Improvement of MARS-MultiD on Analysis of ECC Bypass with Newly-developed Friction Models

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1. Introduction

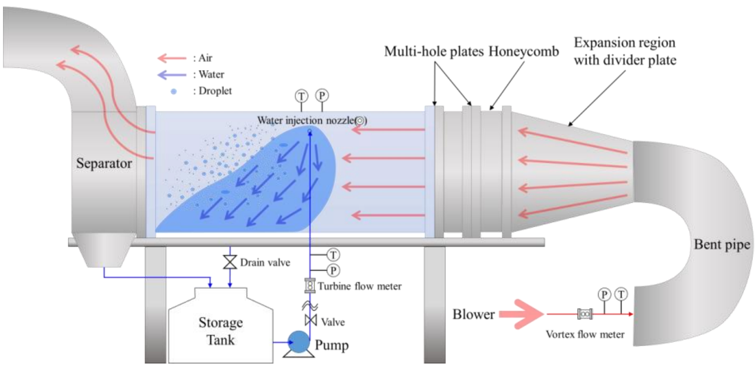
In the upper part of the downcomer, highly convective steam flow exists, and in a direct vessel injection (DVI) system of Advanced Power Reactor 1400 (APR1400) in particular, the emergency core coolant (ECC) interacts with the lateral steam flow during the reflood phase in the large-break LOCA (LBLOCA). Therefore, accurate prediction of this phenomenon is important to evaluate the core cooling capability of the safety injection system. The present study was conducted to validate the constitutive friction models in MARS-MultiD which are used for analysis of ECC bypass and improve the code with newly-developed friction models.

2. Two-dimensional Film Flow Experiments

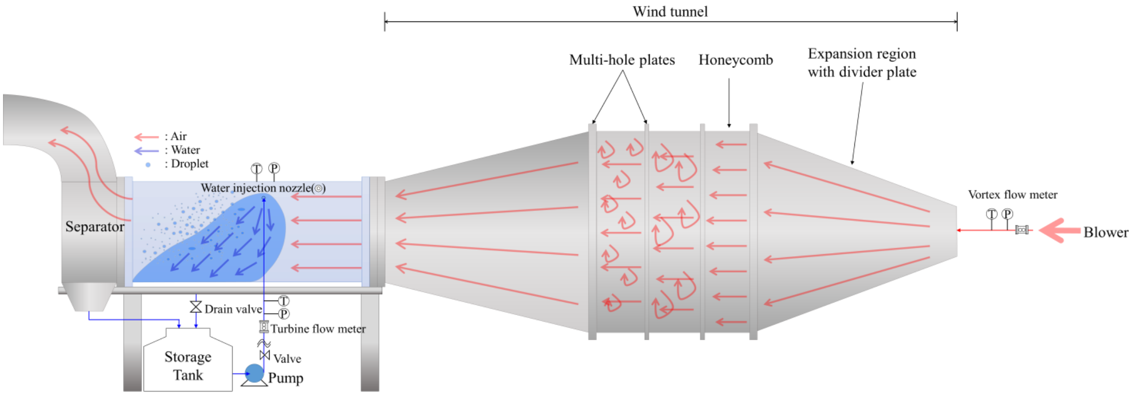
The two-dimensional air-water film flow experiment was described concretely in previous paper [1]. In this paper, the experiment will be touched with brief explanation.

2.1 Features of Experiments

Local measurement experiments for the two-dimensional air-water film flow were designed to produce physical variables; liquid film velocity and thickness. To simulate two-dimensional air-water film flow, duct-shaped acrylic experimental facilities with 1/10 and 1/5 reduced scales were manufactured following the upper downcomer of APR1400. Acrylic test sections were used to measure the local liquid film velocity and thickness of the two-dimensional film flow. The tests selected the air and water as working fluids, and the flow directions were illustrated in Fig. 1. The test matrix was shown in the Table I.



(a) 1/10 scaled test facility



(b) 1/5 scaled test facility

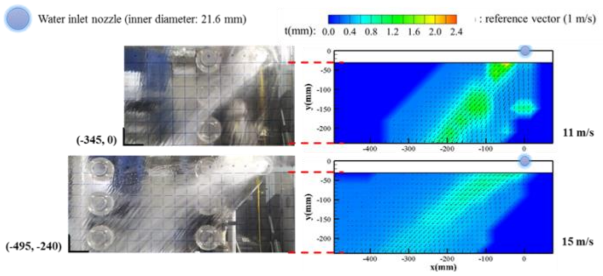
Fig. 1. 1/10 and 1/5 scaled test facility

