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Simulation of Two-group IATE models with EAGLE code

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1. Introduction

The two-group transport equation should be employed in order to describe correctly the interfacial area transport in various two phase flow regimes, especially at the bubbly-to-slug flow transition. This is because the differences in bubble sizes or shapes cause substantial differences in their transport mechanisms and interaction phenomena. The basic concept of two-group interfacial area transport equations have been formulated and demonstrated for vertical gas-liquid bubbly-to-slug flow transition by Hibiki and his co-workers [1]. More than twelve adjustable parameters need to be determined based on extensive experimental database. It should be noted that these parameters were adjusted only in one-dimensional approach by area-averaged flow parameters in a vertical pipe under adiabatic and steady conditions. This obviously brings up the following experimental issue: how to adjust all these parameters as independently as possible by considering experiments where a single physical phenomenon is of importance. The vertical air-water loop (VAWL) has been used for investigating the transport phenomena of two-phase flow at Korea Atomic Energy Research Institute (KAERI). The data for local void fraction and interfacial area concentration are measured by using five-sensor conductivity probe method and classified into two groups, the small spherical bubble group and the cap/slug one. The initial bubble size, which has a big influence on the interaction mechanism between phases, was controlled. In the present work, two-group interfacial area transport equation (IATE) was implemented in the EAGLE code and assessed against VAWL data. The purpose of this study is to investigate the capability of coefficients derived by Hibiki [1] in the two-group interfacial area transport equations with CFD code.

2. Two-group IATE

In the flow regimes beyond bubbly flows with no phase changes, the substantial differences in sizes and shape of bubbles require that the one-group IATE be extended to the two-group IATE models as described in equations (1), (2). Ψ_1, Ψ_2 denote the factor depending on the shape of the bubbles, respectively. The subscript specifies the bubble group. For spherical bubbles, $\psi_1 = 1/36\pi$, whereas for cap bubbles with the shape of semi-sphere, $\psi_1 = 4/243\pi$.

$$
\begin{aligned}
\frac{\partial a_{i,1}}{\partial t} + \nabla\cdot\left(a_{i,1}\vec{v}_{b,1}\right) &= \frac{1}{3\psi_1}\left(\frac{\alpha_1}{a_{i,1}}\right)^2 \left[S_{RC,1} + S_{TI,1} + S_{WE,122} + S_{TI,212}\right] \\
&\quad + \frac{2}{3}\left(\frac{a_{i,1}}{\alpha_1}\right)\left[\frac{\partial \alpha_1}{\partial t} + \nabla\cdot\left(\alpha_1\vec{v}_{b,1}\right)\right] \\
&= \Phi_{RC,1} + \Phi_{TI,1} + \Phi_{WE,122} + \Phi_{TI,212} + \Phi_{VT,1}
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial a_{i,2}}{\partial t} + \nabla\cdot\left(a_{i,2}\vec{v}_{b,2}\right) &= \frac{1}{3\psi_2}\left(\frac{\alpha_2}{a_{i,2}}\right)^2 \left[S_{WE,2} + S_{TI,2}\right] \\
&\quad + \frac{2}{3}\left(\frac{a_{i,2}}{\alpha_2}\right)\left[\frac{\partial \alpha_2}{\partial t} + \nabla\cdot\left(\alpha_2\vec{v}_{b,2}\right)\right] \\
&= \Phi_{WE,2} + \Phi_{TI,2} + \Phi_{VT,2}
\end{aligned}
$$

Sauter mean diameter of each bubble group is calculated by the following relation:

