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Simulation of particle mixing and segregation in bidisperse gas fluidized beds

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HIGHLIGHTS

- The axial segregation in hydrodynamic models of binary mixtures has been studied.
- Detailed comparisons have been made between DEM and experimental results.
- Some comparisons have been made between MFM and experimental results.
- Focus has been made on the role of drag relation in axial segregation.
- The drag relation from DNS performed better.

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ABSTRACT

The mixing and segregation of particles of various types in gas–solid fluidized beds is a common phenomenon that is observed in experimental investigations. Generally, it is necessary to understand the phenomenon of mixing and segregation in gas-fluidized beds for the optimal design operation and scale-up of many industrial processes. To gain more insight into these, bed dynamics have been studied using a fully coupled Computational Fluid Dynamics/Discrete Element Method model (CFD/DEM), in which the particles are tracked individually using Newton′s law of motion, and a newly developed continuum-based Multi-Fluid Model [MFM, van Sint Annaland et al. (2009a). Chem. Eng. Sci. 64, 4222–4236]. Rigorous comparisons have been made between results from laboratory experiments and the CFD/DEM and MFM. The CFD/DEM was found to reliably predict the segregation rates in low beds, provided that an appropriate gas-particle drag relation is used that accounts for the effect of polydispersity.

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1. Introduction

In the past 20 years, the use of simulation models in the study of gas–solid fluidized systems has become increasingly popular. Initially, models in which the gas and solid phases were treated as interpenetrating continua were developed. These models incorporate the kinetic theory of granular flow, which is essentially an extension of the kinetic theory of dense gases to that of inelastic particles. Though the continuum models have been applied to multi-component mixtures, difficulties are encountered due to the large sets of equations that must be solved and more research on the description of the frictional stresses is required to improve the prediction of the model (van Sint Annaland et al., 2009a).

However, in more recent times, with increasing capacity of computational resources, the more detailed Computational Fluid Dynamics/Discrete Element Method (CFD/DEM) was developed. Although limited in scale due to yet some computational limitations, the CFD/DEM can be deployed for systems in which the total number of particles in the system are up to a few millions. The CFD/DEM is essentially an Euler–Lagrangian model in which the solid particles are treated individually with their motion and interactions tracked over time. Tsuji et al. (1993) extended the work of Cundall and Strack′s (1979) to 2D gas-fluidized bed by developing a soft-sphere discrete particle model in which the particle are allowed to overlap slightly from which the contact forces are calculated. Kawaguchi et al. (1998) compared the results from 3D motion of particles to 2D motion in which the particles do not move in the depth direction. Hoomans et al. (1996) used a hard-sphere based DEM to study bubble and slug formation in a 2D gas-fluidised bed. Mikami et al. (1998) studied cohesive powder behavior using an extension of the work of Tsuji et al.

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(1993). Thereafter, several researchers used the CFD/DEM to investigate the segregation behavior of beds with mixtures. Hoomans et al. (1998) further extended an earlier model (Hoomans et al., 1996) to simulate segregation in beds consisting of particles of equal density, but different sizes as well as for systems consisting of particles of equal size, but different densities. Bokkers et al. (2004) successfully predicted experimentally measured segregation rates in their CFD/DEM simulation of bidisperse bed. Feng et al. (2004) developed a CFD/DEM model to study the segregation and mixing of binary mixtures in a gas-fluidized bed of large thickness using periodic boundary conditions for the front and rear walls. More recently, Tagami et al. (2009) used the CFD/DEM to simulate monodisperse, binary and ternary systems. Furthermore, Farzaneh et al. (2011) used a novel Lagrangian particle tracking method to study fuel particle mixing in fluidized beds and Norouzi et al. (2012) used the CFD/DEM to investigate the influence of fines in the segregation behavior of binary mixtures.

Although some of the earlier works did make some comparisons between the CFD/DEM and experiments their scope was rather limited. For a model to be valid, not only must it predict adequately the bubbling characteristics and porosity distribution in a multi-component system but also the degree and rate of mixing and segregation. It is desirable to assess how well the model performs when tested against laboratory experiments with changing bed conditions. In this work, a soft-sphere DEM has been used to study the dynamics of segregation in the bidisperse fluidized beds. The CFD/DEM bed conditions were set equal to those in the experiments of Goldschmidt et al. (2003) and Olaofe et al. (2013). In addition, we also performed additional simulations with a recently developed Multi-Fluid Model (MFM). Detailed comparisons have been made between the simulation and experimental results in this study. Note that the models used in this work were successfully tested for grid dependency previously (CFD/DEM: Link et al., 2005 and MFM: Wang et al., 2009).

