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Effect of particle frictional sliding during collisions on modeling the hydrodynamics of binary particle mixtures in bubbling fluidized beds

Hanbin Zhong [a,b], Xingying Lan [a,*], Jinsen Gao [a], Chunming Xu [a]

[a] State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China
[b] College of Chemistry and Chemical Engineering, Xi'an Shiyou University, Xi'an, Shaanxi 710065, China

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ABSTRACT

When modeling the hydrodynamics of binary particle mixtures differing in size and density in gas-solid bubbling fluidized beds by the multi-fluid Eulerian model incorporating the kinetic theory of granular flow, the momentum exchange between two different particle species should be accounted by the particle–particle drag. The parametric studies of the particle–particle friction coefficient in the Syamlal particle–particle drag model were performed to evaluate the particle frictional sliding effect during collisions on the segregation and mixing behavior of binary particle mixtures. The predicted jetsam concentration distributions were compared with the available experimental data in both the axial and radial directions. The results indicate that the particle frictional sliding behavior during collisions influences the segregation and mixing process in different ways. The particle frictional sliding effect during collisions should be accurately considered when modeling the hydrodynamics of binary particle mixtures, especially for the segregation process.

1. Introduction

In chemical industries, the fluidized beds handling particle mixtures differing in size and/or density (e.g., fluidized bed coal combustors, fluidized bed polymerization, drug manufacturing) exhibit different hydrodynamics compared with monodisperse systems and should be therefore treated with great attention. The binary particle mixtures tend to be well-mixed at high fluidization velocities, while segregate over a wide range of superficial velocities greater than the minimum fluidization velocity. The particles sinking towards the bottom of bed are named as jetsam, while others rising towards the bed surface are referred to as flotsam [1]. Whether the segregation or mixing of particle mixtures is beneficial for the process depends on the practical demands. For example, the segregation is desirable in classifiers [2], while in pharmaceutical industry the drug particles and ingredients should be well-mixed before tableting [3]. Therefore, during the past several decades, the segregation and mixing behavior of binary particle mixtures have been extensively studied experimentally, and it is believed that the segregation mainly depends on the differences in size and density, as well as on the fluid velocity [2,4,5].

In recent years, with the rapid development of computational ability, computational fluid dynamics (CFD) has been increasingly employed as an efficient tool to investigate the complex hydrodynamic behavior of fluidized beds. Typically, there are two different CFD methods for modeling fluidized beds, i.e., Eulerian–Lagrangian method and Eulerian–Eulerian method. For both methods, the gas phase is described using the continuum equations, while the solids are handled by different methods. In the Eulerian–Lagrangian approach, the particle phases are described by tracking the motion of individual particles, and the detailed forces exerted on each particles can be simulated, while the solids are considered as fully interpenetrating continua subject to continuity and momentum equations in the Eulerian–Eulerian method. There are two approaches based on the Eulerian–Eulerian method available to model binary particle mixtures. The first approach is characterized by the use of separate momentum equations for each particle species [6–8], while the second approach considers all particle species as one particle mixture phase [9]. When modeling binary systems using the first approach, an extra interaction term is required to account the momentum exchange between two different particle species. Although this extra contribution should be termed as particle–particle interaction force, which might encompass several contributions including drag force, it is often referred to as particle–particle drag force [10]. Owoyemi et al. [10] investigated the role of particle–particle drag on the mixing and segregation of binary particle mixtures using Eulerian–Eulerian method. When the particle–particle drag force was neglected, the segregation was somewhat overestimated. Hence, they concluded that the particle–particle drag hindered the motion of jetsam toward the bottom of bed and enhanced the mixing behavior. Feng et al. [11] studied the mixing and segregation of binary particle mixtures by means of the Eulerian–Lagrangian approach. The particle–particle interaction, which includes the contact forces between the

* Corresponding author at: State Key Laboratory of Heavy Oil Processing, China University of Petroleum-Beijing, 18 Fuxue Road, Changping, Beijing 102249, China. Tel.: +86 10 89731773.
E-mail address: lanxy@cup.edu.cn (X. Lan).

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Table 1
Governing equations and constitutive equations.

Governing equations

1. Continuity equations of gas and solid phases

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right)+\nabla\cdot\left(\alpha_g\rho_g\overrightarrow{v_g}\right)=0,\frac{\partial}{\partial t}\left(\alpha_{pi}\rho_{pi}\right)+\nabla\cdot\left(\alpha_{pi}\rho_{pi}\overrightarrow{v_{pi}}\right)=0,\alpha_g+\sum_{k=1}^{2}\alpha_{pk}=1 \tag{1}$$

