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Circulation of Geldart D type particles: Part II—Low solids fluxes Measurements and computation under dilute conditions

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ABSTRACT

In Part I of this paper, solids slugging phenomena were studied for high solids fluxes. In this study, the solids slugging was eliminated for extremely low solids fluxes. Here, gamma ray densitometry and PIV techniques were used to measure radially averaged solids volume fractions, and solids laminar and turbulent properties near the wall, respectively.

The PIV system measured turbulent properties for solids, such as stresses, granular temperatures, and dispersion coefficients, non-invasively near the wall, in the developing region. This study was the first known measurement of solids dispersion coefficients in the axial and radial directions, using the PIV technique. A two-dimensional kinetic theory based IIT CFD code was used to perform simulations. The measured and computed radially averaged total granular temperatures, axial and radial solids and axial gas dispersion coefficients, reasonably agreed with the literature. This study also showed the capabilities of the kinetic theory based CFD codes to reasonably match the solids dispersion coefficients measured using the PIV technique.

1. Introduction

The circulating fluidized beds (CFBs) exhibit complex hydrodynamics due to the interactions between gas and solid phases. One of the main parameters required for good understanding of the CFBs is the solids velocity, as it affects mixing, and heat and mass transfer, which can influence the overall reaction rate in fluidized bed reactors. Similar to the axial mixing of solids, the radial mixing of solids is also very important, otherwise, the conversion efficiency reduces due to poor contact of solids with gas.

Zhang et al. (2009) described solids mixing as a significant parameter in designing fluidized bed reactors, especially for reactors processing solids feedstock, such as fluidized bed boilers for coal combustion and fluid catalytic cracking (FCC) regenerators for burning coke deposited in catalysts. The mixing influences the residence time distribution (RTD) in a fluidized bed, hence, affecting the reaction conversion and selectivity. Solids mixing is generally studied using saline (Bader et al., 1988; Rhodes et al., 1991), ferromagnetic (Avidan and Yerushalmi, 1985), thermal (Lee and Kim, 1990), radioactive (May, 1959; Ambler et al., 1990; Mostoufi and Chaouki, 2001), carbon (Winaya et al., 2007) or phosphorescent (Wei et al., 1998; Ran et al., 2001; Du et al., 2002) tracers. However, experiments with solid tracers are difficult to carry out in fluidized beds due to the lack of continuous sampling; need for frequent replacements; existence of residual tracers; transferring of heat to gas flow and column walls; safety concerns; applications in only dilute fluidized bed systems. Hence, a non-invasive particle image velocimetry (PIV) technique (Gidaspow et al., 2004; Tartan and Gidaspow, 2004; Jung et al., 2005) can be used to measure solids mixing using a colored rotating transparency to obtain the direction of the movement of particles in the fluidized bed systems.

In this study, the gamma ray densitometry was used to measure radially averaged solids volume fractions. The operation of the IIT riser under high gas velocity–low solids flux conditions almost eliminated solids slugging phenomena observed in Part I of this paper (Kashyap et al., 2011). The PIV technique was utilized to measure laminar and turbulent properties for Geldart D type particles, simultaneously in the axial and radial directions, such as instantaneous and hydrodynamic velocities, laminar and Reynolds stresses, laminar and turbulent granular temperatures, and laminar and turbulent dispersion coefficients, near the wall. This study was the first to utilize PIV technique to measure solids dispersion coefficients in the axial and radial directions using autocorrelation method.

The hydrodynamics of the fluidized particles were modeled using a two-dimensional kinetic theory based IIT CFD code with standard gas–solid drag, without modification. The CFD simulations near the wall computed the axial solids velocity, laminar and turbulent granular temperatures, axial laminar and turbulent

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solids dispersion coefficients, and radial laminar solids dispersion coefficients, close to the measurements. The measurements and computations showed good agreement for the radially averaged solids volume fractions. The radially averaged total granular temperatures, axial and radial solids and axial gas dispersion coefficients, were in reasonable agreement with the literature. This study showed the capabilities of the kinetic theory based CFD codes, such as the IIT CFD code, to design fluidized bed reactors without using properties, such as dispersion coefficients, as inputs, and to reasonably match solids dispersion coefficients with the experiments.

2. Measurements of solids volume fractions

2.1. Experimental setup

A two-story circulating fluidized bed (CFB) or riser described in Part I of this paper (Kashyap et al., submitted for publication), was used in this study.

