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Effects of momentum transfer on particle dispersions of dense gas–particle two-phase turbulent flows

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ABSTRACT

A modified momentum transfer coefficient of dense gas–particle two-phase turbulent flows is developed and its effect on particle dispersion characteristics in high particle concentration turbulent downer flows has been numerically simulated incorporating into a second-order moment (USM) two-phase turbulent model and the kinetic theory of granular flow (KTGF) to consider particle–particle collisions. The particle fractions, the time-averaged axial particle velocity, the particle velocities fluctuation, and their correlations between gas and particle phases based on the anisotropic behaviors and the particle collision frequency are obtained and compared using traditional momentum transfer coefficients proposed by Wen (1966), Difelice (1985), Lu (2003) and Beetstra (2007). Predicted results of presented model are in good agreement with experimental measurement by Wang et al. (1992). The particle fluctuation velocity and its fluctuation velocity correlations along axial–axial and radial–radial directions have stronger anisotropic behaviors. Furthermore, the presented model is in a better accordance with Lu's model in light of particle axial velocity fluctuation, particle temperature, particle kinetic energy and correlations of particle–gas axial–axial velocity fluctuation. Also, they are larger than those of other models. Beetstra's model is not suitable for this downer simulation due to the relative lower particle volume fraction, particle collision and particle kinetic energy.

1. Introduction

Circulating fluidized beds (CFBs) have been widely applied in the chemical industry due to its practical application behaviors, such as riser, downer and cyclone [1]. Compared to those of dense gas–particle flows in riser, downer reactor has many advantages, i.e. good gas–solids contact, less gas and solids back-mixing, a short contact time, uniform flow and more uniform residence time distribution, etc. [2–10]. However, it has still some limitations for better quantitatively understanding of the interaction between gas and particle phases and particle dispersion characteristics. Generally, as for dilute gas–particle turbulent flows, one-way or two-way coupling effects neglecting particle–particle collisions are considered. But, regarding to the higher particle volume fraction flows, four-way coupling effects considered particle and particle collisions must be incorporated [11,12]. Meanwhile, particle–particle collision will play an important role in two-phase turbulent flow behaviors.

Except for the traditional experiment measurement approach, computational fluid dynamics (CFD) approach has been extensively utilized to predict hydrodynamics in CFB with the rapidly increasing computer hardware technique in recent years. The modeling and simulation can be classified into two approaches, that is: Eulerian–Lagrangian discrete particle and Eulerian–Eulerian two-fluid approaches. In the Eulerian–Lagrangian approach, numerous discrete particles are tracked and inter-particle collisions are simulated using a hard sphere or a soft sphere model. In the Eulerian–Eulerian two fluid approach for dense gas–particle turbulent flows, the constitutive relation for particle–particle collisions can be obtained from the kinetic theory of granular flows by Lun et al. and Ding and Gidaspow [13,14]. It is similar to analogy between the dense-gas kinetic theory and the particle random fluctuation due to particle–particle collisions, which causes the transfer of particle momentum and produces particle pressure and particle viscosity. Particle pressure and viscosity depend on the magnitude of small-scale particle fluctuations, which can be described by the particle pseudo-thermal energy from the particle stress and dissipation through the inelastic collision between particles.

Compared with these two approaches, because of the huge computation consumption for discrete particle model in industry applications, two-fluid model are superior to the discrete particle model and successfully applied many years. Sinclair and Jackson

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Nomenclature

D	diffusion term
e	coefficient of restitution particles
e_{eff}	effective coefficient of restitution
e_t	tangential coefficient of restitution
f	frequency
g	gravitational force
g_0	radial distribution function
k	kinetic energy
G	production term
P	pressure
R	correlation term
t	time
V, v	velocity
Greek alphabets	
α	volume fraction
β	drag coefficient
δ	kronic-delta unit tensor
ε	dissipation term
θ	particle temperature
μ	dynamic viscosity
ν	kinematic viscosity
Π	pressure-strain term
ρ	density
τ	stress tensor
Subscripts	
i, j,k, l	coordinates directions
coll	collision
g	gas
p	particle
r	relaxation
max	maximum
min	minimum

