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Dense gas–liquid–solid flow in a slurry bubble column: Measurements of dynamic characteristics, gas volume fraction and bubble size distribution

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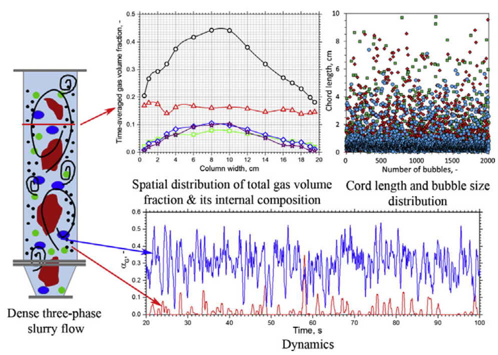
HIGHLIGHTS

- Dynamics of dense three-phase slurry flow characterized using gas volume fraction fluctuations.
- Effect of solid loading on internal composition of gas volume fraction (contained in different bubble size groups) measured.
- Spatial distribution of chord length and bubble size distribution measured for different gas velocities and solid loadings.

GRAPHICAL ABSTRACT



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ABSTRACT

Dense three-phase slurry flows are important in several industrial processes (e.g., Methanol/ DME synthesis, Fischer Tropsch synthesis). In the present work, gas–liquid–solid flow in a pseudo 3D slurry bubble column is characterized under dense flow conditions for superficial gas velocity (U_G) of 5–30 cm s^{-1} and overall solid loading ($\langle\alpha_S\rangle$) of 0–40 vol.%. In-house developed voidage probes were used to measure local gas volume fraction fluctuations. The high frequency fluctuations (~1–10 Hz) caused by individual bubbles or swarms of bubbles were found to increase with increase in $\langle\alpha_S\rangle$ and U_G. The low frequency oscillations (~< 1 Hz) corresponding to column-scale recirculating flow were found to decrease with increase in $\langle\alpha_S\rangle$. Importantly, time-averaged gas volume fraction and its internal composition (i.e. gas volume fraction contained in different bubble size groups) and bubble size distribution were measured at different locations in the slurry bubble column. With an increase in $\langle\alpha_S\rangle$, local gas volume fraction was found to decrease, accompanied by an increase in bubble size. Based on the distribution of bubble chord lengths, the gas volume fraction contained in different bubble size groups was measured for different $\langle\alpha_S\rangle$ and U_G. With increase in $\langle\alpha_S\rangle$, the gas volume fraction for small bubbles was found to decrease while that for large bubbles was found to increase. Under the dense flow conditions (at high U_G and $\langle\alpha_S\rangle$), while small bubbles were found to accumulate near the column walls, as indicated by the wall peaking in $\overline{\alpha}_G$ profiles, large bubbles/gas slugs were found to flow predominantly through the column center. In addition to the new experimental data, the present work helps to improve the understanding of dense slurry flows that will aid the development and verification of Eulerian multiphase models.

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Nomenclature

Notations
D column depth (cm)
H column height (cm)
W column width (cm)

Greek letters
α_G instantaneous (local) gas volume fraction (–)
$\langle \alpha_S \rangle$ overall solid volume fraction or solid loading (–)
σ variance as calculated in Eq. (2)
τ characteristic time scale (s)

Abbreviations
BSD Bubble Size Distribution
CLD Chord Length Distribution
PDF Probability Distribution Function
PSD Power Spectral Density
SBCR Slurry Bubble Column Reactor

1. Introduction

Slurry bubble column reactors (SBCRs) are widely used in chemical process industry to perform a variety of solid–catalyzed gas–liquid reactions. For example, in Gas–to–Liquid (GTL) technologies for the conversion of synthesis gas to fuel additives such as Methanol, Dimethyl Ether (DME) and conversion of syngas to a variety of liquid fuels using the Fischer–Tropsch (F–T) synthesis, the slurry reactors are preferred. Inspite of their technological importance, owing to complex nature of three-phase flows, slurry bubble columns pose several challenges in their design and scale-up. During the past couple of decades, significant efforts have been made to develop and to validate computational fluid dynamics (CFD) based models to simulate dispersed gas–liquid flows (e.g. see review articles by Joshi (2001), Rafique et al. (2004)). However, the published literature on numerical simulations of dense gas–liquid–solid flows is rather limited (e.g., Rampure et al., 2003; Panneerselvam et al., 2009) and in order to progress further it is important to develop detailed understanding of dense slurry flows and to characterize the hydrodynamics at superficial gas velocities and solid loadings that are relevant to the industrial applications of SBCRs.

