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Three-component solids velocity measurements in the middle section of a riser

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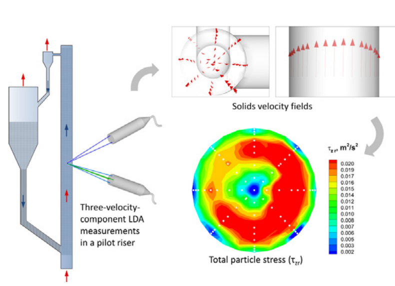
HIGHLIGHTS

- Three solids velocity components are measured in a pilot riser middle section.
- Developed axial solids velocity fields are observed at 2 m above the solids inlet.
- For all conditions studied the flow remains anisotropic even when fully developed.
- Total particle shear stress (*zr*) profiles reach a maximum value at *r*/*R*≈0.6.
- Particle fluctuation energy indicates a flow dominated by wall-particle collisions.

GRAPHICAL ABSTRACT



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ABSTRACT

Coincident three-component solids velocity measurements are performed in a 8.7-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 and 5.3 m/s at riser heights from 0.9 to 5.5 m and with an average solids volume fraction of 0.0002. At the lower riser heights, the solids flow is observed to be highly disturbed due to the asymmetrical position of both the air and solids inlet. A fully developed parabolic axial solids velocity field is observed about 2 m above the solids inlet line. The measured radial and azimuthal particle velocity components are significantly smaller than the axial one. The particle velocity fluctuations in the axial flow direction are larger than in the radial and azimuthal directions, showing that the solids flow is anisotropic. However, both the radial and azimuthal velocity fluctuations are higher than the corresponding mean velocities, as observed when studying the turbulence intensity in the three directions. All fluctuating velocities are decreasing significantly with increasing riser height, i.e. as the flow becomes more developed. No average down-flow of solids is recorded, not even close to the wall, due to the highly diluted flow. The total particle shear stress profiles designate a mean transport of fluctuating momentum along the riser radius due to velocity fluctuations. The particle fluctuation energy calculated based on experimental data indicates that the solids flow is dominated by wall-particle rather than intra-particle collisions.

1. Introduction

Gas–solid flow structures in the riser of a Circulating Fluidized Bed (CFB) reactor affect heat, mass and momentum transfer as well as the residence time of the phases in the riser. As these

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phenomena influence the reaction rates, conversion and yields, the overall performance of a reactor is amongst other determined by the reactor hydrodynamics. Several efforts to model the flow structures in a riser have been made (Almuttahar and Taghipour, 2008; Andreux et al., 2008; Andrews et al., 2005; Benyahia et al., 2007; Gao et al., 2009; He et al., 2009; Huilin et al., 2003; Zimmermann and Taghipour, 2005) and research in this area is still in progress in many groups (e.g. Benyahia, 2012; Shuai et al., 2012). However, the numerical complexity and the enormous computational load require the introduction of significant modeling simplifications (Berruti et al., 1995). At present, most of the riser simulations remain limited to calculating the gas–solid two-phase flow in a simplified two-dimensional (*2-D*) riser domain. Therefore, no reconstruction of the three-dimensional (*3-D*) nature of the solids flow in the riser can be achieved. In view of the importance of flow structures, this simplified approach does not allow to determine different mechanisms inducing the complex state of motion (Wang et al., 2010). As a consequence, hydrodynamic modeling of a riser has not yet been entirely successful (Berruti et al., 1995).

Due to the complexity of the gas–solid two-phase flow, accurate experimental measurements of the riser flow are as difficult to obtain as reliable calculation data. The development of theoretical models and empirical equations allowing a more correct simulation of riser flow suffers from this lack of relevant experimental data. Model validation and refinement based on experimental data remain problematic (Bhusarapu et al., 2006; Godfroy et al., 1999). Furthermore, the majority of the available experimental data for gas–solid two-phase riser flow are mostly *2-D* in nature, providing two coincidentally measured solids velocity components. Two-component experimental data are insufficient to validate and refine existing models or develop new accurate computational flow models for an in nature *3-D* flow (Bhusarapu et al., 2006). Precise experimental data providing coincident measurements of the three components of the solids velocity vectors are needed to gain insight into the *3-D* flow characteristics along the entire riser height.

