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Two-dimensional Modeling of a Direct ECC Bypass in the APR1400 Downcomer

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1. Introduction

In a nuclear reactor vessel downcomer incorporating the safety feature of a direct vessel injection (DVI), the direct bypass of an emergency core coolant (ECC) occurs during the reflood phase of a large-break loss-of-coolant accident (LBLOCA) due to a momentum transfer between the downward liquid film and transverse gas. Direct ECC bypass is reportedly the major bypass mechanism of an ECC, and various experiments have been performed to obtain detailed information about the ECC bypass in a DVI downcomer. In the present study, an analytical model for a direct ECC bypass was developed from two-dimensional governing equations for predicting the ECC bypass fraction. The effect of a steam condensation was not considered in the present study hence the gas-liquid interaction in an adiabatic condition was examined. Moreover, the effect of the entrainment from the downcomer water surface was excluded for a simple direct ECC bypass modeling.

The present model was evaluated by comparing its results with the experimental data obtained from the 1/7- and 1/5-scale models of the APR1400 downcomer. The calculations were performed for various correlations of the interfacial friction factor, which is the most crucial factor of the present modeling.

2. Governing Equations

The control volume of a two-dimensional film flow in a downcomer annulus is indicated in Fig. 1, which includes the forces acting on each phase. The following assumptions were made in the present analysis:
(1) The radial velocities of the gas and liquid are neglected.
(2) The lateral gas flow is assumed to be dominant during the direct ECC bypass.
(3) The liquid velocity perpendicular to a cross section of the control volume is assumed to be uniform.
(4) The effects of a curvature are neglected.
(5) The pressure is the same in the liquid and gas phases at any particular location.
(6) The thickness of the liquid film is the same on the inner and outer walls.
(7) The droplet entrainment from the liquid film is neglected.

In the control volume, the x-directional force balances of each phase are as follows: for the gas flow

$$-(P_2-P_1)_x \cdot D_2 H - 2\int_A \tau_{i,x} dA = 0 \qquad (1)$$

and for the liquid flow

$$\begin{aligned}&-(P_2-P_1)_x \cdot 2D_1 H + 2\int_A \tau_{i,x} dA - 2\int_A \tau_{wf,x} dA \\ &= \rho_f u_{f2}^2 2D_1 H + \rho_f(\upsilon_{f2}-\upsilon_{f1}) 2D_1 \int_0^W u_f dx\end{aligned} \qquad (2)$$

From these equations, the pressure-loss term can be eliminated by assumption (5):

$$\frac{2\int_A \tau_{wf,x} dA}{(1-\alpha)} - \frac{2\int_A \tau_{i,x} dA}{\alpha(1-\alpha)} = -\rho_f u_{f2}^2 DH - \rho_f(\upsilon_{f2}-\upsilon_{f1}) D\int_0^W u_f dx \qquad (3)$$

Similarly, the y-directional force balances of each phase can be expressed as

$$\begin{aligned}&\frac{2\int_A \tau_{wf,y} dA}{(1-\alpha)} + \frac{2\int_A \tau_{i,y} dA}{\alpha(1-\alpha)} - (\rho_f-\rho_g) gDWH \\ &= \rho_f(\upsilon_{f2}^2-\upsilon_{f1}^2) DW + \rho_f u_{f2} D\int_0^H \upsilon_f dy\end{aligned} \qquad (4)$$

For the wall and interfacial shear stresses we introduce the following constitutive relations:

$$\int_A \tau_{wf,m} dA = \int_0^H \int_0^W \frac{1}{2}\rho_f f_{wf} u_{f,m} \sqrt{u_f^2+\upsilon_f^2}\, dxdy \qquad (5)$$

$$\int_A \tau_{i,m} dA = \int_0^H \int_0^W \frac{1}{2}\rho_g f_i (u_{g,m}-u_{f,m}) \sqrt{(u_g-u_f)^2+\upsilon_f{}^2}\, dxdy \qquad (6)$$

where m is direction (x or y).

