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Simulations of vertical jet penetration using a filtered two-fluid model in a gas–solid fluidized bed

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ABSTRACT

The influence of a vertical jet located at the distributor in a cylindrical fluidized bed on the flow behavior of gas and particles was predicted using a filtered two-fluid model proposed by Sundaresan and coworkers. The distributions of volume fraction and the velocity of particles along the lateral direction were investigated for different jet velocities by analyzing the simulated results. The vertical jet penetration lengths at the different gas jet velocities have been obtained and compared with predictions derived from empirical correlations; the predicted air jet penetration length is discussed. Agreement between the numerical simulations and experimental results has been achieved.

Introduction

Gas distributors in industrial-scale gas–solid fluidized beds typically contain a number of orifices or openings through which the fluidizing gas flows (Geldart, 1986; Kunii & Levenspiel, 1991). The number and size of the orifices are designed to provide a sufficiently high pressure drop across the distributor in order to ensure a uniform gas distribution. Therefore, irrespective of the type of distributor, the free area for flow is typically no more than a few percent of the bed area. This gives rise to orifice velocities that can be more than an order of magnitude larger than the superficial gas velocity. High orifice velocities lead to the formation of vertical jets that break down into bubbles when the momentum of the vertical gas jets is dissipated (Geldart, 1986). The vertical gas jets promote good gas–solid contact through particle entrainment. High rates of reaction, mass transfer and heat transfer in the distributor region are known to be caused by the introduction of fresh gases, as they provide the maximum driving force for transfer or reaction. Therefore, understanding the hydrodynamics of the gas and solids resulting from the introduction of vertical gas jets is essential to improve reactor design and process optimization.

Computational fluid dynamics (CFD) has become an important tool for understanding the flow behavior of gas and particles in bubbling fluidized beds (Gidaspow, 1994; Jackson, 2000). The Eulerian–Eulerian approach (commonly referred to as the two-fluid model), consists of both gas and solid phases, which are modeled as continuous and fully inter-penetrating. Zhang, Pei, Brandani, Chen, and Yang (2012) have simulated the flow pattern and jet penetration depth in the gas–solid fluidized bed with double jets under equal and unequal gas velocities. These numerical simulations were carried out using CFX4.4, FORTRAN subroutines, a commercial CFD code, together with user-defined. Utikar and Ranade (2007) performed simulations of rectangular fluidized beds operated with a central jet using an Eulerian–Eulerian two-fluid model based on the kinetic theory of granular flows. The predicted results were compared with the experimental data and previously published correlations, yet there was only partial agreement. Patil, van Sint Annaland, and Kuipers (2005) simulated the flow behavior of gas and particles in a bubbling fluidized bed with a single orifice. A jet in the center was modeled by using two closure models, one semi-empirical model assuming a constant viscosity of the solid phase and a second model based on the kinetic theory of granular flow. Numerical simulations showed that bubble growth at a jet nozzle is mainly determined by the drag experienced by the gas percolating through the compaction region around the bubble interface, which is not significantly influenced by particle–particle interactions. Simulations showed that a two-fluid model with the kinetic theory of granular flow is applicable if the distribution of particles in a computational cell can be assumed to be homogeneous, whereas modifications are needed to account for bubbles smaller than the computational cell. This indicates that an adequate mod-

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eling of the gas–solid drag force is essential to predict the correct hydrodynamics of gas and particles in the fluidized beds.

Sundaresan and coworkers derived filtered drag, solids pressure, and viscosity correlations from filtering highly resolved simulations. Agrawal, Loezos, Syamlal, and Sundaresan (2001) showed that subgrid-scale structures of bubbles in bubbling fluidized beds affect flow behavior at the macro scale and that these structures must be accounted for through additional closure relations. Igci, Andrews, Sundaresan, Pannala, and O'Brien (2008) proposed models for the filtered drag coefficient, the filtered particle phase pressure, and the filtered particle phase viscosity. It has been shown that the filtered two-fluid model simulations are able to predict the Reynolds-stress-like velocity fluctuations appropriately. The objective of this study is to simulate the vertical air jet located at the distributor in a fluidized bed of particles using a filtered two-fluid model proposed by Sundaresan and coworkers. A range of jet velocities have been simulated, and the results of these simulations were validated against the available experimental data with a vertical air jet at the distributor within a bubbling fluidized bed.