2.2. System properties

The particles used for the circulation in the IIT CFB were alumina ceramic particles, with the mean size of 1093 μm and the density of 2985 kg/m^3, lying in the category of Geldart D type particles (Gidaspow, 1994). Table 1 gives details on the system geometry and properties in Cases A and B analyzed in this study. The solids volume fractions and turbulent properties for solids were measured using the gamma ray densitometer and particle image velocimetry (PIV), respectively. The solids volume fractions were measured in Cases A and B, whereas, the turbulent properties were measured only in Case B. The solids volume fractions were measured in the riser section: axially (y-axis) at a height of 4.5 m from the supporting grid at the bottom of the riser, radially averaged (x-axis), and tangentially at the plane $z=0$ (passing through the center). The turbulent properties were measured in the riser section: axially (y-axis) at a height of 4.5 m from the supporting grid at the bottom of the riser, radially (x-axis) near the right wall or away from the side inlet at the bottom of the CFB, and at the plane $z=0$ (passing through the center).

Elaborative details pertaining to the system properties, such as the packing fraction, minimum fluidization velocity, terminal velocity, minimum slugging velocity, time step, etc., given in Table 1 are same as those from Part I of this paper (Kashyap et al., 2011).

The experiments were performed by varying the superficial gas velocity between 12.43 and 19.4 m/s, which was much higher than the terminal velocity of the particles. The solids fluxes into the riser controlled by moving the gate value installed in the pipe connecting the downcomer with the riser were significantly lower than those in Part I of this paper (Kashyap et al., 2011). In both Cases A and B in this study, the gate valve connecting the downcomer with the riser was slightly opened, with the opening smaller in Case B. At low solids fluxes in this study, the solids slugging phenomena observed in Part I of this paper (Kashyap et al., 2011) were eliminated at a height of 4.5 m, and was reduced significantly in the dense bottom section. The time averaging for different experimental runs was done at steady state for time periods from 0–18 to 0–42 s.

2.3. Gamma ray densitometry

The gamma ray densitometry technique used for the measurement of solids volume fractions is described in Part I of this paper (Kashyap et al., 2011).

2.4. Description of gamma ray densitometer system

The voltage data from the gamma ray densitometer were recorded by the data collection system for conversion to the solids volume fractions for 18–42 s with a 1 ms sampling time, for each experimental run. This gave a total of 18,000–42,000 points

Table 1
System geometry and properties for solids volume fraction measurements using gamma ray densitometer.

Geometry/property, symbol	Case A Value	Case B Value	Unit
Riser pipe material	Acrylic	Acrylic	Dimensionless
Riser inner diameter, D	0.0762	0.0762	m
Riser height, H	7.3	7.3	m
Measuring axial distance from the bottom of reactor, $H_{measurement}$	4.5	4.5	m
Measuring horizontal distance from right wall of riser, $X_{measurement}$ (Kashyap et al., 2011)	0–0.0762 (radially averaged)	0–0.0762 (radially averaged)	m
Measuring distance from the plane, $z=0$, $Z_{measurement}$ (Kashyap et al., 2011)	0 (passing through center)	0 (passing through center)	m
Downcomer inner diameter, $D_{downcomer}$	0.1016	0.1016	m
Bottom connecting pipe diameter, $D_{bottom\ connecting\ pipe}$	0.0762	0.0762	m
Bottom connecting pipe angle with horizontal, $\alpha_{horizontal}$	45	45	deg
Particle diameter, d_p	1093	1093	μm
Particle density, ρ_s	2985	2985	kg/m^3
Packing fraction, $\varepsilon_{s,\ max.}$	0.66	0.66	Dimensionless
Fluidizing gas	Air	Air	Dimensionless
Operating temperature, T_g	298	298	K
Gas density, ρ_g	1.2	1.2	kg/m^3
Gas viscosity, μ_g	1.8×10^{-5}	1.8×10^{-5}	kg/(m s)
Terminal velocity, U_t	9.93	9.93	m/s
Minimum fluidization velocity, U_{mf}	0.68	0.68	m/s
Minimum slugging velocity, U_{ms}	1.48	1.48	m/s
Superficial gas velocities, U_g	19.4, 19.14, 18.64, 18.38, 17.86	12.43	m/s
Riser inlet solids flux condition	Slightly opened gate valve	Slightly opened gate valve (less than that in Case A)	Dimensionless
Time step, Δt	1×10^{-3}	1×10^{-3}	s
Steady state for time averaging, t_{steady}	Variable between runs	Variable between runs	s