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Numerical simulation of single and multiple gas jets in bubbling fluidized beds

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ABSTRACT

The behavior of single and multiple horizontal gas jet injections into a rectangular bubbling fluidized bed are studied with three-dimensional numerical simulations. The jet penetrations as well as the interactions between the jet and the surrounding gas, solids, bubbles, and other jets are investigated. As far as the average jet penetration length is concerned, limited influence of each jet on the others is observed in multiple jet injections until the jets start to overlap. The effect of the secondary gas injection on the flow hydrodynamics in the bed is examined for multiple jet injections with different jetting velocities and arrangements. It is found that the secondary gas injection mainly affects the hydrodynamics of the upper section above the injection level, while its effect is nearly negligible below the injection. Above the injection level, more particles are brought upward and the circulation of solids is promoted. Furthermore, the tendency of slugging inside the bed is observed at high secondary injection flow rates.

1. Introduction

In many industrial processes, the gas or liquid is often added into fluidized bed reactors through a series of horizontal or inclined nozzles. The feed injection is usually used to enhance the mixing, stimulate solids flow, and control NO_x emission and bed temperature (Rajan and Christoff, 1982; Varol and Atimtay, 2007). It is important to ensure the jet penetration is sufficient to distribute the feed reactant across the cross-section of the column to minimize the lateral gradient in reactant concentration. On the other hand, the attrition of particles and wall wear caused by extremely deep penetrations should be avoided. In order to improve the performance of the reactor, it is necessary to have the knowledge of the jet behavior and hydrodynamics inside the system.

There has been a considerable amount of work that studies the horizontal injection of gas or gas–liquid jets into fluidized beds (Merry, 1971; Xuereb et al., 1991a, 1991b; Chen and Weinstein, 1993; Chyang et al., 1997; Copan et al., 2001; Al Sherehy, 2002; Ariyapadi et al., 2003, 2004; Link et al., 2009; Gryczka et al., 2009). The jet behaviors, including the gas discharge modes, jet penetration lengths, and jet expansion angles, have been studied using various experimental methods, most of which are based on direct visual observation of the phenomena, such as photographic or high-speed cine film analysis technologies (Merry, 1971; Chyang et al., 1997; Hong et al., 1997; Copan et al., 2001) and X-ray systems (Chen and Weinstein, 1993; Ariyapadi et al., 2003, 2004). Due to the limitation of the technologies used in direct visual observation, the bed is usually very thin or the jet has to be injected close to the wall. Inevitably, the side wall affects the jet behavior. A systematic experimental investigation of the detailed jet behavior free from these limitations is still not feasible.

In practice, injections of multiple jets are almost always encountered. Consequently, it is necessary to investigate the interaction between these jets in addition to single jet behavior. Unfortunately, studies of horizontal jets in fluidized bed reactors were mainly focused on a single jet. Research on multiple horizontal jets in fluidized beds is very limited. Donald et al. (2004) investigated penetration of single jet, interacting pairs of jets, and five jets entering together into a bubbling fluidized bed of FCC particles. They found that a jet was affected more by another jet below it than by neighboring jets at the same level, and the influence from a jet above it was minimal. Jets issuing from nozzles at the same level influenced each other when they overlapped. Several papers investigating the effect of secondary air injection through multiple nozzles on the flow hydrodynamics in circulating fluidized beds have been published (Cho et al., 1994; Marzocchella and Arena, 1996; Knoebig and Werther, 1999; Kim and Shakourzadeh, 2000). The effects of secondary gas injection on the mixing behavior of gas and solids, as well as heat transfer, were investigated (Ran et al., 2001; Koksal and Hamdullahpur, 2004; Koksal et al., 2008). In all these studies, only the overall bed hydrodynamics such as pressure drop, solids hold-up, particle velocity were measured to analyze the effect of secondary gas injection. The behavior of the gas jets was not reported.

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Hong et al. (1997) performed two-dimensional simulations to study the inclined jet penetration into a fluidized bed. In their article, simulation results regarding only the jet penetration length were reported, which agreed well with their experimental measurements. However, it is not justified to simplify the problem with a two-dimensional assumption considering its inherent three-dimensional characteristics. For this reason, Tyler and Mees (1999) conducted a three-dimensional simulation to investigate the influence of a horizontal feed jet on fluidized bed hydrodynamics, but only preliminary results were reported. Li et al. (2008) carried out a three-dimensional numerical simulation of a single horizontal gas jet into a cylindrical gas–solid fluidized bed of laboratory scale. The jet penetration lengths and jet expansion angles were predicted with numerical simulations and a good agreement with the experimental findings in the literature was attained. With the rapid development of high speed computers, modeling and numerical simulation of fluidization units have become an important tool in understanding and predicting the hydrodynamics in fluidized bed reactors.

