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A HIGH-SPEED X-RAY DETECTOR SYSTEM FOR NONINVASIVE FLUID FLOW MEASUREMENTS

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ABSTRACT

The opaque nature of many multiphase flows has long posed a significant challenge to the visualization and measurement of desired characteristics. To overcome this difficulty, X-ray imaging, both in the form of radiography and computed tomography, has been used successfully to quantify various multiphase flow phenomena. However, the relatively low temporal resolution of typical X-ray systems limit their use to moderately slow flows and time-average values. This paper discusses the development of an X-ray detection system capable of high-speed radiographic imaging that can be used to visualize multiphase flows. Details of the hardware will be given and then applied to sample multiphase flows in which X-ray radiographic images of up to 1,000 frames per second were realized. The sample flows address two different multiphase flow arrangements. The first is a gas-liquid system representative of a small bubble column. The second is a gas-solid system typically found in a fluidized bed operation. Sample images are presented and potential challenges and solutions are discussed.

INTRODUCTION

The use of dynamic X-ray imaging started with the development of fluoroscopic X-ray systems, which used a phosphor screen to convert X-rays into visible light that an observer would view directly [1]. While these systems allowed scientists to view flows in real time, they could not record data for later analysis or slow down events too fast to be observed by the human eye. The use of X-ray sensitive film allowed for the direct recording of data, but due to the relative insensitivity of X-ray film, this process required long exposures or high X-ray intensity, and time consuming development processes [2,3]. Therefore, it was not until the development of digital X-ray detection systems that time-sequenced radiography became the powerful tool for fluid flow research it is today [4].

However, the current state of X-ray imaging still generally limits time sequences to standard video frame rates. Most direct X-ray detectors are only capable of 30 frames per second (FPS), and indirect detectors are limited by the decay rate of the phosphor screen [5,6]. Flash X-ray systems use high-power, short duration X-ray pulses to take images at higher speeds, but are generally limited to generating a small number of frames because of energy storage bank recharge times and anode deterioration [3,4]. For example, Romero and Smith [7] used flash X-ray radiography to examine fluidized beds, but were limited to two radiographs, at different spatial locations, per experiment. Heindel and Monefeldt [8,9] later used flash X-ray to examine pulp suspensions in bubble columns, and although they achieved 30 nanosecond exposure time, they were limited to single X-ray frames. Finally, Grady and Kipp [10] and Boyer et al. [3] used flash radiography to image projectiles, with Boyer et al. achieving up to 50 consecutive frames before significant anode deterioration.

Synchrotron X-ray sources have also been used to image fluids at high speed [11–13]. For example, Royer et al. [12] observed impact-induced granular jets at frame rates up to 5000 FPS using the Advanced Photon Source at Argonne National Laboratory. MacPhee et al. [11] was able to image shock wave generation in high-pressure sprays at over 100,000 FPS, also using the Advanced Photon Source. However, synchrotron sources are cost prohibitive for most fluid flow research.

Finally, there have been a few studies using continuous X-ray sources to examine systems at high speed. One early, moderately high speed fluid study was completed by Rowe and Partridge [14], who used an X-ray intensifier and cinematographic film camera to achieve frame rates of 50 FPS.

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A more recent study by Zolfaghari et al. [15] used a digital CCD camera and X-ray intensifier to observe current interruption in a circuit breaker at 4000 FPS. However, the high material density and well-defined material boundaries inside a circuit breaker require a less sensitive system than one typically needed for fluid flow visualization.

This paper will summarize current efforts to produce high-speed radiographic images of highly dynamic opaque multiphase flows using an X-ray image intensifier and high-speed camera.

