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Modeling of cluster structure-dependent drag with Eulerian approach for circulating fluidized beds

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ABSTRACT

Flow behavior of gas and solids is simulated in combination the gas–solid two-fluid model with a cluster structure-dependent (CSD) drag coefficient model. The dispersed phase is modeled by a Eulerian approach based upon the kinetic theory of granular flow (KTGF) including models for describing the dispersed phase interactions with the continuous phase. The drag forces of gas–solid phases are predicted from the local structure parameters of the dense and dilute phases based on the minimization of the energy consumed by heterogeneous drag. The cluster structure-dependent (CSD) drag coefficients are incorporated into the two-fluid model to simulate flow behavior of gas and particles in a riser. Simulation results indicate that the dynamic formation and dissolution of clusters can be captured with the cluster structure-dependent drag coefficient model. Simulated solid velocity and concentration of particles profiles are in reasonable agreement with experimental results.

1. Introduction

Experiments and simulations indicate that particle clusters have been found to be significant in circulating fluidized beds (CFB). Knowledge of the properties of particle clusters is useful in predicting radial and axial gas–solid flow patterns and mixing phenomena. Some researchers have incorporated the concept of particle clusters into hydrodynamic models of fluidized beds leading to improved predictions of experimental behavior. Yerushalmi et al. [1] developed a model for predicting cluster size by assuming that the clusters had a uniform size and an inner solids concentration was the same as that of the particles at incipient fluidization. Matsen [2] observed that the formation of particle clusters had high slip velocities and were less likely to be entrained. O'Brien and Syamlal [3] concluded that particle clusters, on the order of ten particle diameters in size, must exist in risers to explain the high drag forces observed in the experiments. Guenther and Breault [4] used the wavelet decomposition of back-scattered light from a fiber optical probe to discern particle clusters in a riser. Their results were in good agreement with O'Brien and Syamlal's calculations that clusters exist as formations of 10 to 20 particles. They also observed that the cluster size was relatively independent of the superficial gas velocity. Horio and Kuroki [5] used a laser sheet technique to visualize particle clusters in circulating fluidized beds. At low loadings, they found that the gas flow did not suspend the particles homogeneously and allowed for gas pockets. The inhomogeneity translated into particle clusters at higher loadings. Noymer and Glicksman [6] used heat transfer measurements at a riser wall to determine that particle clusters were on the order of 10 mm in size. Rhodes et al. [7] observed particle swarms with lengths of 10 to 15 mm. Soong et al. [8] developed criteria using statistical methodology to identify particle clusters based on their experimental data. Sharma et al. [9] used a capacitance probes to examine the density within a cluster. In a fast fluidized bed, they found that cluster density was about 2.4 times the emulsion density. Cocco et al. [10] used a high-speed video imaging system to measure particle clusters in a fluidized bed. The clusters and the corresponding drag forces may result in the formation of larger clusters. Recently, the same criterion was used to characterize cluster dynamics from numerical simulations [11,12]. Andrews et al. [13] developed a new methodology to compute particle cluster sizes. They used the concepts of filtering common in the direct numerical simulation of single-phase flow. Subbarao [14] postulated that there was a relationship between bubbles and cluster formation. It is assumed that the bed consists of cluster and void phases, and particles move as clusters by the drag of fluid flowing through void phase. The void phase serves as a concentrator of particles, which promotes clustering. Harris et al. [15] presented correlations for predicting the properties of cluster of particles traveling near the riser wall. The correlations were developed from experimental data published in the literature for vertical risers ranging from laboratory to industrial scale. A semi-empirical model was proposed by Werther et al. [16] with the consideration of the core-annulus model in the CFB combustor. Four

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fluid dynamical zones are distinguished: bottom zone, splash zone, upper dilute zone and exit zone. The combination of the simulations with the measurements yields a clear picture of the combustion processes in the combustion chamber.

The formation of clusters influences on interaction between gas and particles phases. The drag distribution is very complex because of the existence of clusters in the risers, which makes the flow heterogeneous. For a homogeneous flow of gas–solid system, the drag is proportional to the number of particles in a grid cell. Thus, the velocity difference between the gas and solid phases is much higher than the terminal velocity of a single particle. However, in the heterogeneous case, the particles in a cluster that is smaller than a computational cell behave like a large particle at a higher terminal velocity. As a result, the drag on the particles is lower than in the homogeneous case, which means that the mean slip velocity in the cell is increased [17]. Nowadays commonly the Eulerian approach is used for the simulation of large scale risers. In the Eulerian approach or two-fluid model both the gas and the granular phases are treated as fully interpenetrating continua. To simulate flow of particles, the kinetic theory of granular flow (KTGF) has found the widest use. This theory is basically an extension of the classical kinetic theory of gases described by Chapman and Cowling [18] to dense particulate flows, describing the particle–particle collisions [19]. The random movements and the nearly elastic collisions of the solid particles make the kinetic theory ideally suited to describe granular flows. The study of Agrawal et al. [20] showed an increase in gas–solids slip velocity as the computational grid was refined and more flow structures were resolved, and the filtered drag models was proposed in the coarse grid simulations of gas–solids flows on the basis of the kinetic theory of granular flow. As indicated by Igci et al. [21], the most important factor in determining the filtered drag coefficient is the averaged solids concentration as the dependence on Reynolds number is weak. Helland et al. [22] proposed a combined drag law taking into account the effects of cluster formation and hindered settling. Yang et al. [23] tried to analyze the drag force dependence on macro-scale flow structure through the EMMS approach. Simulation results demonstrate the reasonableness of the EMMS approach in resolving the heterogeneous structure and describing the dependence of drag coefficient on structure parameters, suggesting the feasibility of this approach to be used as a sub-grid closure law for drag coefficient [24–26]. Simulated results have shown that the gas–solid two-phase flows are heterogeneous on both an overall and a local scale in a riser, which greatly influences the drag between the gas and solid phases. The formulation presented by Ergun [27] and Wen and Yu [28] are often used in the numerical simulations of fluidization. The former is used where the suspension is dense, whereas the latter is used where the suspension is dilute. However, the formulation by Wen and Yu cannot correctly describe the effects of the local heterogeneity [29], which leads to errors in the predicted particle distributions.

