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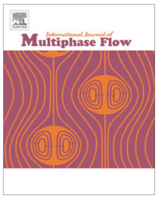

Review

Analysis of dynamic bias error in X-ray tomographic reconstructions of a three-phase flow system

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ABSTRACT

Void fraction is one of the most important parameters to analyze various properties of multi-phase flows. Bubbles can arrange themselves in different manners and their distribution across the flow cross-section changes with time. Projection data (collected from a computerized tomographic scanner) for such a cross-section is not instantaneous in nature so time-averaging (over measurement interval) is required to obtain phase distributions. Two different types of averaging schemes are discussed in this work and it is shown that inappropriate averaging results in a significant dynamic bias effect (DB) leading to erroneous images.

This analysis is performed on a three-phase bubble column reactor in which air, water and poly vinyl chloride (PVC) are used as representatives of gas, liquid and solid phases. Measurements have been performed for two different levels of this column. First Kanpur Theorem (KT-1) is implemented to select "good" projection data which is then used in the tomographic reconstruction step. Characterization of reconstructed cross-sections is done by Second Kanpur Theorem (KT-2). This approach provides a comprehensive strategy to compare quantitatively cross sectional void-fraction patterns obtained for different measurement levels. We observe that DB error is approximately 3 times more when air velocity is increased from 0.06 m/s to 0.14 m/s.

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1. Introduction

Multi-phase flow behavior is characterized by phase distributions, velocity profile, flow patterns and several other parameters. Study of cross-sectional bubble distribution is important for design and maintenance aspects of fluid flow based equipments in several industries. A variety of invasive techniques have been used to determine the distributions of different phases for such cases (Tsuji and Morikawa, 1982; Holger, 2000). The major drawback of these techniques is that they disturb the flow field. Computerized tomography (CT) is used widely as a non-invasive technique which gives point-wise information over the entire cross-section. This technique is used commonly in medical diagnostic area and it also has a large number of applications in many other industries such as nuclear, chemical and pharmaceutical. Its application in multi-phase flows is increasing during last few years for identification of flow patterns and various other parameters (Dyakowski, 1996; Munshi et al., 1998; Hampel et al., 2007; Bruvik et al., 2010; Johansen et al., 2010; Maad et al., 2010). This technique, however, requires time independent projection data-sets for accurate reconstructions. Dynamic bias error (DB) arises in the reconstruction step if the scanning time for flow cross-section is more than the flow speed. This dynamic bias behavior depends on different flow conditions. It is, therefore, required to analyze and eliminate this error for precise 2measurements of phases.

This DB formula was derived earlier (Harms and Laratta, 1973; Laratta and Harms, 1974) for a liquid voided channel. A steady state assumption was made and it was shown that error depends on higher moments of void fraction about its mean. The thickness of channel was reported as an important parameter in DB formulation and it was suggested to use thin test sections and/or using radiation source of low attenuation to minimize this error. It was also reported that transient void variations show less DB error for the case of zero and full mean voids. A dual source method was proposed by LeVert (1974) and it was shown that the ratio of dynamic to static void condition (for a single photon) increases with increase in void-fraction while it decreases in case of dual photon source. The mean void-fraction, obtained from dual source method, is independent of thickness of flowing fluid. Andersson et al. (2012) have given a method to make a first-order dynamic bias error correction. This method requires a priori information about the flow or the variance of void-fraction. Nature of photon counts shows pure Poisson distribution in case of static object. It is slightly different in case of dynamic objects and the correction for counts rates was applied in this study. Hampel and Wagner (2011) have introduced a method for correct temporal averaging in transmission radiometry. Statistical nature of radiation detection was also taken into account. Singular value decomposition method was used there to obtain results for simulated as well as experimental data. Barrett (1974) has used discrete time-interval transmission method to determine void statistics in boiling channels. Accuracy of measurement of void-fraction is increased if the measurement time-interval is small but this step introduces statistical counting errors. A method was proposed in this study to minimize this statistical error with respect to the systematic error due to finiteness of measurement time.

