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Numerical simulation and experimental validation of gas–solid flow in the riser of a dense fluidized bed reactor

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ABSTRACT

Gas–solid flow in the riser of a dense fluidized bed using Geldart B particles (sand), at high gas velocity (7.6–15.5 m/s) and with comparatively high solid flux (140–333.8 kg/m^2 s), was investigated experimentally and simulated by computational fluid dynamics (CFD), both two- and three-dimensional and using the Gidaspow, O'Brien-Syamlal, Koch-Hill-Ladd and EMMS drag models. The results predicted by EMMS drag model showed the best agreement with experimental results. Calculated axial solids hold-up profiles, in particular, are well consistent with experimental data. The flow structure in the riser was well represented by the CFD results, which also indicated the cause of cluster formation. Complex hydrodynamical behaviors of particle cluster were observed. The relative motion between gas and solid phases and axial heterogeneity in the three subzones of the riser were also investigated, and were found to be consistent with predicted flow structure. The model could well depict the difference between the two exit configurations used, viz., semi-bend smooth exit and T-shaped abrupt exit. The numerical results indicate that the proposed EMMS method gives better agreement with the experimental results as compared with the Gidaspow, O'Brien-Syamlal, Koch-Hill-Ladd models. As a result, the proposed drag force model can be used as an efficient approach for the dense gas–solid two-phase flow.

1. Introduction

In the hydrodynamic modeling of gas–solid flow, the CFD code provides rapid and detailed information for CFB risers (Horio & Kuroki, 1994; Pugsley, Patience, Berruti, & Chaouki, 1992; van der Hoef, Ye, & van Sint Annaland, 2006). Among the many numerical studies, Capes and Nakamura (1973) designed a core-annulus model to reflect experimental observation of a dilute up-flowing core surrounded by a dense down-flowing annulus, though not inclusive of the inlet and exit zones of the riser; Anderson and Jackson (1968), Gidaspow (1994) treated the gas and solid phases as continua, described by Navier–Stokes equations; while the kinetic theory of granular flow (KTGF) (Anderson, & Jackson, 1968; Gidaspow, 1994) based on molecular dynamics introduced the concept of granular temperature to model the solid phase pressure and viscosity; Jin and Zheng (1999) proposed that, owing to schlepping of the gas, in the smooth condition, almost all solids left the main bed without the increment of solid concentration near the top exit zone. When the abrupt exit is considered, however, a vacuum will be formed and the solid concentration near the top will substantially increase. Pugsley, Lapointe, Hirschberg, & Werther (1997) introduced the conception of the exit effects on the axial pressure distribution. Horio and Kuroki (1994), as well as van Den Moortel, Santini, Tadrist, & Pantaloni (1998), carried out flow visualization of the heterogeneous structure of particles and clusters in CFB; and Helland, Bournot, Occelli, & Tadrist (2006) proposed two combined possible drag force laws upon studying the effect of clusters on gas-particle flow behavior.

As a general model for heterogeneous flow characteristics in risers, Li and Kwauk (1994) proposed the energy minimization multi-scale (EMMS) model, in which a minimal energy term was introduced to close the conservation equations. The EMMS model divided the fluid field into three scales to signify the dense, dilute and inter phases. The original EMMS model was established only for steady flow, although the improved EMMS model (Li et al., 2005) which soon followed considers particle acceleration and effective inter-phase interaction. The dilute and dense phase accelerations, a_f and a_c, were introduced accordingly by Wang and Li (2007) into the EMMS model, to represent the different drag forces of particles in the dilute and dense phases respectively. However, little has

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Nomenclature

C_{D0}	effective drag coefficient for a single particle
C_D	effective drag coefficient for system
d_s	particle diameter, m
d_{c1}	cluster diameter, m
ρ_g, ρ_s	density of gas and particle, kg/m^3
f	volume fraction of dense phase
U_g, U_s	superficial velocity of gas and particle, m/s
u_g, u_s	true velocity of gas and particle, m/s
U_{si}, U_{sc}, U_{sf}	superficial slip velocity in inter phase, dense phase and dilute phase, m/s
U_{pc}, U_{pf}	superficial solid velocity in dense phase and dilute phase, m/s
U_c, U_f	superficial velocity in dense phase and dilute phase, m/s
U_{mf}	minimum superficial velocity, m/s
ε_c, ε_f	voidage of dense phase and dilute phase
ε_g	average voidage
a_c, a_f	acceleration of particles in dense and dilute phase, m/s^2
β	drag coefficient for a control volume, kg/m^3
μ_s	solid viscosity
μ_s^*	solid dynamic viscosity
H_d	heterogeneity index
G_s	solid flux, kg/m^2 s
N_{st}	mass specific energy consumption for particles, W/kg

been published relative to exits effect of CFB by using the EMMS model.