A numerical method using an improved drag model should be able to describe the heterogeneity within a computational cell caused by the clusters. In present work, the cluster structure-dependent (CSD) drag coefficient model is proposed. The CSD drag coefficient model is incorporated into the two-fluid model. The gas–solid flow behavior in the riser is simulated and compared with experimental results published in the literature.

2. Gas–solids two-fluid model

In the present work, an Eulerian multi-fluid model, which considers the conservation of mass and momentum for the solid and gas phases, has been adopted. The kinetic theory of granular flow, which considers the conservation of solid fluctuation energy, has been used for closure. Conservation equations of mass and momentum of both phases result from the statistical average of instantaneous local transport equations. The governing equations are given below.

2.1. Governing equations of gas and solids phases

For simplifications, the following hypotheses are considered: (1) both phases are assumed to be isothermal, and no interface mass transfer is assumed; (2) the solid phase is characterized by a mean particle diameter and density. Both phases are continuous assuming a single gas phase and a single solid phase. The governing equations for each phase and the constitutive relations are given in Table 1. The continuity for gas phase and solids phase is expressed by Eqs. (T1-1) and (T1-2). Mass exchanges between the phases, e.g. due to reaction, is not considered.

The momentum balance for the gas phase is given by the Navier–Stokes equation, modified to include an interphase momentum transfer term [19]

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g \boldsymbol{u}_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g \boldsymbol{u}_g \boldsymbol{u}_g\right) = \varepsilon_g \nabla \cdot \boldsymbol{\tau}_g + \varepsilon_g \rho_g \boldsymbol{g} - \varepsilon_g \nabla p + F_{gs} \quad (1)$$

The stress tensor of gas phase τ_g is represented by Eq. (T1-6), where μ_g is the viscosity of gas phase. For simplification, a constant viscosity of gas phase is used in the present work.

The particle phase momentum equation is similar to the one for the gas phase, but contains the gradient of the particle pressure according to model A proposed by Gidaspow [19]. The solids phase momentum balance is given by:

$$\frac{\partial}{\partial t}(\varepsilon_s \rho_s \boldsymbol{u}_s) + \nabla \cdot (\varepsilon_s \rho_s \boldsymbol{u}_s \boldsymbol{u}_s) = -\varepsilon_s \nabla p - \nabla p_s + \nabla \cdot \boldsymbol{\tau}_s + \varepsilon_s \rho_s \boldsymbol{g} - F_{gs} \quad (2)$$

where p is the fluid pressure, and p_s is the solids pressure. The solids stress tensor is expressed in terms of the bulk solids viscosity, ξ_s, and shear solids viscosity, μ_s, and expressed by Eq. (T1-7).

Inter-particle collisions play a crucial role in sufficiently dense suspensions. Equivalent to the thermodynamic temperature for gases, the granular temperature can be introduced as a measure for the energy of the fluctuating velocity of the particles [19,30,31]. The granular temperature, θ, is defined as: $\theta = C^2/3$, where C is the particle fluctuating velocity. The equation of conservation of solids fluctuating energy is expressed by Eq. (T1-5).

The particle pressure represents the particle normal forces due to particle–particle interaction. Its description based on the kinetic theory of granular flow was developed. In this approach, both the kinetic and the collisional influence are taken into account. The kinetic portion describes the influence of particle translations, whereas the collisional term accounts for the momentum transfer by direct collisions [19,30]. The particle pressure is calculated by Eq. (T1-8).

The shear viscosity accounts for the tangential forces. The shear viscosity of particles is calculated by Eq. (T1-9). The bulk viscosity formulates the resistance of solid particles to compression and expansion and is expressed by Eq. (T1-10). The conductivity of granular energy is expressed by Eq. (T1-11).

The rate of dissipation of fluctuation kinetic energy due to particle collisions and the rate of energy dissipation per unit volume resulting from the transfer of gas phase fluctuations to the particle phase fluctuations are calculated by Eqs. (T1-12) and (T1-14).

2.2. Cluster structure-dependent (CSD) drag model

In a riser, gas and particles are considered to be either in the particle-rich dense phase or in the gas-rich dilute phase. This means that in a grid cell, as shown in Fig. 1, particle movements are in the form of clusters in the dense phase or in the form of a dispersed particle in the dilute phase. The volume fractions of dense and dilute phases are defined as $f_{den} = V_{den}/V$ and $f_{dil} = V_{dil}/V$, where V is the control volume of a grid cell, V_{den} and V_{dil} are the respective volumes of dense and dilute phases in a grid cell. The porosities of dense phase