EXPERIMENTAL SETUP

This study used the X-ray Flow Visualization Facility at Iowa State University [16]. However, the image acquisition system was modified from its standard arrangement to significantly increase the imaging speed. The standard LORAD LPX 200 X-ray source was used to provide the radiation. This source provides a conical, polychromatic X-ray beam at voltages up to 200kV, and currents up to 10mA, with a maximum power output of 900W. This source was paired with a Precise Optics PS164X image intensifier to convert the X-ray photons into viable light. This particular detector is designed to use a remotely controlled C-mount lens paired with a CCD camera, such as the DVC-1412 used in previous studies [16]. However, to increase the speed of the system, the CCD camera was removed and replaced with a CMOS-based Photron FASTCAM SA5 high-speed camera. The SA5 is well suited for this application due to both its resolution (1024 x 1024 pixels) and speed (7000 FPS at full resolution, up to 1,000,000 FPS at reduced resolution). It is also extremely sensitive (ISO 10,000 equivalent), enabling it to image at high frame rates despite the low light intensity inherent in X-ray detectors. The use of this camera also required replacing the stock lens with a 50 mm F-mount lens, compatible with the new camera. Furthermore, a custom lens mount was required on the camera to shorten the flange focal length by 3.13 mm (0.125"), and allow the lens to achieve the true infinite focus required by the intensifier optics. Finally, the camera was shielded all the way around by a 6.35 mm (0.25") thick lead shield to prevent damage to the camera from the high intensity radiation. The X-ray setup is schematically represented in Figure 1.

All images were acquired using the standard acquisition software provided with the SA5. This produced a sequence of 12-bit tiff images. These images were then processed using a custom software package to normalize the images and remove the pincushion artifact caused by the image intensifier. The result of this processing can be seen in Figure 2, which shows the raw and corrected image of a calibration grid. This calibration grid is a sheet of 1.9 mm (0.074") thick stainless steel with an array of 2 mm (0.078") holes drilled at 12.7 mm (0.5") on center intervals, both vertically and horizontally. The corrections cause some artifacts at the edges of the image; however, this is outside the area of interest, so its effect is negligable.

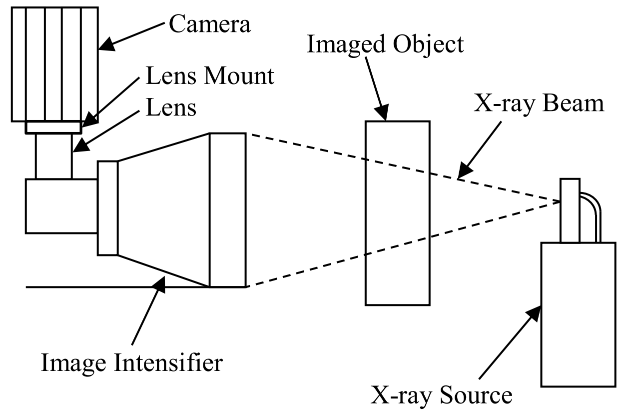

Figure 1: Imaging setup. Note that the image intensifier has an internal mirror to allow the camera to be mounted out of the primary X-ray beam. Lead shielding is omitted from the schematic for clarity.

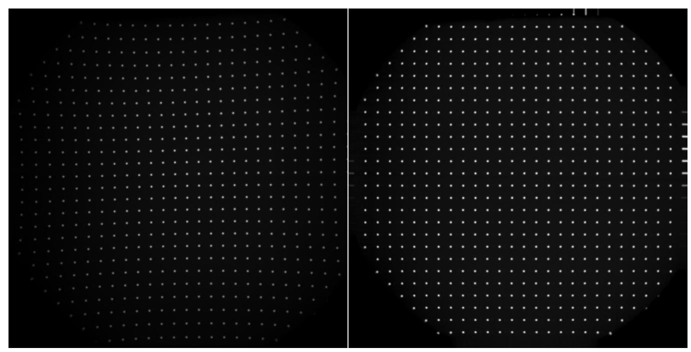

Figure 2: Comparison of a radiograph of a calibration grid before and after image processing. (Unmodified frame, left, processed frame, right.)

Two flow systems were used in this study. The first is an 8 cm (3.15") diameter bubble column. It was filled to a height of two bed diameters with water, and air was injected from the bottom through a central 1 cm (0.39") diameter by 1.5 cm high (0.59") porous injector. For the imaging of this system, the flow rate was held constant at 50 LPM by a computerize flow controller, producing a superficial gas velocity of 17 cm/s in which the flow regime was clearly churn turbulent. Once the flow was operating at a steady flow rate, the camera was trigged to take a 1,000 frame sequence. Each image in this sequence was acquired at full resolution (1024 x 1024 pixels), with an exposure of 16.3 microseconds and each image was taken one millisecond apart (1000 FPS). The short exposure reduced the effects of motion blurring, while the 1000 FPS frame rate was selected to provide the longest dataset possible, while still keeping the inter-frame movement small. To achieve an exposure this short the X-ray power was set at 100 kV and 9.0 mA.

