Powder Technology 327 (2018) 70–78

Contents lists available at ScienceDirect

Powder Technology

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

Usefulness of multi-solids pneumatic transport bed data for evaluation and validation of binary solids computational simulation models

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ARTICLE INFO

Article history:
Received 7 July 2017
Received in revised form 30 October 2017
Accepted 7 December 2017
Available online 12 December 2017

Keywords:
Fluidization
Coarse particle terminal velocity
Fine particle holdup
Binary mixture

ABSTRACT

The hydrodynamics of the binary mixture system in the multisolid pneumatic transport bed (MPTB), where a fine-particle laden gas flows through a coarse particle bed, was investigated by computational fluid dynamics (CFD) simulation. A pseudo-homogeneous method, which considers the gas phase and the fine particle phase as one pseudo-homogeneous dilute phase, was proposed to predict the coarse particle terminal velocity. In the second approach, the fine particle and coarse particle are treated separately, with the structure-based drag model developed in our previous study being used to simulate the coarse particle terminal velocity and fine particle holdup in the coarse particle bed. The simulation results of the two methods showed reasonable agreement with the experimental data under different operating conditions. As observed in the experiment, the terminal velocity of coarse particles decreases with increasing the fine particle flow rate, and the reduction is more significant for larger coarse particles. Besides, the fine particle holdup increases with the decrease of the diameter of coarse particles. These results demonstrated that the multisolid pneumatic transport system can serve as a simple binary system, with its coarse particle terminal velocity and fine particle holdup being used for the verification and validation of binary-particle CFB models.

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1. Introduction

A multisolid pneumatic transport bed (MPTB) consists of a fludized coarse particle bed (Geldart group D) and circulating fine particles (Geldart group A/B) carried by high velocity gases, which has been used in various industrial processes, such as combustion of coal, petroleum coke and paper mill wastes [1]. In such a binary particle circulating fluidized bed system, a unique fluidized regime is maintained in which the gas velocity is required to be less than the terminal velocity of coarse particles so as to keep the coarse particles remaining in the riser side. Besides, the collision between the slow-moving coarse particles and fast-moving fine particles increases the holdup of fine particles in the dense fluidized bed of coarse particles. The residence time of circulating particles, heat transfer and mass transfer are significantly influenced by the holdup of fine particles. Thus, it is essential to be able to predict the terminal velocity of coarse particles and holdup of fine particles in the MPTB.

Previous researchers mainly focused on experimental investigations of the influence of particles properties on the terminal velocity of coarse particles and holdup of fine particles. Geldart and Pope [2] observed that the carryover of coarse particles from a bubbling fluidized bed was promoter by the addition of fines, due to the increased drag exerted by fine particles to the coarse particles. Similarly, Satijia and Fan [3] found that the coarse particle terminal velocity decreased with increasing the fine particle flow rate in a MPTB. Moreover, the holdup of fine particles increased with increasing coarse particle density and fine particle diameter, and decreased with increasing coarse particle diameter [4]. Zhu et al. [5] found that in the air and coarse polyvinyl chloride particle spouted bed, the addition of fine FCC particles into the spouting air could reduce the minimum spouting velocity, increase the bed pressure drop and reduce the maximum spoutable bed height. Studies on the segregation behaviour of coarse particles in dense medium gas-solid bubbling bed revealed that the segregation performance mainly depends on operating gas velocity and the presence of smaller bubbles gives better coal separation [6–9]. The hydrodynamics plays a significant role in influencing the heat transfer and chemical reaction rate. Bi et al. [10] used fine Fe/FCC catalyst particles and found that the superimposition of coarse glass bead particles in a multisolid circulating fluidized bed (CFB) riser improved ozone conversions. Huang et al. [11] used coarse catalyst particles and fine adsorbent particles in a CFB riser and found that the fine particles can enhance the efficiency of mass transfer and heat transfer.

Apart from experimental studies, mechanistic models were also developed to predict the terminal velocity of coarse particles and holdup of fine particles. Based on an empirically correlated interaction coefficient, Fan et al. [12] developed a momentum balance model to reasonably account for the fine particle holdup in the packed dense bed of

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https://doi.org/10.1016/j.powtec.2017.12.038
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Table 1
Governing equations for two-fluid model and constitutive equations.

