To correct this error, KAERI modified the friction terms in SPACE-3D to consider the velocity vector. Then the results from the modified SPACE-3D was shown in Fig. 8 (Case-3). The calculated liquid film velocity of modified SPACE-3D was not much different from that of default SPACE-3D. The liquid film thickness of modified SPACE-3D was slightly thicker than that of default SPACE-3D reflecting the effect of the increasing friction due to modified velocity term. Even though the calculation results did not improved in predicting the local variables, it is not the problem of the modified code, but the problem of the wall friction model in code.



(a) 0 m/s



(b) 15 m/s

Fig. 8. Comparison of the liquid film velocity and thickness (Case-3)

4. Conclusion

In this study, the two-phase cross flow experiment was modeled by SPACE-3D to validate the wall friction model in multi-dimensional module. Compared with the experiment, SPACE-3D underestimated the liquid film velocity and overestimated the liquid film thickness. From these results, it was clarified that the Wallis correlation which is used as a wall friction model in SPACE-3D overestimates the wall friction. On the other hand, H.T.F.S. correlation which is used as the wall friction in MARS-multiD underestimates the wall friction. Therefore, the correlation of the wall friction that predicts the results between that of Wallis and H.T.F.S. should be used in SPACE-3D to agree well with experimental results.

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