Table I: Test matrix for scaling effect test

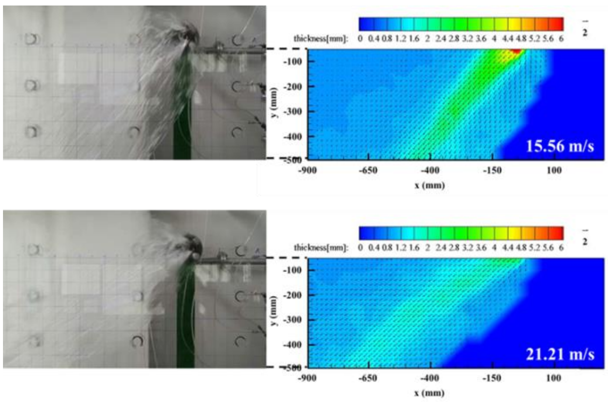
	Nozzle (m)	Water (m/s)	Lateral air (m/s)		
Real	0.216	2	15 ~ 45		
1/10 test	0.022	0.63	7	11	15
1/5 test	0.043	0.89	9.90	15.56	21.21

2.2 Experimental Results

Figure 2 presents the local liquid film velocity and thickness results in 1/10 and 1/5 scales tests. In the graph, the vectors indicate the liquid film velocity, and the gradation of the contours indicates the thickness distribution.



(a) 1/10 scaled test



(b) 1/5 scaled test

Fig. 2. Local liquid film velocity and thickness

2.3 Criteria for Onset of Entrainment

The entrainment is a significant phenomenon to characterize the interfacial conditions. Therefore, several previous studies were carried out to define the criteria of 'onset of entrainment'. Recently, Berna [2] proposed the general concept which is that the 'onset of entrainment' is defined by threshold values of air velocity and Re_f. In this study, the general concept of 'onset of entrainment' was applied to define the criteria.

First of all, the local phenomena with forces acting on the interface should be considered. When the falling liquid film interacts with lateral air flow, the 'onset of entrainment' can be defined by local forces, such as, interfacial shear stress, inertia force and viscous force in the liquid film, surface tension, and gravity force according to Rayleigh-Taylor instability due to density oscillation. The effect of interfacial shear stress can be expressed as dimensionless superficial velocity of lateral air. The force balance between gravity force and surface tension can be characterized as *Bo* number. The Re_f was used as representative dimensionless number as to the inertia force and the viscous force in the liquid film. The dimensionless superficial velocity of lateral air (j_g^*), *Bo* and Re_f numbers were used to define the onset of entrainment. As shown in the Fig. 6, when the x-axis is the ratio between Re_f and *Bo* and y-axis is j_g^*, the criteria of 'onset of entrainment' can be expressed with newly proposed dimensionless number, *En* (Eq. (1)). The *En* is defined as multiplier of the ratio between Re_f and *Bo* and j_g^*.

$$En \equiv \frac{Re_f}{Bo} j_g^* \qquad (1)$$

where, $Re_f = \frac{(1-\alpha)\rho_f V_f D_h}{\mu_f}$,

$$Bo = \frac{(\rho_f - \rho_g) g D_h^2}{\sigma},$$

$$j_g^* = \frac{\dot{m}_g}{\rho_g A_{flow}} \left[\frac{\rho_g}{(\rho_f - \rho_g) g D_{gap}} \right]^{1/2}.$$

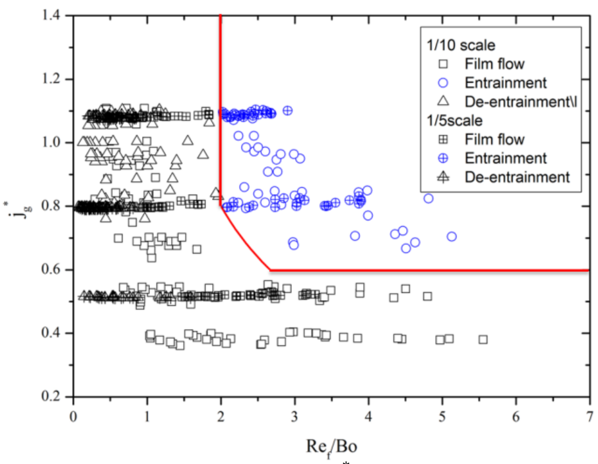


Fig. 3. Onset of entrainment with j_g^*, *Bo* and Re_f

3. Development of Wall and Interfacial Friction Models

With some physical assumptions, the local measurement results, averaged liquid film velocity and thickness, could be used to produce local physical parameters; wall and interfacial friction factors.

