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CFD investigation of particle fluctuation characteristics of bidisperse mixture in a gas–solid fluidized bed

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HIGHLIGHTS

- ▶ We simulate the dynamic behavior of a bidisperse mixture by multi-fluid CFD model.
- ▶ The laminar and turbulent granular temperature of flotsam and jetsam is calculated.
- ▶ The computed vertical turbulent energy spectra of flotsam and jetsam are analyzed.
- ▶ The intermittence variation with operation conditions is shown by flatness factor.
- ▶ The diffusivities for flotsam and jetsam are calculated to measure the mass transfer.

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ABSTRACT

Particle fluctuation characteristics of a bidisperse mixture in a gas–solid fluidized bed by the multi-fluid Eulerian–Eulerian model in CFD simulation have been presented. The numerical method is verified by solid volume fraction and granular temperature experimental data from literature. The laminar and turbulent granular temperature profiles of flotsam and jetsam at different gas velocities are calculated, connecting with bubble and particle hydrodynamic behavior and flow pattern in the fluidized bed. The computed vertical turbulent energy spectra of flotsam and jetsam are compared and applied to indicate the particle motion intensity and inhomogeneity of turbulent energy dissipation. The energy spectra capture the Levy–Kolmogorov law in inertial range at high frequency. The flatness factor of wavelet decomposition coefficients of particle fluctuating velocity is shown to analyze the flow field intermittence variation with position and gas velocity. Moreover, the diffusivities for flotsam and jetsam are calculated to measure the mass transfer quality of particles.

1. Introduction

Fluidized beds are widely used in various commercial processes including chemical, petroleum, biochemical and food industries because of their large areas of contact between different phases which enhances the chemical reactions. However, the precise analysis of the flow field has not been achieved yet because of the complex phenomena between gas and particles (Lu et al., 2003). In many cases, industrial gas–solid fluidized beds treat polydisperse mixtures of particles with broad distributions of size and/or density. These mixtures of particles can segregate over a wide range of superficial velocities, which is important in classifiers (Olivieri et al., 2009). Particles that sink towards the bottom are known as jetsam, while those rising towards bed surface are called flotsam. Particle segregation is strongly related to the particle fluctuation and bubble motion. Therefore, in order to obtain detailed knowledge about the polydisperse mixture hydrodynamics in the fluidized bed, we need to investigate the characteristics of particle fluctuation, bubble formation and bubble growth.

Granular temperature is a parameter that describes the random motion of a dense dusty gas of particles in a fluidized bed (Campbell, 1990, which is calculated by particle fluctuating velocity. The granular temperature can be obtained by acoustic shot noise (ASN) technique (Cody et al., 1996), CCD technique (Gidaspow and Huilin, 1998), PIV technique (Tartan and Gidaspow, 2004) and laser Doppler velocimetry (LDV) (Pandey and Turton, 2006). According to experimental results, two kinds of granular temperature exist. The first is the laminarlike granular temperature due to individual particle oscillations, and the second is the turbulent granular temperature caused by motion of particle clusters or bubbles (Gidaspow et al., 2004). In bubbling and turbulent fluidized beds, the turbulent granular temperature calculated from Reynolds normal stresses is much larger than the

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laminarlike granular temperature. Due to the difficulty in identifying the granular temperature of different kinds of particles, there are seldom experimental granular temperature data for bidisperse or polydisperse systems. Wildman and Huntley (2000) use a video camera to measure the two granular temperatures in a binary vibrofluidized bed. However, it is not applied in gas–solid bubbling and turbulent fluidized bed.

Another important parameter determining the two-phase mixing and transferring characteristics is the particle turbulent energy. It expresses as the particle Reynolds normal and shear stress. Cui and Fan (2004, 2005) analyze the turbulent energy distribution in gas–liquid and gas–liquid–solid flow systems, indicating the Kolmogorov $-5/3$ law obeyed in the inertial range of energy spectrum. However, in the low Reynolds number flow, the Kolmogrov $-5/3$ law will be deviated due to the intermittent nature of the turbulent energy dissipation rate (Camussi and Guj, 1997). Meanwhile the Levy–Kolmogrov law (Chen and Zhou, 2005) is obeyed. Intermittence is related to the presence of rare but strong velocity gradients that are generated by highly coherent structures (She et al., 1991). In homogeneous flow, the intermittence is measured by the flatness factor of wavelet decomposition coefficients of fluctuation velocity (Onorato et al., 2000; Jiang and Zhang, 2005).

To represent the powder handling ability and mass transfer characteristics of a fluidized bed, the particle diffusivity or dispersion coefficients are introduced. A review of the literatures (Bi et al., 2000; Du et al., 2003) shows that they vary by five orders of magnitude and there exists no reliable predictive theory for estimating these diffusivities. The diffusivity is usually obtained by formulas in monodisperse particle systems (Ruckenstein, 1966; Shi and Fan, 1985; Gidaspow, 1994), however, the diffusivity of bidisperse mixture in a gas–solid fluidized bed has not been calculated yet.

