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Interfacial Drag Laws and Drift-Flux Model Used in Nuclear Reactor System Analysis Codes

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1. Introduction

One of the collective works done at KAERI for the development of a best-estimate reactor system safety analysis code is summarized in this paper. Different interfacial drag laws and the drift-flux model[1] described in the literatures cited in four reactor system analysis code manuals, RELPA5-3D, TRAC-M, COBRA-TF and CATHARE, have been reviewed. One of the major results is that the interfacial drag laws can be consistently used for different two-phase flow regimes and flow orientations while the drift-flux model has its inherent limitation when applying it to horizontal flows. It should be noted, however, that the drift-flux model is known to be abundantly accurate[2] for vertical flows.

2. Interfacial Drag Laws

The interfacial drag laws can be categorized into for two different flow geometries[3,4] which are for the dispersed flows (bubbly, droplet) and for the separate flows (annular, stratified). For the separated flows, the phasic interface can be simply defined and the average velocities can be consistently related with those used in the drag law development, that is, the wall-friction type. In this case, the interfacial drag is a unique momentum source for the adiabatic two-phase flow. The interfacial momentum sources, such as the interfacial pressure effect and the two-phase virtual mass force can be safely neglected, except for the horizontally stratified flow.

On the other hand, for the dispersed flows, the average interfacial force cannot be directly related with the single isolated particle drag law. To clarify this concern, we may need to write the steady-state averaged momentum equation as follows:

$$\begin{aligned} 0 &= -\nabla(\alpha p^X) + \nabla \bullet [\alpha(\boldsymbol{\tau}^X + \boldsymbol{\tau}^{Re})] + \mathbf{M}_i \\ &\quad + \alpha\rho^X \mathbf{g} + \mathbf{M}^w \end{aligned}, \qquad (1)$$

for each phase where $\mathbf{M}_i$ is the interfacial force within which the so-called interfacial drag is embedded. By definition, the interfacial force is induced by the pressure distribution and the interfacial shear stress (normal and tangential to the interface) around each phase. In general, the interfacial drag does not reflect all of these effects. It should be noted that one of significant ideas of taking into account this effect is to model the phasic *interfacial pressure difference* for the dispersed two-phase flow.

Due to this reason, unrealistic simulations of phasic slip for the dispersed two-phase flows may be experienced, especially for the horizontal flows where the net gravity vanishes. In this case, the phasic slip is controlled by the average interfacial shear (the viscous effect) and the interfacial pressure difference (the inviscid effect). Among all of the system safety analysis codes reviewed in this study, none has the interfacial pressure difference or a similar model.

It should be noted that all of the interfacial drag models shown in Table 1 have been developed for an infinite pool of liquid or a straight pipe.

3. Drift-Flux Model

In RELAP5-3D and CHATARE codes, the drift-flux model is extensively used for the dispersed two-phase flows as shown in Table 1. To incorporate the drift-flux model into the framework of the averaged two-fluid model, the phasic momentum balance needed to be reconsidered. In other words, the difference momentum equation should be satisfied in terms of the drift-flux parameters. Putney[5] provided a theoretical foundation of this for RELAP5-3D where the net gravity force and the wall friction forces were assumed to be balanced with the forces formulated by the drift-flux model.

To clarify this assumption, let us write the difference momentum equation:

$$\begin{aligned} &\mathbf{M}_{ig} + \alpha_l \nabla \bullet [\alpha_g \boldsymbol{\tau}_g{}^X] - \alpha_g \nabla \bullet [\alpha_l \boldsymbol{\tau}_l{}^X] \\ &\quad = \alpha_l \alpha_g \Delta\rho^X \mathbf{g} - \alpha_l \mathbf{M}_g^w + \alpha_g \mathbf{M}_l^w \end{aligned}, \qquad (2)$$

where the two-phase Reynolds stress and the difference between phasic pressures are neglected.

The first terms of each side of Eq.(2) are assumed to be separately balanced, and the rest of terms on each side be balanced. Therefore, in RELAP5-3D, the drag in terms of the drift-flux parameter is given by

$$\mathbf{f}_{gl} = \frac{\alpha_g \alpha_l^3 \Delta\rho^X \mathbf{g}}{V_{gj}|V_{gj}|} \qquad (3)$$

This assumption may be valid for the vertical flows where the local slip can be dominantly induced by the net gravity force whereas the profile slip by the wall friction and the shear. However, the momentum error due to this assumption can be increased for the inclined flows where the profile slip can be a mixed effect of the wall friction and the interfacial force. It should be noted that the mixture flow velocity may also affect the validity of this assumption.

