Drag Models for Annular Flow in SPACE Code

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1. Introduction

SPACE code is a system code for predicting the thermal-hydraulic behaviors of PWR nuclear power plants. Recently, drag models in annular flow have been improved. The present study describes the drag models in annular flow and shows their validation results.

2. Drag models

2.1 Wall drag

In SPACE code, the H.T.F.S correlation (Claxton et al. 1972) had been used to calculate wall drags for all flow regimes. Through various validation tests, however we found that this model underpredicts relatively wall drag in annular flow. Hence, the H.T.F.S correlation has been replaced by the Wallis (1969) correlation according to Yao and Ghiaasiaan (1996).

$$\left(\frac{dp}{dx}\right)_{2\phi,annular} = \phi_l^2\left[\frac{2 f_l' |G_l| G_l}{D_h \rho_l}\right] \tag{1}$$

$$\phi_l^2 = \frac{1}{\alpha_l^2} \tag{2}$$

Here, f'_l is the Fanning friction factor based on the liquid film Reynolds number.

The transition to single-phase gas flow is handled by considering the breakdown of the liquid film into rivulets. Film breakdown is assumed to occur when the film thickness becomes less than a critical value given by Mikielewicz and Moszynskl (1976).

$$\delta_{\min} = 0.35\left(\frac{15\sigma\mu_l^2}{g^2\rho_l^3}\right)^{1/5} \tag{3}$$

The fraction of wall surface in contact with the liquid phase is assumed by

$$f_{\text{wet}} = \min\left[1.0, \left(\frac{D_h \alpha_l}{4\delta_{\min}}\right)^{1/4}\right]. \tag{4}$$

The final pressure drop in annular flow is calculated as follows:

$$\left(\frac{dp}{dx}\right)_{2\phi} = \left(\frac{dp}{dx}\right)_{2\phi,annular} f_{\text{wet}} + \left(\frac{dp}{dx}\right)_{1\phi,gas}(1 - f_{\text{wet}}) \tag{5}$$

The subscript 1φ,gas represents the single-phase gas flow.

2.2 Interfacial drag

Different correlations are used in accordance with the flow direction and the gas Reynolds number. Asali et al. (1985) proposed implicit correlations based on air-liquid experiments in pipes with 2.29cm and 4.2cm diameters. The liquid was a mixture of water and glycerin. The correlation corresponding to the roll wave regime in Asali et al. (1985) is used for turbulent flow.

$$F_{igl} = \frac{1}{2}\rho_g f_i a_{igl} |v_g - v_l|(v_g - v_l) \tag{6}$$

$$f_i = \begin{cases} f_s & , \mathrm{Re_g} < 1500 \\ \text{Linear interpolation} & , 1500 \le \mathrm{Re_g} < 2300 \\ f_t & , 2300 \le \mathrm{Re_g} \end{cases} \tag{7}$$

$$\begin{aligned} f_t &= f_s\left(1 + 0.45\mathrm{Re}_g^{-0.2}\max[0.0, m_g^+ - 4.0]\right), \text{upflow/hoizontal annular} \\ &= f_s\left(1 + 0.45\mathrm{Re}_g^{-0.2}\max[0.0, m_g^+ - 5.9]\right), \text{other annular} \end{aligned} \tag{8}$$

$$\mathrm{Re}_g = \max\left[50, \frac{\alpha_g \rho_g |v_g - v_l| D_h}{\mu_g}\right] \tag{9}$$

$$m_g^+ = 0.19\left(\frac{\alpha_l \rho_l \max[10^{-9}, |v_l|] D_h}{\mu_l}\right)^{0.7} \frac{\mu_l}{\mu_g}\sqrt{\frac{\rho_g}{\rho_l}} \tag{10}$$

$$a_{igl} = f_{wet}\frac{4\sqrt{1-\alpha_l}}{D_h} \tag{11}$$

Here, f_s is the gas Fanning friction factor for a smooth channel. m_g^+ is computed based on the assumption that the interfacial shear stress is equal to the wall shear stress owing to high gas velocity, which makes it possible to use the correlation explicitly. Detailed description can be found in Kim et al. (2011).