An experimental study was done by Thiyagarajan et al. (1991) to determine fluctuations in voids for a liquid metal magneto hydrodynamic (LMMHD) system. The deviation of measured values from actual time-averaged voids was calculated. It was reported there that the accuracy (of measurements) depends upon void fluctuations and attenuation coefficient of the material. This accuracy can be increased if the degree of void fluctuations is known. The case, where it is not known, the maximum deviation between measured values and true time-averaged phase fraction can also be estimated. A further study, on an LMMHD system, has been done by Jayakumar and Munshi (1999) to measure uncertainty in tomographic reconstruction of void profiles. It was reported there that DB error increases as phase fraction of air is increased and it attains a maximum value in the range of 0.5–0.6. It then decreases with further increase in air fraction. Munshi and Vaidya (1994) have reported a sensitivity analysis (of two-phase flow tomographic reconstructions) based on Poisson uncertainty in projection data. Statistical errors are found to be more near the center of pipe. A mathematical formulation was given by Wyman and Harms (1985) to minimize error due to void dynamics and radiation source fluctuations in a two-phase flow system. It was concluded that the total void-fraction error is specified by a probability density function whose mean value is determined by the non-constancy of void fraction. Liu and Wang (1992) have proposed a simple plane model to correct the time variation effect due to fluctuation of voids in a two-phase flow system. A slug flow pattern was studied using this model as this pattern has high void-fraction variance. This model was applied to calculate the ratio of photon transmission probability between static and dynamic void conditions. A corrected average void-fraction was determined by using this ratio along with a modified photon-attenuation method. Void-fraction measurement accuracy was within ±2% using this correction procedure.

Void distribution and mass-transfer coefficient get affected by the presence of solid particles (Koide et al., 1984; Sada et al., 1986; Banisi et al., 1995; Li and Prakash, 2000; Mena et al., 2005). Dual effect of solid particles (in homogeneous–heterogeneous flow regime) was observed by Mena et al. (2005). Experiments were conducted at different solid loadings ranging from 0% to 30% of total volume of the bubble column. It was reported that homogeneous regime stabilizes at low solid loadings but it destabilizes for higher loadings. The effect of solid particles on gas hold-up was also studied by Banisi et al. (1995). Gas hold-up reduces with the presence of solid particles and this reduction effect is more when solid concentration is between 0% and 15%. This effect also increases with decrease in particle size. The effect of type of solid particles (hydrophilic, hydrophobic) on gas hold-up was also investigated in this analysis.

An experiment was performed at Leibniz University Hannover (Gulati et al., 2010) and it involved a three-phase bubble column reactor. Three phases in this column were air, water and PVC particles. Measurements were taken for different air velocities of 0.06 m/s, 0.08 m/s, 0.12 m/s, 0.14 m/s and water velocities of 0 m/s 0.025 m/s, 0.05 m/s and 0.07 m/s. This bubble column was scanned with three different solid concentrations of 0%, 5% and 10% of the total volume. Projection data was collected at 1.7 m height (from the sparger) and “KT-1” approach, developed originally for non-destructive testing (Munshi et al., 1991, 1993; Munshi, 1992), was used to reconstruct meaningful flow images. This approach, based on Sobolev space concept (Adams, 1975), helped in rejecting “bad” projection data and identifying transition phenomenon from homogeneous to heterogeneous flow regime. Athe et al. (2013) have investigated the same bubble column at different measuring level, 3.2 m. Flow cross-sections were characterized with two different approaches, “KT-1 signature” and “fractal” analysis. It was reported that both approaches led to the same conclusion about the flow pattern. Shakya et al. (2013) have made a comparative analysis for the two levels (1.7 m and 3.2 m) of this bubble column using “KT-2” approach reported originally for non-destructive testing (Munshi et al., 1994). This approach is based on an inverse error theorem and it characterizes the flow cross-sections “globally” as compared to the “local” formulation of “KT-1 signature” approach.