Different drift-flux correlations[6,7,8] have been validated for RELAP5-3D codes in many flow geometries, for example, the pool swell level can be very accurately predicted by the EPRI correlation[8] under high system pressure conditions (> 20 bars).

3. Conclusion

This work may help to establish the theoretical validity and limitations of interfacial drag models. The interfacial drag models being used in the nuclear reactor system analysis codes are found to be quite uniform. All of them may be used within the tolerance of the state-of-the-art two-phase flow technology if used with proper limitations. Finally, it may need further effort to cast the drift-flux model into an average two-fluid model for a wider range of flow orientations.

Table 1. Interfacial Drag Models Used in Nuclear Reactor System Analysis Codes

	RELAP5-3D	TRAC-M	COBRA-TF	CATHARE
Bubbly	$C_D = \frac{24(1+0.1Re_p^{0.75})}{Re_p}$ Drift-flux	$C_D = \begin{cases} 240.0 & Re_b < 0.1031 \\ \frac{24.0}{Re_b}(1.0+0.15Re_b^{0.687}) & 0.1031 < Re_b < 989 \\ 0.44 & Re_b > 989 \end{cases}$	$C_D = \frac{24(1+0.1Re_p^{0.75})}{Re_p}$: spherical $C_{D_b} = \frac{\sqrt{2}}{3} N_\mu Re'_b (1-\alpha_v)^2$: distorted	$\tau_I = \alpha(1-\alpha)\frac{\rho_\mu(1-C_0\alpha)^2}{C_m^2 L_m} \lvert V_G - C_K V_L \rvert (V_G - C_K V_L)$ Drift-flux
Slug	$C_D = 10.9\frac{D'}{D}(1-\alpha_b)^3$:Taylor bubble $C_D = \frac{24(1+0.1Re_p^{0.75})}{Re_p}$: small bubble Drift-flux	Same as above with varying bubble diameter	$C_{D_b} = \frac{8}{3}(1-\alpha_v)^2$: cap $C_{D_b} = 0.45(1-\alpha_v)^2$: lower limit	Drift-flux
Churn	Drift-flux	$c_{itrans} = c_{iam}W_t + C_{ibs}(1-W_t)$ with $W_t = 4\alpha - 2$		Drift-flux
Ann.-mist	$f_i = \frac{64}{Re_i}$ for $Re_i \le 500$ $= \left(\frac{1500-Re_i}{1000}\right)\frac{64}{Re_i} + \left(\frac{Re_i-500}{1000}\right)$ $\times 0.02\{1+150[1-(1-\alpha_{ff})^{1/2}]\}$ for $500 < Re_i < 1500$ $= 0.02\{1+150[1-(1-\alpha_{ff})^{1/2}]\}$	$f_i = 0.005[1+75(1-\alpha)]$	Max of $f_i = f_s$ $\{1+1400F$ $\times\left[1-\exp\left(-\frac{1}{G}\frac{(1+1400F)^{3/2}}{13.2F}\right)\right]\}$ with $f_s = 0.046Re_v^{-0.20}$ and $f_i = 5\times 0.0025[1+75\alpha_1]$	$f_i = 0.005[1+75(1-\alpha)]$
Drop	$C_D = \frac{24(1+0.1Re_p^{0.75})}{Re_p}$	$C_D = \frac{24(1+0.1Re_d^{0.75})}{Re_d}$	C_{D_b} $= \max\left[\frac{24}{Re_d}(1.0+0.1Re_d^{0.75}), 0.45\right]$	$C_D = \frac{24}{Re_d} + \frac{3.6}{Re_d^{0.313}}$ $+ \frac{0.42}{1+4.15E^{-4}/Re_d^{1.16}}$
Strat/Hor.	$f_i = \max\left(\frac{64}{Re_i}, \frac{0.3164}{Re_i^{0.25}}\right)$ $Re_i = \frac{\rho_g \lvert v_g - v_f \rvert D_i}{\mu_g}$ with $D_i = \frac{\alpha_g \pi D}{\theta + \sin\theta}$	$f_i = 1.84 f_{wg}$ $f_{wg} = \begin{cases} 16.0Re_g^{-1} & \text{laminar} \\ 0.079Re_g^{-0.25} & Re_g < 10^5 \\ 0.0008+0.05525Re_g^{-0.23} & Re_g \ge 10^5 \end{cases}$	$f_i = 0.0025[1+75\alpha_1]$	$f_i = 0.0025[1+75\alpha_1]$

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