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Numerical study of bubble break-up in bubbly flows using a deterministic Euler–Lagrange framework

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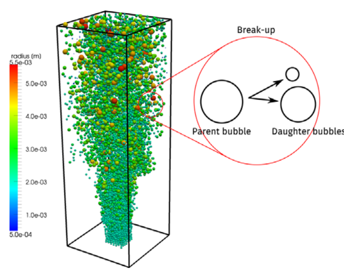
HIGHLIGHTS

- A simulation framework for heterogeneous bubbly flow is presented.
- A Lagrangian breakup model is proposed.
- The daughter size distribution does not influence the bubble size distribution (BSD).
- The critical Weber number and superficial gas velocity significantly affect the BSD.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work we present a numerical model to predict the bubble size distribution in turbulent bubbly flows. The continuous phase is described by the volume-averaged Navier–Stokes equations, which are solved on an Eulerian grid, whereas the dispersed or bubble phase is treated in a Lagrangian manner, where each individual bubble is tracked throughout the computational domain. Collisions between bubbles are described by means of a hard-sphere model. Coalescence of bubbles is modeled via a stochastic inter-particle encounter model. A break-up model is implemented with a break-up constraint on the basis of a critical Weber value augmented with a model for the daughter size distribution. A numerical parameter study is performed of the bubble break-up model implemented in the deterministic Euler–Lagrange framework and its effect on the bubble size distribution (BSD) is reported. A square bubble column operated at a superficial gas velocity of 2 cm/s is chosen as a simulation base case to evaluate the parameters. The parameters that are varied are the values of the critical Weber number (We_{crit}), the daughter size distribution (β) and the superficial gas velocity (v_{sup}). Changes in the values of We_{crit} and v_{sup} have a significant impact on the overall BSD, while a different shaped β did not show a significant difference.

1. Introduction

In turbulent bubbly flows, coalescence and break-up of bubbles determine the bubble size distribution and the corresponding interfacial area. Hence, these phenomena play a crucial role in mass and heat transfer operations in bubbly flows. To predict the bubble size distribution in industrial bubbly flows, the population balance equation (PBE) embedded in the Euler–Euler model is often used. Traditionally the Euler–Euler model treats the dispersed gas phase as a separate continuum with averaged properties, i.e. mean bubble diameter. The disadvantage is that the information regarding individual bubbles is not available. To retain the bubble size distribution a PBE is employed. The PBE handles the evolution of the size distribution of the dispersed phase

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statistically through coalescence and break-up models. The PBE or number density transport equation considers bubbles entering and leaving a control volume through different mechanisms, such as convection, break-up/coalescence or evaporation/condensation. Many mathematical models presented in the literature for coalescence and break-up of bubbles (or droplets) are derived for the use in the PBE. Lasheras et al. (2002) and Liao and Lucas (2009) have given excellent reviews of literature break-up models; and Liao and Lucas (2010) for coalescence models.

Contrary to the classical Euler–Euler model, Euler–Lagrange models offer the advantage that the bubble size distribution is produced as part of the solution, provided that appropriate coalescence and break-up models are incorporated. Sungkorn et al. (2012) belong to the very few, who adopted the Euler–Lagrange framework to study the bubble size distribution (BSD). In their model, bubble parcels are treated in a Lagrangian manner, employing the break-up model of Prince and Blanch (1990) and the coalescence model of Luo and Svendsen (1996). Instead of bubble parcels, Darmana et al. (2006) tracked individual bubbles and treats coalescence in a deterministic fashion after contact of two individual bubbles. The proposed coalescence model is based on the stochastic model of Sommerfeld et al. (2003) whereas break-up of individual bubbles was not incorporated. Building upon the work of Darmana et al. (2006), a deterministic Euler–Lagrange model is presented in this chapter along with the implementation of a bubble break-up model. Similar to coalescence models, incorporation of break-up models originally developed for PBE models in the Euler–Lagrange model is not straightforward. This is due to differences in the mathematical representation, however the underlying physics to represent these phenomena will still hold. The associated constraints can still be used to formulate criterions for coalescence and break-up in the Euler–Lagrange model. Coalescence models for the PBE are given in terms of a coalescence frequency:

$$\Theta_{co}(d_i, d_j) = h_{coll}(d_i, d_j)\gamma_{co}(d_i, d_j) \tag{1}$$

where $h_{coll}(d_i, d_j)$ is the collision frequency between two bubbles with diameters of d_i and d_j; and $\gamma_{co}(d_i, d_j)$ is the corresponding coalescence efficiency. In the Euler–Lagrange framework the collision frequency is readily available. So, using the underlying premise of the coalescence efficiency, a coalescence constraint can be derived for the use in the Euler–Lagrange framework. Such is the coalescence model in the current framework proposed by Darmana et al. (2006). However, coalescence models for the PBE do not give information regarding the location of the resulting coalesced bubble and an assumption must be made regarding the positioning of the newly formed bubble.