By substituting the wall and interfacial shear stress terms into Eqs. (3) and (4) and dividing all the terms by the gravitational term in Eq. (4), the Wallis parameters of each phase are derived as nondimensional variables of the gas and liquid velocity:

$$j_{km}^* = \alpha_k u_{km}\left[\frac{\rho_k}{(\rho_f-\rho_g)\cdot g\cdot D}\right]^{1/2} = \frac{\dot m_{km}}{\rho_k A_m}\left[\frac{\rho_k}{(\rho_f-\rho_g)\cdot g\cdot D}\right]^{1/2} \qquad (7)$$

where k is the phase (f or g).

The nondimensional equations of the film flow in a downcomer annulus are written as

$$\begin{aligned}&-\frac{\left(j_{fx,2}^*\right)^2}{(1-\alpha)^2}\frac{D}{W} - \frac{j_{fx,2}^*(j_{fy,2}^*-j_{fy,1}^*)}{2(1-\alpha)^2}\frac{D}{H} \\ &= \int_0^1\int_0^1 f_{wf}\left[\frac{j_{fx,2}^* x^*}{(1-\alpha)^2}\right]\sqrt{\left[\frac{j_{fx,2}^* x^*}{(1-\alpha)}\right]^2 + \left[\frac{j_{fy,2}^*}{(1-\alpha)} + \frac{j_{fx,2}^* y^*}{(1-\alpha)}\left(\frac{H}{W}\right)\right]^2}\, dx^* dy^* \\ &-\int_0^1\int_0^1 \frac{f_i\left[\frac{j_{gx}^*}{\alpha^2(1-\alpha)} - \frac{j_{fx,2}^* x^*}{\alpha(1-\alpha)^2}\sqrt{\frac{\rho_g}{\rho_f}}\right]}{\sqrt{\left[\frac{j_{gx}^*}{\alpha} - \frac{j_{fx,2}^* x^*}{(1-\alpha)}\sqrt{\frac{\rho_g}{\rho_f}}\right]^2 + \frac{\rho_g}{\rho_f}\left[\frac{j_{fy,2}^*}{(1-\alpha)} + \frac{j_{fx,2}^* y^*}{(1-\alpha)}\left(\frac{H}{W}\right)\right]^2}}\, dx^* dy^*\end{aligned} \qquad (8)$$

$$\begin{aligned}&\frac{\left(j_{fy,2}^*\right)^2 - \left(j_{fy,1}^*\right)^2}{(1-\alpha)^2}\frac{D}{H} + \frac{j_{fx,2}^*\left(j_{fy,1}^*+j_{fy,2}^*\right)}{2(1-\alpha)^2}\frac{D}{W} + 1 \\ &= \int_0^1\int_0^1 f_{wf}\left[\frac{j_{fy,2}^*}{(1-\alpha)^2} + \frac{j_{fx,2}^* y^*}{(1-\alpha)^2}\left(\frac{H}{W}\right)\right]\sqrt{\left[\frac{j_{fx,2}^* x^*}{(1-\alpha)}\right]^2 + \left[\frac{j_{fy,2}^*}{(1-\alpha)} + \frac{j_{fx,2}^* y^*}{(1-\alpha)}\left(\frac{H}{W}\right)\right]^2}\, dx^* dy^* \\ &+\int_0^1\int_0^1 \frac{f_i\left(\sqrt{\frac{\rho_g}{\rho_f}}\right)\left[\frac{j_{fy,2}^*}{\alpha(1-\alpha)^2} + \frac{j_{fx,2}^* y^*}{\alpha(1-\alpha)^2}\left(\frac{H}{W}\right)\right]}{\sqrt{\left[\frac{j_{gx}^*}{\alpha} - \frac{j_{fx,2}^* x^*}{(1-\alpha)}\sqrt{\frac{\rho_g}{\rho_f}}\right]^2 + \frac{\rho_g}{\rho_f}\left[\frac{j_{fy,2}^*}{(1-\alpha)} + \frac{j_{fx,2}^* y^*}{(1-\alpha)}\left(\frac{H}{W}\right)\right]^2}}\, dx^* dy^*\end{aligned} \qquad (9)$$

Dimensionless mass conservation of a liquid phase is given by

$$j_{fy,1}^{*} = j_{fy,2}^{*} + j_{fx,2}^{*}\left(\frac{H}{W}\right) \tag{10}$$

If the values of the width (W) and height (H) of the control volume, the dimensionless gas superficial velocity (j_{gx}^{*}), the dimensionless liquid superficial velocity at the inlet of the liquid ($j_{fy,1}^{*}$), and the constitutive relations regarding the wall and interfacial friction factors are given, we can numerically obtain three solutions of Eqs. (8), (9), and (10): the void fraction (α), and the dimensionless superficial liquid velocities at the transverse outlet ($j_{fx,2}^{*}$) and the bottom outlet ($j_{fy,2}^{*}$). Detailed procedures to obtain the input values (W, H, j_{gx}^{*} and $j_{fy,1}^{*}$) and the constitutive relations (f_i and f_w) are described in reference [1].