Filtered gas–particles two-fluid model equations

In general, the two-fluid model equations for gas and particle phases are derived by translating Newton's equations of motion for a single particle directly into continuum equations representing the momentum balances for the solid phase. The filtered two-fluid model equations are obtained by performing a spatial average of the microscopic two-fluid model equations. As a result of the filtering procedure, the effect of the fine-scale gas–particle flow structure occurring on length scales smaller than the filter size is captured through residual terms that must be constituted from theoretical considerations or from filtering the results of fine-grid two-fluid model simulations. Filtered models have been shown to yield quantitatively similar macroscopic behavior to that observed in fine-grid simulations of identical systems (Igci et al., 2008; Ozel, Fede, & Simonin, 2013).

The two-fluid model consists of mass and momentum balances for gas and particle phases. The filtered continuity balances of the gas and particle phases without chemical reactions proposed by Igci et al. (2008) are:

$$\frac{\partial}{\partial t}(\varepsilon_g\rho_g)+\nabla\cdot(\varepsilon_g\rho_g\mathbf{u}_g)=0, \tag{1}$$

$$\frac{\partial}{\partial t}(\varepsilon_s\rho_s)+\nabla\cdot(\varepsilon_s\rho_s\mathbf{u}_s)=0, \tag{2}$$

where ρ_s and ρ_g denote the densities of the particle and gas phase respectively. $\mathbf{u}_s$ and $\mathbf{u}_g$ are the filtered velocity of the particle and gas phase respectively. ε_s and ε_g are the filtered volume fractions of the particle and gas phase respectively (which add up to unity).

The momentum balances of the gas and particle phase without chemical reactions, proposed by Igci et al. (2008) are:

$$\frac{\partial}{\partial t}(\varepsilon_g\rho_g\mathbf{u}_g)+\nabla\cdot(\varepsilon_g\rho_g\mathbf{u}_g\mathbf{u}_g)=-\varepsilon_g\nabla p_g +\varepsilon_g\rho_g\mathbf{g}+\beta_{gs}(\mathbf{u}_g-\mathbf{u}_s)+\nabla\cdot\boldsymbol{\tau}_g, \tag{3}$$

$$\frac{\partial}{\partial t}(\varepsilon_s\rho_s\mathbf{u}_s)+\nabla\cdot(\varepsilon_s\rho_s\mathbf{u}_s\mathbf{u}_s)=-\varepsilon_s\nabla p_g +\nabla p_s+\nabla\cdot\boldsymbol{\tau}_s+\varepsilon_s\rho_s\mathbf{g}+\beta_{gs}(\mathbf{u}_g-\mathbf{u}_s), \tag{4}$$

where $\mathbf{g}$ is the gravitational acceleration, and β_{gs} is the filtered drag coefficient. $\boldsymbol{\tau}_s$ and $\boldsymbol{\tau}_g$ are the stress tensors of the particle and gas phase, respectively. The stress tensor of the gas phase is calculated by a Newtonian-type approximation with a constant viscosity. For the particle phase, the stress tensor is expressed as a function of the filtered viscosity as follows:

$$\boldsymbol{\tau}_s=\mu_s\left\{\left[\nabla\mathbf{u}_s+(\nabla\mathbf{u}_s)^{\mathrm{T}}\right]-\frac{1}{3}(\nabla\cdot\mathbf{u}_s)\mathbf{I}\right\}. \tag{5}$$

