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Modelling of the turbulent gas–particle flow structure in a two-dimensional circulating fluidized bed riser

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Abstract

The gas–particle turbulent flow in a circulating fluidized bed (*CFB*) riser is investigated numerically by large eddy simulation (*LES*) coupled with Lagrangian approach. The gas phase model is based on locally averaged two-dimensional Navier–Stokes equations (N–S Eqs.) for two-phase flow with fluid turbulence calculated by LES, in which the effect of particles on subgrid-scale (*SGS*) gas flow is taken into account. The particles' motion is treated by a Lagrangian approach, in which the particles are assumed to interact through binary, instantaneous, and non-elastic collisions. The model predicts the heterogeneous particle flow structure and the gas and particle mean velocities and turbulent intensities. The gas turbulence induces particle lateral dispersion. The instantaneous gas turbulent intensity is attenuated by the formation of clusters, whereas the intensity is enhanced by the increase of gas–particle interactions. Globally, the presence of clusters enhances the gas turbulent intensity. Finally, the turbulent model is noticeably affected by an empirically assigned gas constant C_k and it consistently predicts values of the gas and particle turbulent intensities higher than those predicted by Smagorinsky's method.

Keywords: Large eddy simulation; Lagrangian approach; Circulating fluidized bed; Four-way coupling; Two-phase flow

1. Introduction

A circulating fluidized bed (CFB) riser is characterized by its turbulence hydrodynamics (Dasgupta et al., 1994; Peirano and Leckner, 1998; Zhou et al., 2000); in addition, such a gas–particle system is inherently unsteady with large suspension density fluctuations (Schnitzlein and Weinstein, 1988). In a vertical tube, the interaction between particles and gas-phase turbulent flows govern the cluster formation and their disappearance (Zelenko et al., 1996). Both experimental and simulated results have revealed a non-uniform distribution of particles over the cross-section of a CFB riser (Horio and Kuroki, 1994; Helland et al., 2000, 2002). Moreover, particle–particle collisions are considered to play an important role in the cluster formation and to cause flow instability even if the global concentration is as low as 0.5% (Tanaka and Tsuji, 1991).

Numerical simulation is a powerful tool for predicting gas–particle flow behavior in a fluidized bed. Many models describe the 2-phase flow in such complicated systems. They can be classified into two categories: Eulerian–Eulerian models and Eulerian–Lagrangian models. The Eulerian–Eulerian approach is currently more developed than the Eulerian–Lagrangian approach (Ding and Gidaspow, 1990; Samuelsberg and Hjertager, 1996; Peirano and Leckner, 1998; Dasgupta et al., 1994; Arastoopour, 2001; Gidaspow et al., 2004). However, interest in the Eulerian–Lagrangian approach is growing as computational capacity increases (Tsuji et al., 1993; Hoomans et al., 1996; Xu and Yu, 1997; Ichiki and Hayakawa, 1995; Yuu et al., 2001a,b; Zhou et al., 2002, 2004; Ibsen et al., 2004; Wang and Rhodes, 2004; Li and Kuipers, 2005).

In recent years, direct numerical simulation (DNS) or large eddy simulation (LES) have become powerful tools for studying 2-phase flow. In LES model, the large, energy containing scales of motions are calculated directly by solving the filtered Navier–Stokes equations (N–S Eqs.), whereas the effects of small (subgrid) scales of motion are modelled (Lesieur and Metais, 1996). One of the main advantages of LES in

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comparison to DNS is that it can treat high Reynolds number flows (Wang and Squires, 1996; Boivin et al., 2000). Two-dimensional LES has been adopted to simulate both single and 2-phase flow (Desjardin and Frankel, 1999; Helland et al., 2000; Koutmos, 2000; Horvat et al., 2001). The two-dimensional model is mainly limited because the bed porosity values in the two-dimensional simulation are not comparable with those in three-dimensional simulation (Bideau and Hansen, 1993). Moreover, the two-dimensional simulation gives less detailed flow patterns than the three-dimensional simulation, as shown by Yamamoto et al. (2001).

In the last decade, the Eulerian–Lagrangian model has been used to simulate gas–particle fluidization. Phenomena such as bubbling, slugging and particle transport in fluidized bed can be simulated (Tsuji et al., 1993; Hoomans et al., 1996; Helland et al., 2000, 2002; Van Wachem et al., 2001; Yuu et al., 2001a). These models all consider four-way coupling, but only a few of them take into account the gas–particle turbulent flow (Helland et al., 2000; Yuu et al., 2001a). Helland et al. (2000) simulate the cluster formation in CFB riser with a total particle concentration of 3%. The gas phase turbulence is calculated on the basis of a two-dimensional LES, in which the turbulent viscosity is modelled using the Deardorff's (1970) SGS model. Yuu et al. (2001a) propose a model that accounts for the effect of the particle on subgrid-scale flows; the turbulent production term and the viscous dissipation term are assumed to balance each other in the kinetic energy equation of the subgrid-scale turbulent flow. With this model, three-dimensional N–S Eqs. and Lagrangian particle motion equations are simultaneously solved to describe the mechanisms of various phenomena such as large complex bubbling flow and cluster formation in turbulent fluidized bed of group-B particles.