[15] firstly built up a laminar gas-phase and laminar particle-phase model for simulating the fully developed flow in vertical pipes. Savage [16] and Gidaspow [17] derived the full equations of kinetic theory for granular flows to couple the effect of gas turbulence. Bolio et al. [18] disclosed the gas turbulent behaviors and particle fluctuation characteristics due to particle collisions using a low Renumber k–ε model. Based on the kinetic theory of granular flows, Lu et al. [19,20] indicated the hydrodynamics of gas–particle flow in riser reactors, in which the gas turbulence is modeled using large eddy simulation. As aforementioned models, they are only considered particle flows as small-scale laminar flow. Thus, as for large-scale fluctuation from particle turbulence, it is failed. In order to solve this problem, Zhou's [21–25] research group have successfully proposed a series of kinetic energy equations for gas and particle phase (k–k_p), second-order or unified second-order moment (SOM, USM) models for dilute and dense gas–particle turbulent flows, i.e. k–ε–k_p model, k–ε–k_p–θ four equations model, k–ε–k_p–ε_p–θ five equations model, USM-θ particle temperature model, and subgrid scale USM model to simulate particle turbulent flows based on the Reynolds-averaged-Navier–Stokes (RANS) and large eddy simulation (LES) methods. In USM model, the anisotropy of both gas and particle two-phase stresses and the interaction between two-phase stresses can be fully considered by establishing the two-phase Reynolds stresses transport equations and their stress correlations. Simulated results of these models are good agreed with the experimental results and have been applied in the field of chemical engineering.

Including effects of particle–particle collisions, the other importance factor on gas–particle two-phase turbulent flow behavior is the momentum transfer process between gas and particle phases, which is typically represented by drag force term. Due to the fact that it is difficult to get a accurate value restricted to different Reynolds numbers and packing fractions, as well as in terms of homogeneity, mono-dispersity, sphericity of the particles, a large number of the gas–solid drag force expressions have been limited in the light of the empirical relations. Although the relations presented by Ergun [26] and Wen and Yu [27] have been the most widely used since 1960s, there is at present no real consensus as to what the most accurate predictions for the drag force is at a given Reynolds numbers and packing fraction. Thus, so far, all correlations were all based on experimental data [26–28]. In order to assure these correlations more accurate in theory, Lu and Gidaspow [20] introduced a weighted average of the two scales switch function to prevent the discontinuous behaviors when solid volume fraction less than 0.2. Beetstra et al. [29] established a the drag force model based on the kinetic theory of granular flows and lattice Boltzmann data for mono-disperse and bi-disperse systems. Even if these corrections have successfully got better results in specified cases, they should be further validated by measurements.

To date, the effects of gas–particle moment transfer represented by transfer coefficient on dense particle dispersion behaviors in downer have never been reported. In the paper, a USM particle temperature model coupled five kinds of transfer coefficient models is used to study and compare the particle transport characteristics and their applications using different models.

2. Conservation equations of two-phase turbulence flows

In this work, the Eulerian–Eulerian two-fluid continuum approach is used due to more suitable for large scale equipments having high solid inventories. In this approach, both phases are treated as interpenetrating continuums, and the ensemble averaging of local instantaneous mass and momentum balances for the each phase are used in formulation of the governing equations. A Second-order moment with particle temperature model based on the kinetic theory of granular flows, firstly proposed by Yu et al. [25]. In this model, the particle anisotropic behaviors and the momentum transfer using traditional Wen's model [27] both fully considered.

Some basic governing equations can be referred the literatures 23 and 25 and the key stresses equations are given as follows:

2.1. Momentum balance equations

$$\frac{\partial(\alpha_g\rho_g\overline{u_{gi}})}{\partial t}+\frac{\partial(\alpha_g\rho_g\overline{u_{gk}}\overline{u_{gi}})}{\partial x_k}=\alpha_g\rho_g g-\alpha_g\frac{\partial\overline{p}}{\partial x_i}+\frac{\partial}{\partial x_k}(\tau_{gik}-\alpha_g\rho_g\overline{u'_{gi}u'_{gk}})-\beta(\overline{u_{gi}}-\overline{u_{si}}) \quad (1)$$

$$\frac{\partial(\alpha_p\rho_p\overline{u_{si}})}{\partial t}+\frac{\partial(\alpha_p\rho_p\overline{u_{pk}}\overline{u_{pi}})}{\partial x_k}=\alpha_p\rho_p g-\alpha_p\frac{\partial\overline{p}}{\partial x_i}-\frac{\partial\overline{p_p}}{\partial x_i}+\frac{\partial}{\partial x_k}\times(\tau_{pik}-\alpha_p\rho_p\overline{u'_{pk}u'_{pi}})+\beta(\overline{u_{gi}}-\overline{u_{pi}}) \quad (2)$$

where g is the gravity acceleration, p the thermodynamic pressure, β the interface momentum transfer coefficient, respectively. τ_g and