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Three-dimensional multi-phase simulation of the mixing and segregation of binary particle mixtures in a two-jet spout fluidized bed

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ABSTRACT

This study presents a three-dimensional numerical study of the mixing and segregation of binary particle mixtures in a two-jet spout fluidized bed based on an Eulerian–Eulerian three-fluid model. Initially, the particle mixtures were premixed and packed in a rectangular fluidized bed. As the calculation began, the gas stream was injected into the bed from the distributor and jet nozzles. The model was validated by comparing the simulated jet penetration depths with corresponding experimental data. The main features of the complex gas–solid flow behaviors and the mechanism of mixing and segregation of the binary mixtures were analyzed. Moreover, further simulations were carried out to evaluate the effects of operating conditions on the mixing and segregation of binary particle mixtures. The results illustrate that mixing can be enhanced by increasing the jet velocity or enlarging the difference of initial proportions of binary particle mixtures.

Introduction

Owing to its advantages of heat and mass transfer, gas–solid mixing, and fuel adaptability, the spout fluidized bed has been widely applied in chemical, energy, and environmental industries (Borini, Andrade, & Freitas, 2009; Calo, Madhavan, Kirchner, & Bain, 2012; El-Naas, Al-Zuhair, & Makhlouf, 2010; Olazar, Arandes, Zabala, Aguayo, & Bilbao, 1997). Materials in spout fluidized bed reactors often consist of multi-component particle mixtures with different densities and/or sizes. To achieve optimal operation for maximal industrial efficiency, it is important to understand the flow hydrodynamics of multi-component particle mixtures in spout fluidized bed reactors.

With advancing developments in numerical methods and computational technology, numerical simulation has become an attractive technique for predicting the dynamics characteristics in gas–solid fluidized beds. The implementation of gas–solid multi-phase modeling mainly involves two approaches: Eulerian–Lagrangian and Eulerian–Eulerian (Benyahia, Arastoopour, Knowlton, & Massah, 2000; Goldschmidt, Beetstra, & Kuipers, 2002; Takeuchi, Wang, & Rhodes, 2004; Yang, Luo, Fang, Zhang, & Fan, 2014; Zhang, Brandani, Bi, & Jiang, 2008).

The Eulerian–Lagrangian approach is based on the particle trajectories and involves solving the equation of motion for each particle, considering the collision of particles and the forces acting on the particles (Azadi, 2011). The discrete element method (DEM) is one of its applications in the fluidized bed field. Cundall and Strack (1979) carried out pioneering work on this discrete numerical model for granular assemblies. More recently, Feng and Yu (2007) studied the mixture and separation characteristics of two-component particles in a fluidized bed, and Ren, Zhong, Jin, Yuan, and Lu (2011) simulated gas–solid turbulent flow in a cylindrical spouted bed. In theory, this approach is ideal because it can not only reproduce flow patterns comparable to physical experiments, but also give quantitative dynamics information. However, with current computational power, DEM simulations are too computationally expensive to be applied in engineering practices (Knowlton, Karri, & Issangya, 2005; Pei, Zhang, Ren, Wen, & Wu, 2010). Presently, researchers tend to use particle clusters instead of actual particles to reduce the number of particle cell and the ultimate computation cost. However, such simplifications will inevitably result in the distortion of simulation results.

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Nomenclature

C	friction coefficient
C_D	drag coefficient
d_p	mean particle diameter (m)
e	coefficient of restitution
g	radial distribution coefficient
$\vec{g}$	gravity acceleration (m/s^2)
G_k	production of turbulent kinetic energy (kg/m s^3)
K	momentum exchange coefficient
P	pressure (Pa)
Re	Reynolds number
u_e	elutriation velocity of mono-particle material (m/s)
$u_{\rm dis}$	gas velocity of distributor (m/s)
$u_{\rm ff}$	full fluidization velocity of binary mixtures (m/s)
$u_{\rm if}$	initial fluidization gas velocity (m/s)
$u_{\rm jet}$	gas velocity of jet (m/s)
$u_{\rm mf}$	minimum fluidization gas velocity (m/s)
$\vec{v}$	instantaneous velocity (m/s)
V_b	volume fraction of RE2 in particle mixtures

Greek letters

α	volume fraction
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
$\varepsilon_{\rm mf}$	minimum fluidization voidage
Θ	granular temperature (m^2/s^2)
κ	turbulent kinetic energy (m^2/s^2)
μ	viscosity (kg/m s)
ξ_p	particle phase bulk viscosity (kg/m s)
ρ	density (kg/m^3)
Π	turbulence exchange terms between the gas and solid phases
$\bar{\bar{\tau}}$	stress–strain tensor (Pa)