2. Momentum equations of gas and solid phases

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\overrightarrow{v_g}\right)+\nabla\cdot\left(\alpha_g\rho_g\overrightarrow{v_g}\,\overrightarrow{v_g}\right)=-\alpha_g\nabla p+\nabla.\overline{\overline{\tau_g}}+\alpha_g\rho_g\vec{g}+\sum_{i=1}^{2}\beta_i\left(\overrightarrow{v_{pi}}-\overrightarrow{v_g}\right) \tag{2}$$

$$\frac{\partial}{\partial t}\left(\alpha_{pi}\rho_{pi}\overrightarrow{v_{pi}}\right)+\nabla\cdot\left(\alpha_{pi}\rho_{pi}\overrightarrow{v_{pi}}\,\overrightarrow{v_{pi}}\right)=-\alpha_{pi}\nabla p+\nabla\cdot\overline{\overline{\tau_{pi}}}+\alpha_{pi}\rho_{pi}\vec{g}+\beta_i\left(\overrightarrow{v_g}-\overrightarrow{v_{pi}}\right)+\zeta_{ik}\left(\overrightarrow{v_{p_k}}-\overrightarrow{v_{p_i}}\right) \tag{3}$$

where

$$\overline{\overline{\tau_g}}=\alpha_g\mu_g\left[\nabla\overrightarrow{v_g}+(\nabla\overrightarrow{v_g})^{\mathrm{T}}-\frac{2}{3}\left(\nabla\cdot\overrightarrow{v_g}\right)\overline{\overline{I}}\right] \tag{4}$$

$$\overline{\overline{\tau_{p_i}}}=\left(-p_{p_i}+\alpha_{p_i}\lambda_{p_i}\nabla\cdot\overrightarrow{v_{p_i}}\right)\overline{\overline{I}}+\alpha_{p_i}\mu_{p_i}\left[\nabla\overrightarrow{v_{p_i}}+(\nabla\overrightarrow{v_{p_i}})^{\mathrm{T}}-\frac{2}{3}\left(\nabla\cdot\overrightarrow{v_{p_i}}\right)\overline{\overline{I}}\right] \tag{5}$$

3. Granular temperature equation [30]

$$\begin{aligned}\frac{3}{2}\left[\frac{\partial}{\partial t}\left(\alpha_{p_i}\rho_{p_i}\Theta_{p_i}\right)+\nabla\cdot\left(\alpha_{p_i}\rho_{p_i}\overrightarrow{v_{p_i}}\Theta_{p_i}\right)\right]=&\ \overline{\overline{\tau_{p_i}}}:\nabla\overrightarrow{v_{p_i}}+\nabla\cdot\left(k_{\Theta_{p_i}}\nabla\Theta_{p_i}\right)\\&-\gamma_{\Theta_{p_i}}-3(\beta_i+\zeta_{ik})\Theta_{p_i}\end{aligned} \tag{6}$$

Constitutive equations

1. Solid pressure

$$p_{p_i}=\left[1+2\sum_{k=1}^{2}\left(\frac{d_{p_i}+d_{p_k}}{2d_{p_i}}\right)^3(1+e_{ik})\alpha_{p_k}g_{ik}\right]\alpha_{p_i}\rho_{p_i}\Theta_{p_i} \tag{7}$$

2. Solid shear viscosity [31,32]

$$\mu_{p_i}=\frac{4}{5}\alpha_{p_i}\rho_{p_i}d_{p_i}g_{ik}(1+e_{ik})\sqrt{\frac{\Theta_{p_i}}{\pi}}+\frac{10\rho_{p_i}d_{p_i}\sqrt{\Theta_{p_i}\pi}}{96\alpha_{p_i}(1+e_{ik})g_{ik}}\left[1+\frac{4}{5}g_{ik}\alpha_{p_i}(1+e_{ik})\right]^2+\frac{p_{p_i}\sin\theta_i}{2\sqrt{I_{2D}}} \tag{8}$$

3. Solid bulk viscosity [33]

$$\lambda_{p_i}=\frac{4}{3}\alpha_{p_i}\rho_{p_i}d_{p_i}g_{ik}(1+e_{ik})\sqrt{\frac{\Theta_{p_i}}{\pi}} \tag{9}$$

4. Diffusion coefficient of granular energy [31]

$$k_{\Theta_{p_i}}=\frac{150\rho_{p_i}d_{p_i}\sqrt{\Theta_{p_i}\pi}}{384(1+e_{ik})g_{ik}}\left[1+\frac{6}{5}\alpha_{p_i}g_{ik}(1+e_{ik})\right]^2+2\rho_{p_i}\alpha_{p_i}^2d_{p_i}(1+e_{ik})g_{ik}\sqrt{\frac{\Theta_{p_i}}{\pi}} \tag{10}$$

5. Collisional energy dissipation [33]

$$\gamma_{\Theta_{p_i}}=\frac{12\left(1+e_{ik}^2\right)g_{ik}}{d_{p_i}\sqrt{\pi}}\rho_{p_i}\alpha_{p_i}^2\Theta_{p_i}^{3/2} \tag{11}$$

