Chemical Engineering Science 160 (2017) 106–112

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Assessment of polydisperse drag models for the size segregation in a bubbling fluidized bed using discrete particle method

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A R T I C L E I N F O

Keywords:
Drag force model
Fluidization
Gas-solid flow
Multiphase flow
CFD-DEM method

A B S T R A C T

Polydisperse gas-particle flow is often encountered in industry and many polydisperse drag models have been developed in literature. In this work, discrete particle method was employed to assess polydisperse drag models for the segregation and mixing of binary gas-particle flow in a bubbling fluidized bed. The degree of particle segregation and the characteristic bubble frequency using different polydisperse drag models were analyzed. It was shown that the results predicted by the model of Rong et al. (2014) are in a best agreement with experimental data with 5.3% errors on average, and two dominant bubble frequencies were found by analyzing the fluctuations of average particle height.

1. Introduction

Fluidized bed technologies have been widely used in chemical engineering, energy utilization and environmental protection. In these practical applications the sizes of particles are normally polydisperse rather than monodisperse and segregation may occur in the reactors. The particle segregation phenomenon has attracted many researchers to investigate because segregation rates and degrees directly affect the efficiency of reaction and heat transfer (Das et al., 2008; Zhou and Wang, 2015). For example, in metallurgical industry the minerals of wide-size distribution need to be classified into several products with different sizes (Sahu et al., 2015), but in coal gasification, it required that the multi-size coal particles mixed well to ensure uniform heat transfer and reaction (Lundberg et al., 2016). Some experimental results have found that lower gas velocity promotes segregation whereas higher gas velocity facilitates mixing process (Goldschmidt et al., 2003; Leboreiro et al., 2008).

In an attempt to figure out the mechanism of segregation and mixing process, numerical methods have been developed such as Eulerian-Eulerian (EE) model (Cooper and Coronella, 2005; Huilin and Gidaspow, 2003; Santos et al., 2016) and Eulerian-Lagrangian (EL) model (Deen et al., 2007; Peng et al., 2016). EE models treat the fluid and solid as interpenetrating continua, therefore, they have great advantages in terms of computational cost as compared to CFD-DEM method, but coarse-grained EL methods, such as MP-PIC method (Snider, 2001; Sundaresan, 2011), can be computationally more effective than EE models, due to the usage of the concept of parcels and of the allowed larger time step. Besides, some researchers have pointed out that EE models have some difficulties in predicting the segregation process and segregation rates quantitatively (Bokkers et al., 2004; Peng et al., 2016). On the other hand, EL models are often used by treating solid phase and gas phase as discrete particles and continuum respectively. By adopting Lagrangian method, EL models are believed to be better in the prediction of segregation and mixing of particles (Deen et al., 2007; Xu and Yu, 1997; Zhu et al., 2007). Furthermore, the drag models are thought as the pivotal factor in closing the interactions between gas and particles no matter of EE model or EL model. A variety of drag models were put forward through fitting either experimental data or direct numerical simulation (DNS) results (Cello et al., 2010; Gidaspow, 1994; Rong et al., 2014; Sarkar et al., 2009). There were also a lot of articles concentrating on the validation and comparison of these drag modes (Beetstra et al., 2007b; Di Renzo et al., 2011; Leboreiro et al., 2008; van Wachem et al., 2001). However no one was well accepted in view of the continuous appearance of new correlations, because these models usually were generated based on different conditions such as dilute or dense system, gas-solid or liquid-solid system and so on. Besides, a lot of drag models deduced from DNS thought static particles (Beetstra et al., 2007a; Hoef et al., 2005; Rong et al., 2013, 2014), it is of a large difference from the actual fluidized beds.

