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Simulations of flow behavior of particles in a liquid-solid fluidized bed using a second-order moments model

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ABSTRACT

Flow behavior of liquid and particles is simulated using an Eulerian-Eulerian two-fluid model based on the theory of granular flow in a liquid-solid fluidized bed. The kinetic interaction of particle collisions is modeled using a second-order moments method. Comparing to simulated results from the kinetic theory of granular flow, the simulated results from the second-order moments method are in agreement with the experimental data of Razzak et al. [25] in a riser. Simulated results indicate that the component of second-order moments in the axial direction is higher than that in the radial direction. The distribution of velocity and volume fraction is predicted at the different inlet liquid velocities. Simulations indicate that axial velocities of particles increase with increasing inlet liquid velocity. The granular temperature is computed from simulations as a function of solid volume fraction. Roughly, the granular temperature increases, reach a maximum, and then decreases with the increase of solid volume fraction. To verify the numerical model further, the liquid-solid flow in the downcomer is simulated, and the simulated results are agreement with the experimental results from Lan et al. [33]. As well as, the liquid-solid circulation fluidized bed loop is investigated, and comparisons with Roy et al. simulations [12] are conducted.

1. Introduction

Liquid-solid fluidized beds are widely used in hydrometallurgical operations, catalytic cracking, ion exchange, adsorption, crystallization, sedimentation, particle classification, etc. [1,2] The process for reliable scale-up and optimum design of industrial fluidized beds is complicated. It is important to understand and have an ability to predict hydrodynamic characteristics. These characteristics influence the reaction and the mass/heat transfer between solid and liquid phases in liquid-solid fluidized beds. Moreover, the spatial distribution of solid volume fraction governs the flow pattern of solid and liquid phases and thus indirectly affects the extent of intermixing and the rates of mass and heat transfer. Detailed information regarding solid distribution and liquid phase flow patterns are difficult or impossible to obtain with experiments, but can be obtained by numerical simulations.

Computational Fluid Dynamics (CFD) is a well-accepted tool to simulate complex multiphase flows and enhance our understanding of the complex phase interactions [3]. Yamada et al. simulated the solid-liquid flows using a Lagrangian-Lagrangian coupling method, which couples the Discrete Element Method (DEM) for the solid phase and the Moving Particle Semi-Implicit (MPS) method for the fluid phase in two-dimensional mill systems [4]. Derksen investigated solid-to-liquid mass transfer as a result of liquid flowing through static and dynamic assemblies of mono-sized solid spheres by means of a Lattice-Boltzmann scheme [5]. For the mass transfer process, the finite volume method of Coupled Overlapping Domains (CODs) is used. It was shown that for moderate solid-over-liquid density ratios, fluidized particle assemblies had lower Sherwood numbers than fixed beds. Li et al. used the Eulerian-Lagrangian method to simulate the liquid-solid countercurrent fluidization in the extraction column [6]. Wan et al. presented solid-liquid two phase flows with a large number of moving particles, a study utilizing the direct numerical simulation incorporating with multigrid FEM fictitious boundary method (FBM) [7]. The presented method treated the fluid part, the calculation of forces and the movement of particles in a subsequent manner.

The Eulerian-Eulerian two-fluid modeling approach is the most commonly used method for the simulation of multiphase flows. It describes both phases as interpenetrating continua where the local instantaneous equations are averaged in a suitable way to allow coarser grids and longer time-steps being used in numerical simulations. Tamburini et al. simulated solid-liquid suspensions in stirred tanks with an Eulerian-Eulerian two-fluid model, and the standard k-ε turbulence model was adopted in the continuous liquid phase [8]. Shirvanian et al. predicated isothermal, two-phase flow of liquid and solid phases in a rectangular spouted vessel using Eulerian-Eulerian multiphase model. Model results in terms of fluid and solid flow properties, such as volume fraction, pressure and velocity fields were validated with experimental results obtained in a rectangular spouted vessel apparatus [9]. The kinetic theory of granular flow was used to describe dense

