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Three-component particle velocity measurements in the bottom section of a riser

M.N. Pantzali, B. De Ceuster, G.B. Marin, G.J. Heynderickx *

Ghent University, Faculty of Engineering and Architecture, Laboratory for Chemical Technology, Technologiepark 914, B-9052 Zwijnaarde, Ghent, Belgium

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ABSTRACT

Coincident three-component particle velocity measurements are performed in an almost 9 m high cylindrical riser (internal diameter 0.10 m) of a pilot-scale cold-flow Circulating Fluidized Bed set-up, using two Laser Doppler Anemometry (LDA) probes. Experiments are performed with superficial gas velocities of 3.5 m/s and 5.3 m/s near the solids inlet line and with an average solids volume fraction of 0.0002. The particle flow is observed to be highly disturbed due to the asymmetrical position of both the gas and the Y-shaped solids inlet line. A jet-like particle flow and a by-passing streaming gas jet around the particles are formed. Just below the solids inlet line a downward oriented particle velocity is measured. Particles are immediately lifted by the ascending gas and spread over the entire cross-sectional tube area. Near the solids inlet line the axial and radial particle velocity fluctuations are of the same order of magnitude as the corresponding mean particle velocity components, showing that the flow is anisotropic. The radial particle velocity fluctuations decrease fast as the radial inflow of particles is transformed into axial particles flow. The turbulence intensity in the inlet section of the dilute riser flow is found to be extremely high, indicating that the flow is far from being fully developed. The total particle shear stress profiles near the solids inlet line indicate a high momentum transfer from radial to axial particle transport. The particle fluctuation energy values calculated based on experimental data are nearly double than the values corresponding in fully developed flow studied previously.

Introduction

Gas–solid flows are commonly encountered in numerous industrial applications and therefore the need to accurately predict and model the gas–solid behavior is crucial for optimal process design. The Two-Fluid Model (TFM) is widely used to simulate gas–solid flow hydrodynamics due to its relatively limited computational cost. However, it is reported in literature (e.g. Passalacqua et al., 2010) that the application of this model for dilute gas–solid flows is not adequate. For dilute gas–solid flow, when applying TFM, a grid-independent calculated flow regime cannot be obtained (Passalacqua and Fox, 2011). Efforts were thus made to develop new hydrodynamic models and corresponding solution techniques (e.g. Desjardins et al., 2008; Passalacqua and Fox, 2011; Passalacqua et al., 2010) that will be able to successfully predict dilute gas–solid flows, while keeping the computational cost as low as possible.

The validation and ongoing development of reliable computational models requires accurate experimental data. Chew et al. (2011) studied experimentally the effect of the solids polydispersity on the riser dilute gas–solid flow and concluded that particle clustering was observed, even in extremely dilute flow. Complete and accurate experimental data on three velocity components in dilute flow riser have been reported in our previous work for the middle section of a riser with fully developed gas–solid flow (Pantzali et al., 2013). To the best of the authors' knowledge, accurate experimental data on dilute gas–solid flow in riser inlet sections, where the solids input is usually abrupt, are hardly available in literature. Van engelandt et al. (2007) experimentally studied riser inlet phenomena of a 35° inclined non-aerated and aerated Y-inlet of particles, combined with a vertical gas inlet. They reported *3-D* but *non-coincident* particle velocity data. Near the solids inlet line, radial gas–solid mixing was observed to be hindered, while by-passing of the solids inlet line jet resulted in steep velocity gradients and off-center maxima in the velocity field. Analyzing the Kolmogorov entropy in a riser, de Castilho and Cremasco (2012) reported that at the inlet of a riser, for very diluted conditions, turbulence and particle–wall interactions prevail, resulting in more chaotic behavior. The present work extents our previous study (Pantzali et al., 2013) to the inlet section of the riser and aims to investigate the solid phase acceleration and the

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* Corresponding author. Tel.: +32 (0)9 331 17 53; fax: +32 (0)9 331 17 59.
E-mail address: Geraldine.Heynderickx@ugent.be (G.J. Heynderickx).

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physics of the flow development following the abrupt solids injection in the gas flow. The *3-D* flow field is reproduced from extensive *coincident* measurements of the three components of the particle velocity field in the bottom section of the riser using a two-probe Laser Doppler Anemometer (LDA). This study provides additional input to study the riser flow hydrodynamics of the SO_2–NO_x Adsorption Process (SNAP) operating under similar conditions as those of the present work (Van engelandt et al., 2007). Insight in jet formation and pneumatic conveying of solids through abrupt bends is gained. More generally, the present study provides the required experimental data for the experimental validation of simulated dilute gas–solid flow calculated using new computational models.