This paper study the applicability and accuracy of several drag models derived from experiments or DNS recently. The simulation of

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http://dx.doi.org/10.1016/j.ces.2016.11.028
Received 27 September 2016; Received in revised form 5 November 2016; Accepted 14 November 2016
Available online 15 November 2016
0009-2509/

the prediction of minimum fluidization velocity by different drag models were conducted firstly. Then the data involved segregation degrees and bubble frequency of experiments were employed to compare the simulation results comprehensively. EL model, also called CFD-DEM method or discrete particle method, was employed in this paper by combining the open software of OpenFOAM and in-house code of DEMMS (Lu et al., 2016, 2014; Xu et al., 2011). It however should be noted that by contrast to our previous studies using the same code (Lu et al., 2016, 2014), in present study, no EMMS drag model (Wang et al., 2008) has been used, because we are studying the fluidization behaviour of very coarse particles with sufficient scale resolution (Carlos Varas et al., 2016; Wang et al., 2009, Wang et al., 2010).

2. Discrete particle method

2.1. Governing equations

The simulation method used in this paper could be divided into two parts: the calculation of gas phase in CPUs and the calculation of solid phase in GPUs. The particles information of volume fraction, velocity and the gas velocity and pressure were exchanged by shared memory blocks. The parallel calculation was developed through the platform of CUDA (Compute Unified Device Architecture). The discrete particle equations were calculated on a single particle by Newton's equation as given below:

$$m_p\frac{d\mathbf{v_p}}{dt} = m_p\mathbf{g} + \mathbf{F_{d,i}} + \mathbf{F_{col}} - V_p\nabla P \tag{1}$$

$$\mathbf{I_i}\frac{dw_i}{dt} = \mathbf{T_i} \tag{2}$$

$$\mathbf{F_{d,i}} = \frac{\beta_0 V_p}{\varepsilon_s}(\mathbf{u_g} - \mathbf{v_p}) \tag{3}$$

$\mathbf{F_{d,i}}$ represents the drag force between gas and solid, $\mathbf{F_{col}}$ is the collision forces among particles. $m_p\mathbf{g}$ is the gravitational force and $V_p\nabla P$ is the pressure gradient force. Soft sphere model is adopted to treat particle-particle and particle wall interactions, details of which can be found in Lu et al. (2014). The governing equations for gas phase are summarized below:

$$\frac{\partial \varepsilon_g\rho_g}{\partial t} + \nabla\cdot(\varepsilon_g\rho_g\mathbf{u_g}) = 0 \tag{4}$$

$$\frac{\partial\left(\varepsilon_g\rho_g\mathbf{u_g}\right)}{\partial t} + \nabla\cdot(\varepsilon_g\rho_g\mathbf{u_g}\mathbf{u_g}) = -\varepsilon_g\nabla P - \frac{\sum_{i=1}^{n}\mathbf{F_{d,i}}}{\Omega} + \nabla\cdot(\varepsilon_g\tau_g) + \varepsilon_g\rho_g\mathbf{g} \tag{5}$$

It should be noted that $\mathbf{u_g}$ is the gas velocity of a grid and $\boldsymbol{\Omega}$ represents the volume size of a single grid.

2.2. Drag models for polydisperse particle system

Over the last decades the monodisperse drag models were deduced through normalized drag $F(\varepsilon_s,\ \mathrm{Re})$ based on Stroke-Einstein equation as shown in Eq. (6). The exponential and linear expressions are generally developed to derive $F(\varepsilon_s,\ \mathrm{Re})$ by experimental data or lattice-Boltzmann simulations as equations of (7) and (8). Furthermore the polydisperse drag models are often achieved by modifying the mono-drag models (Beetstra et al., 2007a; Cello et al., 2010; Rong et al., 2014; Sarkar et al., 2009).

$$F(\varepsilon_s,\ \mathrm{Re}) = F_{drag}/(3\pi\mu dU) \tag{6}$$

$$F(\varepsilon_s,\ \mathrm{Re}) = F(\varepsilon_s,\ 0) + \alpha(\varepsilon_s)\mathrm{Re} \tag{7}$$

$$F(\varepsilon_s,\ \mathrm{Re}) = F(0,\ \mathrm{Re})\varepsilon_s^{-\beta} \tag{8}$$

