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Dynamics of gas–liquid flow in a cylindrical bubble column: Comparison of electrical resistance tomography and voidage probe measurements

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ABSTRACT

Gas–liquid flow in bubble columns is inherently unsteady, and dynamics of such flow is known to influence local mixing, mass and heat transport and therefore, the performance of bubble column reactors. The present work is carried out to verify dynamics of gas–liquid flow measured using time-resolved Electrical Resistance Tomography (ERT) with the measurements performed using in-house developed voidage probes. Experiments were performed in a cylindrical bubble column under dilute to dense conditions (superficial gas velocity (U_G) in the range of 1–40 cm/s). The instantaneous and time-averaged gas volume fraction distribution was measured using the ERT and voidage probes for uniform and local spargers. The time-averaged gas volume fraction measured using both the techniques was found in a quantitative agreement for all U_G and sparger configurations considered in the present work. The low-frequency oscillations (< 1 Hz) generated by meandering motion of bubble plume and high-frequency oscillations (1–10 Hz) generated by bubble-scale processes, measured using the ERT and voidage probes were in a satisfactory agreement. The results reported in the present work will help to benchmark the ERT to infer the dynamics of gas–liquid flow and to validate the dynamic characteristics predicted using CFD models under dense flow conditions.

1. Introduction

Several technologically important process equipment used in power generation, chemical and bio-chemical industries involve dense gas–liquid flows with or without phase change, for example, bubble columns, gas–liquid stirred vessels, boilers and other process equipment. For efficient design and scale-up of these reactors or process equipment, measurement of gas volume fraction distribution is important in addition to other flow/process variables, especially under dense operating conditions that are relevant to the industry. Bubble column is one of the aforementioned process equipment that is used extensively as a contactor or a reactor due to several advantages e.g. high heat- and mass-transfer rates, low operating and maintenance costs. Gas–liquid flows in bubble columns are inherently unsteady in nature and dynamics of such flows is known to influence mixing, heat and mass transport performance of bubble columns. It is, therefore, important to characterize the dynamics of gas–liquid flow, particularly under dense flow conditions.

Over last few decades, several intrusive (e.g. voidage probes (conductivity or resistivity probes), optical fiber probes etc. (Boyer et al., 2002; Buwa and Ranade, 2005; Cartellier and Barrau, 1998; Chabot et al., 1998; Chaumat et al., 2007; Magaud et al., 2001; Moujaes, 1990; Shiea et al., 2013)) and non-intrusive (e.g. γ-ray tomography, electrical resistance tomography (ERT), electrical impedance tomography (EIT), X-ray tomography etc. (Dickin and Wang, 1996; Roy et al., 1997; Warsito and Fan, 2001; Warsito et al., 2007; Young et al., 1991)) techniques have been developed and used for the measurement of gas volume fraction distribution in bubble columns. The intrusive techniques provide local/point measurements whereas non-intrusive techniques provide distribution over a cross-section with different spatial and time resolutions. The advantages and disadvantages of different intrusive and non-intrusive techniques and their applications to multiphase flows are discussed in detail in the review articles by Boyer et al. (2002); Chaouki et al. (1997) and Mudde (2010).

While conventional X-ray tomography (except the recent developments on ultrafast X-ray tomography) and γ-ray tomography provide time-averaged measurements, ERT is a non-intrusive technique that provides time-resolved measurements. Further, unlike safety and cost issues associated with X-ray or γ-ray tomography, ERT can be applied to laboratory- and to large-scale bubble columns easily for online measurements of gas volume fraction distribution. It measures the electrical conductivity of mixture by applying a voltage to the electrodes mounted on the column periphery and subsequently volume fraction of a phase, averaged over a certain volume, is calculated (Dickin and

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Nomenclature

D	diameter, cm
H	height, cm
T	time, s
U	superficial gas velocity, cm/s
W	width, cm

Subscript

G	gas
mc	mixture conductivity

Greek Letters

α	volume fraction
$\bar{\alpha}$	time-averaged volume fraction
θ	angular direction
τ_{MA}	time scale, s
σ	conductivity, mS/cm

Wang, 1996; Kim et al., 2011). Several researchers have used ERT to measure time-averaged gas volume fraction distribution in bubble columns of internal diameters in the range of 5–28 cm (Fransolet et al., 2001, 2005; Hulatt and Thomas, 2011; Ishkintana and Bennington, 2010; Jin et al., 2007, 2013b; Olerni et al., 2013; Sharifi and Young, 2013; Toye et al., 2005; Wang et al., 2001; Yenjaichon et al., 2013). However, to the best of author's knowledge there exists only one report (Olerni et al., 2013) in which the spatial distribution of gas volume fraction measured by ERT was verified using an independent measurement technique. Olerni et al. (2013) compared the radial distribution of time-averaged gas volume fraction using ERT and wire mesh sensor (WMS) for a bubble column (ID=5 cm and U_G=8.5–50.8 cm/s). While the time-averaged gas volume fraction profiles measured by both the techniques were in a good agreement for gas volume fraction less than 30%, they reported that the gas volume fraction above 30% was underestimated by ERT measurements. Importantly, to the best of author's knowledge, there are no literature which compare local gas volume fraction fluctuations measured by ERT with an independent measurement technique.

