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Three-dimensional simulations of air–water bubbly flows

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ABSTRACT

Interfacial area transport equation (IATE) is considered promising to evaluate dynamic changes of the interfacial area concentration in gas–liquid two-phase flows, which is of significance in characterizing the interfacial structure of the flows. Efforts were made by the authors in the past on the implementation of the IATE into computational fluid dynamics codes, such as Fluent. However, it remained unclear whether the IATE model coefficients derived from one-dimensional IATE model calibrations can be applied to three-dimensional simulations. The current study aimed to examine, primarily by investigating the lateral profiles of phase distributions, the applicability of the coefficients obtained from the one-dimensional IATE model calibration to a three-dimensional simulation of bubbly flow in a pipe. In addition, effects of the lift force on the lateral phase distributions were studied. A new set of the IATE model coefficients was suggested for a three-dimensional bubbly flow simulation. Good agreement was obtained with the updated coefficients between the predicted and measured flow parameters.

1. Introduction

In the two-fluid model, knowledge of the interfaces that separate different phases in two-phase flows is a key to accurately predict gas–liquid two-phase flows. To characterize the interfacial structure, the interfacial area concentration (IAC), a geometric parameter defined as the total interfacial surface per unit mixture volume, is introduced (Ishii and Mishima, 1980). There are several ongoing studies to model the IAC, one of which is the development of the interfacial area transport equation (IATE). Pioneering work on the formulation of the IATE was performed by Kocamustafaogullari and Ishii (1995). It was emphasized that the IATE was capable of modelling changes in the two-phase flow structure dynamically and mechanistically since it takes into account the bubble coalescence and disintegration caused by fluid particle interactions as well as phase changes due to boiling, evaporation or condensation. In generalized gas–liquid two-phase flows, bubbles observed in different sizes and shapes behave differently in terms of relative motion and interaction mechanisms. In view of this, bubbles are categorized into various groups with its own transport phenomena analogous to the basic concept of multigroup neutron transport theory. For a special case of bubbly flows, all of the bubbles are in spherical or distorted shape and thus can be treated as one group; therefore, a one-group IATE was recommended and developed (Wu et al., 1998). It is also noteworthy that two-group IATE has been proposed to be applicable to a wide range of flow regimes beyond bubbly flows (Fu and Ishii, 2003a; Smith, 2002; Sun et al., 2004).

One of the challenges in establishing the IATE is to construct appropriate closure relations of bubble–bubble and bubble–eddy interactions. Previous studies show that for most bubbly flows there were three major mechanisms, namely, bubble disintegration caused by the impact of turbulence eddies (TI), bubble coalescence due to wake entrainment (WE), and bubble coalescence caused by turbulence-driven random collisions (RC). Theoretical model of each mechanism was derived with adjustable coefficients that varied with flow channel configuration (Kim, 1999; Ishii et al., 2002; Kim et al., 2003). Continuous efforts have been made to determine these coefficients by comparing numerical results to experimental measurements. Kim (1999) used the one-dimensional two-fluid model and a one-dimensional one-group IATE to calculate the phase distributions for flow in a narrow rectangular channel. During this calibration process, the values of the coefficients in the one-dimensional one-group IATE were suggested based on comparisons with experimental data. Similar work was carried out by Ishii et al. (2002) later for bubbly flows in different sizes of circular pipes. All of their work showed acceptable predictions of flow parameters along the flow direction.