3.1 Physical assumptions

The physical assumptions are as follows.

1) Magnitudes of pressure difference of two fluids are almost same in the same direction.
2) Wall and interfacial friction factors are calculated with the averaged velocities of air and liquid film in the depth direction.
3) Wall and interfacial friction factors are independent of flow directions and maintained as constants.

With local experimental data from two-dimensional film flow, the wall and interfacial friction factors could be calculated by momentum conservation equations.

3.2 Wall Friction Models

Following the reference of Yao and Ghiaasiaan [3], they proposed Wallis' two-phase multiplier correlation [4]. If the Wallis' two-phase multiplier correlation was applied, the wall friction factors must be same with calculation results by single-phase wall friction factor models. As shown in the Fig 8, the wall friction factors with Wallis' correlation show better agreement with experimental results. However, the wall friction factors tend to be larger when the liquid film is thin enough about liquid fraction under 5%.

As shown in the Fig 4, when the low Re_f number was less than 2200, the wall friction factors were underestimated than experimental results. In order to resolve the problem, the empirical correlation which was the best fit function from wall friction factors by experimental results in the laminar flow range (Re_f < 2200) was proposed as follows.

$$\Phi_f^2 = \frac{1}{(1-\alpha)^2}\left(\frac{128}{\mathrm{Re}_f} + 4 + 0.008\,\mathrm{Re}_f\right) \qquad \mathrm{Re}_f < 2200$$
$$= \frac{1}{(1-\alpha)^2} \qquad \mathrm{Re}_f > 3000 \qquad (2)$$

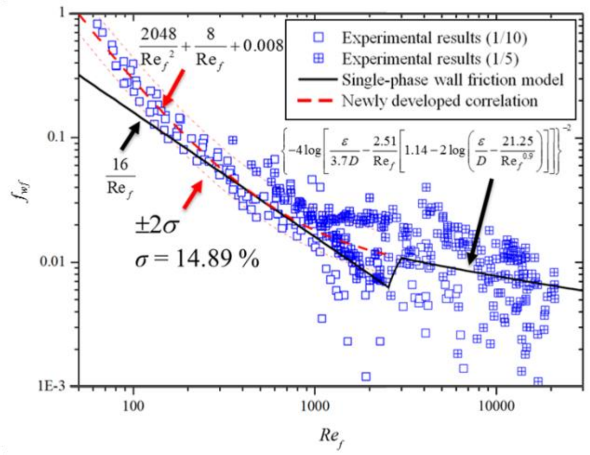


Fig. 4. Wall friction factors and new wall friction model

3.3 Interfacial Friction Models

Several models and correlation as to the interfacial friction factor, f_i, have been proposed, since it is one of the most important parameters to characterize two-phase flow. The previous studies were conducted in fully-developed flow conditions. And the interfacial friction factors were calculated by boundary variables. However, in this study, the flow condition was not fully-developed and the interfacial friction factors were calculated by local measured data. Therefore, the local measured data contain more specific information according to local phenomena, so the interfacial friction factor model should be developed to consider local phenomenon, especially 'onset of entrainment'.

Before the entrainment occurs in film flow, a mechanistic interfacial friction model was developed with the concept of roughness of thin film which was proposed by R.Kumar [5] as described in Eq (3). Though they could not define the modeling constant and intercept of y-axis, these were defined by experimental results in this study. The intercept of y-axis mean when the liquid film is vanished in the duct, the friction factor between single-phase gas and wall converges to 0.005. This mechanistic model has a limitation since it doesn't consider the entrained droplets in deriving the dimensionless velocity profile in a duct. If the roughness effect in the Eq. (3) was defined with liquid fraction and entrainment number, the interfacial friction factor model can be expressed as:

$$f_i = \frac{1}{4}\left[1.879 - 49.12\frac{h}{D_h}En\right]^{-2} - 0.0658 \qquad (3)$$

The roughness effect (k_s/t) is a multiplication between one-fourth of liquid fraction (h/D_h) and entrainment number (En).

$$\frac{k_s}{t} \approx \frac{h}{D_h}En \ \text{ and } \ En \equiv \frac{\mathrm{Re}_f}{Bo}j_g^* \qquad (4)$$

And an empirical correlation was proposed in the film flow with entrainment condition. Finally, the interfacial friction model for two-dimensional film flow was developed as follows.

$$f_i = \frac{1}{4}\left[1.879 - 49.12\left(\frac{h}{D_h}En\right)\right]^{-2} \text{-0.0658}$$
$$\left(En < 1.6,\ \ \frac{\mathrm{Re}_f}{Bo} < 2,\ \text{ and }\ j_g^* < 0.6\right) \qquad (5)$$
$$= 0.797\left(\frac{h}{D_h}En\right)^{0.618}$$
$$\left(En \geq 1.6,\ \ \frac{\mathrm{Re}_f}{Bo} \geq 2,\ \text{ and }\ j_g^* \geq 0.6\right)$$

As illustrated in Fig. 5, the newly developed interfacial friction model by interfacial friction factors from the experimental results of two-dimensional film flow is valid in case with $\frac{h}{D_h}En < 0.055$.

