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Comparison of void fraction measurements using different techniques in two-phase flow bubble column reactors

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ABSTRACT

Local, area and volume average void fraction measurements have been conducted in gas-liquid two-phase flow through vertical pipes of different diameters under different modes of operation covering up-flow, down-flow and batch bubble column. The measurement techniques used include gamma ray densitometry, electrical resistance tomography (ERT), wire mesh sensor (WMS), optical void probe, and pressure transducers. The consistency among different measurement techniques has been examined by comparing the local, area and volume-average void fraction measurements made using the above methods in the same test section under the same flow conditions. The accuracy of the measurement techniques has been found to depend significantly on the mode of two-phase flow operation. The results show that the gamma densitometry and the pressure transducers can produce highly reliable measurements independent of the mode of operation. However, the optical void probe was found to underestimate the local values of void fractions, particularly, in the case of a co-current down-flow with sub-millimeter sized bubbles. Also, the electrical resistance tomography technique was found to be the least reliable method, as it underestimated the void fraction in the co-current up-flow as well as co-current down-flow operation. The accuracy of the wire mesh sensor was strongly dependent on the size of the bubbles relative to the wire mesh spacing.

1. Introduction

Gas-liquid two-phase flows are often found in chemical, biochemical, petro-chemical and metallurgical industries as well as nuclear power plants (Kalaga et al., 2017, Bhusare et al., 2017). Despite the wide-spread use of two-phase flow in different types of reactors, the methodology used for the design and scale-up is mainly based on experience and intuition, and perhaps some heuristic “rule-of-thumb” and empirical correlations (Kalaga, 2015). The most important and challenging step in designing a two-phase reactor is the prediction of void fraction which determines the performance of the reactor. There are many correlations for void fraction prediction but their accuracy ultimately depends on the reliability of the data obtained using different measurement techniques.

The instantaneous and time averaged values of local, area and volume average void fraction in two-phase flow reactors are important design parameters irrespective of the mode of reactor operation such as a batch bubble column, and co-current up-flow and down-flow reactors. Different modes of operation lead to different local void fraction distributions and average void fraction values which in turn exert numerous direct and indirect influences on the reactor performance (Hernandez-Alvarado et al., 2016a). In recent decades, several advanced techniques for void fraction measurement have been developed to obtain accurate and reliable experimental data on local, area and volume averaged void fractions. The present work first reviews several such void fraction measurement techniques and then compares the data obtained in three different two-phase flow configurations using four different measurement techniques: gamma densitometry, optical void probe, Electrical Resistance Tomography (ERT) and Wire Mesh Sensor (WMS).

Gamma-ray densitometry is a widely used non-invasive measurement technique for measuring the line (or chord) averaged void fraction developed in the early 1950s. Hewitt and Whalley (1980) employed the gamma densitometry and differential pressure measurement method to obtain the void fraction in upward two-phase flow. Kawaji et al. (1987) and

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Chan et al. (1999) used strong gamma sources to measure chordal average void fractions in high pressure/high temperature steam-water flows in 180 mm ID and 889 mm ID steel pipes, respectively. Schollenberger et al. (1997) derived an analytical solution for converting the chordal averaged void fraction to radial void fraction profiles. Several researchers have used this technique for studying the void fraction profiles in several types of multiphase reactors: a conventional bubble column (Veera and Joshi, 1999,2000), high pressure industrial bubble columns (Jin et al., 2004,2005), horizontal pipe flows (Li et al., 2007), and downward pipe flow in external loop airlift reactors (Cao et al., 2008). Also, Stahl and Von Rohr (2004) reported on the accuracy of the void fraction measurements using a single beam gamma-densitometry for gas-liquid two phase flows in pipes. Gamma densitometry was reported to be the most reliable technique for measuring radial profiles as well as cross sectional distributions of void fraction by employing the use of multiple detectors (Kalaga et al., 2009; Chavan et al., 2009; Nadler and Mewes, 1995).

An optical void probe is an intrusive device for measuring the local void fraction in gas-liquid two phase flow. Single tip optical fiber probes are used to measure the instantaneous and time averaged local void fractions, in two or three phase flows. Hanata (1972) reported the local void fraction data obtained in two-phase flow of liquid metal-air and found a reasonable agreement with the pressure gradient method. Galaup and Delhaye (1976) developed a miniaturized optical probe to detect local void fraction and interface passages to obtain local gas velocities. Annunziato and Girardi (1985) reported and analyzed the local void fraction fluctuations in upward air-water two-phase flow and compared the optical void probe measurements with gamma densitometry and differential pressure measurements. Recently, the development of multi-tip optical probes has been underway to obtain the bubble size, bubble velocities and flow regime transition (Shen et al., 2016; Besagni and Inzoli, 2016; Liu et al., 2014; Sun et al., 2013). However, there has been no discussion on the effect of probe orientation on local void fraction measurements, especially in bubbly flows containing large and small bubbles moving in opposite directions.