The objective of the current study is to investigate numerically the horizontal gas injection into a bubbling fluidized bed. By means of the three-dimensional numerical simulation, a single horizontal jet issuing into the bubbling fluidized bed is investigated to obtain a better understanding of the jet behavior. The interactions between the jet and the surrounding gas, solids as well as the ascending bubbles in the system are analyzed and compared with experimental observations reported in the literature. Multiple horizontal jet injections at the same level are simulated as well. The interaction between jets and its influence on the jet penetration are evaluated. The effect of the secondary gas injection on the hydrodynamics of the bubbling fluidized bed is determined by analyzing the solids holdup, gas and solids velocities, and mean bubble sizes. In addition, the mixing of secondary gas in the column is investigated and results are reported elsewhere (Li et al., 2009).

2. Numerical models

In the current study, the Multiphase Flow with Interphase eXchanges (MFIX) CFD code, available from the US Department of Energy's National Energy Technology Laboratory (NETL) at https://mfix.netl.doe.gov is used to solve the partial differential equations system with closure relations from the Eulerian–Eulerian model (Syamlal et al., 1993). MFIX is a general-purpose computer code for modeling the hydrodynamics, heat transfer, and chemical reactions in fluid–solids systems, which has been successfully used for describing bubbling and circulating fluidized beds and spouted beds (McKeen and Pugsley, 2003; Syamlal and O'Brien, 2003; Benyahia et al., 2005; Das Sharma et al., 2006). For the flow without chemical reactions, as considered in the current study, the hydrodynamic model equations are summarized in Table 1. The model consists of mass and momentum balances as well as closure correlations (Benyahia et al., 2007).

In MFIX, the governing equations for the solids phase are closed by the kinetic granular theory. In kinetic granular theory, it is assumed that the random motion of particles is analogous to the thermal motion of molecules in a gas. A so-called granular temperature, which is proportional to the mean square of the random particle velocity based on Maxwellian velocity distribution, is defined to model the turbulent fluctuating energy of the solids phase. Constitutive relations for the solids phase stress tensor can be derived based on the kinetic theory (Lun et al., 1984). Many research groups have been involved in numerical simulations with kinetic granular theory, and encouraging results have been reported in literature (Enwald et al., 1996; Samuelsberg and Hjertager, 1996; Lu and Gidaspow, 2003; McKeen and Pugsley, 2003; Syamlal and O'Brien, 2003; Hansen et al., 2004; Huanpeng et al., 2004; Benyahia et al., 2005; Das Sharma et al., 2006).

For the dense gas–solid flows such as fluidized beds, the turbulence of the particulate phase is usually modeled with granular temperature based on kinetic granular theory (Gidaspow, 1994). The turbulence of the carrier phase is not of primary concern as particle-particle collisions dominate the flow (Crowe et al., 1996).

Table 1
Summary of MFIX equations.

A. *Governing equations*

(a) Continuity equations

Gas phase $\frac{\partial}{\partial t}(\varepsilon_g \rho_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{V}_g) = 0$

Solids phase $\frac{\partial}{\partial t}(\varepsilon_s \rho_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{V}_s) = 0$

(b) Momentum equations

Gas phase $\frac{\partial}{\partial t}(\varepsilon_g \rho_g \vec{V}_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{V}_g \vec{V}_g) = \nabla \cdot \bar{\bar{\tau}}_g - \varepsilon_g \nabla P + \varepsilon_g \rho_g g - I_{gs}$

Solids phase $\frac{\partial}{\partial t}(\varepsilon_s \rho_s \vec{V}_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{V}_s \vec{V}_s) = \nabla \cdot \bar{\bar{\tau}}_s - \varepsilon_s \nabla P + \varepsilon_s \rho_s g + I_{gs}$

