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Investigation of mixing behaviors in a spouted bed with different density particles using discrete element method

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ABSTRACT

This paper presents the mixing behaviors of binary particle mixtures with equal diameter and different density within a spouted bed by three-dimensional coupled computational fluid dynamics (CFD) and discrete element method (DEM).The particle motion is modeled by the DEM, and the gas motion is modeled by the $k-\varepsilon$ two equation turbulent model. The numerical computation is based on a cylindrical spouted bed which the inside diameter, height and conical base are 200 mm, 700 mm, and 60°, respectively. Binary particle mixtures are composed of spherical particles with equal diameter of 4 mm and the heavy-over-light density ratio ranges from 1 to 4. The mixing process, evaluation of mixing quality, particle circulation and distribution of particle concentration along both radial and axial directions are obtained on the basis of simulations. The mixing process is illustrated by the development of solid flow patterns with time. The results show that the process of particle mixing mainly contains three stages: macro-mixing stage, micro-mixing stage and stable mixing stage. The mixing quality is described by Lacy mixing index, and is evaluated by two parameters: mixing degree at the mixing equilibrium phase and the time required reaching the steady value. The effect of sample size act on the mixing degree is also investigated and an optimum size is found. The results show that the mixing quality increases with increasing of gas velocity and decreases with increasing particle density differences of the binary mixture. By comparing the typical trajectories for two tracer particles with different densities, the mixing mechanism is further analyzed. Besides, the mixing rate in radial and axial directions is characterized by the time required for the concentration of the mixtures constituent to maintain a basic equilibrium. It is found that the mixing process along the axial direction is slower than that of the radial direction, and in both directions, mixture with smaller component density difference shows a higher mixing rate and better mixing uniformity.

1. Introduction

The spouted bed technique, which was originally developed as a method for drying granular solids, has proved to be a promising technology. As an effective configuration, spouted bed was greatly regarded for its ability of carrying out a remarkably wide range of applications [1,2]. In the early applications of spouted bed, particles with uniform density and narrow size distributions were generally used. However, the application of spouted bed has been significantly extended in recent years: two or more types of particles with different density and size are present simultaneously. For example, the coating of prosthetic devices by pyrolytic carbon formed by high temperature pyrolysis of hydrocarbons. The bed in this process consists of spherical heat carrier particles which have to be continuously renewed in order to achieve steady state condition [3]. Likewise, in the flash pyrolysis of biomass, a small proportion of sand is always mixed with the biomass and used as inert solids to promote solids circulation. Furthermore, the spent char particles are of lower density than the nonconverted particles, knowledge of the mixing behavior is needed to promote the extraction of char particle [4].

Compared with the fluidized bed, the spouted bed allows for the treatment of particulate materials which are coarser in size and narrower in particle size distribution. Moreover, the spouted bed has its unique characteristics, including good particle circulation, effective fluid–particle contact, high rates of heat and mass transfer, making spouted bed capable of performing certain biomass processes more effectively than fluidized bed. However, the mixing behavior of particles in spouted beds is very complicated and unique, since particles undergo cyclic recirculation between the spout, annulus and fountain regions, each region is with a specific flow behavior. Many studies have been made in the past in order to better understand the mixing mechanism and predict the behavior of mixing in the spouted bed., such as the investigation of factors affecting the mixing, including variations of solids [5,6], the variations of operating conditions [3,7,8], the characteristics of mixing equipment [9], and the development of empirical and theoretical correlations and models [10–12].

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However, experimental analysis of particle mixing behavior in spouted bed is frequently restricted by the practical conditions, and a series of errors may occur during the research work. For example, the sampling errors caused by the sampling method, including the locations of sampling, the sample size and the number of samples; the lack of particle-scale information, such as trajectories of particles at any arbitrary positions. Moreover, the requirement of particle properties can be hardly satisfied on experimental test (i.e. particle diameter and density).

