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A cone-beam compensated back-projection algorithm for X-ray particle tracking velocimetry

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ABSTRACT

Characterizing multiphase or granular flows is difficult due to the opaque nature of the system. While invasive measurement techniques provide detailed information about a single point, assessing the entire system is a laborious task due to the large number of samples required. Therefore, significant work has gone into developing noninvasive methods of measuring these flow systems. In this study, identical pairs of X-ray source/detector systems are used to provide two simultaneous but independent X-ray radiographic projections, which are then coupled together to perform X-ray stereographic imaging of a granular flow. A cone-beam compensated back-projection algorithm is developed for X-ray particle tracking velocimetry (XPTV). This method accurately corrects for the X-ray's cone-beam geometry, which is ignored in parallel-beam back-projection methods. To demonstrate the need for the cone-beam compensation, a direct comparison between the cone-beam and parallel-beam back-projection algorithms is used, and significant differences are presented. These methods are then used to perform XPTV in a double screw mixer, allowing the position and velocity of individual tracer particles to be characterized.

1. Introduction

In many multiphase flows of industrial interest, it is difficult to measure and/or visualize the flow due to the opaque nature of the flow. For example, gas–liquid bubble column flows are often impossible to measure visually because the difference in refractive index between air and water distorts measurements at moderate (5%) or higher gas fractions [1]. In the case of granular mixing, the granules themselves are usually opaque, making visual measurements below the surface of the flow impossible. One way to overcome this limitation is the use of invasive probes; however, such probes only provide a single point-measurement and their presence has the potential to disrupt the flow [2]. Therefore, significant effort has gone into developing noninvasive methods of flow measurement [3,4].

Many of the noninvasive measurement methods for multiphase flows have significant trade-offs between temporal and spatial resolution. One of the more common noninvasive measurement methods is electrical capacitance tomography (ECT). ECT operates using electrodes placed around the wall of a flow, which are energized sequentially. When one electrode is energized, the remaining electrodes are used to measure the electrical capacitance in the system. These measurements can then be reconstructed into a two-dimensional (2D) slice of electrical permittivity, which can be correlated to material properties. While ECT systems are capable of measuring full tomographic slices at speeds above 1000 frames per second (FPS), they are limited in spatial resolution [5], typically on the order of 5% or more of the vessel or pipe diameter [6].

In addition to ECT, there are several other tomographic techniques that have been applied to multiphase flows. Among these are gamma-ray tomography [7], X-ray tomography [8], magnetic resonance imaging (MRI) [9], and ultrasonic tomography [10]. All these techniques provide good spatial resolution and have the capability to take three-dimensional (3D) measurements of flows. However, these techniques generally suffer from very poor temporal resolution, and individual scans can take on the order of an hour or more to acquire [3], and thus are better suited for time-average measurements or extremely slow-moving processes. While there are efforts to improve the temporal resolutions of these techniques, such as by using X-ray tomography scans from electron beam sources or multiple sources, such techniques do so at the cost of spatial resolution and increased reconstruction artifacts [11,12].

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One noninvasive measurement technique that has been shown to provide a balance between spatial and temporal resolution is X-ray particle tracking velocimetry (XPTV) [1,13]. XPTV is an extension of X-ray radiography in which one or more X-ray attenuating tracer particles are placed in the flow [14]. A time-sequence of radiographs is taken, from which the location of each particle is determined in each frame. By using two temporally synchronized but independent X-ray source/detector pairs, a 3D particle location can be determined [15]. XPTV has been shown to obtain temporal resolutions of up to 1000 FPS for 2D studies [16], and 25 FPS for 3D studies [1]. However, one drawback of several previous XPTV studies is its failure to account for the conical beam geometry of the X-ray source [13,14,16–20]. When the cone-beam is assumed to be parallel, the tracer particle's position and resulting velocities will be incorrect. This paper provides a correction for this error and demonstrates a sample application for which it would not be possible to properly image without the correction. Another drawback of some previous XPTV measurements is the time difference between the acquisition of the two independent projections [21]. While small, this difference can make it difficult to match a particle between frames, and poses a challenge for the determination of the particle velocity. This problem is further exacerbated by high flow velocities. In this study, this challenge is overcome by using temporally synchronized X-ray imaging equipment.

To demonstrate the usefulness of the cone-beam back-projection, XPTV is performed in a double screw mixer allowing the position and velocity of individual tracer particles to be characterized. Double screw mixers are currently being used in various industrial applications. For example, double screw pyrolyzers are being developed for the thermochemical conversion of biomass into bio-oil. The screw pyrolyzer's heat transfer rates and resulting bio-oil yields are significantly influenced by its ability to mechanically mix high density inert heat carrier media (e.g., stainless steel shot, refractory sand, etc.) with low density biomass particles (e.g., red oak chips, switchgrass, etc.) [22]. However, characterizing the granular mixing process is difficult due to the opaque nature of the screw pyrolyzer and granular materials. In this study, these two complications are overcome by using an X-ray transparent double screw mixer that geometrically resembles double screw pyrolyzers and by using XPTV to characterize the granular flow.