Continuity equations ($i = 1$ or 2 for single or binary systems)

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

$$\frac{\partial(\varepsilon_{si}\rho_{si})}{\partial t}+\nabla\cdot(\varepsilon_{si}\rho_{si}\overrightarrow{u_{si}})=0$$

$$\varepsilon_g+\sum_{i=1}\varepsilon_{si}=1$$

Momentum equations

$$\frac{\partial(\varepsilon_g\rho_g\vec{u}_g)}{\partial t}+\nabla\cdot(\varepsilon_g\rho_g\vec{u}_g\vec{u}_g)=-\varepsilon_g\nabla p_g+\varepsilon_g\rho_g\vec{g}+\nabla\cdot\overline{\overline{\tau_g}}+\sum_{i=1}\beta_{si}(\vec{u}_{si}-\vec{u}_g)$$

$$\frac{\partial}{\partial t}(\varepsilon_{si}\rho_{si}\overrightarrow{u_{si}})+\nabla\cdot(\varepsilon_{si}\rho_{si}\overrightarrow{u_{si}}\overrightarrow{u_{si}})=-\varepsilon_{si}\nabla p-\nabla p_{si}+\varepsilon_{si}\rho_{si}\vec{g}+\nabla\cdot\overline{\overline{\tau_{si}}}+\beta_{si}(\overrightarrow{u_{si}}-\overrightarrow{u_g})+\xi_{ik}(\overrightarrow{u_{sk}}-\overrightarrow{u_{si}})$$

Granular temperature equation

$$\frac{3}{2}\left[\frac{\partial(\varepsilon_{si}\rho_{si}\Theta_{si})}{\partial t}+\nabla\cdot(\varepsilon_{si}\rho_{si}\vec{u}_{si}\Theta_{si})\right]=\overline{\overline{\tau_{si}}}:\nabla\vec{u}_{si}+\nabla\cdot(k_{\Theta_{si}}\nabla\Theta_{si})-\gamma_{\Theta_{si}}-3(\beta_{si}+\xi_{ik})\Theta_{si}$$

Solid pressure

$$p_{si}=\varepsilon_{si}\rho_{si}\Theta_{si}+2\sum_{i=1}\left(\frac{d_{si}+d_{sk}}{2d_{pi}}\right)^3\varepsilon_{si}\varepsilon_{sk}(1+e_{ik})\rho_{si}g_{ik}\Theta_{si}$$

Solid phase shear viscosity [48,49]

$$\mu_{si}=\mu_{s,kin_i}+\mu_{s,s,col_i}+\mu_{s.fr_i}$$

$$\mu_{s,kin_i}=\frac{5\rho_{si}d_{si}\sqrt{\pi\Theta_{si}}}{48\varepsilon_{si}(1+e_{ik})g_{ik}}\left[1+\frac{4}{5}g_{ik}\varepsilon_{si}(1+e_{ik})\right]^2$$

$$\mu_{s,s,col_i}=\frac{4}{5\sqrt{\pi}}\varepsilon_{si}\rho_{si}g_{ik}d_{si}(1+e_{ik})\sqrt{\Theta_{si}}$$

$$\mu_{s.fr_i}=\frac{p_{si}\sin\phi_i}{2\sqrt{I_{2D}}}$$

Solid phase bulk viscosity [50]

$$\lambda_s=\frac{4}{3\sqrt{\pi}}\varepsilon_{si}\rho_{si}d_{si}g_{ik}(1+e_{ik})\sqrt{\Theta_{si}}$$

Diffusion coefficient of granular energy [48]

$$k_{\Theta si}=\frac{150p_{si}d_{si}\sqrt{\pi\Theta_{si}}}{384(1+e_{ik})g_{ik}}\left[1+\frac{6}{5}g_{ik}\varepsilon_{si}(1+e_{ik})\right]^2+2p_{si}\varepsilon_{si}^2d_{si}(1+e_{ik})g_{ik}\sqrt{\frac{\Theta_{si}}{\pi}}$$

Collisional energy dissipation [50]

$$\gamma_{\Theta_{si}}=\frac{12(1-e_{ik}^2)}{d_{si}\sqrt{\pi}}\varepsilon_{si}^2\rho_{si}g_{ik}\Theta_{si}^{3/2}$$

Radial distribution function [40,42]

$$g_{ik}=\frac{d_{si}g_{si}+d_{sk}g_{sk}}{d_{si}+d_{sk}}$$

$$g_{si}=\left[1-\left(\frac{1-\varepsilon_g}{\varepsilon_{s,\max}}\right)^{1/3}\right]^{-1}$$

the MPTB. Subsequently, Satija and Fan [3] and Kitano et al. [4] adopted the similar method to predict the terminal velocity of coarse particles and the fine particle holdup in the fluidized dense bed of the MPTB, respectively.

