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X-ray computed tomography in large bubble columns

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Abstract

X-ray computed tomography (CT) is used to explore the differences in a semi-batch bubble column operated at superficial gas velocities of $U_g = 3$, 10, and 18 cm/s. Air–water or air–water–cellulose fiber systems comprise the multiphase flow, and the bubble column has a 32.1 cm internal diameter. A CT image of a phantom object composed of several air-filled tubes immersed in water is used to identify several characteristic features of the X-ray CT system. CT images are then compared between air–water and air–water–cellulose fiber systems. When the fiber mass fraction is 0.1%, gas holdup is slightly higher than that of the air–water system in the column center and near the column wall. In 1.0% cellulose fiber slurries, gas holdup is lower than that of air–water results at all radial positions.

Keywords: Bubble column; Hydrodynamics; Instrumentation; Multiphase flow; Tomography; Visualization

1. Introduction

Multiphase flows consisting of any combination of gas, liquid, and solid phase exist in several different industries. Fuel production, energy generation, chemical production, pulp and paper processing, food processing, and wastewater treatment are just some examples of where multiphase flows can be found (Dudukovic et al., 1999). Multiphase flow hydrodynamics and operations are quite complex, and while many industries utilize multiphase flows, a better understanding of the transport and hydrodynamic characteristics are needed for process improvement and optimization. In order to identify internal flow characteristics of multiphase flows, one can use either invasive measurement techniques or noninvasive methods. All invasive methods can potentially alter the internal flow, but noninvasive methods eliminate this concern. X-ray imaging is one noninvasive measuring technique that can be used for analyzing internal objects and structures that are characteristic of a given multiphase flow operation.

X-ray computed tomography has been used by some researchers for multiphase flow characterization due to its high spatial resolution (Hervieu et al., 2001; Marchot et al., 2001; Schmit et al., 2004). X-ray stereography uses information from two two-dimensional projections to determine the three-dimensional location of features within an object (Doering, 1992; Jensen and Gray, 2004). An extension of stereographic imaging is X-ray particle tracking velocimetry (XPTV), where two X-ray sources track X-ray absorbent particles via point mapping (Seeger et al., 2003; Kertzscher et al., 2004).

Other noninvasive methods have been developed for studying multiphase flows, many of which have been documented by Chaouki et al. (1997). Two of these methods include gamma densitometry tomography (GDT) and electrical capacitance tomography (ECT). Gamma densitometry tomography uses gamma-rays to measure the radial attenuation distribution through a multiphase system, which is

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then used to calculate local phase holdup (Shollenberger et al., 1997; George et al., 2001; Kemoun et al., 2001, Veera (2001), Veera et al., 2001; Dudukovic, 2002). Electrical capacitance tomography is a fast but low-resolution imaging technique that estimates the phase holdup based on capacitance measurements. The results are generally qualitative, and researchers use different algorithms to obtain their results (Schmitz and Mewes, 2000; Mwambela and Johansen, 2001; Dyakowski and Jaworski, 2003; Warsito and Fan, 2001, 2003).

This study describes a multiphase flow visualization facility that is capable of X-ray radiography, X-ray computed tomography, and X-ray stereography imaging of large-scale systems. Imaging of a static multiphase system is presented to demonstrate the CT system. Computed tomography imaging of a gas–liquid–fiber multiphase system is then completed using a 4.87 m tall, 32.1 cm ID bubble column to identify local gas phase variations.

2. Experimental setup

The X-ray imaging system consists of two X-ray sources and two image intensifiers, offset 90° from each other. The X-ray sources and image intensifiers are mounted on a slewing ring with a 101.4 cm ID which allows complete rotation around the bubble column. A schematic of the X-ray visualization facility is shown in Fig. 1.

Two LORAD LPX200 portable X-ray tubes with beryllium windows and a 1.5 mm focal spot size provide the X-ray sources. The maximum power is 900 W with adjustable voltage (10–200 kV) and current (0.1–10.0 mA) capabilities. The windows provide a 60° horizontal and 40° vertical conical beam. A 1 mm copper filter has been added to the tube windows to suppress low energy radiation, and a 2.86 cm diameter collimator is used to limit the beam to the diameter of the bubble column.

The image intensifiers are Precise Optics PS164X 40.6 cm diameter screen detectors with an output image diameter of 35.0 mm. The CCD cameras that read the image from each intensifier are DVC-1412 monochrome digital cameras with a pick up area of 8.98 mm × 6.71 mm. A Precise Optics P1002-4000 motorized lens focuses the image intensifier output onto the CCD camera pick up area. The pixel size is 6.45 μm × 6.45 μm, and the active pixels are 1388(H) × 1024(V). The cameras have binning capabilities of 1 × 1 at 10 frames/s (fps), 2 × 2 at 20 fps, 4 × 4 at 40 fps, and 8 × 8 at 60 fps; hence the resulting optics render the effective imaging pixel size dependent on the camera binning setting.

The slewing ring is driven by a Parker stepper motor and controlled by the data acquisition computer. X-ray images are taken every 1° around a 360° path and result in a time-averaged local phase distribution CT. A single source/detector pair is used for the CT data presented below. The dual source/detector pairs are being used for X-ray stereographic imaging that is currently under development. The X-ray sources can be finely adjusted vertically in order to center the beam on the detectors. The image intensifiers can slide in a radial direction in order to move the intensifiers close to the bubble column, thereby changing the magnification of the column in the image. While the rotating ring is set in place vertically, the bubble column itself rests on a vertical lift that allows for imaging different axial locations of the bubble column. Images presented below are all taken at a fixed column height of 290 cm, corresponding to approximately 9 column diameters. The images are taken at that height in order to ensure the flow regime is fully developed and to avoid any influence of the initial gas distribution.

The bubble column used for this experiment is composed of four 1.22 m acrylic cylindrical sections with a $D=32.1$ cm internal diameter. A stainless steel distributor plate containing $N = 953$, $d_o = 1$ mm diameter holes producing an open area ratio ($A = N(d_o/D)^2$) of 0.95% is used to evenly disperse air through the bubble column bottom. The superficial gas velocity can be varied from 1 to 20 cm/s, but in this study, superficial gas velocities of 3, 10, and 18 cm/s are used. The slurries used in this study are composed of cellulose fibers suspended in water. The fibers had a length-weighted average fiber length of 2.3 mm, and results from two slurries with fiber mass fractions of 0.1% and 1.0% are presented below. Cellulose fibers have a dry density of $\sim 1500\,\mathrm{kg/m^3}$. When wet, they swell considerably and the center, which is hollow, fills with water. Since the fiber mass fractions in this study are relatively low, and a wet fiber has similar X-ray absorption characteristics compared to water, the water–fiber slurries are considered a single pseudo-fluid for the purpose of this study.

2.1. Computed tomography reconstruction

X-ray computed tomography (CT) generates a two-dimensional cross-sectional image of an object showing internal details. An X-ray source illuminates the object of interest and projects the resultant X-ray intensity onto an imaging device. Projections from each orientation are collected and reconstructed with standard algorithms (Barrett and Swindell, 1981; Hsieh, 2003), generating an image of the object cross-section. In the X-ray facility used in this study, multiple slices can be acquired simultaneously by considering different rows of the CCD camera, and the resulting data can be reconstructed to provide three-dimensional CT images of the time-averaged phase distribution.

In order to acquire, analyze, and manipulate the data in this study, custom software was designed and written to integrate motion control and data acquisition for computed tomography and stereographic data collection (under development). The reconstruction algorithm used is filtered back-projection. The code is an in-house developed code at the Center for Nondestructive Evaluation (CNDE).