The second flow system consisted of a 15.24 cm (6") internal diameter fluidized bed that was filled to a height of one bed diameter with crushed walnut shell, sieved to a particle size

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range of 500-600 microns. Air was injected from the bottom through a distributor plate [17]. The air flow through this system was maintained at 280 LPM (2 times minimum fluidization) by the computerized flow controller for a superficial gas velocity of 26 cm/s. For this system, 10,000 frames were acquired at 1000 FPS and full resolution. However, for this test a longer exposure was required to provide enough intensity to image the thicker flow. In this case, an exposure of 50.2 microseconds was used and the X-ray power was set at 80 kV and 7 mA.

The fluidized bed flow was also seeded with a tracer particle to allow the analysis of the particle movement from the image sequence. This particle was a 2.03 mm (0.08") diameter lead sphere, inside an 8 mm diameter (0.315") foam sphere [18]. In order to track this particle, a normalized cross-correlation method was used. This method computes the similarity between a template image (in this case a radiograph of just the particle) and each point in the image. The particle tracking then finds the point of highest correlation, and marks that as the particle location [19,20].

RESULTS AND DISCUSSION

An analysis of the bubble column sequence shows that the air tends to rise in the center of the column, with recirculation currents along the edges of the column. Once the air reaches approximately 1.5 column diameters above the bottom of the column, a foam-like region of high gas fraction begins, which matches closely with visual observations of the column's operation. By tracking the leading edge of bubbles as they rise the velocity of the bubble can be ascertained. For the bubble in Figure 3, this measurement yields a result of 55.4 cm/s ± 0.1 cm/s.

The examination of the fluidized bed sequence shows that the distributor plate maintains a relatively even distribution of bubbles across the bed (Figure 4). This is consistent with the findings of Drake and Heindel obtained through X-ray computed tomography scans [17]. Furthermore, the addition of a tracer particle to the flow allowed for the evaluation of granular movement within the flow (Figure 5).

The tracking of the particle revealed downward flow zones at both sides of the bed, as projected onto the X-ray detector. However, these zones do not appear to be large enough to trap the particle fully, as it never reaches the bottom of the bed throughout the entire test. While this is just a small sample of particle motion inside a fluidized bed, it shows the clarity with which particle tracking data may be obtained using high-speed radiography. Previous research using the same normalized cross-correlation algorithm was only able to identify the particle correctly 70-95% of the time. Using the high-speed radiographs, the particle was correctly identified 99.98% of the time. This increase can be attributed to the extremely short exposure time, as compared to earlier studies,