The filtered viscosity of the particle phase is:

$$\frac{\mu_s g}{\rho_s v_t^3}=\begin{cases}\dfrac{\mu_{kin}g}{\rho_s v_t^3}+F_\mu(\varepsilon_s-0.59)(-1.22\varepsilon_s-0.7\varepsilon_s^2-2\varepsilon_s^3), & \varepsilon_s\le 0.59\\ \dfrac{\mu_{kin}g}{\rho_s v_t^3}, & \varepsilon_s>0.59\end{cases} \tag{6}$$

$$F_\mu=0.37({Fr_f}^{-1.22})(0.28{Fr_f}^{-0.43}+1)^{-1},\ \text{and}\ Fr_f^{-1}=g\Delta_f/v_t^2, \tag{7}$$

where v_t is the terminal velocity of the particles, and Δ_f is the filter size. The kinetic model term is:

$$\frac{\mu_{kin}g}{\rho_s v_t^3}=\begin{cases}1720\varepsilon_s^4-215\varepsilon_s^3+9.81\varepsilon_s^2-0.207\varepsilon_s+0.00254, & \varepsilon_s\le 0.02\\ 2.72\varepsilon_s^4-1.55\varepsilon_s^3+0.329\varepsilon_s^2-0.0296\varepsilon_s+0.00136, & 0.02<\varepsilon_s\le 0.2\\ -0.0128\varepsilon_s^3+0.0107\varepsilon_s^2-0.0005\varepsilon_s+0.000335, & 0.2<\varepsilon_s\le 0.6095\\ -23.6\varepsilon_s^2+28.0\varepsilon_s+8.3, & \varepsilon_s>0.6095\end{cases} \tag{8}$$

The filtered solid pressure is a function of the filtered solid volume fraction, and is expressed by:

$$\frac{p_s}{\rho_s v_t^2}=\begin{cases}\dfrac{p_{kin}}{\rho_s v_t^2}+F_p(\varepsilon_s-0.59)(-1.69\varepsilon_s-4.16\varepsilon_s^2+11\varepsilon_s^3), & \varepsilon_s\le 0.59\\ \dfrac{p_{kin}}{\rho_s v_t^2}, & \varepsilon_s>0.59\end{cases} \tag{9}$$

$$F_p=0.48\left({Fr_f}^{-0.86}\right)\left(1-\exp\left(-\frac{{Fr_f}^{-1}}{1.4}\right)\right), \tag{10}$$

where the kinetic model term is:

$$\frac{p_{kin}}{\rho_s v_t^2}=\begin{cases}-10.4\varepsilon_s^2+0.310\varepsilon_s, & \varepsilon_s\le 0.0131\\ -0.185\varepsilon_s^3+0.066\varepsilon_s^2-0.000183\varepsilon_s+0.00232, & 0.0131<\varepsilon_s\le 0.29\\ -0.00978\varepsilon_s+0.00615, & 0.29<\varepsilon_s\le 0.595\\ -6.62\varepsilon_s^3+49.5\varepsilon_s^2-50.3\varepsilon_s+13.8, & \varepsilon_s>0.595\end{cases} \tag{11}$$

Note that we do not consider the bulk viscosity in the filtered model. Parmentier, Simonin, and Delsart (2012) argued that the filtered stress corrections are less important to capture macroscopic quantities, and have shown that the filtered interphase drag is the most significant correction in the filtered model equations. The filtered gas–solid drag was found to be sufficient to accurately predict the flow behavior of particles in fluidized beds. Igci et al. (2008) presented a methodology where highly resolved two-fluid model simulations of the gas–particle flow in a periodic domain were filtered to deduce residual correlations for the corresponding filtered two-fluid model equations. Their approach has been verified for coarse grid simulations of risers. According to Eqs. (3) and (4) their filtered drag coefficient reads:

$$\beta_{gs}=\frac{3}{4}C_D\frac{\rho_g(1-\varepsilon_s)\varepsilon_s|u_g-u_s|}{d_p}(1-\varepsilon_s)^{-2.65}(1-C) \tag{12}$$

$$C=\frac{{Fr_f}^{-1.6}}{{Fr_f}^{-1.6}+0.4}h_1(\varepsilon_s)h_2(\varepsilon_s) \tag{13}$$