The calculation of drag force would convert to solve the normalized drag force $F(\varepsilon_s,\ \mathrm{Re})$. According to linear Eq. (7), some researchers (Blake, 1921; Burke and Plummer, 1928) gave the expressions as follows:

$$F(\varepsilon_s,\ 0) = \frac{a\varepsilon_s}{18(1-\varepsilon_s)^2},\ \ \alpha(\varepsilon_s) = \frac{b}{18(1-\varepsilon_s)^2} \tag{9}$$

Ergun (1952) conducted experiments with 640 types of particles by pressure analysis and given the exact parameters for a=150 and b=1.75. However on the basis of Eq. (8), more researchers concluded the expression of $F(0,\ \mathrm{Re})$ for a single particle firstly and classified the fluid dynamics to several different regime such as Stroke flow, Allen flow or turbulent flow. Then by measuring the particles terminal velocity in the suspensions, the expression β can be achieved. Wen and Yu (1966) suggested Schiler and Nauman equation (Schiller and Naumann, 1933) for $F(0,\ \mathrm{Re})$ and β=3.7. Gidaspow et al. combined the linear equation of Ergun and exponential equation of Wen and Yu to express the system for $0.2<\varepsilon_s$ and $0\le\varepsilon_s\le 0.2$ (Gidaspow, 1994), respectively. Although some questions were put forward to modify Gidaspow et al. model (Hill et al., 2001; Hoomans et al., 1996), it is still widely applied in various simulation software and industrial productions. More other expressions deduced from DNS adopted similar method to acquire the expression of Eqs. (7) and (8) by fitting the data of the simulations. Except for above derivations, researchers have also done efforts to modify the pressure gradient term in Eq. (1) because for multi-sizes system the pressure drop is closely related to the particle surface area rather than volume fraction and their method could distinctly improve the models' accuracy (Feng and Yu, 2004).

Two methods have been raised by extending the monodisperse drag to achieve polydisperse drag models. Firstly, we could directly calculate drag force of each particle by using mono-disperse drag model to sum all the drag forces of different types of particles. The parameters of $\mathrm{Re_i}$ and ε_{si} use the individual particle. The second calculation is to adopt average parameters of system to derive the total drag force f_d and then distribute to different types particles through a certain rule, the average parameters of system such as average diameter $<d>$ and Reynolds number Re are given:

$$x_i = \frac{\varepsilon_{si}}{\varepsilon_s},\ \ \varepsilon_s = \sum_{i=1}^{c}\varepsilon_{si},\ \ <d> = \left[\sum_{i=1}^{c}\frac{x_i}{d_i}\right]^{-1},\ \ y_i = \frac{d_i}{<d>},$$
$$\mathrm{Re} = \frac{\varepsilon_g\rho_g <d> \mathrm{U}_{slip}}{\mu} \tag{10}$$

U_{slip} represents the slip velocity between gas and particles. Table 1 listed four expressions that will be applied in this paper. Except for Gidaspow et al.'s model, the other drag models are all calculated using the second method. Sarkar et al.'s model and Rong et al.'s model were deduced based on lattice-Boltzmann simulations while the Gidaspow et al.'s model is through experiments. Cello et al.'s model is a semi-empirical model by fitting the simulation data from Hoef et al. (2005) and Hill et al. (2001), plus deriving from model of Turton and Levenspiel (1986). Fig. 1 presents the drag force ratio of large particle and small particle as functions of Reynolds number and porosity by different models.

3. Simulation conditions

The main aims of this paper were to assess the available polydisperse drag models for predicting segregation and mixing of binary gas-solid flow in a bubbling fluidized bed and to study the size segregation mechanism which may not easily observed through experiments. The simulation results are finally compared to the experiments of Goldschmidt et al. (2003) where the binary glass particles of 1.5 mm and 2.5 mm were fluidized by air in a pseudo-2D transparent bed and the image analysis technique was conducted by digital camera. The