$$D_{b,k} = \frac{6\alpha_k}{a_{i,k}}$$

Table 1: IATE Source and sink terms for Group-1 bubble

Random collission [1+1 → 1]	$\Phi_{RC,1} = -\left(\frac{\alpha_1}{a_{i,1}}\right)^2 \frac{\Gamma^0_{RC,1}\alpha_1^2\varepsilon^{1/3}}{D_{b,1}^{11/3}\left(\alpha_{RC,max}-\alpha\right)}$ $exp\left(-K^0_{RC,1}\sqrt[6]{\frac{D_{b,1}^5\rho_f^3\varepsilon^2}{\sigma^3}}\right)$	$\Gamma^0_{RC,1} = 0.351$ $K^0_{RC,1} = 0.258$
Turbulent impact [1 → 1 + 1]	$\Phi_{TI,1} = \left(\frac{\alpha_1}{a_{i,1}}\right)^2 \frac{\Gamma^0_{TI,1}\alpha_1(1-\alpha)\varepsilon^{1/3}}{D_{b,1}^{11/3}\left(\alpha_{TI,max}-\alpha\right)}$ $exp\left(-\frac{K^0_{TI,1}\sigma}{\rho_f D_{b,1}^{5/3}\varepsilon^{2/3}}\right)$	$\Gamma^0_{TI,1} = 1.12$ $K^0_{TI,1} = 6.85$
Wake entrainment [1 + 2 → 2]	$\Phi_{WE,122} = -\left(\frac{\alpha_1}{a_{i,1}}\right)^2 \frac{\Gamma^0_{WE,12}\alpha_1\alpha_2}{D_{b,1}^3 D_{b,2}}\left(v_{b,2}-v_f\right)$ $exp\left(-K^0_{WE,12}\sqrt[6]{\frac{\rho_f^3\varepsilon^2}{\sigma^3}\left(\frac{D_{b,1}D_{b,2}}{D_{b,1}+D_{b,2}}\right)^5}\right)$	$\Gamma^0_{WE,12} = 24.9$ $K^0_{WE,12} = 0.460$
Turbulent impact [2 → 1 + 2]	$\Phi_{TI,212} = \left(\frac{\alpha_1}{a_{i,1}}\right)^2 \frac{\Gamma^0_{TI,12}\alpha_2(1-\alpha)\varepsilon^{1/3}}{D_{b,2}^{11/3}}$ $exp\left(-K^0_{TI,12}\sigma\frac{\left\{\left(D_{b,2}^3-D_{b,1}^3\right)^{2/3}+\left(D_{b,2}^2-D_{b,1}^2\right)\right\}}{\rho_f D_{b,2}^{11/3}\varepsilon^{2/3}}\right)$	$\Gamma^0_{TI,12} = 317$ $K^0_{TI,12} = 11.7$
Void transport [Pressure variation]	$\Phi_{VT,1} = \frac{2}{3}\left(\frac{a_{i,1}}{\alpha_1}\right)\left[\frac{\partial\alpha_1}{\partial t} + \nabla\cdot\left(\alpha_1\vec{v}_{b,1}\right)\right]$ $\left(\nabla\cdot\left(\alpha_1\vec{v}_{b,1}\right) = \frac{\alpha_1 v_{b,1}}{\rho_g}\frac{\rho_{gref}}{p_{ref}}\frac{dp}{dz}\right)$	

The sink and source terms in the above equations are listed in Table 1,2,3. The detail of mass balance and momentum equations for liquid phase and two groups of bubble can be found in [Hibiki,2000]. For simplicity, in current calculation process, the bubble velocities of two groups are assumed to be identical. Selecting the proper models for interphase force is crucial for two-phase flow modeling. In this study, the interface drag model of Ishii and Zuber taken into account the effect of a multiparticle was adopted. The lift force coefficient C_L was set to 0.01. The wall lubrication force model developed by Antal et al. (1991) and the turbulent dispersion force model of RPI were chosen. The standard k-ε turbulence model is used to model the turbulence for continuous phase.

Table 2: IATE Source and sink terms for Group-2 bubble

Wake entrainment [2 + 2 → 2]	$\Phi_{WE,122} = -\left(\frac{\alpha_2}{a_{i,2}}\right)^2 \frac{\Gamma^0_{WE,2}\alpha_2^2}{D_{b,2}^4}(v_{b,2}-v_f)$ $\exp\left(-K^0_{WE,2}\sqrt[6]{\frac{\rho_f^3\varepsilon^2 D_{b,2}^5}{\sigma^3}}\right)$	$\Gamma^0_{WE,2} = 63.7$ $K^0_{WE,2} = 0.258$
Turbulent impact [2 → 2 + 2]	$\Phi_{TI,2} = \left(\frac{\alpha_2}{a_{i,2}}\right)^2 \frac{\Gamma^0_{TI,2}\alpha_2(1-\alpha)\varepsilon^{1/3}}{D_{b,2}^{11/3}(\alpha_{TI,max}-\alpha)}$ $\exp\left(-\frac{K^0_{TI,2}\sigma}{\rho_f D_{b,2}^{5/3}\varepsilon^{2/3}}\right)$	$\Gamma^0_{TI,2} = 4.26$ $K^0_{TI,2} = 6.85$
Void transport [Pressure variation]	$\Phi_{VT,2} = \frac{2}{3}\left(\frac{a_{i,2}}{\alpha_2}\right)\left[\frac{\partial\alpha_2}{\partial t}+\nabla\cdot(\alpha_2\vec{v}_{b,2})\right]$ $\left(\nabla\cdot(\alpha_2\vec{v}_{b,2}) = \frac{\alpha_2 v_{b,2}}{\rho_g}\frac{\rho_{gref}}{p_{ref}}\frac{dp}{dz}\right)$	

