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CFD simulation of bubble column flows: An explicit algebraic Reynolds stress model approach

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ABSTRACT

CFD study of flow hydrodynamics has been conducted in transient Euler–Euler environment by using commercial simulation software Ansys CFX 14.0. First, three different wall lubrication force models are compared. Afterwards, the influence of turbulent dispersion force models has been analyzed. Finally, the performance of Explicit Algebraic Reynolds Stress Model (EARSM) combined with $k-\varepsilon$ and Baseline (BSL) models has been tested. Three different combinations of EARSM were included with two cases incorporating the Bubble Induced Turbulence (BIT) as well (i.e. EARSM $k-\varepsilon$ BIT, EARSM BSL, EARSM BSL BIT). All simulations were compared for average velocity and turbulent kinetic energy profiles with experiments. The performance of these models was also compared with Re-Normalization Group (RNG) and $k-\varepsilon$ models. EARSM $k-\varepsilon$ model was unable to capture the axial liquid as well as gas phase velocities close to experimental values. On contrary, EARSM BSL and EARSM BSL BIT were more successful in predicting the velocity profiles and showed good agreement with experiments, with EARSM BSL slightly less accurate in predicting axial velocity profiles. All models predicted the turbulent kinetic energy profiles reasonably good both quantitatively as well as qualitatively, while near the bottom of the column; EARSM $k-\varepsilon$ slightly under predicted the turbulent quantities. Thus, EARSM combined with BSL and BIT can be effectively exploited for simulating flow fields and turbulent quantities.

1. Introduction

In a range of industries concerned with chemical, biochemical, metallurgical and petrochemical operations (Deckwer, 1992; Dudukovic, 1999; Dudukovic et al., 2002) bubble columns are utilized. With the development of more powerful computers in past decade more focus has been on developing and improving tools in field of CFD modeling of bubble column flows.

To simulate bubble column flows, two methods are mostly used namely Euler–Euler (E–E) (Joshi, 2001; Sokolichin and Eigenberger, 2004; Mudde and Simonin, 1999; Dhotre and Joshi, 2004; Ekambara et al., 2005) and Euler–Lagrange (E–L) (Lapin and Lubbert, 1994; Devanathan et al., 1995; Delnoij et al., 1997, 1999; Lain et al., 1999; Buwa et al., 2006). In the E–L approach, continuum description has been prescribed for liquid phase, while bubbles are tracked individually in the gas system by solving forces exerting on the bubbles. The positive aspect of this method is that it can easily consider the bubble–bubble interactions, whereas its application is limited to smaller systems, since for larger systems more equations need to be solved. In the E–E method, dynamics of the gas phase are ensemble averaged just like liquid phase to get set of Euler equations. Lower computational cost compared to E–L approach is a major advantage for this approach especially for cases with higher void fractions of dispersed phase. 3D transient behavior is required to be included so as to predict the gas–liquid flow physics. It means that 3D unsteady calculations have to be considered, which are computationally very challenging, which also suggests adopting E–E approach despite of accuracy limitations towards formulating closure laws, because of its best compromise between accuracy and computational efforts for such investigations.

A key problem in bubble column simulations is to capture the physics involved. The interphase forces (e.g. drag, turbulent dispersion, wall lubrication and lift forces) and turbulence in the bubble columns can be affected due to interaction among gas and liquid phase. Hence, it is very important to model turbulence and interphase forces appropriately, in order to capture the physics properly. Precise modeling of interphase forces is still a challenging task in CFD of bubble column flows, even though plenty of literature is reported on this matter (Clift et al., 1978; Ervin and

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Tryggvason, 1997; Magnaudet and Eames, 2000; Tomiyama, 1998; Tomiyama et al., 2002). Though previous studies (Deen, 2001; Masood and Delgado, 2014) show that mainly drag and lift forces are prevailing. Other forces such as turbulent dispersion and wall lubrication could be contributing factor in the interfacial momentum transport. Bai et al. (2011) and Masood and Delgado (2014) have considered wall lubrication force in the study of bubble column flows. However, as per our knowledge no comparison study of different wall lubrication force models in case of square bubble columns has been carried out so far in the previous investigations. Therefore, a wall lubrication force model comparison has been included in the current study.

Similarly, not too many studies considered turbulent dispersion force, which also brings out bubble dispersion, into bubbly flow numerical investigations (Smith, 1998; Tabib et al., 2008; Li et al., 2009; Rahimi and Karimi, 2011; Silva et al., 2012; Ziegenhein, 2013) and out of those who did, almost none gave any comparison of turbulence dispersion force models. In this study, an effort has been made to include the comparison of turbulent dispersion models of Burns et al. (2004) and Lopez de Bertodano (1991) into 3D square bubble column flows.