Laser Doppler Anemometry (LDA) is an optical measuring technique, widely used for studying the gas–solid flow in transparent risers (Ibsen et al., 2002; Mathiesen et al., 1999, 2000; Van den Moortel et al., 1998; Van Engelandt et al., 2007). Even though LDA is generally considered a non-intrusive measuring technique, seeding particles have to be introduced in the flow if the aim is to study the gas flow field. However, when studying the solids flow, the LDA technique is absolutely non-intrusive, as no seeding particles are to be injected. The major disadvantage of an optical measuring technique like LDA is that it can be used for very dilute particle flows only. For denser particle flows as mostly encountered in industrial CFBs, the flow becomes opaque and experimental observation of the flow structures in the center of the riser becomes impossible. Nevertheless, the study of riser flows more dilute than industrial ones remains interesting in order to understand the fundamental mechanisms that prevail in gas–solid flow. The simulation models applied to calculate dilute flow fields can be verified and improved. Next, they can be extended to more complex dense flows, where the interaction between gas turbulence and particle fluctuations becomes significant (Benyahia et al., 2000). Thus, using a non-intrusive 3-D LDA measuring technique, providing accurate three-component solids velocity fields in dilute riser flow, valuable data can be obtained in view of improving the modeling of riser flow.

As mentioned previously, mostly coincident measurements of two components of the solids velocity vector are reported in literature. In the presented study, the 3-D riser flow in the middle section of a pilot riser set-up is studied experimentally. The three components of a solids velocity vector are measured coincidentally. As the solids enter the riser through a one-sided solids inlet configuration, a distinct 3-D flow field is created near the solids inlet. Extensive coincident measurements of the three components of the solids velocity field in the middle section of the riser, difficult to find in the riser-related literature, have been acquired using a two-probe LDA.

2. Experimental set-up and conditions

The CFB pilot set-up mainly consists of an 8.7 m long and 0.1 m diameter Pyrex glass cylindrical riser, two glass cyclones, a fluidized bed storage tank for the particles, a 2 m long and 0.08 m diameter standpipe/solids inlet line and a mechanical iris valve to regulate the solids flow into the riser. A detailed description has been given in previous publications (De Wilde et al., 2005; Van Engelandt et al., 2007, 2011). The riser is operated in 'cold flow', that is only non-reactive particle flow patterns are studied. The solids used are FCC-E catalyst particles with a density of 1550 kg/m^3 and a Sauter mean diameter of 77 μm, classified as Geldart Group A particles (Geldart, 1973). The gas phase, humidified air, enters the riser via the bottom through a 0.05 m diameter line. This 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. The riser operates at atmospheric conditions. Experimental data are obtained with volumetric flow rates of 100 and 150 Nm^3/h in the air inlet line, corresponding with a superficial air velocity in the riser of 3.5 and 5.3 m/s, respectively. The solids flux rate in the riser is 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 experimental results are presented using the cylindrical coordinate system (r,θ,z) as defined in Fig. 1. The air inlet tube is situated in the $\theta=90^o$ plane. The solids enter the riser through a single sided inlet situated in the $\theta=0^o$ plane, inclined 35° clockwise as compared to the z-axis.

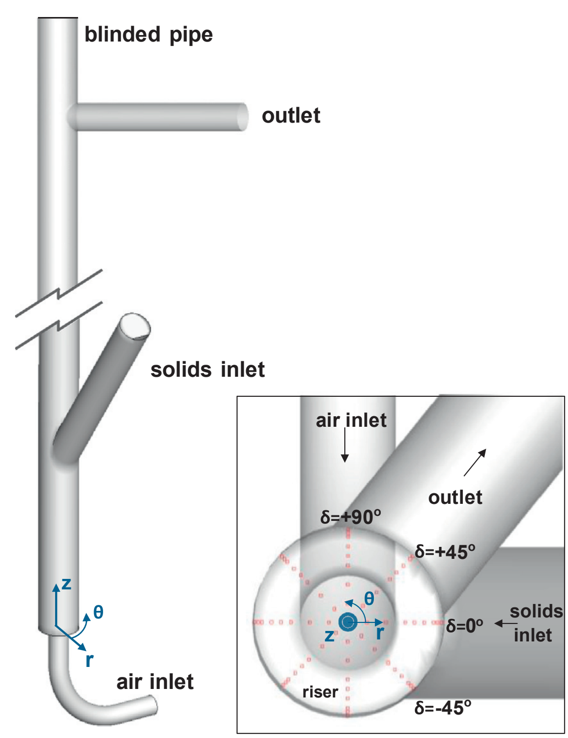

Fig. 1. Riser inlet and outlet section and detail of the riser $r\theta$ cross section indicating the measuring planes.