The application of the non-invasive Electrical Resistance Tomography technique for the cross sectional distribution of void fraction in two-phase flow was initially reported in the early 2000s (Deng et al., 2001; Ma et al., 2001; Fransol et al., 2001). Dong et al. (2005) extended their work to dual plane ERT for the void fraction and dispersed phase velocity measurements. Yu (2008) reported on the errors in the measured average void fraction values to be within 8% for a pipe filled with a stagnant salt solution (liquid phase) and polyester bars to simulate the foam (gas phase). A new voidage measurement method was proposed for gas-liquid two-phase flows based on ERT and Otsu algorithm. Jia et al. (2015) and Parsi et al. (2015) have recently compared the spatial and temporal gas holdup distributions obtained from the ERT and the wire mesh sensor techniques and validated them against the volume averaged void fractions obtained using pairs of pressure transducers. They found that the friction pressure loss cannot be neglected, particularly when the void fraction is less than 0.2 for liquid flow rates higher than 8×10^{-4} m^3/s and gas flow rates lower than 4×10^{-4} m^3/s.

The wire mesh sensor (WMS), also known as electrode wire mesh tomography, is an intrusive technique for measuring the cross-sectional distribution of the void fraction developed by Prasser and co-workers in the late 1990s (Prasser et al., 1998,2001; Richter et al., 2002). WMS has a capability to produce instantaneous void fraction distribution data over the flow channel cross section at a rate of 1,200 frames per second and with a spatial resolution of about 2–3 mm (Prasser et al., 2002). Wangjiraniran et al. (2003) investigated the intrusiveness of the wires in the WMS on the void fraction measurement. The level of disturbance to the two-phase flow was estimated from the deviation of flow properties between successive measurement planes, and the contribution of deceleration and bubble deformation to the flow disturbance was related to the flow condition. Huang et al. (2007) reported that the WMS has the advantages of high sensitivity, high spatial-temporal resolution, high signal-to-noise ratio and no need for reconstruction algorithms. They also reported that the disturbance and error could be neglected in the range of their operation. The feasibility and applicability of WMS for different gas-liquid and liquid-liquid flows was investigated by Velasco and Rodriguez (2015). They stated that the WMS can provide multitudes of information including local, chordal, cross-sectional and in-situ volume profiles/distributions of phase fraction. Wire mesh sensors have also been implemented in horizontal two-phase flow (Lam Loh et al., 2016; Lessard, 2014) and co-current downward two-phase flow (Lokanathan and Hibiki, 2016).

As briefly reviewed above, many publications have reported on void fraction measurements in two-phase flow using different techniques, with each technique having its own advantages and disadvantages. However, to our knowledge, no publication has reported on the consistency among multiple measurement techniques, and there is a need to systematically assess the advantages and limitations of different void fraction measurement methods using the same test section under the same two-phase flow conditions. To this end, void fraction measurements have been made in this work using an optical void probe, Electrical Resistance Tomography, Wire Mesh Sensor, gamma densitometry, and pairs of pressure transducers (dP_T). The consistency among different measurement methods has been investigated in different modes of two-phase flow operation including a batch bubble column, co-current upward and co-current downward flows in vertical pipes of different diameters.

2. Experimental set-up and measurement techniques

In the present work, gas-liquid two-phase flow experiments have been performed with air and water under ambient conditions in vertical pipes of different diameters (D) and heights (H) for different modes of operation (co-current up-flow, co-current down-flow, and batch bubble column). As shown in Fig. 1, three test sections (A, B and C) were used to compare the void fraction measurements made with different measurements techniques. The test section A (Fig. 1a) had a diameter of 100 mm and a height of 128 cm, and was operated in a batch bubble column and co-current up-flow mode with 75 PPM of potassium chloride (KCl). In this test section, gamma ray densitometer, optical void probe and ERT measurements were made and compared against each other for each mode of operation. The test section B (Fig. 1b) had a diameter of 100 mm and a height of 64 cm, and was operated in a co-current down-flow mode with downward liquid (with 10 PPM of sodium dodecyl sulfate (SDS), 75 PPM of potassium chloride (KCl)) and upward gas flows. The void fraction was measured with an optical void probe, ERT, gamma ray densitometer and a pair of pressure transducers. The test section C (Fig. 1c) with a diameter of 300 mm and a height of 120 cm, was operated in a batch bubble column mode with 75 PPM of potassium chloride (KCl) for comparison of the void fraction measurements obtained with a Wire Mesh Sensor, gamma densitometer and ERT.

In the batch bubble column operation, the liquid in the column was stagnant, and the gas was sparged from the bottom. In the co-current up-flow operation, liquid was injected from the bottom while the gas was injected from a sparger located at the bottom of the test section. In this operation, both the bubbles and liquid flowed upward reducing the residence time of the bubbles when compared to the bubble column operation. Similarly, in the co-

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