The modeling of fluidized bed is challenging because of the complex fluid dynamic behavior of dense multiphase systems. In recent years, computational fluid dynamics (CFD) has become a powerful tool for gas–solid flow simulation. The kinetic theory of granular flow (KTGF) based Eulerian–Eulerian model has been widely applied in gas–solid bed simulation (Ahuja and Patwardhan (2008)) analyze; Li et al., 2009; Hamzeheiand Rahimzadeh 2009; Hosseini et al., 2010) and dynamic parameter calculation. For polydisperse systems, Goldschmidt et al. (2001) use a multi-fluid Eulerian model to study the influence of restitution coefficient on the segregation behavior of dense gas–solid fluidized bed. Lu et al. (2001, 2003) give an extension to binary mixtures of particulate material in a riser and in a bubbling fluidized bed using kinetic theory of dense gases, involving kinetic theory with unequal granular temperatures between different particle phases. van Sint Annaland et al. (2009) calculate the granular temperature of the segregating system by a new multi-fluid model and the discrete particle model. The results of the two models agree reasonably well. Although the laminar and turbulent granular temperatures of monodisperse particles in gas–solid fluidized bed have been calculated (Jiradilok et al., 2006; Chalermsinsuwan et al., 2009; Chalermsinsuwan et al., 2011), it still receives limited attention on these two kinds of granular temperature for bidisperse mixture.

In order to investigate the fluctuation of hydrodynamic parameters with frequency, the power spectrum is applied in the simulated results. Ding and Gidaspow (1990) first predict the instantaneous porosities and compare the power spectrum of porosity oscillation with experimental results. Chandrasekaran et al. (2005) compare the CFD simulated and experimental pressure fluctuation power spectrum, and find the power law relationships are different for the simulated and experimental data. Jiradilok et al. (2006, 2008) compute the particle turbulent energy spectrum in a riser. Sun et al. (2011) calculate the particle vertical turbulent energy spectrum in a turbulent fluidized bed. The Levy–Kolmogorov law is obeyed in the inertial range and indicates the intermittence of flow field. However, the particle energy spectrum and intermittence of bidisperse mixture flow field has not been investigated.

In this paper, the particle fluctuation characteristics of bidisperse mixture in a gas–solid fluidized bed are simulated by the multi-fluid Eulerian–Eulerian model based on KTGF. The experimental data of volume fraction and granular temperature profiles in literature are used to verify the model. The laminar and turbulent granular temperatures of flotsam and jetsam at different gas velocities are calculated, in order to obtain the particle and bubble hydrodynamic information. The computed particle turbulent energy spectrum is proposed to describe the particle motion intensity and inhomogeneity of turbulent energy dissipation, while the flatness factors of wavelet decomposition coefficients of particle fluctuation velocity are applied to represent the intermittence of flow field. Based on the simulated granular temperature and volume fraction, the diffusivities of flotsam and jetsam are calculated. In addition to determine the bubble behavior and its effects on particle motion at different gas velocities, the volume fraction distributions of gas and jetsam are analyzed. This work provides an exploration of particle fluctuation characteristics of the bidisperse mixture in a gas–solid fluidized bed by CFD simulation.

2. Apparatus and materials

In this work, the experimental system investigated by Olivieri et al. (2004) is studied. The experimental apparatus is 120 mm wide and 1500 high, whose lower part is made up of an assembly of cylindrical segments, dividing the bed into six parts to measure the mixture composition. The particle mixture in the fluidized bed is composed of two Geldart B group particle phases differing in size and density (System 1 in Olivieri's work). The first phase named jetsam has a mean diameter of 125 μm and density of 2600 kg/m^3, while the second phase named flotsam has a mean diameter of 375 μm and density of 600 kg/m^3. Before fluidization the bed is filled with a mixture at jetsam volume fraction $X_{j0}=0.2$. As stated by Chiba et al. (1980) and Yang (2003), the density differences usually overtake size differences. Therefore, in this mixture, the particles with smaller diameter but high density act as jetsam.

In Olivieri's experiments (Olivieri et al., 2004), the fluidized bed is operated at ambient pressure and temperature. In the initial state, the bed is packed and completely mixed. The bed height is 144 mm and the gas volume fraction equals to 0.4. After the fluidized bed reached the steady state, the bed is "frozen" by suddenly cutting off the fluidizing gas supply. The cylindrical segments are then disassembled one at a time to obtain the axial distributions of solids.

3. CFD model and simulation method

In the present work, a multi-fluid model based on the Eulerian–Eulerian approach is developed to describe the segregation/mixing behavior of bidisperse mixture in a gas–solid fluidized bed (Coroneo et al., 2011). The multi-fluid model is based on the extended two-fluid model, which depicts the turbulence of particle phases by the kinetic theory of granular flow. With this approach, both the gas phase and particle phases are considered as inter-penetrating continua. The gas phase is the primary phase while the particle phases are second or dispersed phases. Each