3. Calculation Results

The interfacial friction factor correlations derived in an upward cocurrent annular flow were first applied to the present model. Fig. 2 shows the calculation results with the Wallis correlation [2], which is the most frequently used in the analyses of a film or annular flow. The figure shows that our results are in good agreement with the corresponding experimental results under low-bypass-fraction conditions (<25%), whereas it underpredicted the fraction at high gas flow rates. Secondly, the interfacial friction factor correlation of Bharathan and Wallis [3], which was developed under vertical countercurrent annular flow conditions, was applied to the current model and the result is shown in Fig. 3. The calculated values correspond well with the experimental data when the bypass fraction is larger than 40%. The Bharathan and Wallis correlation, however, resulted in a considerable overprediction under the low-bypass-fraction condition. This result suggests the presence of a transition point in the liquid film from a tough film to a smooth film, and this transition should be considered when implementing interfacial friction factor models. The criterion of the transition from a smooth to an agitated film remains unclear, and hence it is necessary to investigate the behavior of a liquid film in a cross flow condition to understand its transition mechanism.

4. Conclusion

In the present study, a new analytical model for a direct ECC bypass was developed from two-dimensional two-phase momentum equations. The ECC bypass fraction was calculated with different interfacial friction factor correlations, and the results were compared with the corresponding experimental data. The results predicted with the current model agreed well with the experimental data at high-bypass-fraction conditions when the interfacial friction factor model developed in a countercurrent flow was incorporated into the model. At a low-bypass-fraction condition, however, the interfacial friction factor models that were derived for cocurrent upward or downward annular flows provided better results than those derived for countercurrent flows.

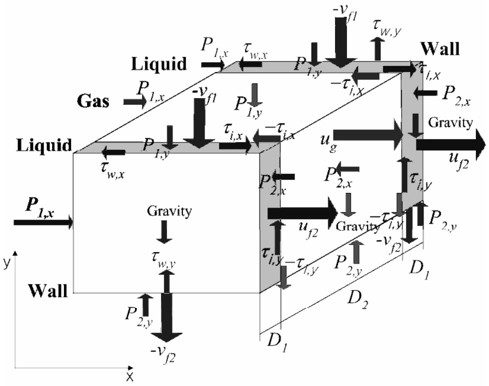

Fig.1 Control Volume

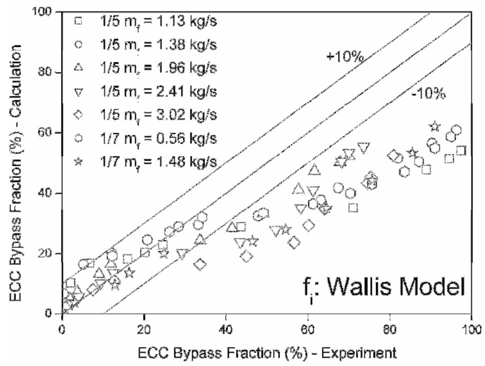

Fig.2 Calculation Result (Wallis model)

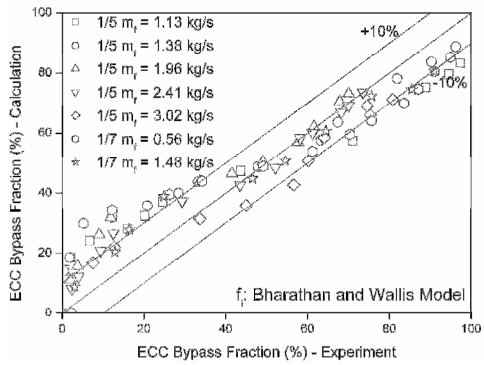

Fig.3 Calculation Result (Bharhthan and Wallis model)

References

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