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Measuring turbulence in a circulating fluidized bed using PIV techniques

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ABSTRACT

This study utilized the particle image velocimetry (PIV) technique, non-invasively near the wall, in the developing region, for the measurements of laminar and turbulent properties during circulation of Geldart B type particles in the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) riser. A novel method was used to measure axial and radial laminar and turbulent solids dispersion coefficients using autocorrelation technique.

The instantaneous and hydrodynamic velocities for the solid phase were measured simultaneously in the axial and radial directions using a CCD camera, with the help of a colored rotating transparency. The measured properties, such as laminar and Reynolds stresses, laminar and turbulent granular temperatures, laminar and turbulent dispersion coefficients and energy spectra exhibited anisotropy. The mixing in the riser was on the level of clusters. The total granular temperatures were in reasonable agreement with the literature values. However, the axial and radial solids dispersion coefficients measured near the wall were slightly lower than the radially averaged values in the literature.

1. Introduction

The literature survey (Gel et al., 2009; Pandey, Turton, Yue, & Shadle, 2004; Radmanesh, Chaouki, & Guy, 2006; Reh, 1971, 1986; Syamlal, Guenther, Gel, & Pannala, 2009; Wang, Yang, Dyakowski, & Liu, 2006) describes extensive use of circulating fluidized beds (CFBs) in industries for catalytic cracking of oil, coal combustion and gasification, manufacturing of fine powders and ceramic, alumina calcinations, etc., due to their ability to operate at different flow regimes, such as turbulent, fast fluidization and dilute transport (Grace, 2000). The primary advantages of a CFB are (Grace, Avidan, & Knowlton, 1997): (1) excellent gas–solid contacting due to lack of bubbles; (2) improved control over heat transfer because of the ability to use the solids circulation flux as an additional variable; (3) reduced cross sectional area in view of high superficial gas velocities; (4) low particle segregation and agglomeration; (5) recirculation loop for separate operations, such as regeneration of catalysts; and (6) ability to operate under high solids flux conditions.

However, CFBs show complex hydrodynamics due to the interactions between the gas and solid phases. One main parameter necessary for understanding the CFBs is the solids velocity, as it affects the mixing, and heat and mass transfer, which can affect the overall reaction rate in fluidized bed reactors. The individual particle and cluster velocities can be used to estimate the turbulent intensities of the solid phase and to estimate granular temperatures and solids dispersion coefficients. The primary concern in measuring solids velocities is to maintain the flow characteristics during measurements. This can be achieved either by utilizing a laser based system or by imaging and particle tracking techniques, in a non-invasive mode of measurement. The primary intrusive and non-intrusive techniques used in the literature are described in Pandey et al. (2004) and elsewhere as: (1) laser Doppler anemometry (LDA) (Zhang, Yang, & Arastoopour, 1996); (2) fiber optic probes (Hartge, Rensner, & Werther, 1988; Herbert, Gauthier, Briens, & Bergougnou, 1994; Horio, Morishita, Tachibana, & Murata, 1988; Issangya, Grace, Bai, & Zhu, 2000; Liu, Grace, & Bi, 2002; Pärssinen & Zhu, 2001; Zhou, Grace, Lim, & Brereton, 1995; Zhu et al., 2001); (3) particle image velocimetry (PIV) (Gidaspow, Jung, & Singh, 2004; Jung, Gidaspow, & Gamwo, 2005; Shi et al., 2002; Tartan & Gidaspow, 2004); (4) stroboscopic analysis (Zheng, Zhu, Grace, Lim, & Brereton, 1992); (5) laser fluorescence methods using tracer species (Hamdullahpur, Pegg, & MacKay, 1987; Morooka, Kusakabe, Ohnishi, Gujima, & Matsuyama, 1989); (6) radioactive particle tracer (Viitanen, 1993); (7) Pitot tube (Bader, Findlay, & Knowlton, 1988); (8) capacitance probe (Louge, Lischer, & Chang, 1990); (9) extraction sampling probes (Herb, Dou, Tuzla, & Chen, 1992; Miller & Gidaspow, 1992; Rhodes, Laussmann, Villain,