6. Radial distribution function

$$g_{ik}=\frac{d_{p_i}g_{p_k}+d_{p_k}g_{p_i}}{d_{p_i}+d_{p_k}},g_{p_i}=\frac{d_{p_i}}{2}\sum_{k=1}^{2}\frac{\alpha_{p_k}}{d_{p_k}}+\left[1-\left(\frac{\alpha_p}{\alpha_{p,\max}}\right)^{\frac{1}{3}}\right]^{-1},\alpha_p=\sum_{k=1}^{2}\alpha_{p_k} \tag{12}$$

Table 1 (*continued*)

Governing equations

$\alpha_{p,\max}$ is determined by the correlations proposed by Fedors and Landel [34] with $d_{p_i}>d_{p_k}$, $X_i=\frac{\alpha_{p_i}}{\alpha_p}$:

for $X_i\le\frac{\alpha_{p_i,\max}}{\alpha_{p_i,\max}+\left(1-\alpha_{p_i,\max}\right)\alpha_{p_k,\max}}$

$$\begin{aligned}\alpha_{p,\max}=&\left[\alpha_{p_i,\max}-\alpha_{p_k,\max}+\left(1-\sqrt{\frac{d_{p_k}}{d_{p_i}}}\right)\left(1-\alpha_{p_i,\max}\right)\alpha_{p_k,\max}\right]\\&\times\left[\alpha_{p_i,\max}+\left(1-\alpha_{p_i,\max}\right)\alpha_{p_k,\max}\right]\frac{X_i}{\alpha_{p_i,\max}}\alpha_{p_k,\max}\end{aligned} \tag{13}$$

otherwise

$$\alpha_{p,\max}=\left(1-\sqrt{\frac{d_{p_k}}{d_{p_i}}}\right)\left[\alpha_{p_i,\max}+\left(1-\alpha_{p_i,\max}\right)\alpha_{p_k,\max}\right](1-X_i)+\alpha_{p_i,\max} \tag{14}$$

7. Gas–solid drag coefficient [31]

$$\beta_i=150\frac{\alpha_{p_i}\left(1-\alpha_g\right)\mu_g}{\alpha_g{d_{p_i}}^2}+1.75\frac{\rho_g\alpha_{p_i}\left|\overrightarrow{v_g}-\overrightarrow{v_{p_i}}\right|}{d_{p_i}},\alpha_g\le 0.8 \tag{15}$$

$$\beta_i=\frac{3}{4}C_D\frac{\alpha_g\alpha_{p_i}\rho_{p_i}\left|\overrightarrow{v_g}-\overrightarrow{v_{p_i}}\right|}{d_{p_i}}{\alpha_g}^{-2.65},\alpha_g>0.8 \tag{16}$$

$$C_D=\begin{cases}\frac{24}{\mathrm{Re}_{p_i}}\left(1+0.15\left(\mathrm{Re}_{p_i}\right)^{0.687}\right) & \left(\mathrm{Re}_{p_i}\le 1000\right)\\ 0.44 & \left(\mathrm{Re}_{p_i}>1000\right)\end{cases} \tag{17}$$

$$\mathrm{Re}_{p_i}=\frac{\alpha_g\rho_g\left|\overrightarrow{v_g}-\overrightarrow{v_{p_i}}\right|d_{p_i}}{\mu_g} \tag{18}$$

8. Solid-solid drag coefficient [15]

$$\zeta_{ik}=\frac{3(1+e_{ik})\left(\frac{\pi}{2}+C_{fr,ik}\frac{\pi^2}{8}\right)\alpha_{p_i}\rho_{p_i}\alpha_{p_k}\rho_{p_k}\left(d_{p_i}+d_{p_k}\right)^2g_{ik}}{2\pi\left(\rho_{p_i}d_{p_i}^3+\rho_{p_k}d_{p_k}^3\right)}\left|\overrightarrow{v_{p_i}}-\overrightarrow{v_{p_k}}\right| \tag{19}$$

same particle species and between different particle species (particle–particle drag in Eulerian–Eulerian approach), was found to play an important role in governing the segregation of particles. Therefore, to successfully simulate the segregation and mixing of binary particle mixtures with the Eulerian–Eulerian method, the particle–particle drag should be accounted accurately.

Recently, it was found that the frictional sliding effects in the particle–particle drag should be considered in the dense fluidized beds. Gera et al. [6,7] introduced the 'hindrance effect' term and Chao et al. [12,13] proposed a large correction coefficient to account for the particle frictional sliding effects. However, these methods only considered the long-term enduring frictional sliding/rolling contacts in the plastic regime ($\alpha_g \le {\alpha_g}^*$) [6,7] or when the total solid volume fraction was over 0.56 [12,13], while the short-term frictional sliding effect during particle collisions haven't attract much attention. Although different particle–particle drag models [12,14–21] have been reported in the literatures, only the Syamlal particle–particle drag model [15] has accounted this effect by the Coulomb's law of friction including the