Recently, capabilities of computational fluid dynamics (CFD) codes together with the IATE model for two-phase flow simulation have been examined. Graf and Papadimitriou (2007) demonstrated that the IAC could be reasonably captured by *FLU*BOX code equipped with the IATE in upward vertical pipe flows. Bae et al. (2008) developed a CFD code based on the finite volume method using the simplified marker and cell algorithm and coupled the two-fluid model and the one-group IATE systematically. Wang

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and Sun (2007, 2009) implemented the one-group IATE into Fluent code and conducted three-dimensional simulations for bubbly flows in a rectangular duct and a round pipe. In addition, Sari et al. (2009) performed two- and three-dimensional simulations of isothermal bubbly flows by introducing the IATE model into the Fluent code. They pointed out that different researchers suggested different adjustable model coefficients for the same bubble interaction mechanism in the IATE model and showed differences between the predictions in the two- and three-dimensional simulations. Alongside with the IATE model, bubble number density (BND) transport equation was also developed to obtain the information on the changes of bubble number density. The BND model was successfully implemented into CFX (Cheung et al., 2007) for three-dimensional simulations. In all of these studies, the model coefficients in the IATE model that were determined based on one-dimensional calibrations were used for either two- or three-dimensional simulations. Nevertheless, the predictions of the lateral phase distributions presented in these studies were considerably improved compared to the numerical results without the IATE model even though there existed some discrepancies with experiments for some flow conditions. The above observation suggests that the disagreement could be caused by the use of the one-dimensional IATE model coefficients in the multi-dimensional simulations. Therefore, in this study, an attempt was made to address this issue.

The principal objectives of the present work are to investigate the contributions of non-uniform lateral phase distributions to the source/sink terms of the one-group IATE and to test the applicability of the coefficients derived by Ishii et al. (2002) to a three-dimensional simulation under pipe bubbly flow conditions. In addition, effects of the lift force on the lateral phase distributions are studied. Finally, a slightly different set of adjustable coefficients in the one-group IATE are suggested for three-dimensional simulations.

2. Implementation approach

Fluent, a control-volume-based code for multiple mesh styles, is chosen as the CFD tool for two-phase flows. In the conventional Fluent 6.3.33 code, however, the interactions among bubbles and between bubbles and turbulent eddies are not taken into account and bubble size must be specified by users (Fluent User's Guide, 2006). In order to capture the dynamic evolution of the interfacial structure, efforts have been made to implement the one-group IATE into Fluent (Wang and Sun, 2009). In what follows, the implementation approach is discussed briefly.

The one-group IATE for an isothermal adiabatic bubbly flow is given as (Wu et al., 1998)

$$\frac{\partial a_i}{\partial t} + \nabla\cdot(a_i\vec{v}_i) \cong \frac{2}{3}\left(\frac{a_i}{\alpha}\right)\left(\frac{\partial\alpha}{\partial t} + \nabla\cdot(\alpha\vec{v}_g)\right) + \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2\sum_j R_j, \quad (1)$$

where a_i, $\vec{v}_i$, α, $\vec{v}_g$ and R_j are the interfacial area concentration, interfacial velocity, void fraction, gas velocity, and bubble number density change rate due to bubble interactions, respectively. If bubbles are well dispersed with spherical or close to spherical shape, the bubble shape factor ψ equals $1/(36\pi)$. In addition, $\vec{v}_i$ may be approximated as $\vec{v}_g$.

Despite the importance of the IAC, this parameter is not used in Fluent. Instead, the code uses the bubble diameter and void fraction information. In the current study, IAC is introduced as a user-defined scalar (UDS) in the gas phase domain, which is solved in Fluent based on the associated transport equation as

$$\frac{\partial(\alpha\rho_g a_i)}{\partial t} + \nabla\cdot(\alpha\rho_g\vec{v}_g a_i - \alpha\Gamma_g\nabla a_i) = S_g, \quad (2)$$

where ρ_g, Γ_g, and S_g denote the gas density, diffusion coefficient of the IAC, and source term, respectively. There is no physical diffusion of the IAC in the flow field, leading Γ_g in Eq. (2) to zero. S_g is determined by a comparison with Eq. (1) as

$$S_g = -(\alpha a_i\rho_g)\nabla\cdot\vec{v}_g + \frac{2a_i\rho_g}{3}\left[\frac{\partial\alpha}{\partial t} + \nabla\cdot(\alpha\vec{v}_g)\right] + \frac{\rho_g\alpha^3}{3\psi a_i^2}(R_{TI} + R_{WE} + R_{RC}). \quad (3)$$