3. Validation

4.1 Falling liquid film test

Liquid film data is used to verify wall drag in annular flow. Initially, the vertical pipe is filled with air. Water is injected from the side into the pipe. The water flows down the pipe, forming a liquid film. The film will reach a constant velocity after a certain distance. The liquid film thickness at cell 2 is compared with the experimental data (USNRC 2007). As shown in Fig. 2,

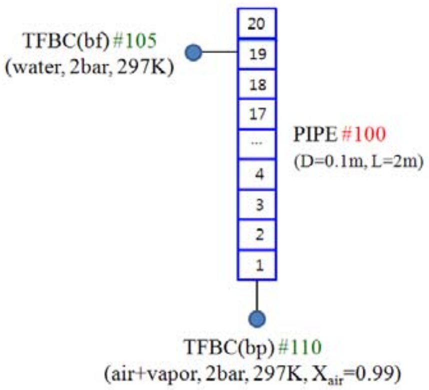

Fig. 1. Nodding diagram for falling liquid film tests

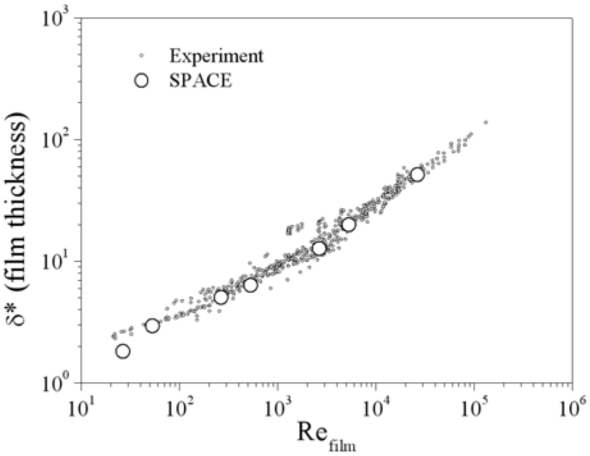

Fig. 2. Comparison between the predictions and the experimental data

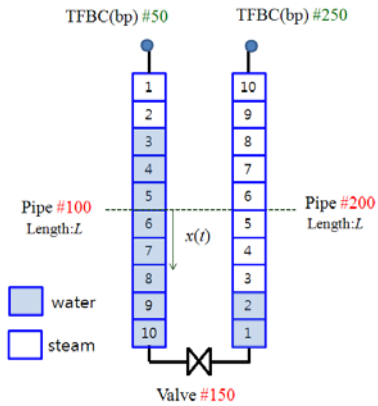

Fig. 3. Nodding diagram for oscillating manometers

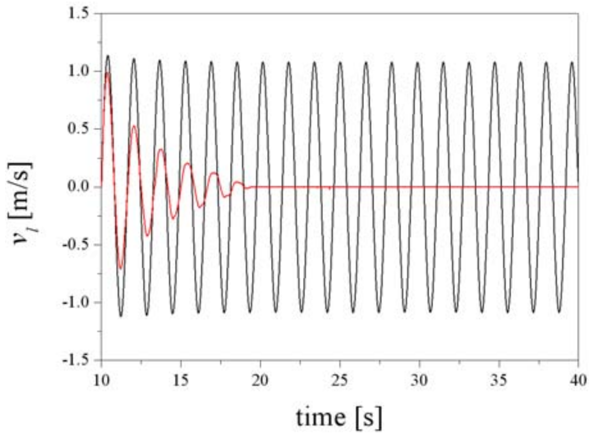

Fig. 4. Liquid velocities of case 1 (without wall drag: black line) and case 2 (with wall drag: red line)

on the whole, the predictions are in fairly good agreements with the experimental data. The film thickness is under-estimated for a low Reynolds number since the Reynolds number is limited to have a value greater than 50 when calculating wall drags in SPACE code.

4.2 Oscillating manometer test

Oscillating manometers are a good candidate to test the interfacial drag since cells undergo every flow direction as well as every normal flow regime. In particular, to our experience, oscillating manometers are greatly affected by interfacial drag in annular flow. Figure 3 shows the initial stage. The channel area is $A=0.0002m^2$, the channel height is L=1.0m. Once the valve is opened at 10s, water starts to show an oscillation motion due to gravity. The system pressure is 100bar, water is 1K sub-cooled, and steam is 1K super-heated. Interfacial heat transfer is turned off in the present simulation. As shown in Fig. 4, liquid velocities are physically correct for both cases.

4. Conclusion

Drag models in annular flow have been improved. Two test problems showed quiet good predictions.

Acknowledgments

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