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flows of particles in fluidized beds [10]. The fluidized particles are treated as a continuum fluid, whose rheologic properties include solid viscosity and solid pressure as a function of the local solid volume fraction and fluctuating motion of the particles act as closures for this theory. Zhang et al. used a two-fluid model incorporating the kinetic theory of granular flow to predict the hydrodynamics of liquid-solid fluidization after a step change in liquid velocity [11]. The results showed that the non-uniform liquid velocity inlet condition has a strong effect on the transient solid volume fractions within the bed and the response time of the bed surface. Roy et al. presented the simulation of the hydrodynamic features of a liquid-solid circulating fluidized bed using an Eulerian-Eulerian approach to deal with the two-phase flow aspects and the kinetic theory of granular flow (KTGF) approach to deal with the solid-fluid interaction [12]. The essential features of the two-phase flow in the riser, the downcomer, the liquid-solid separator at the top and the solids return feed pipe at the bottom were all captured well in these simulations. The granular temperature θ can be defined as θ ≤ $\boldsymbol{C}\cdot\boldsymbol{C}$>/3, where $\boldsymbol{C}$ is the random fluctuation velocity of particles, that is also measurement of the random motion of the particles [13]. Moreover granular temperature can describe the momentum transport between collisional particles and model kinetic transport mechanisms for fluctuating kinetic energy of particles due to collisions of particles [14]. As is well-known, the granular temperature in the kinetic theory of granular flow is based on isotropy. The granular temperature is anisotropic for real solid-liquid flow, where particles move relative to the local average velocity and transport their momentum. As for liquid-solid two-phase flow, collisions between particles or particles and walls are available. Alexeev et al. used the soft particle model to investigate the motion of vertically vibrated granular layers in a vertically oscillating vessel in the gravity field [15]. The results showed that the distribution of fluctuating velocity of particles was anisotropic. Kuwata et al. predicted turbulence in porous media based on the second-order moments model [16]. Zhou et al. investigated the effect of swirl number on the flow field and turbulence properties by simulating swirling gas-particle flows using second-order moments model [17]. Liu et al. built up a new multiphase unified-second-order moments multiphase turbulence model (MUSM) to simulate the hydrodynamics of swirling gas-particle flows with binary particle mixtures [18]. Liu et al. derived Monte-Carlo incorporating with second-order moments two-phase turbulence model to predict swirling gas-particle flows, where the stochastic particle motion equation was closed by Langevin equation [19]. Liu et al. used unified a second-order moments two-phase turbulence model to simulate the dense gas-particle flows in downer, where this model accounted for the anisotropy of gas-solid two-phase stresses and the interaction between two-phase stresses [20]. Zhou et al. derived a second-order moments three-phase turbulence model to simulate complex turbulent gas-liquid-solid flows according to the mass-weighed and time-averaged equations for gas-liquid-solid turbulence [21]. Fox proposed a quadrature-based third-order moment closure to moment equations for non-uniform flow, where the weights and abscissas are key components of closures [22]. Fan and Fox used the direct quadrature method of moments to analyze effects of operating conditions on particle segregation rate size distribution in the fluidized bed at different operation in gas-solid fluidized beds [23]. Numerical simulations mentioned above indicates that the second-order moments two-phase turbulence model for dense fluid-particle flows is needed to predict the inhomogeneous flow structure, where the correlation of fluctuating velocities of particles is derived.

To date, the second-order moments method is the first application of simulating on flow behavior of liquid-solid riser. The anisotropic characteristic of fluctuation is predicted based on second-order moments of particles in a liquid-solid riser. Present work has shown that a liquid-solid two-phase flow model with a second-order moments method for solids phase is required to predict hydrodynamic behavior in liquid-solid fluidized beds. The collisional interaction of particles is modeled on the basis of the second-order moments method proposed by Dan et al. [24]. Distributions of second-order moments of fluctuating velocity are provided in the liquid-solid fluidized bed. Calculated solid volume fractions are compared with experimental data measured by Razzak et al. in the liquid-solid fluidized bed [25]. The simulations on the liquid-solid two-phase flows with the kinetic theory of granular flow are conducted, and an attempt has been made to interpret differences of simulated results in the two different models. The effect of liquid velocity on distributions of second-order moments, solid volume fractions and velocity are predicted.