Wu et al. (1998) identified three major interaction mechanisms in bubbly flows: bubble break-up due to the impact of turbulent eddies (R_{TI}), bubble coalescence caused by the wake entrainment (R_{WE}), and bubble coalescence due to the random collision driven by turbulence (R_{RC}). They were modelled by Wu et al. (1998) and Kim (1999) as

$$R_{TI} = \frac{C_{TI}\psi}{6}\left(\frac{a_i^4}{\alpha^3}\vec{v}_t\right)\sqrt{1 - \frac{We_{cr}}{We}}\exp\left(-\frac{We_{cr}}{We}\right), \quad \text{if } We > We_{cr}, \quad (4)$$

$$R_{WE} = -36\psi^2 C_{WE} C_D^{1/3}\frac{a_i^4\vec{v}_r}{\alpha^2}, \quad (5)$$

$$R_{RC} = -\frac{36\psi^2 C_{RC} a_i^4\vec{v}_t}{\alpha^2\alpha_{\max}^{1/3}\left(\alpha_{\max}^{1/3} - \alpha^{1/3}\right)}\left[1 - \exp\left(-\frac{C\alpha_{\max}^{1/3}\alpha^{1/3}}{\left(\alpha_{\max}^{1/3} - \alpha^{1/3}\right)}\right)\right]. \quad (6)$$

In Eq. (4), We is the Weber number, defined as the ratio of the bubble turbulent inertial energy to the surface energy as

$$We = \rho_f|\vec{v}_t|^2 D_{avg}/\sigma, \quad (7)$$

where ρ_f, $\vec{v}_t$, D_{avg}, and σ are, respectively, the liquid density, turbulent velocity for the liquid phase, average diameter of bubbles, and surface tension between the two phases. The critical value, We_{cr}, is used to describe the balance state between the cohesive force due to surface tension and disruptive force by the turbulent eddies. In Eqs. (4)–(6), C_D, $\vec{v}_r$, and $\alpha_{\max}$ are the drag coefficient, relative velocity between the gas and liquid phases, and void fraction at the bubble maximum packing, respectively. Furthermore, C_{TI}, C_{WE}, C_{RC}, and C are the adjustable model coefficients, whose values were obtained earlier from several one-dimensional benchmarks based on an extensive database (Kim, 1999; Ishii et al., 2002; Kim et al., 2003). More details of the IATE implementation into Fluent are referred to Wang and Sun (2009).

3. Interfacial forces

The interfacial area concentration affects the flow field through the interfacial mass, momentum, and energy transfer. Assuming no mass exchange between the two phases for adiabatic flow, the ensemble-averaged momentum equation for the gas phase in the Eulerian multiphase model is written as (Fluent User's Guide, 2006)

$$\frac{\partial(\alpha\rho_g\vec{v}_g)}{\partial t} + \nabla\cdot\left(\alpha\rho_g\vec{v}_g\vec{v}_g\right) = -\alpha\nabla p + \nabla\cdot\bar{\bar{\tau}}_g + \alpha\rho_g\vec{g} + \vec{R}_{fg} + \vec{F}_g + \vec{F}_l + \vec{F}_{vm}, \quad (8)$$

where p, $\bar{\bar{\tau}}_g$, $\vec{g}$, $\vec{R}_{fg}$, $\vec{F}_g$, $\vec{F}_l$, and $\vec{F}_{vm}$ are the pressure, stress–strain tensor, gravitational acceleration, interaction force, additional external body force, lift force, and virtual mass force, respectively. The interaction force is comparable to the steady-state drag force, given by

$$\vec{R}_{fg} \approx -\frac{a_i}{8}C_D\rho_f\vec{v}_r|\vec{v}_r|\left(\frac{D_{sm}}{D_d}\right). \quad (9)$$