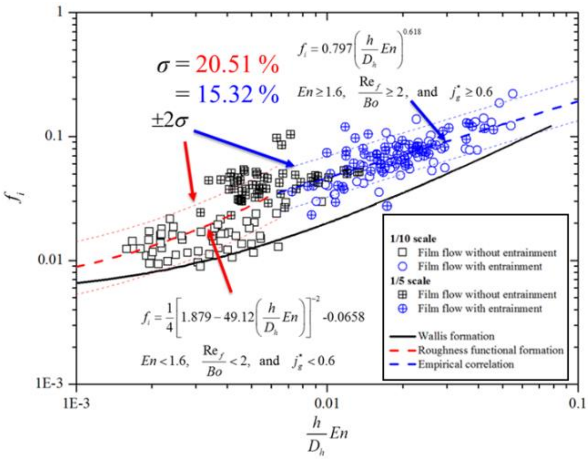


Fig. 5. New interfacial friction model with *En*

4. Validation of Modified MARS-MultiD

The Multi-dimensional Investigation in the Downcomer Annular Simulation (MIDAS) is a steam-water test facility, which was 1/5 scaled down from APR 1400 MWe PWR [6].

4.1 Features of Experiment

It was mainly focused on the investigation of the multi-dimensional thermal-hydraulic phenomena in the downcomer annulus during the reflood phase of a postulated LBLOCA. The geometrical scaling ratio is 1/4.93 relative to the APR-1400. The MIDAS experiment was unique separate effect test which used steam-water as working fluids in the annulus geometry for simulation ECC bypass in the upper downcomer. The direct ECC bypass tests were carried out in cases of DVI-4 (the nearest to the broken cold leg) injection, DVI-2 (the farthest from the broken cold leg) injection, and DVI-2&4 injection, respectively.

4.2 Comparison Results

The different results of previous and modified MARS-MultiD can be confirmed in Fig. 6. The modified wall friction model makes thicker and broader distribution of liquid fraction. DVI-4 (the nearest to the broken cold leg) injection tests show that the direct bypass fraction increases drastically as the steam flow rate increases. The modified MARS-MultiD produces more realistic results because the point of increase delayed to experimental one. Since the increased wall shear stress hold the liquid film against interfacial shear stress by circumferential vapor flow, the onset point of bypass was delayed. In DVI-2 test, most of the injected ECC water penetrates into lower downcomer with previous MARS-MultiD. However, the modified MARS-MultiD yielded more realistic result. These characteristic in each of DVI-2 and DVI-4 tests is reflected into the DVI-2&4 tests. It was also improved with modified MARS-MultiD.

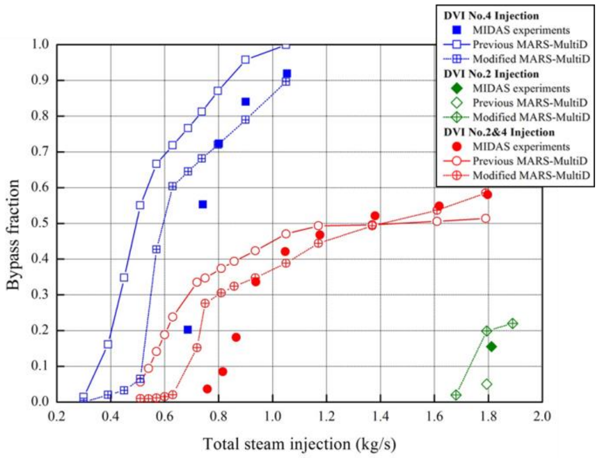


Fig. 6. Comparison results of bypass fraction

5. Conclusions

This study presents investigation results as to the two-dimensional film flow phenomena of simulated two-phase cross flow in the downcomer. The local experimental data were used to characterize the flow pattern on the interface of liquid film, and the 'onset of entrainment' can be expressed with newly proposed non-dimensional number, *En*. And the experimental results were used to develop wall and interfacial friction models. The MARS-MultiD was modified with newly developed wall and interfacial friction models. Also the modified MARS-MultiD was validated with MIDAS experiments

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