In the past, several experiments have been performed to characterize the dynamics of gas–liquid flow in bubble columns using different measurement techniques. For example, videography (Delnoij et al., 1997), wall pressure fluctuations (Drahoš et al., 1991; Letzel et al., 1997; Vial et al., 2001), Particle Image Velocimetry (PIV) (Besbes et al., 2015; Lin et al., 1996; Mudde et al., 1997), Laser Doppler Anemometer (LDA) (Becker et al., 1999; Borchers et al., 1999), conductivity probe (Buwa and Ranade, 2002, 2005) etc. Delnoij et al. (1997) performed videography experiments to observe the plume oscillation frequency at different H/D (height to diameter) ratio. Later, based on local liquid velocity fluctuations time series, plume oscillation frequencies were measured by different researchers (Becker et al., 1999; Pfleger et al., 1999). In their experiments (Becker et al., 1999; Pfleger et al., 1999), LDA was used to measure the time evolution of local liquid velocity. However, these studies were limited to low gas flow rate and particular sparger configurations. Buwa and Ranade (2002) used wall pressure fluctuation measurements to investigate the effect of gas velocity and sparger configurations on bubble plume oscillations. Later, Buwa and Ranade (2005) used voidage probes to characterize the dynamics of gas–liquid flow in a rectangular bubble column using instantaneous gas volume fraction fluctuation measurements. Effects of H/W (height to width) ratio, sparger configurations and superficial gas velocity on the dynamics of gas–liquid flow was studied quantitatively. It was reported that the low-frequency oscillations were caused by meandering bubble plume, which in turn are governed by sparger configurations and physical properties of the liquid phase. However, these studies were limited to low gas flow rates (U_G < 1 cm/s) and pseudo 2D (rectangular) bubble columns.

The present work was carried out with multiple objectives: (1) to verify the abilities of ERT to measure time-resolved instantaneous local gas volume fraction with the measurements performed using in-house developed voidage probes, (2) to compare dynamics of reactor (column)-scale and bubble-scale processes measured using ERT and voidage probes under dilute to dense conditions, and (3) to compare the time-averaged gas volume fraction distribution measured using both the techniques for a wide range of U_G (1–40 cm/s) and for different sparger configurations. The experimental set–up and measurement techniques are described briefly in Section 2 and the results are discussed in Section 3.

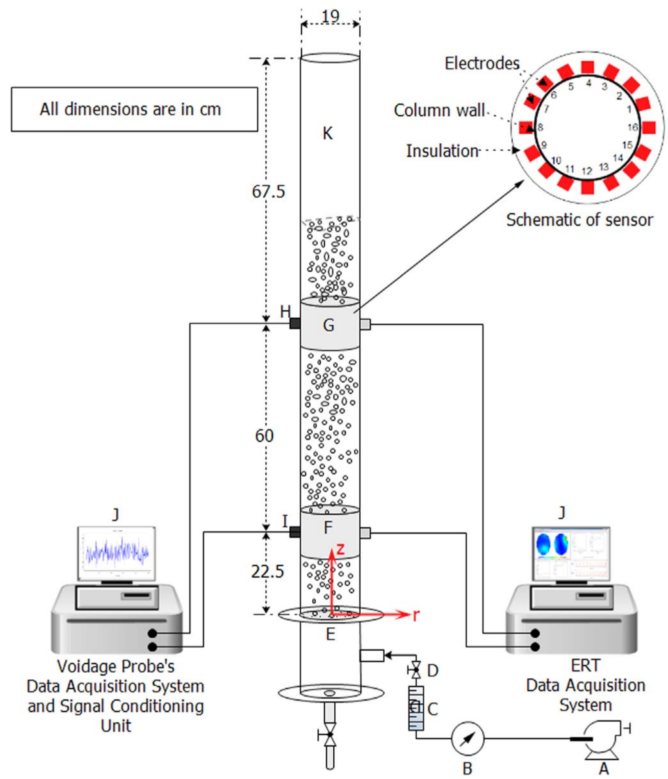

Fig. 1. Schematic of experimental set-up (A. compressor, B. pressure regulator, C. rotameter, D. needle valve, E. sparger, (F, G). ERT sensors, (H, I). voidage probe port, J. PC, K. bubble column and schematic of senor in the inset).

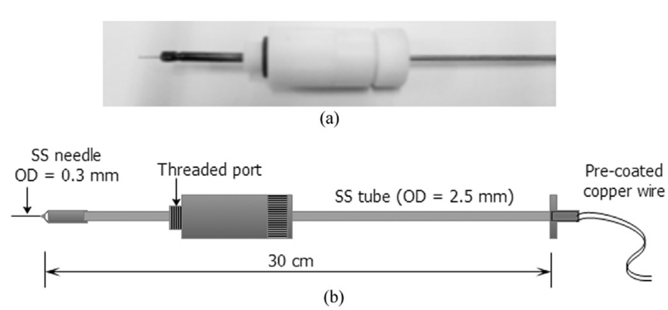

Fig. 2. In-house developed voidage probe (a) photograph and (b) schematic.