International Journal of Multiphase Flow 66 (2014) 46–61

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Solid velocity and concentration fluctuations in highly concentrated liquid–solid (slurry) pipe flows

S.A. Hashemi *, A. Sadighian, S.I.A. Shah, R.S. Sanders

Department of Chemical and Materials Engineering, University of Alberta, Edmonton, AB T6G 2V4, Canada

ARTICLE INFO

Article history:
Received 13 January 2013
Received in revised form 11 May 2014
Accepted 26 June 2014
Available online 10 July 2014

Keywords:
Solid–liquid flow
Electrical impedance tomography
Concentration fluctuations

ABSTRACT

Solid velocity and concentration fluctuations were measured for concentrated sand-water mixtures (20–35% solid by volume) in horizontal pipe flow using Electrical Impedance Tomography (EIT). Narrowly sized sand (d_{50} = 100 μm) was used to prepare each slurry tested in a 52 mm (i.d.) horizontal pipe loop at mixture velocities (2–5 m/s) that were significantly above the deposition velocity. The EIT measurements were used to obtain solid velocity and concentration fluctuation maps. Results show that the magnitude of the local solid concentration fluctuations is greater near the pipe wall and increases as the mixture velocity increases. Additionally, the concentration fluctuations are greater near the pipe invert, particularly at lower mixture velocities and/or concentrations where the solid concentration profiles are asymmetric. The Fast Fourier Transform (FFT) method was employed to study the power spectral density of these fluctuations. This analysis indicates that concentration fluctuations are produced almost entirely by particle–fluid turbulence interactions, rather than through particle–particle or particle–wall interactions. Comparison of the particle diameter with the characteristic turbulent length scales shows that the particles interact with turbulent eddies in the dissipative range, which is in accordance with the power spectral density analysis. The findings presented here are consistent with previous studies of fluidized beds and gravity-driven flows.

1. Introduction

Pipeline flows of coarse-particle slurries are of great importance in many industries, including hard-rock mining, oil sands production, and nuclear waste treatment. Industrial slurries have different particle sizes and hence the relative positions and velocities of these particles play an important role in pipeline design and operation. An improved understanding of the complex behaviour of these flows and the physics behind them will help to improve models needed to predict, for example, frictional pressure losses, optimal operating velocities, and pipeline wear.

Highly concentrated two-phase flows are generally unsteady and previous experiments have shown that velocities and concentrations of both phases undergo fluctuations about their mean values (Zenit and Hunt, 2000). Parameters such as collisional particle pressure or granular temperature are used to describe the solid fluctuations. Presently, different models describing particle interactions, e.g. kinetic theory (Jenkins and Savage, 1983), are commonly found in commercial CFD (Computational Fluid Dynamics) packages. However, these models have not been widely compared with experimental results, especially for liquid–solid flows. The Zenit et al. (1997) experimental study of collisional pressure in liquid–solid fluidized bed showed the unsatisfactory performance of current models, which is mainly a consequence of the lack of understanding of the physics and mechanisms that govern the behaviour of these complex systems.

One of the barriers to improved understanding and model development is the difficulty associated with making the appropriate measurements (Zenit and Hunt, 1998), particularly for highly concentrated coarse-particle slurries where the axial velocities are high and mixtures are opaque.

One of the most thorough studies of solid fluctuations in concentrated liquid–solid flow is the experimental investigation of Zenit and Hunt (2000). They measured the cross-sectional averaged solid concentration fluctuations in a fluidized bed and for gravity driven flow, for large particles with different diameters and densities. They compared their results with the Buyevich and Kapbasov (1994) model. In this model, the solid concentration fluctuation is only a function of solid concentration. Zenit and Hunt (2000) found that the averaged solid concentration fluctuations are a function of both solid concentration and Stokes number with

* Corresponding author.
E-mail addresses: reza.hashemi@ualberta.ca (S.A. Hashemi), sadighia@ualberta.ca (A. Sadighian), sshah@ualberta.ca (S.I.A. Shah), ssanders@ualberta.ca (R.S. Sanders).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.06.007
0301-9322/

the magnitude of the fluctuations increasing with increasing Stokes number. This was in accord with their previous findings; that is, high frequency fluctuations are mainly due to direct collisions and the power of an immersed collision increased as the Stokes number increased (Zenit and Hunt, 1999). They concluded that the Buyevich and Kapbasov (1994) model relates to the condition where Stokes number tends to infinity.

Picciotto et al. (2005) studied the interactions between a dispersed solid and fluid turbulence in a turbulent channel flow. They noted that interaction between particles and coherent turbulent structures near the wall results in streamwise velocity fluctuations in solid velocity. Their results show that solid streamwise velocity fluctuations are higher near the wall and decrease with increasing distance from the wall. They also show that the magnitude of these fluctuations increases with increasing particle Stokes number.

Kechroud et al. (2010) studied the dynamic behaviour of the continuous phase in a solid–liquid fluidized bed. They compared their measurements of liquid velocity fluctuations with solid concentration fluctuations from Didwania and Homsy (1981) and Zenit and Hunt (2000). They found a high degree of similarity between liquid velocity fluctuations and solid concentration fluctuations.