Proper turbulence modeling of continuous phase is also a significant subject. Different models [Standard $k-\varepsilon$, Re-Normalization Group (RNG) $k-\varepsilon$, Reynolds Stress Model (RSM), Large Eddy Simulation (LES)] have been tested. Several works (Lakehal et al., 2002; Deen et al., 2001; Bove et al., 2004; Bombardelli et al., 2006; Zhang et al., 2006) have investigated LES models and reported better resolved flows with LES. But LES also has limitations when it comes to providing much finer detail at the cost of extra computational efforts (Tabib et al., 2008). RSM models have also found to be marginally better in estimating the average flow fields than $k-\varepsilon$ models (Tabib et al., 2008). Although $k-\varepsilon$ models have found to be simple and computationally less expensive (Joshi, 2001; Sokolichin and Eigenberger, 2004; Rafique et al., 2004) and can predict average flow field reasonably well. But they fail to predict turbulence in bubble column flows since these models assume isotropic turbulence whereas flow in bubble columns is anisotropic (Jakobsen et al., 2005). Laborde-Boutet et al. (2009) compared different $k-\varepsilon$ models and found that RNG $k-\varepsilon$ model predicted higher rates of turbulent dissipation compared to other $k-\varepsilon$ models. Nevertheless, at present there are neither clear guidelines nor recommendations that suggest turbulence model capable of predicting reasonably well, both flow field as well as turbulence, in the bubble columns without the expense of large computational resources.

Explicit Algebraic Reynolds Stress Model (EARSM) can be regarded as an effective tool to simulate the turbulence in the bubble column flows. Under this subset nonlinear constitutive model, higher order physical description on the RSM level is partly relocated to the two equation modeling level. As a consequence, making it computationally less expensive than RSM, and simultaneously, making it able to properly reproduce some important attributes of turbulence (e.g. anisotropic mechanism) which are beyond the capabilities of Linear Eddy Viscosity models. To the best of our knowledge, only Masood and Delgado (2014) have used the EARSM model for bubble column flow simulations. They found that EARSM model was superior in capturing the turbulent quantities but failed to predict the average flow field in comparison with the experiments. Therefore, further investigations are required in order to improve the overall predictive performance of EARSM model.

After going through previously published work, it is obvious that further studies are necessary to consider the following:

1. Very few researchers have included wall lubrication force into the numerical investigations of bubble column flows and out of those who did; almost none included wall lubrication force model comparison into the CFD study of square bubbly column flows. Therefore, in the overall CFD analysis, the wall lubrication force model comparison study needs to be incorporated.
2. Turbulent dispersion force has been included in the previous investigations but no comparison of different turbulent dispersion force models, as per knowledge, has been considered in the numerical investigations of 3D square bubble column flows.
3. To the best of our knowledge, this is only second time that EARSM model has been used to simulate the bubble column.
4. Similarly, no numerical investigations have been performed using combination of EARSM and Baseline models for bubbly flows.

In this study, an effort has been made to improve the flow field predictive performance of EARSM model in bubble column flows without losing the quality prediction capabilities of turbulent quantities and mediocre computational requirements. For that matter, three models comprising of EARSM (Wallin and Johansson, 2000) (two combined with the Baseline (BSL) Menter, 1994 model and one with $k-\varepsilon$ model) are investigated in detail. Also impact of Bubble Induced Turbulence (BIT) of Sato and Sekoguchi (1975) on EARSM modulations has been investigated. These models (EARSM-BSL and EARSM-BSL-BIT), according to our knowledge, have not been investigated so far for the modeling of bubble column flows. Also performance of these models has been compared with RNG and $k-\varepsilon$ models and Deen's (2001) experiments. Furthermore, effect of different wall lubrication and turbulent dispersion force models has been studied. All CFD investigations have been performed for square bubble columns in 3D transient E–E framework for single hole sparger.

2. Mathematical formulation

2.1. Governing equations

The governing differential equations for mass and momentum (one for each phase), while neglecting the interphase mass transfer, can be given as:

$$\frac{\partial}{\partial t}(\rho_k\alpha_k) + \nabla(\rho_k\alpha_k\mathbf{u}_k) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_k\alpha_k\mathbf{u}_k) + \nabla(\rho_k\alpha_k\mathbf{u}_k\mathbf{u}_k) = -\nabla(\alpha_k\tau_k) - \alpha_k\nabla P + \alpha_k\rho_k\mathbf{g} + \mathbf{F}_{I,k}. \tag{2}$$

In expression (2), the stress tensor read as:

$$\tau_k = -\mu_{eff}\left[(\nabla\mathbf{u}_k) + (\nabla\mathbf{u}_k)^T - \frac{2}{3}I(\nabla\mathbf{u}_k)\right], \tag{3}$$

herein, μ_{eff} gives liquid phase effective viscosity which in turn is composed of molecular viscosity, turbulence viscosity and notably the one correlated to turbulence induced by bubbles.

$$\mu_{eff,L} = \mu_L + \mu_{T,L} + \mu_{BIT,L}, \tag{4}$$

wherein, gas phase effective viscosity is estimated as under:

$$\mu_{eff,G} = \mu_{eff,L}\frac{\rho_G}{\rho_L}. \tag{5}$$

The effects induced by displacement of the liquid phase as bubbles pass by, is often referred as bubble induced or pseudo-turbulence. Several formulations can be exploited to depict the effects in case of turbulence induced by the bubbles. Here, the model of Sato and Sekoguchi (1975) has been employed.

$$\mu_{BIT,L} = \rho_L C_{\mu,BIT}\alpha_G d_B|\mathbf{u}_G - \mathbf{u}_L|, \tag{6}$$