A revised drag force based on the EMMS model for the special conditions for the experimental apparatus of this paper was proposed with the aim of better analyzing the flow characteristics and the effect of exit configurations for risers operating at high solid flux (140–333.8 kg/m^2 s) and high superficial gas velocity (7.6–15.5 m/s) using Geldart B particles.

2. Experimental apparatus

The experimental study of measuring solids circulation rate and solid concentration profiles in a cold circulating fluidized bed (CFB) with the square cross-section and two kinds of exits at high gas velocities has been carried out. The riser is $0.27 \times 0.27 \times 10.4\,m^3$. Bed materiel is the sand with the density of 2630 kg/m^3 and the average particle diameter of 330 μm. Particle terminal velocity is 2.14 m/s and minimum fluidization velocity is 0.09 m/s. Furthermore, the circular section cold experimental apparatus is also researched by modifying the square cross-section system. Fig. 1 is a schematic diagram of the system. Fig. 1(a) and (b) is the square cross-section system and the circular cross-section system, respectively. Fig. 2 shows the abrupt T-shape and smooth semi-bend exit configurations.

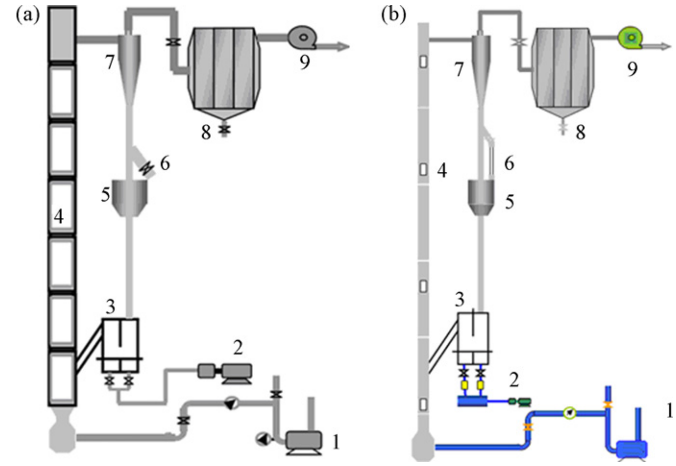

Fig. 1. Schematic diagram of the dense CFB. 1-roots blower, 2-compressor, 3-U-feeder, 4-main bed, 5-storage tank, 6-Gs testing, 7-cyclone, 8-bag filter, 9-fan. (a) square cross-section riser; (b) circular cross-section riser.

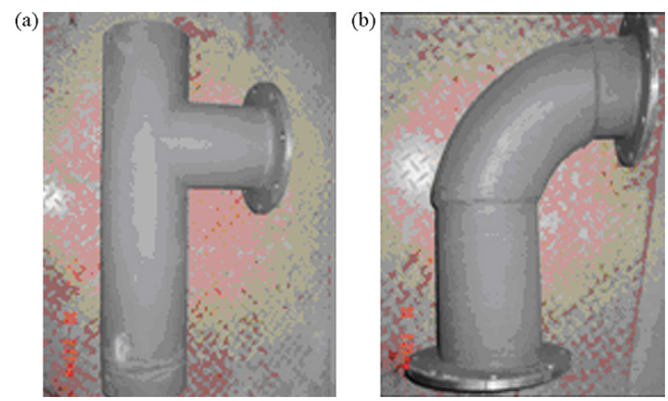

Fig. 2. Abrupt T and smooth semi-bend exits. (a) abrupt T-shape exit; (b)smooth semi-bend exit.

Air from roots blower flows directly to the bottom of the riser. Air from the compressor flows to the U-feeder and bag filter. Particles in the riser are sent to the cyclone carried by air, then form particle-seal in the recycle downcomer, at last return to the main bed.

In steady condition, solids circulation rate(G_s) is calculated by measuring the mass in the testing section in certain time intervals. The complex hydrodynamical behaviors are observed in the experiment. The back-mixing and clusters near the wall of riser can also be observed.

3. Simulation conditions

Both two- and three-dimensional simulation are implemented on the bench-scale test rig. Owing to the key role of drag forces, several drag models were employed in our simulations, such as the Koch-Hill-Ladd model and the Gidaspow model (Wang et al. (2009)), for the purpose of finding a feasible model for the dense

Table 1
Values of A_i under different operation conditions.

	Case 1 (G_s = 165 kg/(m^2 s))	Case 2 (G_s = 140 kg/(m^2 s))	Case 3 (G_s = 113 kg/(m^2 s))
A_0	−134.46462	−109.00413	−87.88475
A_1	866.37784	703.09085	567.4818
A_2	−2225.76833	−1808.52814	−1461.60469
A_3	2850.5944	2319.59511	1877.5835
A_4	−1820.60775	−1484.02076	−1203.5397