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Review

Hydrodynamic simulations of gas–solid spouted bed with a draft tube

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ABSTRACT

Flow behavior of particles in a two-dimensional spouted bed with a draft tube is studied using a continuous kinetic-friction stresses model. The kinetic stress of particles is predicted from kinetic theory of granular flow, while the friction stress is computed from a model proposed by Johnson et al. (1990). A stitching function is used to smooth from the rapid shearing viscous regime to the slow shearing plastic regime. The distributions of concentration and velocities of particles are predicted in the spouted bed with a draft tube. Simulated results compare with the vertical velocity of particles (Zhao et al., 2008) measured and in the spout bed with draft plates and solid circulation rate (Ishikura et al., 2003) measured in the spouted bed with a draft tube. The impact of the friction stress of particles on the spout, annulus, fountain and entrancement regions is analyzed in gas–solid spouted bed with a draft tube. Numerical results show that the gas flow rate through the annulus increases with the increase of the entrainment zone. The solids circulation rate decreases with the decrease of inlet gas velocity and the height of the entrainment zone. The effect of spouting gas velocity on distributions of concentration, velocity and particle circulation is discussed.

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1. Introduction

Conventional spouted bed technology in gas–solid system has been proven to be an effective means of contacting for gas and solid particles. A spouted bed typically displays three distinct regions: a central spout, annulus between the spout and the walls, and a fountain region at the top of spout (Epstein and Grace, 1997). The concentration of particle varies from almost zero in the spout region to its maximum packing limit in the annulus region, leading to a complex recirculation pattern and diverse gas–particle interactions. Extensive information about spouted beds can be found in Mathur and Epstein (1974). Recent research on biomass multiphase flow in spouted beds is reviewed (Cui and

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Grace, 2008). However, it has a drawback if the particle history is to be closely controlled, because particles can enter the spout from the annulus at all levels, resulting essentially in random behavior of these particles. The insertion of an axially positioned draft tube into the conventional spouted bed has shown potential advantages due to the stability and the flexibility. A spouted bed with a draft tube has two defining characteristics: (1) the draft tube where the particles and gases are removed from the bottom of the annular bed and transported upwards in either a dilute or a dense phase mixture. (2) the annular bed that surrounds the draft tube where the particles move downward as a moving packed bed. Ijichi et al. (1998) reviewed the flow characteristics of a spouted bed with a draft tube. The applications of spouted bed with a draft tube include coal combustion (Konduri et al., 1995), pneumatic conveying (Milne et al., 1992), pyrolysis of hydrocarbon (Stocker et al., 1989) and particle circulation (Ji et al., 1998). Kalwar and Raghavan (1992) investigated the spout pressure drop and minimum spouting superficial velocity in a two-dimensional gas-spouted bed. The feature of the spouted bed with a draft tube is reported by Grbavcic et al. (1992).

Numerical simulation has evolved into a useful tool to obtain detailed information about the flow phenomena in spouted beds. Computational fluid dynamics (CFD) studies have become popular in the field of gas–solid two-phase flow. In the two-fluid model (TFM) approach, the gas and solid phases are mathematically treated as interpenetrating continua. The dynamic behavior of a gas–solid spouted bed was predicted by Lefroy and Davidson (1969) using one-dimensional particle momentum balances in the spout. Huilin et al. (2001) used an Eulerian method wherein the constitutive equations describing the solids pressure, viscosity and elasticity moduli were implemented in a hydrodynamic simulation model. The distributions of concentrations and velocities of gas phase and particles across the spouted bed were examined, and the agreement was obtained between numerical results and experimental data. To reduce the amount of empiricism, more fundamental closures for the stresses of particles have been developed based on the application of kinetic theory for dense gases to particulate assemblies (Savage and Jeffrey, 1981; Jenkins and Savage, 1983; Lun et al., 1984; Ding and Gidaspow, 1990; Gidaspow, 1994). The kinetic theory of granular flow is based on the analogy between the thermal motion of the gas molecules in the kinetic theory of gases (Chapman and Cowling, 1990) and the random motion of solid particles. Huilin et al. (2004) simulated experiments of He et al. (1994) for a cylindrical spouted bed and experiments of San Jose et al. (1998) for a conical spouted bed based on the kinetic-frictional constitutive model. The kinetic-frictional constitutive model treats the kinetic and frictional stresses of particles additively. The kinetic stress of particles is modeled using the kinetic theory of granular flow, while the friction stress is from the combination of the normal frictional stress model proposed by Johnson et al. (1990) and the modified frictional shear viscosity model proposed by Syamlal et al. (1993). Recently, using a kinetic-frictional constitutive model, Shirvanian et al. (2006) simulated the concentration of particles in the rectangular spout bed by means of FLUENT code, and compared with experimental data. Wang et al. (2006) predicted the axial and radial distributions of static pressures and vertical particle velocities of conical spouted beds by means of a commercial FLUENT code. Wu and Mujumdar (2008) simulated gas–particle flow behavior in a spout-fluid bed using a commercial fluid dynamics code FLUENT version 6.2. The overall flow patterns within the cylindrical spouted bed, i.e. a stable spout region, a fountain and an annular region were correctly predicted. However, in comparison to conical spouted beds without draft tube, relatively little has been published on spouted beds with draft tube. Flow behavior of particles in a two-dimensional spouted bed dryer with a draft tube was simulated (Szafran and Kmiec, 2007). A heat- and mass-transfer model was added as compiled executable code by means of UDF programming to FLUENT 6.1 in the simulations of spouted bed dryer with a draft tube (Szafran and Kmiec, 2004). The distributions of porosity and velocity are predicted for different designs of the draft tube in an internally circulating fluidized bed (Marschall and Mleczko, 1999). Because of the complex interactions between the gas and particles, in-depth knowledge about the draft tube effect on flow behavior of particles in spouted bed is useful in predicting performance of spouted bed reactors with a draft tube.