B. *Constitutive equations*

(a) Gas stress tensor

$$\bar{\bar{\tau}}_g = 2\mu_{ge}\bar{\bar{S}}_g$$

$$\bar{\bar{S}}_g = \tfrac{1}{2}(\nabla \vec{V}_g + (\nabla \vec{V}_g)^T) - \tfrac{1}{3}\nabla \cdot \vec{V}_g \bar{\bar{I}}$$

$$\mu_{ge} = Min(\mu_{\max}, \mu_g + \mu_t)$$

$$\mu_t = \varepsilon_g \rho_g (0.1\Delta)^2 \sqrt{\bar{\bar{D}}_g : \bar{\bar{D}}_g}$$

$$\Delta = (\Delta x \Delta y \Delta z)^{1/3}$$

$$\bar{\bar{D}}_g = \tfrac{1}{2}(\nabla \vec{V}_g + (\nabla \vec{V}_g)^T)$$

(b) Solids stress tensor

$$\bar{\bar{\tau}}_s = (-P_s + \eta \mu_b \nabla \cdot \vec{V}_s)\bar{\bar{I}} + 2\mu_s \bar{\bar{S}}_s$$

$$\bar{\bar{S}}_s = \tfrac{1}{2}(\nabla \vec{V}_s + (\nabla \vec{V}_s)^T) - \tfrac{1}{3}\nabla \cdot \vec{V}_s \bar{\bar{I}}$$

$$P_s = \varepsilon_s \rho_s \Theta_s [1 + 4 g_0 \varepsilon_s \eta]$$

$$\mu_s = \left(\tfrac{2+\alpha}{3}\right)\left[\tfrac{\mu_s^*}{g_0 \eta (2-\eta)}\left(1 + \tfrac{8}{5}\eta g_0 \varepsilon_s\right)\left(1 + \tfrac{8}{5}\eta(3\eta - 2) g_0 \varepsilon_s\right) + \tfrac{3}{5}\eta \mu_b\right]$$

$$\mu_s^* = \frac{\varepsilon_s \rho_s \Theta_s g_0 \mu}{\varepsilon_s \rho_s \Theta_s g_0 + \frac{2\beta\mu}{\varepsilon_s \rho_s}}$$

$$\mu = \tfrac{5}{96}\rho_s d_s \sqrt{\pi\Theta}$$

$$\mu_b = \tfrac{256}{5\pi}\mu \varepsilon_s^2 g_0$$

$$\eta = \tfrac{1+e}{2}$$

(c) Granular temperature

$$\Theta_s = \left[\frac{-(K_1 \varepsilon_s + \rho_s) Tr(\bar{\bar{D}}_s)}{2K_4 \varepsilon_s} + \frac{\sqrt{(K_1 \varepsilon_s)^2 Tr^2(\bar{\bar{D}}_s) + 4K_4 \varepsilon_s [2K_3 Tr(\bar{\bar{D}}_s^2) + K_2 Tr^2(\bar{\bar{D}}_s)]}}{2K_4 \varepsilon_s}\right]^2$$

$$K_1 = 2(1-e)\rho_s g_0$$

$$K_2 = \tfrac{4}{3\sqrt{\pi}} d_s \rho_s (1+e) g_0 \varepsilon_s - \tfrac{2}{3}K_3$$

$$K_3 = \tfrac{d_s \rho_s}{2}\left\{\tfrac{\sqrt{\pi}}{3(3-e)}\left[\tfrac{(3e+1)}{2} + \tfrac{2}{5}(1+e)(3e-1) g_0 \varepsilon_s\right] + \tfrac{8\varepsilon_s}{5\sqrt{\pi}} g_0 (1+e)\right\}$$

$$K_4 = \frac{12(1-e^2)\rho_s g_0}{d_s \sqrt{\pi}}$$

(d) Inter-phase momentum exchange

$$I_{gs} = \beta(\vec{V}_g - \vec{V}_s)$$

$$\beta = \begin{cases} 150 \frac{\varepsilon_s^2 \mu_g}{\varepsilon_g d_s^2} + 1.75 \frac{\varepsilon_s \rho_g |\vec{V}_s - \vec{V}_g|}{d_s} & \text{if } \varepsilon_s > 0.2 \\ \frac{3}{4} C_d \varepsilon_g^{-2.65} \frac{\varepsilon_s \varepsilon_g \rho_g |\vec{V}_s - \vec{V}_g|}{d_s} & \text{if } \varepsilon_s \le 0.2 \end{cases}$$

$$C_d = \begin{cases} \frac{24}{Re \cdot \varepsilon_g}(1 + 0.15 (Re \cdot \varepsilon_g)^{0.687}) & \text{if } Re \cdot \varepsilon_g < 1000 \\ 0.44 & \text{if } Re \cdot \varepsilon_g \ge 1000 \end{cases}$$

$$Re = \frac{\rho_g |\vec{V}_s - \vec{V}_g| d_s}{\mu_g}$$

(e) Ideal gas law

$$P = \rho_g \frac{R}{M_g} T_g$$

(f) Total enthalpy

$$h_{total} = C_p T_g + \tfrac{1}{2}|\vec{V}_g|^2$$