Experimental set-up and conditions

The cold-flow pilot CFB consists of an almost 9 m long and 0.1 m diameter Pyrex glass cylindrical riser. A detailed description has been given in previous publications (e.g. Pantzali et al., 2013; Van engelandt et al., 2007; Van Engelandt et al., 2011). The solids used are FCC-E catalyst particles with a density of 1550 kg/m^3 and a mean diameter of 67 μm, classified as Geldart A particles (Geldart, 1973). The gas phase, humidified air, enters at the bottom of the riser via a 90° bent tube of 0.05 m diameter, coaxially to the riser. The gas inlet line expands to the riser diameter at 0.3 m above ground level (Fig. 1). The origin (0,0,0) of the cylindrical coordinate system (r,θ,z) corresponds to the center point of this expansion ring, where r, θ, z are the radial, azimuthal and axial coordinates respectively. The azimuthal coordinate is considered positive in the counter-clockwise direction with $\theta = 0°$ defined as the angle of the solids inlet line. With this convention the axis of the air inlet tube is situated at $\theta = 90°$. The particles enter the riser asymmetrically, through a single-sided inlet situated in the $\theta = 0°$ plane, 35° clockwise inclined as compared to the z-axis. The intersection of the riser and the solids inlet line is positioned at a height of 0.47 m to 0.63 m above the axes origin. In the present study, the riser has a blinded T-outlet with a 0.1 m diameter and a 0.34 m extension height, positioned at $\theta = 51°$. The riser operates at atmospheric conditions. Experimental data are obtained with volumetric gas flow rates of 100 Nm^3/h and 150 Nm^3/h in the gas inlet line, corresponding with a superficial gas velocity in the riser of 3.5 m/s and 5.3 m/s, respectively. The solids flux rate in the riser is kept constant at 1 kg/m^2 s, implying that the mean solids volume fraction, ε_s, is less than 0.0002 and the mass loading, m, defined as the ratio of solids mass flux to fluid mass flux (Rao et al., 2012), is less than 0.24 for all experiments. The operating conditions of the present work are similar to those of SNAP (Van engelandt et al., 2007).

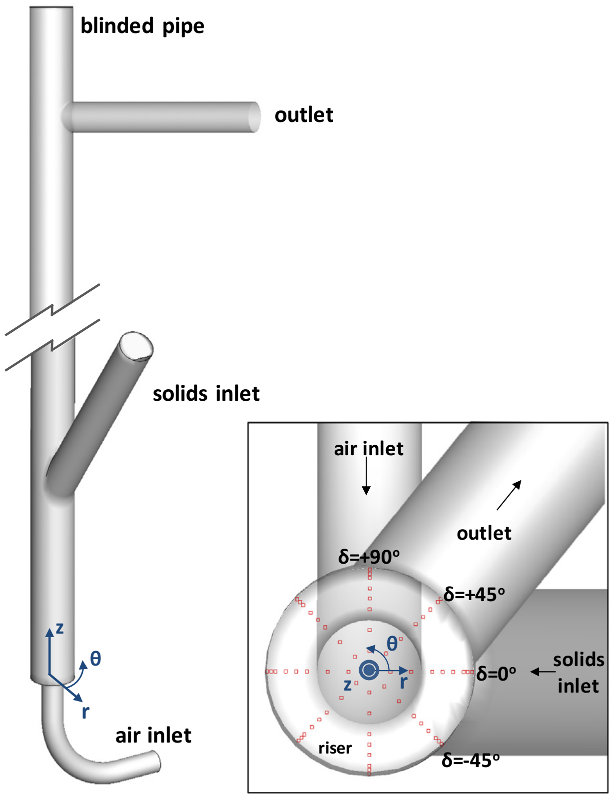

Fig. 1. Riser inlet and outlet section and detail of the riser $r\theta$ cross section indicating the measuring planes (Pantzali et al., 2013).

The experimental set-up is equipped with a two-probe LDA that allows performing *coincident* three-component particle velocity measurements in the gas–solid two-phase riser flow. Details are provided elsewhere (Pantzali et al., 2013). As the particle size is relatively large, the particles cannot be used as 'tracers' for the gas flow. Adding tracers to the solids flow will allow determining gas velocity fields next to the solids velocity fields. The latter extension of the experimental research is currently under consideration. Results will be published in a following paper. Currently, the probes are positioned on a $r\theta$ plane with a 90° angle in between them. They are fixed on a traverse manifold that enables to alter the relative position of the two probes, as well as to stepwise and accurately reposition the combined measuring volume relatively to the riser. The LDA with the traverse manifold is placed inside the cabin of an elevator, which allows positioning the LDA at any desired riser height. In the present study, measurements are performed along the riser diameter at four angular positions marked as δ-angles (Fig. 1) at six riser heights between 0.45 m and 0.70 m to study the turbulent flow field in the vicinity of the Y-shaped solids inlet line. Experiments at each position have been repeated three times after shut-down and restart of the set-up preferably on different days. In a previous publication presenting measurements in the middle section of the riser (Pantzali et al., 2013) error bars represented the 95% confidence intervals, i.e. twice the standard deviation, based on the numerous particle velocity recordings of a single experiment. In the present work, error bars are stricter, representing the 95% confidence interval based on the values of the three different measurements.

Results and discussion

General observations

The particle flow close to the solids inlet line can be visually observed by typical images, such as those in Fig. 2. Videos S1 and S2 in the online Supplementary Materials allow a better insight into the particle flow. Due to the solids inlet line configuration, the particles enter the riser with a negative, that is downward oriented, axial velocity component. Due to gravity, the particles slide over the bottom wall of the inlet tube. Thus, they enter the riser at a height of $z = 0.47$ m. The ascending gas decelerates and reverses the downward flow of the particles, creating a jet-like particle flow close to the solids inlet line. The gas preferentially by-passes the particles at the riser wall opposite to the solids inlet line, as shown in Fig. 2. The fraction of the riser cross-sectional area that is occupied by the particles near the solids inlet line decreases with increasing gas flow rate (Fig. 2).

Detailed particle velocity fields and flow features

As mentioned before, the results presented in this study are gathered along the riser diameter at four angular positions,