Numerical simulation is considered to be a useful tool to obtain detailed information on dense gas–solid flow without disturbing the flow field. One of the most attractive approaches is the CFD–DEM (Computational Fluid Dynamics–Discrete Element Method). It can provide dynamic information, such as the trajectories of and transient forces acting on individual particles, which is extremely difficult to obtain by physical methods [13,14]. Therefore, CFD–DEM approach has been developed rapidly from 1990s, and is fully proved to be unparalleled and with great versatility.

The CFD–DEM approach is especially suitable to provide an insight into the solid mixing in dense gas–solid flows. For the DEM algorithm allows the dynamic simulation of the solid phase motion by tracking individual particles along the system, this function provides the possibility to investigate the mixing behavior of spouted beds by endowing these solids with different densities. But the existed analyzed dedicated to the study of the particle mixing by CFD–DEM are concentrated in fluidized bed. Most of them studied the mixing behavior of a single species [15–19], only a few studies are focus on binary mixtures of particles of different size or density [20–23]. Some general knowledge has been obtained, for example, jetsam (larger or heavier particles) tends to accumulate in bottom de-fluidized layer, while flotsam (smaller or lighter particles) tends to move to top fluidized layer, the density ratio has a strong influence on the mixing quality. However, studies of the mixing process in spouted bed is still limited, Zhang et al. [24] investigated the particle mixing behavior in a spout-fluid bed, Zhu et al. [25] studied the mixing characteristics of the dry and wet particles in a rectangular spouted bed. However, both of them are dealing with the constituents of uniform particles. Therefore, to overcome this gap, there is a need to analyze the effect of density difference between the two solids in the spouted bed by CFD–DEM.

The objective of the present work is to study the mixing mechanism in a cylindrical spouted bed with a conical base by 3D CFD–DEM simulation. In particular, the standard $k-\varepsilon$ two equation model is coupled to model the turbulent gas solid flow. This study is focusing on investigating the effects of component density ratio and spouting gas velocity on the particle mixing quality, the distribution of axial and radial particle concentration degree. Particle mixing process of the proposed spouted bed is discussed based on analyzing the flow patterns. Besides, there is a further comparison and analysis about the trajectories of selected individual particles.

2. Computational models

The DEM has been proved as a powerful approach to investigate the mixing process as it can provide precise description of both particle–particle and particle–wall interaction and fluid–particle interaction. In the present model, the motion of each individual particle is calculated from the Newton's equation, the translational and rotational motions of particle i are given by

$$m_i \frac{d\vec{v}_{pi}}{dt} = m_i \vec{g} + \vec{F}_{C,i} + \vec{F}_{D,i} + \vec{F}_{LS,i} + \vec{F}_{LM,i} \tag{1}$$

$$I_i \frac{d\vec{w}_{pi}}{dt} = \sum_{j=1}^{n_i} \left(\vec{T}_{tij} + \vec{T}_{nij} \right) \tag{2}$$

$\vec{v}_{pi}$ is the velocity of particle i, $\vec{w}_{pi}$ is the rotational velocity of particle i and I_i is the inertia of particle. Torques $\vec{T}_{tij}$ and $\vec{T}_{nij}$ are generated by the tangential forces and the rolling friction, respectively [26].

The total force acting on particle i due to particle collision is denoted as F

$$\vec{F}_{C,i} = \sum_{j=1}^{n} \left(\vec{F}_{cnij} + \vec{F}_{ctij} + \vec{F}_{dnij} + \vec{F}_{dtij} \right). \tag{3}$$

The Hertz–Mindlin no-slip model is applied on the normal contact force $\vec{F}_{cnij}$ and the tangential contact force $\vec{F}_{ctij}$. It is based on the classical Hertz's theory [27] for normal direction and the simplifications from the model developed by Mindlin and Deresiewicz [28] for tangential direction. While the normal and tangential damping force, $\vec{F}_{dnij}$ and $\vec{F}_{dtij}$, are cited from Raji [29].

The particle–fluid interaction forces in Eq. (1) include the drag force, Magnus lift force and Saffman lift force, which are defined as $\vec{F}_{D,i}$, $\vec{F}_{LS,i}$ and $\vec{F}_{LM,i}$ respectively. The detailed information is listed in Table 1.