2. Liquid-solid flow model with second-order moments method

In the present work, an Eulerian-Eulerian two-fluid model, which considers the conservation of mass and momentum for the solid and liquid phases, has been adopted. For this approach, governing equations in each phase are solved separately. Conservation equations of mass and momentum of both phases result from the statistical average of instantaneous local transport equations. The governing equations for liquid and solids phases are given in Table 1. The detailed mathematical and theoretical bases of this approach are presented elsewhere by Dan et al. [24] and Lu et al. [14]. In the work presented here, both phases are assumed to be isothermal, and no interface mass transfer is assumed. The moment M_N is equal to the generic $(N+1)$th-order moment of the fluctuating velocities divided by the number density of particles n; besides the generic $(N+1)$th-order moment of the fluctuating velocities

$$\boldsymbol{M}_N(\boldsymbol{x},t)=\overline{\underbrace{\boldsymbol{C}\boldsymbol{C}\cdots\boldsymbol{C}}_{N}}=\frac{1}{n(\boldsymbol{x},t)}\int\underbrace{\boldsymbol{C}\boldsymbol{C}\cdots\boldsymbol{C}}_{N}f(\boldsymbol{c},\boldsymbol{x},t)d\boldsymbol{c} \tag{1}$$

where f ($\mathbf{c}$, $\mathbf{x}$, t) is the single particle velocity probability density function. The second-order moment (M_{ij}) with $N=2$ gives the fluctuation energy of particles.

The solids phase is characterized by a mean particle diameter and density. There exists a single liquid phase and a single solid phase which are modeled as continuum. The continuity equation for phase j ($j=l$ for liquid phase or s for solids) [13] is:

$$\frac{\partial}{\partial t}\left(\alpha_j\rho_j\right)+\nabla\cdot\left(\alpha_j\rho_j\boldsymbol{u}_j\right)=0 \tag{2}$$

where α_j is the volume fractions of each phases, $\boldsymbol{u}$ the velocity vector, and ρ the density.

The momentum balance for the liquid phase is given by the Navier-Stokes equation, modified to include an interphase momentum transfer term

$$\frac{\partial}{\partial t}(\alpha_l\rho_l\boldsymbol{u}_l)+\nabla\cdot(\alpha_l\rho_l\boldsymbol{u}_l\boldsymbol{u}_j)=\alpha_l\nabla\cdot\boldsymbol{\tau}_l+\alpha_l\rho_l\boldsymbol{g}-\alpha_l\nabla p_l+\beta(\boldsymbol{u}_s-\boldsymbol{u}_l) \tag{3}$$

where $\boldsymbol{g}$ is the gravitational acceleration, p the thermodynamic pressure, and τ_l the viscous stress tensor shown in Table 1. β is the interface momentum transfer coefficient which is calculated by the Huilin-Gidaspow model [26,27]. The effective viscosity of the liquid phase is$\mu_f=\mu_l+\mu_t$. The eddy viscosity for the liquid phase is calculated as$\mu_t=c_\mu\rho_l k^2/\varepsilon$. Here k represents the turbulent kinetic energy and ε represents the dissipation rate of turbulent kinetic energy. The turbulent kinetic energy and dissipation rate of liquid phase is described by a standard k-ε turbulence model. Assuming the influence of the dispersed particles on the liquid phase is neglected, the transport equations associated with these parameters are

$$\frac{\partial}{\partial t}(\rho_l\alpha_l k)+\nabla\cdot(\rho_l\alpha_l\boldsymbol{u}_l k)=\nabla\left(\alpha_l\frac{\mu_t}{\sigma_k}\cdot\nabla k\right)+\alpha_l\mu_t\left[\nabla\boldsymbol{u}_l+\nabla(\boldsymbol{u}_l)^T\right]:\nabla\boldsymbol{u}_l-\rho_l\alpha_l\varepsilon \tag{4}$$