With the advancement of the computational capability, computational fluid dynamics (CFD) method has been extended from mono-particle system to binary/multi-solid particle systems in recent years with a number of attempts to verify and validate the models against experimental data. Holloway et al. [13] presented a study to demonstrate the need for filtered models for bidisperse gas-solid flows. Subsequently, Holloway and Sundaresan [14] separately examined the dependence of various interactions (filtered fluid-particle drag coefficient, particle-particle drag coefficient, and particle stress) on simple filtered quantities in the binary mixture flow. Zhou et al. [15] studied binary particles in CFB risers by performing an extension of EMMS drag model, and found that the modified EMMS model can predict the mixing and segregation pattern in risers. Zhang et al. [16] employed discrete particle method to assess polydisperse drag models for the mixing and segregation of binary gas-solid flow, and claimed that the model of Rong et al. [17] can get the best simulation results. Qi et al. [18] simulated the separation behaviours of fine particles in large dense medium cyclones, and provided several modifications of the design to improve the separation efficiency of fine particles. Chu et al. [19] found that the solids loading effect heavily depends on particle size.

However, some CFD models are not fully validated because of the complexity of binary gas-solid flows. Leboreiro et al. [20] developed a drag model specifically for binary mixtures using Lattice-Boltzmann simulations, and compared the impact of various drag models on segregation of binary particle system in bubbling fluidized beds of Geldart B particles. However, the authors did not compare their simulation results with experimental data to assess which drag model gave better agreement with measured segregation profiles. Schneiderbauer et al. [21] presented a hybrid model of Eulerian and Lagrangian for the binary gas-solid fluidized bed, and claimed that the simulation results were in "good agreement" with the experiment based on qualitative profiles of the instantaneous volume fraction rather than quantitative evaluation. Schellander et al. [22] proposed an Eulerian and Lagrangian hybrid model (EUgran + Poly) to simulate multi-solid flows, with modified particle cluster drag model, boundary conditions and granular phase model after Schneiderbauer et al. [23] The article concluded that the first modification "improved results" and the other two modifications were "highly effective", but failed to show which modification plays an effective role in the simulation results because of the fair agreement of the measured and simulated results. These results suggest that CFD validation might be better made with simple or less complex geometry under less demanding flow conditions, and the effectiveness of each modification might be better tested separately, as suggested by several authors [24,25].

Table 2
Characteristics of fine particles [3].

Type of particle	Particle diameter (μm)	Particle density ($g\ cm^{-3}$)	Sphericity factor
Fine sand	155	2.446	0.66
Coarse sand	245	2.446	0.72

As pointed out by Grace and Taghipour [26], several general guidelines should be followed on the validation of simulation models, including (1) the experimental data which are used for comparison purposes must have a high accuracy and wide acceptance; (2) wherever possible, both numerical and experimental runs should be performed by two independent groups; (3) input conditions and separate variables should be covered as broad as possible; (4) shortcomings in the comparison between the experimental and numerical errors should be admitted and the models are improved based on discrepancies; (5) correlations which can best represent the physics of fluidized beds should be used.

So far, most studies on binary/multi-solids fluidized beds have focused on predicting the segregation and mixing of the binary system of Geldart A/B particles in the bubbling/turbulent beds or fast fluidized beds with both large and small particles in circulation as a mixture. So far no attempts have been made to simulate the MPTB, which resembles a transition between the binary system without solids circulation and the binary system with both large and small particles in circulation. Due to its distinct features, such as the two distinct fine and coarse particle phases with one percolating through the other, reliable and accurately measured terminal velocity of coarse particles and fine particle holdup in the dense fluidized bed, MPTB can be an ideal simple binary system for the verification and validation of CFD models for binary circulating fluidized beds and the tuning of model parameters such as the drag coefficient and fine-coarse particle interactions.

In this study, we for the first time illustrate the usefulness of the MPTB system for evaluating a pseudo-homogeneous model and a structure-based drag model based on the comparison of predicted and measured terminal velocity of coarse particles and the holdup of fine particles, based on the experimental data available in the literature under different operating conditions.

Table 3
Characteristics of coarse particles [3].

Type of particle	Particle diameter (mm)	Particle density ($g\ cm^{-3}$)	Sphericity factor
Aluminum	2.32	3.537	0.838
Aluminum	5.50	3.537	0.990
Aluminum	6.96	3.537	0.920
Glass beads	3.00	2.520	1.000
Glass beads	4.00	2.470	1.000
Glass beads	6.00	2.225	1.000

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