The experimental verification of CFD models for SBCRs was performed mainly using time-averaged flow characteristics (Rampure et al., 2003; Panneerselvam et al., 2009). However, in case of inherently unsteady flow (for example, unsteady gas-liquid/gas-liquid-solid flow as considered in the present work), the underlying flow changes with time and space. While the ability of CFD models to simulate the dynamics of gas–liquid bubbly flows at low U_G has been verified, it is not known if such models could predict the dynamics of dense (churn turbulent) gas–liquid and gas–liquid–solid flows. In the present work, therefore, the dynamics/transient behavior of dense gas–liquid–solid flow is investigated experimentally.

Different measurement techniques have been used to investigate the gas-liquid-solid flow in slurry bubble columns, for example, visualization techniques (e.g., Lau et al., 2010), tomographic techniques (e.g., Warsito and Fan, 2001; Rados et al., 2005; Rabha et al., 2013b), pressure sensors (e.g., Chilekar et al., 2005; Ruthiya et al., 2005), dynamic disengagement techniques (e.g., Krishna et al., 1997), optic fiber probes (e.g., Wang et al., 2001; Xue et al., 2008), electrical conductivity/resistivity probes (e.g., Rampure et al., 2007; Zhang et al., 2010). The voidage (electrical conductivity) probes and optic fiber probes are usually preferred due to their ability to measure the local "point wise" flow quantities under high gas volume fraction, (> 10 %), while optical techniques (e.g., high-speed visualization) cannot be used for dense flow conditions, X-ray or gamma-ray tomography often provide time-averaged measurements (except ultra-fast X-ray tomography). Since the focus of the present work is to measure fluctuations arising because of column-scale and bubble-scale flow, gas volume fraction distribution as per bubble size groups and bubble size distribution, voidage (electrical conductivity) probes are used in the present work.

In recent years, several attempts have been made to investigate dynamic characteristics of gas–liquid–solid flow in SBCRs. Several researchers have measured pressure fluctuations in three-phase slurry bubble columns and have used them to identify the flow regimes and transition between homogeneous and heterogeneous regimes. (e.g., Xie et al., 2003, 2004; Barghi et al., 2004; Ruthiya et al., 2005; Chilekar et al., 2005; Li et al., 2014). A few researchers have also measured void fraction fluctuations in slurry bubble columns (e.g., Reese et al., 1996; Bukur et al., 1996). Xie et al. (2003, 2004) recorded pressure fluctuations in gas-liquid-pulp flow at one particular location in the column. They analyzed the pressure fluctuations using statistical parameters such as standard deviation, skewness and kurtosis, auto-correlation function and reported the flow regime map. Chilekar et al. (2005) recorded pressure fluctuations in a SBCR and performed statistical analysis of the fluctuations to calculate bubble size distribution, but it is not clear if such pressure fluctuations (mounted on the walls) can provide detailed information on local flow structures/fluctuations caused by individual bubbles or swarm of bubbles. Ruthiya et al. (2005) measured pressure fluctuations using wall-mounted pressure sensors in 2D and 3D slurry bubble columns for U_G in the range of 2–25 cm s^{-1} and for $\langle \alpha_S \rangle$ < 2 vol.%. They investigated different flow regimes and regime transition based on the average frequency of pressure fluctuations. Most recently, Li et al. (2014) analyzed pressure fluctuations using advanced statistical methods for flow regime identification in a three-phase slurry reactor for U_G of 0.7–8 cm s^{-1} and for $\langle \alpha_S \rangle$ of 9 vol.%.

Compared to several reports on pressure fluctuations measurements in SBCRs, the experimental data on α_G fluctuations is rather limited. Reese et al. (1996) investigated the hydrodynamic flow behavior in a three-phase slurry bubble column under dilute flow conditions ($U_G \leqslant$5 cm s^{-1} and $\langle \alpha_S \rangle \leqslant$1 wt.%) by analyzing normalized bubble passing frequencies of the void fraction signal obtained using light transmittance probe. Bukur et al. (1996) analyzed fluctuating signals obtained from nuclear density gauge (NDG) and reported different statistical parameters and spectral density function and the radial and axial distribution of gas volume fraction in SBCR operated at $U_G \leqslant$12 cm s^{-1} and $\langle \alpha_S \rangle \leqslant$30 wt.%. However, the detailed description of different column–scale and bubble–scale flow structures in SBCRs, especially, under the dense flow conditions is lacking.

Several researchers have measured overall gas volume fraction in SBCRs for a wide range of U_G (up to 80 cm s^{-1}) and $\langle \alpha_S \rangle$ (up to 40–45 vol.%) (e.g., Gandhi et al., 1999; Schweitzer et al., 2001; Warsito and Fan, 2001; Vandu et al., 2004; Rados et al., 2005;