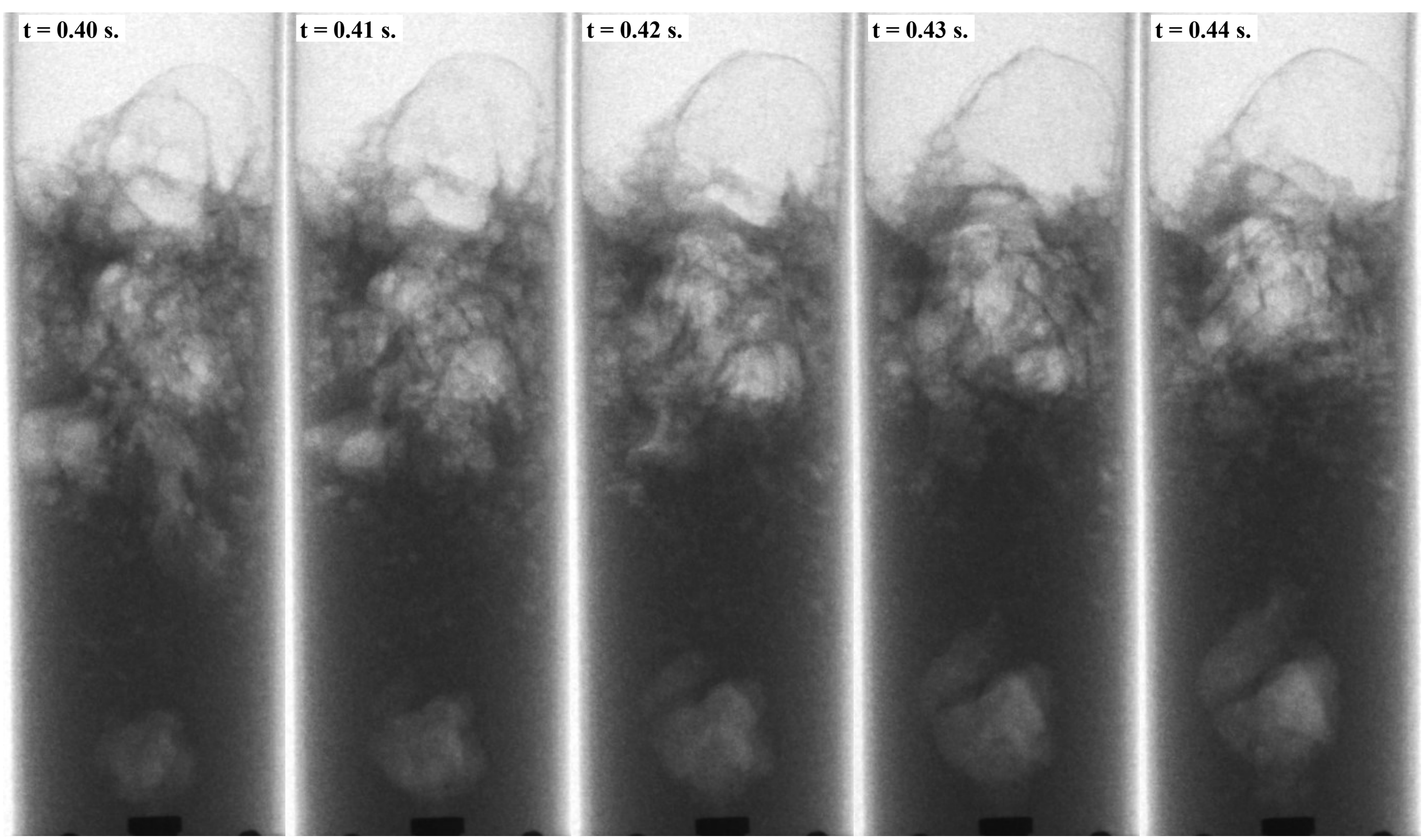

Figure 3: Gas-liquid system; bubble rising from the injector from time t=0.40 s to t=0.44 s. Every tenth frame is shown to exhibit the bubble movement clearly. Bubbles are identified by the lighter gray regions.

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which eliminates motion blur.

Both flows show the ability of the X-ray system to image at high speeds. The primary limitations of high-speed X-ray imaging with a tube source (output image intensity and phosphor decay) were non-issues in this case. The full output power of the source was sufficient to provide a bright enough output image from the intensifier that exposures down to 16.3 microseconds could be obtain while still using more than 75% of the cameras intensity range. If some loss of intensity range is acceptable, the exposure times could be cut further. As for the phosphor decay, no effects from the time response were found at 1000 FPS. This provides enough speed to examine many flows of industrial interest in depth. Furthermore, the exposure times used are short enough that the frame rates could be increase significantly if the phosphor decay is fast enough.

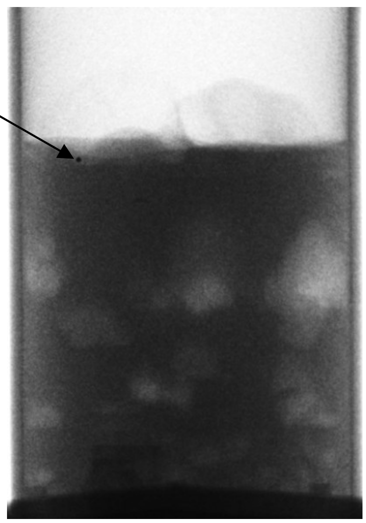

Figure 4: Gas-solid system; gas distribution at t = 1.050 s. Air bubbles are identified by the lighter gray regions.

FUTURE WORK

Several steps need to be taken in the future to improve this system. First, the time response of phosphor screens in the image intensifier needs to be quantified. While there was no observable affect at 1000 FPS, increasing the frame rate another order of magnitude or more may start to incur blurring due to the time response of the phosphor. The point at which this blurring starts to become an issue will be one of the key limiting factors in pushing for even higher speed radiographs.

Another important factor to consider moving forward will be the expansion of this research into the third spatial dimension. Most fluid flows, including the ones examined in this paper, are three-dimensional in nature. By using radiographs from a single viewpoint, the third spatial dimension is lost, limiting the applicability of the results. However, many modern high-speed cameras allow frames to be synchronized between cameras, theoretically allowing for two or more angles of a flow to be imaged simultaneously. This will be particularly useful for particle tracking applications.