2. Computational fluid dynamics/discrete element method (CFD/DEM)

The computational fluid dynamics/discrete element method (CFD/DEM) is essentially the Euler–Lagrange model in which the gas phase is treated as a continuum and the particles are tracked individually by solving the Newtonian equations of motion with a collision model to account for the non-ideal particle–particle and/or particle–wall interactions. Among the advantages of this model are the relative ease of incorporating an arbitrary distribution of particle properties, like size and density, and the possibility of incorporating detailed particle–particle interaction models. However, one major drawback in the use of the CFD/DEM is the limitation of the number of particles resulting from CPU requirements. In the previously developed CFD/DEM (van der Hoef et al., 2006) used in this study the particle–particle interaction are based on the time-step driven soft particle model. The main equations of the model are given in Table 1.

3. The CFD/DEM simulation settings

First, some simulations run were carried out to ascertain the ability of CFD/DEM to predict the segregation dynamics of the experimental beds in Goldschmidt et al. (2003). Thereafter more simulation runs were conducted to study the capabilities of the Euler–Langrange model with respect to reproducing the results reported by Olaofe et al. (2013). In this section, details of the simulation bed settings are given.

Table 1
CFD/DEM model equations in vector notation.

Linear	$m_a \frac{d^2 \mathrm{r}_a}{dt^2} = \mathrm{F}_{contact,a} + \mathrm{F}_{pp,a} + \mathrm{F}_{ext,a}$	(T1-1)
Rotational	$\mathbf{I}_a \frac{d\omega_a}{dt} = \mathbf{T}_a$	(T1-2)
Gas-phase continuity equation		
	$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla \cdot (\varepsilon\rho\mathbf{u}) = 0$	(T1-3)
$\frac{\partial(\varepsilon\rho u)}{\partial t} + \nabla \cdot (\varepsilon\rho uu) = -\varepsilon\nabla P - S_p - \nabla \cdot \left\{ \varepsilon\left(\left(\lambda - \frac{2}{3}\mu \right)(\nabla \cdot u)\bar{I} - \mu(\nabla u + (\nabla u)^T) \right) \right\} + \varepsilon\rho g$		(T1-4)
$S_p = \frac{1}{V} \int \sum_{a=1}^{Npart} \frac{\beta V_a}{1-\varepsilon}(u - v_a)\delta(r - r_a)dV$		(T1-5)

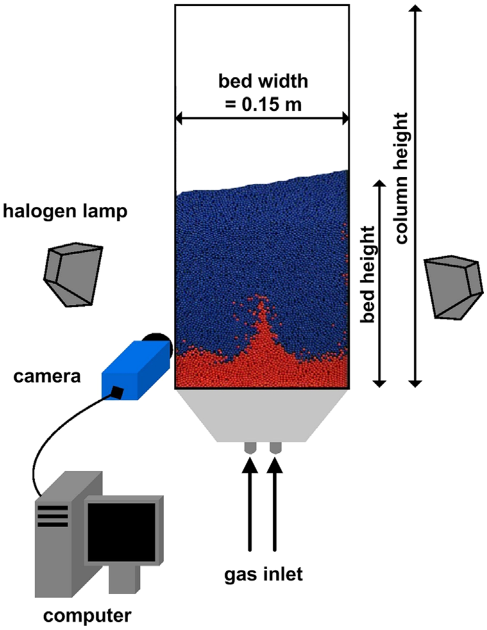

Fig. 1. Schematic of the experimental fluidized bed used by Goldschmidt et al. (2003).

3.1. Goldschmidt et al. (2003) Beds (Cases A–C)

The fluidized beds simulated in this work were set to mimic as closely as possible the conditions reported in the experiments by Goldschmidt et al. (2003). The fluidization experiments were conducted in a bed that was 15 cm wide, 1.5 cm deep and 70 cm high. The bed was made of glass material, and air, to which steam was added to mitigate electrostatic effect in the bed, was applied as the fluidization gas. A schematic representation of the bed in Goldschmidt et al. (2003) is shown in Fig. 1. Colored glass beads of the same density (2526 kg/m^3) but different sizes (1.5 and 2.5 mm) were used in the segregation experiments. The illuminated bed motion was recorded with a color digital video camera at a frame rate of 25 frames per second. The dynamics of segregation was then determined from the aggregate evolution of local mixture compositions, determined via digital image analysis, with time.

Details of the CFD/DEM parameters and the various bed configurations are given in Tables 2 and 3, respectively. In the CFD/DEM simulation of bidisperse beds the size of the computational cell has to conform to two contrasting requirements. One is that the cell should be large enough to give the appropriate estimates of the local void fraction, necessary for calculation of fluid-particle drag, around particles. On the other hand the cell should be fine enough to solve accurately the governing equations

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