Table 3: Void Transport source and sink terms

Wake entrainment [1 + 2 → 2]	$\Psi_{WE,122} = -\left(\frac{\alpha_1}{a_{i,1}}\right)^3 \frac{3\Gamma^0_{WE,12}\alpha_1\alpha_2}{D_{b,1}^3 D_{b,2}}(v_{b,2}-v_f)$ $\exp\left(-K^0_{WE,12}\sqrt[6]{\frac{\rho_f^3\varepsilon^2}{\sigma^3}\left(\frac{D_{b,1}D_{b,2}}{D_{b,1}+D_{b,2}}\right)^5}\right)$ $\left(\Psi_{WE,122} = 3\left(\frac{\alpha_1}{a_{i,1}}\right)\Phi_{WE,122} = \frac{D_{b,1}}{2}\Phi_{WE,122}\right)$	$\Gamma^0_{WE,12} = 24.9$ $K^0_{WE,12} = 0.460$
Turbulent impact [2 → 1 + 2]	$\psi_{TI,212} = \left(\frac{\alpha_1}{a_{i,1}}\right)^2 \frac{\alpha_2}{a_{i,2}} \frac{3\Gamma^0_{TI,12}\alpha_2(1-\alpha)\varepsilon^{1/3}}{D_{b,2}^{11/3}}$ $\exp\left(-K^0_{TI,12}\sigma\frac{\left\{(D_{b,2}^3-D_{b,1}^3)^{2/3}+(D_{b,2}^2-D_{b,1}^2)\right\}}{\rho_f D_{b,2}^{11/3}\varepsilon^{2/3}}\right)$ $\left(\psi_{TI,212} = 3\left(\frac{\alpha_1}{a_{i,1}}\right)\Phi_{TI,212} = \frac{D_{b,1}}{2}\Phi_{TI,212}\right)$	$\Gamma^0_{TI,12} = 317$ $K^0_{TI,12} = 11.7$
Void transport [Pressure variation]	$\psi_{VT,1} = -\frac{\alpha_1 v_{b,1}}{\rho_g}\nabla\cdot\rho_g$ $\left(\nabla\cdot(\alpha_1\vec{v}_{b,1}) = \frac{\alpha_1 v_{b,1}}{\rho_g}\frac{d\rho_g}{dz} = \frac{\alpha_1 v_{b,1}}{\rho_g}\frac{\rho_{gref}}{p_{ref}}\frac{dp}{dz}\right)$	

3. Results

The VAWL experimental data provides a lot of useful local parameter for vertical upward air-water flows in a round tube with an inner diameter of 80 mm, especially local interfacial area concentration, void fraction of two groups of bubbles, which were measured at 16 points in radial distribution as well as at three axial locations of z/D = 12.2, 42.2, and 100.7 [2]. In this study, the local parameters at the axial location of z/D = 12.2 were selected as initial conditions. A zero-gradient condition was taken into account at the outlet boundary. The grid sensitivity was carried out. A grid composed of 20 (radial) x 80 (axial) axisymmetric cells in a cylindrical coordinate was found to be proper. The simulation results were compared with the experimental data at the axial location of z/D = 42.2 and 100.7. Figure 1 shows the typical result which demonstrates the prediction capability of the EAGLE code.

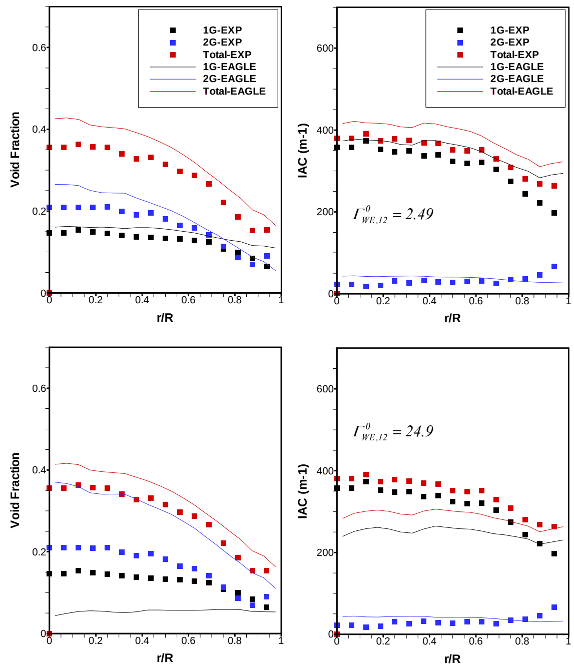

Fig. 1 j_f = 0.5 m/s, j_g = 0.288 m/s, z/D = 42.2

4. Conclusions

Results presented in this study show that the prediction of the interfacial area transport equation strongly depends on the set of adjustable coefficients in two-group IATE models.

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