Similar to the coalescence frequency, the break-up frequency for the PBE is given as

$$\Theta_{bu}(d_i) = h_{bu}(d_i)\gamma_{bu}(d_i) \tag{2}$$

where $h_{bu}(d_i)$ is the arrival frequency of eddies interacting with a bubble and $\gamma_{bu}(d_i)$ is the break-up efficiency. In the Euler–Lagrange framework, the underlying premise of the break-up efficiency can be used as a break-up constraint. To complete the break-up model, we need a size distribution $\beta(d_i)$ of daughter bubbles formed from the break-up of a parent bubble of size d_i. Also, the locations of the resulting daughter bubbles are not given and assumptions are to be made concerning the placement of the daughter bubbles after the break-up event.

In the following sections, the Euler–Lagrange model and the implemented coalescence model will be described. A break-up model based on the constraint of a critical Weber value is proposed along with the daughter size distribution. Subsequently the numerical implementation of the model in the Euler–Lagrange framework is described. And finally, we present a numerical parameter study of the break-up model implemented in the Euler–Lagrange framework and the effect on the resulting BSD.

2. Euler–Lagrange model

In the Euler–Lagrange model, each individual bubble is treated in a Lagrangian manner, while the liquid phase motion is computed on an Eulerian grid, taking into account the coupling or interaction between the gas and the liquid phase. Bubble–bubble collisions are modeled by means of a hard sphere model following the work of Hoomans et al. (1996) and Delnoij et al. (1997, 1999).

2.1. Liquid phase hydrodynamics

The liquid phase is represented by the volume-averaged Navier–Stokes equations, defined by the continuity and momentum equations:

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot \alpha_l \rho_l \mathbf{u} = 0 \tag{3}$$

$$\frac{\partial}{\partial t}(\alpha_l \rho_l \mathbf{u}) + \nabla \cdot \alpha_l \rho_l \mathbf{u}\mathbf{u} = -\alpha_l \nabla P - \nabla \cdot \alpha_l \tau_l + \alpha_l \rho_l \mathbf{g} + \Phi \tag{4}$$

The presence of the bubbles is reflected by the liquid phase volume fraction α_l and the interphase momentum transfer rate Φ due to the interface forces between the liquid and the bubbles. The liquid phase flow is assumed to be Newtonian and a subgrid-scale model by Vreman (2004) is employed for the turbulence. In an earlier study Darmana et al. (2007) have compared the model by Vreman (2004) to the model by Smagorinsky (1963). It was decided to use by Vreman (2004) model rather than the Smagorinsky (1963) model, as it inherently accounts for the reduction of the energy dissipation in near-wall regions.

2.2. Bubble dynamics

The bubble motion is obtained by solving Newton's second law for each individual bubble. The forces are taken into account by the net force $\sum \mathbf{F}$, experienced by each individual bubble. Then the equations of motion are written as

$$\rho_g V_b \frac{d\mathbf{v}}{dt} = \sum \mathbf{F}, \quad \frac{d\mathbf{r}_b}{dt} = \mathbf{v} \tag{5}$$

where $\mathbf{v}$ is the velocity, V_b is the volume and $\mathbf{r}_b$ is the bubble location of the bubble. The net force acting on each individual bubble is assumed to consist of separate and uncoupled distributions originating from gravity, far field pressure, drag, lift, virtual mass and wall-interaction:

$$\sum \mathbf{F} = \mathbf{F}_G + \mathbf{F}_P + \mathbf{F}_D + \mathbf{F}_L + \mathbf{F}_{VM} + \mathbf{F}_W \tag{6}$$

To close the force balance equation, correlations are needed for the drag (Roghair et al., 2011), lift (Tomiyama et al., 2002), virtual mass (Auton, 1987) and wall-interaction (Tomiyama et al., 1995). These are listed in Table 1. Details on the forces and the numerical implementation are given in the work of Darmana et al. (2006). It should be noted that Euler–Lagrange model is limited by the shape of the bubble, which is in this case assumed to be spherical.

3. Coalescence model

For the description of the coalescence process, three main theories have been proposed, the kinetic collision model (Howarth, 1964; Sovova, 1981), the film drainage model (Sagert and Quinn, 1976; Lee et al., 1987; Prince and Blanch, 1990; Chesters, 1991; Tsouris and Tavlarides, 1994) and the critical velocity model (Lehr et al., 2002). In the kinetic collision or