Subscripts

g	gas phase
p	solid phase *p*
s	solid phase *s*

The Eulerian–Eulerian approach, because of its much lower CPU and memory space requirements, is becoming an increasingly popular method to predict complicated gas–solid flow behaviors in fluidized beds. In this approach, the solid phase is considered to be a continuous phase interpenetrating and interacting with the gas phase, and each solid phase has an independent density, size, and other properties (Fan & Fox, 2008). However, only a few studies have been conducted in a multi-phase flow field. Cooper and Coronella (2005) took the lead in building a multi-fluid model of a fluidized bed. By comparing their calculated results with DEM and experimental methods, Fan and Fox (2008) proved the feasibility of the Eulerian–Eulerian multi-phase model for the simulation of multi-component fluidized beds. Coroneo, Mazzei, Lettieri, Paglianti, and Montante (2011) predicted the main features of binary segregating fluidized beds of particles differing in size and density. However, to simplify the theoretical models and reduce the computational time, the three-dimensional fluidized beds in their simulations were all simplified as two-dimensional, which could lead to relatively large deviations because of the different influences of the bed walls, the geometry on the flow pattern, and other aspects (Asegehegn, Schreiber, & Krautz, 2012; Van der Hoef, van Sint Annaland, & Kuipers, 2004; Villa Briongos & Guardiola, 2005). Moreover, the reactors they modeled are all conventional bubbling fluidized beds having uniform distributions, rather than spout fluidized beds with unique flow patterns. Therefore, it is necessary to develop three-dimensional Eulerian–Eulerian multi-phase models to predict flow characteristics in spout fluidized beds.

In this study, a comprehensive three-dimensional Eulerian–Eulerian three-fluid model was developed to study the fluidization characteristics and jet dynamics of binary particle mixtures in a two-jet spout fluidized bed. The main features of the complex gas–solid flow behaviors and the mechanisms of mixing and segregation of the binary particle mixtures were deeply analyzed. Moreover, further simulations were performed to evaluate the effects of operating variables on mixing and segregation of binary particle mixtures. Model validation was also accomplished by comparing the simulated jet penetration depths with corresponding experimental data (Pei et al., 2011). The combination of the multi-phase flow model with a three-dimensional geometry in this study provides a more reliable simulation for the multi-component fluidized bed.

Model description and simulation method

As shown in Fig. 1, the experimental apparatus is a rectangular two-jet spout fluidized bed with a cross-section area of 0.30 × 0.025 m^2 and a total height of 2.30 m. Two rectangular nozzles 0.01 m wide and 0.025 m long are symmetrically arranged at the bottom of the bed and separated by a distance of 0.09 m (center-to-center distance). More details about this device can be found elsewhere (Pei et al., 2011).

The CFD simulations in this work were based on the Eulerian–Eulerian multi-phase model. In this model, equations were written under incompressible, isothermal, turbulent flow conditions. The equations of continuity and momentum balance for each computation cell are described next.

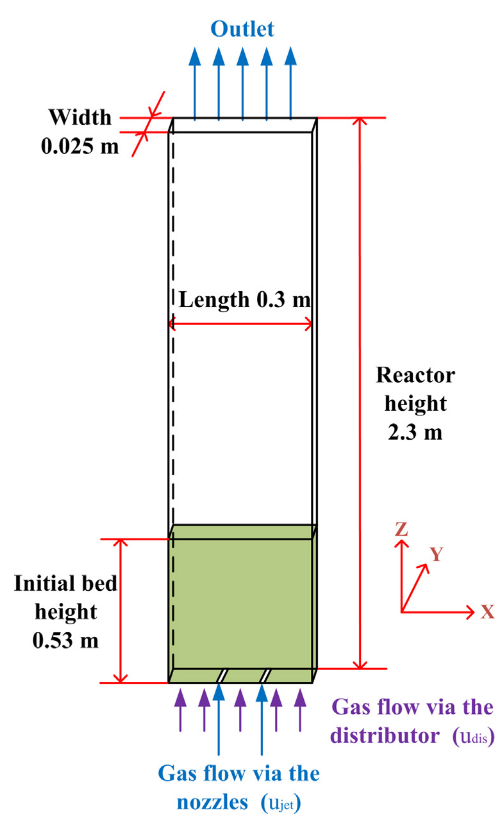

Fig. 1. Sketch of the rectangular two-jet fluidized bed.