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Numerical simulation of 3-phase fluidized bed particle segregation

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HIGHLIGHTS

- CFD simulation of density-based coal beneficiation.
- Experimentally validation of 2D and 3D, 3-phase simulation model.
- Modification of Syamlal-O'Brien drag model and solid–solid restitution coefficients.
- Comparison of 3-phase, 2D versus 3D simulation model performance.

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ABSTRACT

Air dense medium fluidized bed technique has been proposed as a viable technique for dry coal beneficiation with acceptable separation efficiency. In the current work, CFD simulation has been used to provide deeper understanding of the bed hydrodynamics in this system. The simulation results have been compared with the experimental data from sedimentation or flotation of 3.675 mm coal particles in a bed of Geldart group B silica sand particles (390 μm, 2600 kg/m^3). The superficial velocity has been adjusted (between minimum fluidization and minimum bubbling) to keep the bed in the particulate regime. The results of several 2D and 3D Eulerian multiphase CFD models have been evaluated and compared with the experimental data of bed expansion, bubble pattern and frequency, and coal particles density classes. It was found that the modification of the coefficients of Syamlal-O'Brien drag model to 0.52 and 5.30369 and solid–solid restitution coefficient of 0.9 would enhance model predictions for both sand fluidized bed and coal segregation compared to the experimental data. Comparison of the simulation results with experiments showed that 3D simulation model performed 29.1% better than similar 2D models.

1. Introduction

Fluidized bed has been extensively used in different industries for several decades, but modeling of such systems is still a challenging task due to the complexity of the underlying physics. Complex hydrodynamic behavior of gas–solid flows, phase interactions and transient behavior of the systems are some of the challenges of the CFD (computational fluid dynamics) modeling of such systems. In spite of significant progress in CFD-based modeling of fluidized bed systems using multiphase models, currently no systematic guideline is defined for proper model parameter selection [1,2] and the results are needed to be validated against experimental data before being used as industrial design guidelines. Grace and Taghipour [3] discussed some of the challenges involved in gas–solid CFD models validation in their paper. Extensive computational time and expense is another challenge for the CFD models. The 2D models are easier and faster to solve but less accurate than 3D models in representing the reality as some features (e.g. wall effect on motion of bubbles and particles) could not be considered properly in 2D. Preliminary 2D simulations can be used as a way to perfect the methodology for more expensive 3D models that come after [4–6].

Broadly speaking, two different approaches are available for numerical modeling of multiphase flows; the discrete particle model (also called Euler–Lagrange or Lagrangian) approach and the Two-Fluid model (TFM) which is also called Eulerian approach [7,8]. In the Eulerian approach which is the most commonly used approach for fluidized bed simulations with high particle loadings [9], different phases are considered as interpenetrating continua [10,11]. It is computationally cost effective compared to Euler–Lagrange method and also more useful when volume fraction of

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Nomenclature

d_i	particle diameter (m)	C_D	drag coefficient
u	superficial air velocity (m/s)	Re	Reynolds number
g	gravitational acceleration (9.81 m/s^2)	ω_i	coefficient
p	pressure (Pa)	e_{ks}	restitution coefficient (solid–solid)
ρ	density (kg/m^3)	$C_{fr,ks}$	coefficient of friction (solid–solid)
μ	viscosity (Pa s)	$g_{0,ks}$	radial distribution coefficient
α	volume fraction	Θi	granular temperature (m^2/s^2)
$\overline{\overline{\tau_s}}$	stress tensor (Pa)	$\gamma_{\Theta s}$	collisional dissipation of energy
$\underline{\lambda}$	bulk viscosity (kg/s m)	ϕ_{gs}	solid–fluid energy exchange coefficient
$\overline{\overline{I}}$	stress tensor dimensionless	$k_{\Theta s}$	diffusion coefficient of granular energy
K_{gs}	exchange coefficient (gs: gas–solid, ks: solid–solid)	I_{2D}	second invariant of the deviatoric stress tensor

phases are comparable or particles are separating due to body forces such as gravity [7,12,13]. A set of conservation equations (momentum and continuity, etc.) is solved for each phase while pressure and interphase exchange coefficients are used to couple the equations [10,14–16]. In case of the granular flows, the kinetic theory of granular flows is employed to obtain the necessary properties of granular flows, which are treated differently than non-granular flows (fluid–fluid).