Varaksin and Polyakov (2000) studied particle velocity fluctuations in an air- solid turbulent pipe flow. They classified the mechanisms for solid velocity fluctuations into four main categories: (1) solid–fluid turbulence interaction, (2) presence of particles with different sizes, i.e. not truly monosized particles, (3) particle–particle and particle–wall collisions and (4) migration of particles to regions with different velocities (streaming mechanism). These four phenomena could also be considered as the main mechanisms producing solid concentration fluctuations.

One of the difficulties associated with experiments involving concentrated multiphase flows is the lack of viable measurement techniques. Common single phase and dilute multiphase flow measuring techniques, such as LDV (Laser Doppler Velocimetry), PIV (Particle Image Velocimetry), and PTV (Particle Tracking Velocimetry) are widely used for transparent flows where the solid concentration is low. However, their capabilities in highly concentrated and opaque flows, such as dense slurry flows, are debatable (Graham et al., 2002).

Advances in measurement techniques in recent years, especially electrical tomography methods, have opened a new window in the experimental study of multiphase flows. The most important advantage of these methods is their ability to perform measurements in concentrated and opaque systems. It also appears that these methods are sufficiently fast and robust enough for slurry flow applications (Dyakowski et al., 2000; Graham et al., 2002; Pachowko et al., 2003). Numerous studies have been conducted where electrical tomography techniques are used on fluid-particle systems, such as pneumatic conveying of granular solids (Zhu et al., 2003; Azzopardi et al., 2008), flow distribution and velocity measurement in a fixed bed reactor (Bolton et al., 2004), hydraulic conveying of materials (Fangary et al., 1998), and fluidization (Azzi et al., 2010). However, only a very limited number of studies directly related to electrical tomography and slurry pipe flow measurements have been published (Dyakowski et al., 2000; Norman and Bonnecaze, 2005; Xu et al., 2009). Applications of electrical tomography to slurry pipeline flow measurements have thus far been restricted to time- and spatial-averaged values of concentration.

The goal of this paper is to investigate the mechanisms that are responsible for the production of high frequency-low amplitude solid concentration and velocity fluctuations in highly concentrated slurry flows. Novel high-frequency Electrical Impedance Tomography (EIT) measurements for highly concentrated pipeline flows of solid–liquid mixtures are used to evaluate the validity and limitations of the analysis. Specifically, solid turbulent intensity and concentration fluctuation and time-averaged solid concentration profiles for slurry flow in a horizontal pipe were measured using Electrical Impedance Tomography. The results were also compared to the models available in the literature to evaluate their capabilities and limitations. Measurements of this type are needed to develop and/or validate numerical simulations of slurry flows.

2. Experimental detail and analysis

2.1. Experiments

A 52 mm (i.d.) horizontal pipeline loop located at the Saskatchewan Research Council (SRC) Pipe Flow Technology Centre, SK, Canada, was used to perform the experiments. The schematic layout of the loop is shown in Fig. 1. The loop includes a centrifugal pump to circulate the slurry at different velocities. Operating volumetric flow rates were measured using a Foxboro 2802-SABA-TS magnetic flow meter. Two heat exchangers were used to keep the operating temperature constant during experiments. Pressure drop along a test section was measured using a Validyne DP15 differential pressure transducer. The transparent observation section was used to ensure that air, which sometimes enters loop during the preparation of the slurries, was completely removed before measurements were taken. The slurries were prepared using

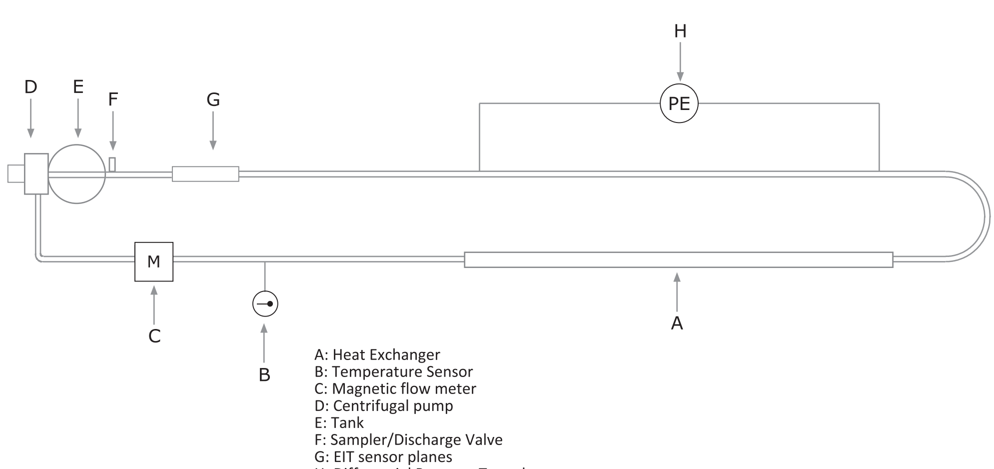

Fig. 1. Schematic of 52 mm horizontal pipe-loop.