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Nomenclature

c_a	instantaneous velocity of particles in axial direction (m/s)
$\bar{c}_i$	mean instantaneous velocity in *i*-direction over entire time period (m/s)
const.	Kolmogorov constant
c_r	instantaneous velocity of particles in radial direction (m/s)
C	fluctuating velocity of a particle (m/s)
C_{ik}	fluctuating velocity of particle *k* in a given volume, in *i*-direction (m/s)
$\langle C_i C_j \rangle$	laminar particle stress (m^2/s^2)
$\overline{C_i C_i}$	root mean square of fluctuating instantaneous velocity (m/s)
d_p	diameter of particles (m)
D	inner diameter of the riser (m)
$D_{downcomer}$	downcomer inner diameter (m)
$D_{i(laminar)}$	laminar dispersion coefficient in *i*-direction (m^2/s)
$D_{i(turbulent)}$	turbulent dispersion coefficient in *i*-direction (m^2/s)
e	particle–particle restitution coefficient
$E_i(n)$	energy spectrum function (m^2/s)
$E_{i(laminar)}(n)$	laminar energy spectrum function (m^2/s)
$E_{i(turbulent)}(n)$	turbulent energy spectrum function (m^2/s)
g	acceleration due to gravity (m/s^2)
g_o	radial distribution function for solid particles
H	riser height (m)
$H_{measurement}$	measuring axial distance from the bottom of reactor (m)
i or *j*	direction
k	particle number in a given volume
ΔL	streak length (m)
M_s	mass flow rate (kg/s)
n	frequency (Hz)
p	any position
P_s	solids pressure (N/m^2)
R_L	autocorrelation coefficient
Re_t	Reynolds number of particles at terminal velocity
t	time interval (s)
Δt	time step (s)
t_{steady}	steady state time range (s)
T_g	thermal gas temperature (K)
T_E	Eulerian integral time scale (s)
T_L	Lagrangian integral time scale (s)
$T_{L(laminar)}$	Lagrangian integral time for particles (s)
$T_{L(turbulent)}$	Lagrangian integral time for clusters (s)
U_g	superficial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
U_t	terminal velocity (m/s)
v_{ik}	hydrodynamic velocity of particle *k* in a given volume, in *i*-direction (m/s)
$\bar{v}_i$	mean hydrodynamic velocity in *i*-direction over entire time period (m/s)
v'	fluctuating hydrodynamic velocity (m/s)
v'_i	fluctuating hydrodynamic velocity in *i*-direction (m/s)
$\overline{v'_i v'_j}$	Reynolds stress (m^2/s^2)
v_s	solids velocity (m/s)
W_s	solids flux into the riser ($kg/(m^2\,s)$)
x	radial direction
$X_{measurement}$	measuring horizontal distance from right wall of riser (m)
y	axial direction
Y	distance in axial direction (m)
z	tangential direction
$Z_{measurement}$	measuring distance from the plane, $z=0$ (m)

Greek letters

α	angle with vertical (°)
$\alpha_{horizontal}$	bottom connecting pipe angle with horizontal (°)
β_{HP}	Hay and Pasquill coefficient
ε_d	dissipation rate by turbulence (m^3/s^4)
ε_s	solids volume fraction, $\varepsilon_s = 1.1 \times \varepsilon'_s$
ε'_s	solids volume fraction
$\varepsilon_{s,max}$	maximum solids volume fraction or packing fraction
μ_g	viscosity of air (kg/(m s))
μ_s	solids shear viscosity (kg/(m s))
$\mu_{s,collisional}$	collisional part of solids viscosity (kg/(m s))
$\mu_{s_{dil.}}$	solid phase dilute viscosity (kg/(m s))
$\mu_{s,kinetic}$	kinetic part of solids viscosity (kg/(m s))
ρ_g	density of air (kg/m^3)
ρ_s	density of particles (kg/m^3)
τ	time lag (s)
$\theta_{laminar}$	laminar granular temperature (m^2/s^2)
$\theta_{laminar,2xy}$	laminar granular temperature due to equal velocity fluctuations in *x* and *z* directions (m^2/s^2)
$\theta_{laminar,xyz}$	laminar granular temperature due to particle stresses in *x*, *y* and *z* directions (m^2/s^2)
θ_{total}	total granular temperature (m^2/s^2)
$\theta_{turbulent}$	turbulent granular temperature (m^2/s^2)
$\theta_{turbulent,2xy}$	turbulent granular temperature due to equal velocity fluctuations in *x* and *z* directions (m^2/s^2)
$\theta_{turbulent,xyz}$	turbulent granular temperature due to particle stresses in *x*, *y* and *z* directions (m^2/s^2)
$\wedge_{f(laminar)}$	laminar space integral scale (m)
$\wedge_{f(turbulent)}$	turbulent space integral scale (m)

Subscript

x, *y* or *z*	direction

& Geldart, 1988); (10) image sensing (Kamiwano & Saito, 1984); (11) video imaging (Saadevandi & Turton, 1998); (12) electrostatic probes (Klinzing, Zaltash, & Myler, 1987); (13) acoustic measurements (Cody, Goldfarb, Storch, & Norris, 1996; Sheen & Raptis, 1987); (14) laser Doppler velocimetry (LDV) (Arastoopour & Yang, 1992; Pandey et al., 2004; Tsuji, Morikawa, & Shiomi, 1984; Van den Moortel, Azario, Santini, & Tadrist, 1998; Wang, Wei, Wang, Jin, & Yu, 1998; Wei, Cheng, Jin, & Yu, 1998; Yang, Jin, Yu, Zhu, & Bi, 1993); (15) diffusing wave spectroscopy (Menon & Durian, 1997); (16) particle tracking velocimetry (PTV) (Wildman & Huntley, 2000; Wildman, 2002).

Breault (2006) described the importance of the development of models to predict conversion and yield of reactant species for reactors. The literature review provided information on various correlations for the axial and radial solids dispersion coefficients, the axial and radial gas dispersion coefficients, and the interphase mass transfer coefficients between the gas and solid phases. A good knowledge of dispersion and mass transfer coefficients is essential in designing fluidized bed reactors, such as gasifiers. However, the dispersion coefficients vary by more than five orders of magnitude in the literature due to the differences in hydrodynamics, locations within fluidized beds, and system geometries and properties (Bi, Ellis, Abba, & Grace, 2000; Breault, 2006; Chalermsinsuwan, Piumsomboon, & Gidaspow, 2009; Du, Fan, Wei, & Warsito, 2002;