This paper will first describe the X-ray Flow Visualization (XFloViz) Facility and the screw mixer that were used to perform granular mixing studies. Next, the two granular material types used and the fabrication of tracer particles will be presented. The cone-beam compensated back-projection algorithm that was implemented, allowing XPTV to be completed, will then be detailed, followed by the necessary calibration procedures. Next, comparisons will be made between the parallel-beam and cone-beam back-projection methods, thus demonstrating the significance of the cone-beam compensation. A sample result from one of the screw mixer's operating conditions will be presented and discussed to demonstrate the usefulness of the methods. Finally, conclusions and recommendations for future work will be made.

2. Experimental procedures

2.1. Equipment

2.1.1. X-ray Flow Visualization Facility

X-ray stereography was performed using the X-ray Flow Visualization (XFloViz) Facility at Iowa State University. Two X-ray source/detector pairs were used to simultaneously capture independent X-ray radiographic projections, which were then coupled together to provide the X-ray stereographic imaging technique. Each X-ray source is a liquid-cooled LORAD LPX200 portable cone-beam source. The cone-beam spans approximately 60° and 40° in the horizontal and vertical directions, respectively. The X-ray sources feature a variable power output with voltage and current ranging from 10 to 200 kV and 0.1 to 10.0 mA, respectively, and a maximum power output of 900 W. Despite the X-ray source/detector pairs being identical in terms of the make and model, some inherent variations do exist, causing the necessary power settings to be slightly different. In this study, X-ray sources one and two featured voltage and current configurations of 140 kV and 3.5 mA, and 150 kV and 3.1 mA, respectively. A single 0.61 mm copper filter was placed in front of each X-ray source to absorb the low energy X-rays prior to entering the imaging region, minimizing beam-hardening effects.

Both detectors are identical Precise Optics PS164X image intensifiers which feature a 40.6 cm input phosphor and 3.5 cm diameter output phosphor. The input phosphor is backed by a vacuum chamber causing the X-ray photons to be re-emitted as electrons in the vacuum chamber. These electrons are accelerated and focused onto the output phosphor using high voltage electric fields. This causes a significantly brighter visible light image on the output phosphor than could be obtained using a direct X-ray to visible light scintillator. Coupled to the image intensifiers are two identical DVC-1412 12-bit, monochrome, charge-coupled device (CCD) cameras. Each camera has a maximum resolution of 1388×1024 active pixels. To improve light sensitivity and increase imaging speed, a 2×2 binning configuration, where the signal from adjacent pixels is added together, was used. This, combined with some cropping, yielded an effective resolution of 640×512 pixels. Using this binning configuration, the cameras captured images in 55 ms increments thus having an effective frame rate of 18.2 FPS. Higher binning settings are available, but were not used as the tracer particle became difficult to discern at lower spatial resolutions. The image exposure time for both cameras was 5 ms to minimize motion blur. The X-ray source/detector pairs were mounted at 90° from one another about the central vertical axis in the XFloViz Facility to provide two independent projections of the object of interest (OOI). Note that two independent projections are required for the stereographic imaging needed for XPTV, but the projections do not have to be at 90° offsets. The 90° offset in the XFloViz Facility allows for the most imaging flexibility and minimizes any potential beam interference between the two X-ray source/detector pairs. The equations presented in this paper are for an imaging facility that features a 90° offset.

The X-ray source/detector pairs are mounted on a slew ring which provides 360° rotation around the OOI. A large stepper motor is used to control the angular alignment of the X-ray source/detector pairs relative to the OOI. Located in the center of the XFloViz Facility is a vertical lift system with a custom leveling platform designed specifically to hold the screw mixer in place. For this study, the position of the X-ray source/detector pairs was held constant with respect to the screw mixer. The screw mixer was positioned with a 45° angle between the mid-line from X-ray source/detector pair one and the screw mixer's axial direction, which provided two important benefits over an orthogonal imaging setup. First, an orthogonal setup would result in one X-ray source imaging through the entire length of the screw mixer, thus requiring higher X-ray source power and increasing the number of superfluous objects in the imaging region. By rotating the screw mixer 45°, both X-ray sources had a relatively short path (albeit longer than in the side-on case) through the OOI and minimal obstructions from superfluous screw mixer components. Secondly, since the screw mixer has a relatively large aspect ratio, utilizing a 45° rotation enables the entire mixing region to be positioned in the imaging region. With an orthogonal setup, a portion of the mixing region is cropped from the imaging region in