In this paper a mathematical approach for modelling and simulating the gas–particle turbulent flow fields in a two-dimensional CFB riser is developed, on the basis of our previous studies (Zhou et al., 2002, 2004). The LES model of Yuu et al. (2001a,b) is here further extended to overcome their assumptions: the magnitude of particle effects on subgrid-scale flow is obtained by solving simultaneously the SGS kinetic energy equation with the equations for filtered mass and momentum conservation. We calculate the gas flow by LES with two-way coupling. For the particle phase calculation, individual particles are tracked by a Lagrangian method. The particle motion consists of collision steps and free flight steps. The inter-particle collision time is evaluated by a deterministic approach. The particle–particle interaction is described as instantaneous, binary, and inelastic collision with friction, and the flight step is determined not only by the fluid but also by its neighboring particles. The interaction forces between fluid and particle, and vice versa, obey Newton's third law. Instantaneous and average gas–particle flow fields are analyzed to study the interactions between the gas turbulence and the particle motion. In particular, we clarify both the effect of particles on subgrid-scale flow and their effects on the gas turbulence intensity when combined with cluster formation. Furthermore, the sensitivity of the turbulent dense 2-phase flow model is also examined.

2. Simulation overview

2.1. Fluid hydrodynamics

The turbulent gas flow in the CFB riser is calculated using LES of the incompressible 2-phase N–S Eqs. a similar approach was used by Zhou et al. (2004) to model bubbling fluidized beds. LES is based on the decomposition of the instantaneous turbulent gas velocity ($\vec{u}_f$) into a large-eddy field ($\tilde{u}_f$) (the resolved or filtered field) and a small-scale turbulence field ($u_f^{(s)}$) (the subgrid or residual field), i.e., $\vec{u}_f = \tilde{u}_f + u_f^{(s)}$. The decomposition is obtained using a low-pass filter with a characteristic length (Δ) of the order of the computational mesh size; $\Delta = (\Delta x \Delta y)^{1/2}$, $\Delta x, \Delta y$ are the cell lengths at different directions. The filtered velocity is defined as

$$\tilde{u}_f(x,t) = \int \vec{u}_f(x',t) G_\Delta(x,x')\,\mathrm{d}x', \tag{1}$$

where G is the filter function that determines the scale of the filtered eddies. More details can be found in Sagaut (2001).

The LES equations for the incompressible gas flows are derived by filtering the 2-phase N–S continuity and momentum equations (Helland et al., 2000; Yuu et al., 2001a)

$$\frac{\partial(\varepsilon\rho_f)}{\partial t} + \frac{\partial(\varepsilon\rho_f\tilde{u}_{f,i})}{\partial x_i} = 0, \tag{2}$$

$$\begin{aligned}\frac{\partial(\varepsilon\rho_f\tilde{u}_{f,i})}{\partial t} + \frac{\partial(\varepsilon\rho_f\tilde{u}_{f,i}\tilde{u}_{f,j})}{\partial x_j} = {} & -\varepsilon\frac{\partial\tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j}(\varepsilon\tilde{\sigma}_{ij}) \\ & + \frac{\partial}{\partial x_j}(\varepsilon\tilde{\tau}_{ij}) + \varepsilon\rho_f\vec{g} + \Psi,\end{aligned} \tag{3}$$

where an overbar $\tilde{\bullet}$ denotes application of the filtering operation, Ψ is the volumetric particle–fluid interaction, $\tilde{\sigma}_{ij} = \rho_f\nu_f(\tilde{S}_{f,ij} - \frac{2}{3}\tilde{S}_{f,kk}\delta_{ij})$ and $\tilde{\tau}_{ij}$ are the SGS stresses and $\tilde{S}_{f,ij} = \partial\tilde{u}_{f,i}/\partial x_j + \partial\tilde{u}_{f,j}/\partial x_i$ is the resolvable strain tensor, $\tilde{\tau}_{ij}$ is modelled as

$$\tilde{\tau}_{ij} = -\rho_f\overline{\tilde{u}'_{f,i}\tilde{u}'_{f,j}} = \rho_f\nu_t\left(\tilde{S}_{f,ij} - \tfrac{2}{3}\tilde{S}_{f,kk}\delta_{ij}\right) - \tfrac{2}{3}\rho_f\tilde{k}_s\delta_{ij}, \tag{4}$$

where $\tilde{u}'_{f,i}$ is the gas fluctuating velocity, $\nu_f = \mu_f/\rho_f$ is the gas kinematic viscosity, μ_f is the gas viscosity, ν_t is the SGS gas kinetic viscosity, δ_{ij} is the Kronecker delta, $\tilde{k}_s$ is the SGS kinetic energy, ε is the porosity, t is the time, p is the gas pressure and ρ_f is the gas density, $i, j = 1, 2$ represent x and y directions, respectively.

The SGS kinetic energy transport equation is obtained from Eq. (3). Terms higher than the third order of the subgrid-scale and pressure correlation terms are neglected. Therefore, the SGS kinetic energy equation can be obtained in the following