A system to complete 3D particle tracking could be installed in the X-ray Flow Visualization Facility at Iowa State University because it already has two identical X-ray source-image intensifier pairs that are installed perpendicular to each other [16]. What is needed to complete the high speed 3D particle tracking system is two identical high speed camera systems with the ability to synchronize images between cameras.

CONCLUSIONS

This work has shown that the pairing of a high-speed camera with an X-ray image intensifier is capable of imaging fluid flows at high speed. The system has been proven to image at 1000 frames per second, with exposures down to 16.3 microseconds. The system is capable of revealing the dynamic details of a fluid flow that cannot be observed with other methods, such as computed tomography. Furthermore, the high quality particle tracking results will provide a powerful quantitative tool to experimentally determine flow velocities inside opaque systems. While more work is required to determine the upper limit of frame rates and to provide three-dimensional imaging capabilities, further development of high-speed X-ray imaging of fluid flows will be of value for the validation of computational models and the understanding of fluid phenomenon.

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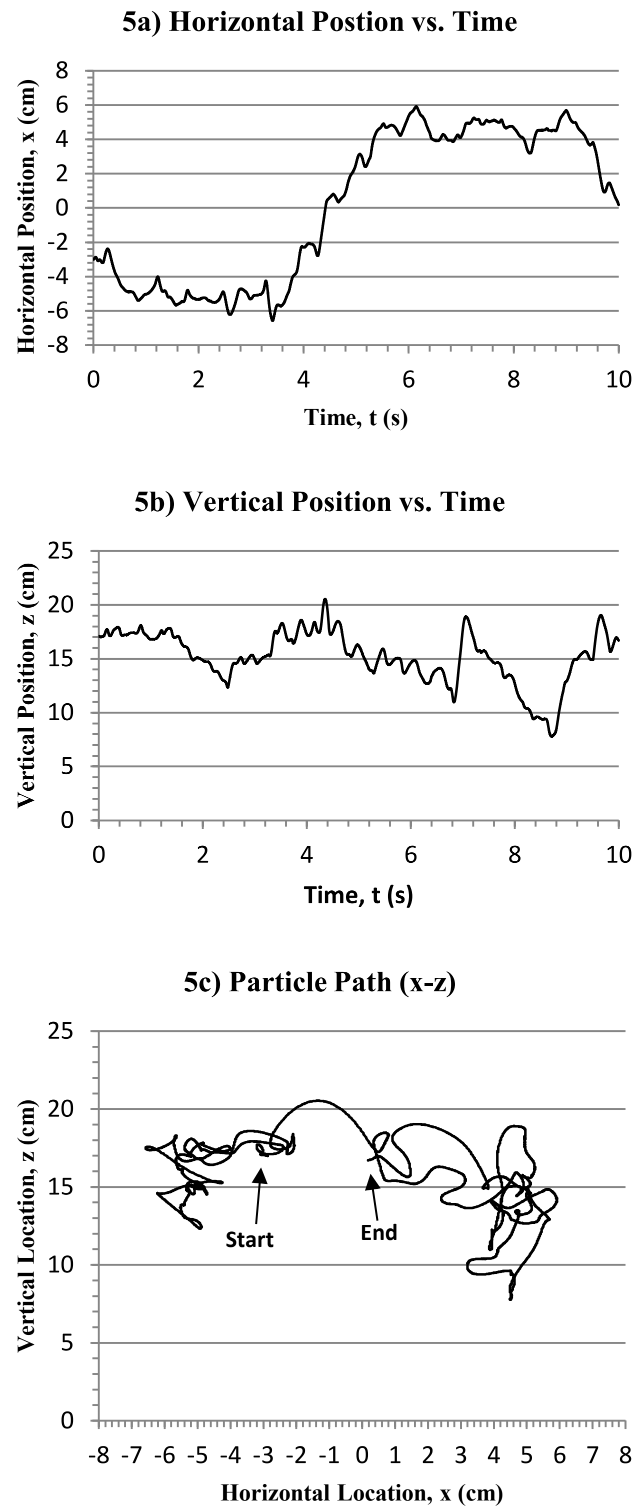

Figure 5: The path of the particle as tracked by the normalized cross-correlation method: (a) x-position vs. time, (b) z-position vs. time, and (c) x-position vs. z-position for a 10 s period.

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