The kinetic theory of granular flow which is an extension of the classic dense gas kinetic theory, is the key approach in simulation of dense collection of nearly elastic spherical particles as a continuum. This theory defines pressure and viscosity of the solid phase through empirical relations considering the energy dissipation due to particle–particle and particle–wall collisions by means of restitution and specularity coefficients, respectively. According to this theory particles dissipate energy as a result of inelastic collisions or because of drag force acting between particles and fluid. The granular temperature is defined to measure the random oscillation of the particles (specific kinetic energy of velocity fluctuations), which is the average of the three variances of the particle's instantaneous velocities [17,14,15,18]. The granular temperature of a species varies spatially through the bed according to the degree of motion. The restitution coefficient quantifies the non-ideal collision of particles, resulting in energy loss [19]. This coefficient can vary between 1, for fully elastic collisions, and 0 for fully inelastic collisions. Lower restitution coefficients means less elastic collisions and consequently higher energy dissipation or more fluctuating kinetic energy [17] while higher restitution coefficient means particles energy conservation during collisions. Due to the high volume fraction of particles in dense beds, any individual particle might be involved with several interactions at the same time and the interaction time could be larger than particle mean free flight time [20,21]. Goldschmidt et al. [17] suggested a restitution coefficient of 0.9, instead of 0.99, as collisions between the particles become less ideal for densely packed beds. It has been reported that applying lower restitution coefficient values (amplifying inelastic behavior) results in more particle packing or sharper porosity contours (viscous bed) and larger bubbles while setting restitution coefficient to 1 can eliminate bubbles in the bed [17,22].

Proper wall condition is critical for proper prediction of solid-wall interaction. Johnson and Jackson [23] introduced a wall boundary condition with two key parameters, the specularity coefficient and the particle-wall restitution coefficient. The former one is responsible for the tangential solid velocity while the latter considers the dissipation of energy due to wall collision. The specularity coefficient varies between 0 for free slip or smooth wall and 1 for no-slip or rough wall condition depending mainly on wall material, type of particles used and wall sloping [24,25]. Recent studies show that changes in the specularity coefficient affect particle velocity, spouting behavior, granular temperature and particle volume fraction not only in the region close to the wall but also in the central regions to some extent. However, it has been found in most cases that the predicted overall bed height for different specularity coefficients are similar and its modification does not significantly affect the overall model performance [24,26,27].

In gas–solid systems, the interphase momentum transfer is represented by the drag force. Calculating the drag force is a challenging task when particles move in a dense mixture since they are affected by not only the fluid phase but also the presence of other surrounding particles. Many different drag models are available in the literature namely Syamlal-O'Brien [16,28,29], Gidaspow [14,28], Wen and Yu [30], Arastoopour [31]. It is sometimes necessary to tune the model coefficients based on the particle size or other specific gas–solid characteristics for better performance of the drag for specific situations. The procedure for modifying Syamlal-O'Brien drag model based on the minimum fluidization velocity of the particles is explained by the authors [28].

It should be noted that applied to a spout bed CFD-based modeling using unsteady laminar Euler–Euler based model (no RANS) Syamlal-O'Brien drag model showed the best agreement with experimental data by He et al. [38,39] in comparison to Gidaspow and Wen–Yu models [40]. However, at the same time the use of Gidaspow drag model in an Euler–Euler model coupled with RANS gives better predictions with experimental data, e.g. see the work by Du et al. [41] Finally it should be noted that recently, Zaho et al. [32] simulated Geldart group B [33] particles using two-phase Eulerian model. Bed pressure drop and density stability were used to compare 2D models (using Syamlal-O'Brien, Wen–Yu and Gidaspow drag functions) and experimental measurements. All models used 5 mm mesh, $U = 1.4\text{–}2.5u_{mf}$, restitution coefficient of 0.9, and no-slip wall. Bed pressure drop and density fluctuations were found to increase by increasing the bed height or velocity in the simulation models. They concluded that Syamlal-O'Brien drag presents better results than Wen–Yu or Gidaspow drag models. Taghipour et al. [20] simulated a glass beads fluidized bed to investigate the effect of drag functions (Syamlal-O'Brien, Wen–Yu and Gidaspow) and restitution coefficient. A 2D bed with 5 mm mesh was considered for the simulations. By increasing the restitution coefficient from 0.9 to 0.99, the elastic particle–particle collisions and conservation of impact energy increased which resulted about 10% bed expansion. The restitution coefficient of 0.99 caused strong particle movement and rigorous bubbling at velocities lower than minimum fluidization velocities regardless of the drag function employed. Almuttahar et al. [9] showed that model prediction improves using free-slip wall condition and modified Syamlal-O'Brien drag provided better results compared to Gidaspow and Arastoopour drag models. Furthermore, laminar model presented better estimation of the experimental data than turbulence models when the same model features are used. Performance of the 2D and 3D Eulerian models were compared by Armstrong