In this work, an Eulerian–Eulerian two-fluid model is used to predict flow behavior of particles in a spouted bed with a draft tube. The kinetic-frictional constitutive model for dense assemblies of solids is incorporated in the simulations where the friction stress is from the combination of the normal frictional stress model proposed by Johnson et al. (1990) and the kinetic stress of particles is modeled using the kinetic theory of granular flow (Gidaspow, 1994). A stitching function is used from the rapid flow to slow flow of particles. A commercial fluid dynamics code, FLUENT version 6.2, is chosen to solve the model equations. The friction-kinetic model is incorporated by means of the user defined functions utility (UDFs). The continuous form of drag force between gas and particle phases is used when stitching the Ergun (1952) and Wen and Yu (1966) correlations. The gas–solid flow behavior in the spouted bed with a draft tube is simulated and compared with experimental results. The overall flow patterns within a spouted bed with a draft tube are predicted. The effect of spouting gas velocity and disengagement height on particle circulation is analyzed.

2. Mathematical model and numerical solution method

2.1. Two-fluid model of gas–solid flow

The Eulerian approach is used for both gas phase and particles phase within spouted beds, taking into account all possible intra- and inter-phase interactions. In this work, it is assumed that flow is to be isothermal. The gas phase is incompressible, and particles are spherical and monosized. The governing equations for the conservation of mass and momentum for each phase and the constitutive relations are given in Table 1. Gas stresses are shown in Eq. (T1-6) where $\mu_g = \mu_l + \mu_t$ is effective gas viscosity (Fan and Zhu, 1998). The turbulent viscosity is determined from a $k-\varepsilon$ turbulent model and expressed by $\mu_t = C_\mu \rho_g k^2/\varepsilon$, where the equations of turbulent kinetic energy and turbulent kinetic energy dissipation rate are expressed by Eqs. (T1-7) and (T1-8). The empirical constants C_1, C_2, C_μ, σ_k and σ_ε are 1.44, 1.92, 0.09, 1.0 and 1.3, respectively. For solid phase, the stress includes a frictional or quasi-static part and a dynamic part (e.g. Savage and Jeffrey, 1981; Gidaspow, 1994). The frictional part represents surface friction and interlocking between particles and is usually assumed to follow Mohr–Coulomb yield criterion. The dynamic part expressed by Eq. (T1-10) accounts for collisions and is modeled by the kinetic theory of granular flow. In addition to the mass and momentum conservation equations for the solid phase, a fluctuation kinetic energy equation, Eq. (T1-5), is also solved to account for the conservation of the fluctuation energy of particles phase, through the implementation of the kinetic theory of granular flow (Gidaspow, 1994). The granular temperature, θ, is defined as: $\theta = \langle \mathbf{c}^2 \rangle /3$, where $\mathbf{c}$ is the particle fluctuating velocity. The particle velocity fluctuation generates a solid pressure in the particulate phase, together with a solid viscosity that resists shearing of the particle assembly. This theory gives closures for the rheologic properties of particles as a function of