It's noticeable that the Magnus lift force and Saffman lift force are considered, as they contribute to the entrainments of particles from the annulus dense region into the spout region, which can lead to a continuous and stable spout in the bed. According to our previous studies, the mean percentage of the sum of the lift forces exceeds 10% of the total force in the spout region and the interface between the spout and the annulus region.

The continuum fluid field is calculated from the continuity equation and the Navier–Stokes equation based on the local mean variables over a computational cell, as given respectively by

$$\frac{\partial}{\partial t}\left(\varepsilon\rho_g\right) + \nabla\cdot\left(\varepsilon\rho_g\vec{u}_g\right) = 0 \tag{4}$$

$$\frac{\partial}{\partial t}\left(\varepsilon\rho_g\vec{u}_g\right) + \nabla\cdot\left(\varepsilon\rho_g\vec{u}_g\cdot\vec{u}_g\right) = -\nabla p + \nabla\cdot\left(\varepsilon\overline{\overline{\tau}}\right) - S_P + \varepsilon\rho_g\vec{g}\,. \tag{5}$$

Where ρ_g and $\vec{u}_g$ are the gas density and the gas velocity vector, ε, p and $\overline{\overline{\tau}}$ are the local void fraction, the static pressure and the fluid viscous stress tensor, respectively. The local void fraction ε is of a considered computational cell is the ratio of the void volume to the volume of the cell, $\varepsilon = 1-\sum_{i=1}^{n_p} V_i/\Delta V$ where n_p indicates the number of

Table 1
Forces acting on particle i.

Forces	Equations
Normal contact force, $\vec{F}_{cnij}$	$\vec{F}_{cnij} = \frac{4}{3}E_{eq}\sqrt{R_{eq}}\delta_{nij}^{3/2}$
Normal damping force, $\vec{F}_{dnij}$	$\vec{F}_{dnij} = -2\sqrt{\frac{5}{6}}\psi\sqrt{S_n m_{eq}}\vec{v}_{nij}$
Tangential contact force, $\vec{F}_{ctij}$	$\vec{F}_{ctij} = S_t\delta_{tij}$
Tangential damping force, $\vec{F}_{dtij}$	$\vec{F}_{dtij} = -2\sqrt{\frac{5}{6}}\psi\sqrt{S_t m_{eq}}\vec{v}_{tij}$
Drag force, $\vec{F}_{D,i}$	$\vec{F}_{D,i} = \frac{\beta}{\rho_g}\left(\vec{u}_g - \vec{v}_{p,i}\right)$
Saffman lift force, $\vec{F}_{LS,i}$	$\vec{F}_{LS,i} = 1.615\left(\vec{u}_g - \vec{v}_{p,i}\right)\left(\rho_g\mu_g\right)^{0.5} d_p^2 C_{LS}\sqrt{\left\lvert\frac{\partial u_g}{\partial n}\right\rvert}\,\mathrm{sgn}\left(\frac{\partial u_g}{\partial n}\right)$
Magnus lift force, $\vec{F}_{LM,i}$	$\vec{F}_{LM,i} = \frac{1}{8}\rho_g v_r^2\pi d_p^2 C_{LM}\frac{\vec{w}_r\times\vec{v}_r}{\lvert\vec{w}_r\rvert\cdot\lvert\vec{v}_r\rvert}$
Where	$R_{eq} = \left[\frac{1}{R_i}+\frac{1}{R_j}\right]^{-1}$, $E_{eq} = \left[\frac{\left(1-\gamma_i^2\right)}{E_i} + \frac{\left(1-\gamma_j^2\right)}{E_j}\right]^{-1}$, $G_{eq} = \left(\frac{1-\gamma_i}{G_i} + \frac{1-\gamma_j}{G_j}\right)^{-1}$,
$S_t = 8G_{eq}\sqrt{R_{eq}\delta_{nij}}$, $S_n = 2E_{eq}\sqrt{R_{eq}\delta_n}$, $\psi = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}$	