Visualizing Fluid Flows With X-Rays

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Abstract
There are several methods available to visualize fluid flows when one has optical access. However, when optical access is limited to near the boundaries or not available at all, alternative visualization methods are required. This paper will describe flow visualization using an X-ray system that is capable of digital X-ray radiography, digital X-ray stereography, and digital X-ray computed tomography (CT). The unique X-ray flow visualization facility will be briefly described, and then flow visualization of various systems will be shown. Radiographs provide a two-dimensional density map of a three dimensional process or object. Radiographic images of various multiphase flows will be presented. When two X-ray sources and detectors simultaneously acquire images of the same process or object from different orientations, stereographic imaging can be completed; this type of imaging will be demonstrated by trickling water through packed columns and by absorbing water in a porous medium. Finally, local time-averaged phase distributions can be determined from X-ray computed tomography (CT) imaging, and this will be shown by comparing CT images from two different gas-liquid sparged columns.

Keywords
Center for Nondestructive Evaluation, flow visualization, multiphase flows, radiography, stereography, tomography, x-ray imaging

Disciplines
Acoustics, Dynamics, and Controls | Computer-Aided Engineering and Design | Fluid Dynamics

Comments
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INTRODUCTION

Many fluids are contained in opaque enclosures (e.g., pipes, fittings, valves, tanks, etc.) or are themselves opaque (e.g., milk, crude oil, shampoo, etc.) making optical flow visualization difficult. Multiphase flows, consisting of any combination of gas, liquid, and/or solid, can also be considered opaque. While many industries utilize opaque and multiphase flows, a better understanding of the transport and hydrodynamic characteristics are needed for process improvement and optimization. Visualizing and quantifying the characteristics of these fluid flows are extremely challenging and are usually limited to invasive measurement methods. The difficulty with invasive methods is that they can alter the internal flow of the system causing interference with realistic process measurements. Noninvasive measurement methods avoid this limitation.

A variety of noninvasive measurement techniques are being developed in an attempt to provide high-quality quantitative data of various flow characteristics and have been reviewed in the literature [1-4]. These techniques include: electrical impedance tomography (EIT) [5, 6], electrical resistance tomography (ERT) [7, 8], electrical capacitance tomography (ECT) [9-15], ultrasonic computed tomography (UCT) [16-18], gamma densitometry tomography (GDT) [6, 19-24], and X-ray computed tomography (XCT) [25-30]. Many of these techniques offer trade-offs when implemented [1, 3, 8, 11]. For example, ECT is very fast (up to 100 tomographic images per second) but the spatial resolution is poor (on the...
order of 10% of the object) and the results are sensitive to the reconstruction algorithm. XCT has excellent spatial resolution (< 0.2% of the object) but poor temporal resolution (it may take several minutes to obtain tomographic data); hence, it is best for providing time-averaged phase distributions. Others have developed individual particle tracking methods using radioactive emitting tracer particles [31-34] or X-ray absorbing particles [35-37]. Yet others have used radiographic (sometimes referred to as fluoroscopic) imaging to view internal flow characteristics of multiphase or opaque flows [38-41].

X-ray imaging is one family of noninvasive measurement techniques used extensively for product testing and evaluation of static objects with complex structures. X-rays can also be used to visualize and quantify opaque fluid flow characteristics, which is the focus of this paper. The following provides a brief summary of the image processing hardware and software used in this unique X-ray flow visualization facility. Imaging capabilities are then demonstrated through various examples.

**EXPERIMENTAL EQUIPMENT**

**X-ray Flow Visualization Facility**

The X-ray flow visualization facility (identified as the XFioViz facility) was designed to accommodate flow systems or static objects that are up to 32 cm in diameter and can span vertically nearly 4 m. The heart of this facility is schematically represented in Fig. 1. The X-ray imaging system consists of two X-ray source/detector pairs, offset 90° from each other. The X-ray sources and detectors are mounted opposite each other on a slewing ring (a donut-shaped gear) with a 1.0 m ID; this allows for complete rotation around the imaging region. Figure 2 shows an actual image of the XFioViz facility with a 32.1 cm diameter bubble column and the two image intensifiers installed. Table 1 summarizes the major components of the overall system. Further details can be found in [42].

![Fig. 1. Schematic of some of the X-ray flow visualization hardware.](image)

![Fig. 2. XFioViz imaging room.](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-ray sources</strong> (2 units)</td>
<td>• 10-200 kV, 0.1-10 mA, 900 W (max)</td>
</tr>
<tr>
<td><strong>Detector A</strong> (2 units) for radiographic, stereographic, and CT imaging</td>
<td>• Image intensifier with 40.6 cm diameter input window</td>
</tr>
<tr>
<td></td>
<td>• CCD camera with 1388(H) x 1024(V) active pixels and frame rate (binning) of 10 fps (1x1), 20 fps (2x2), 40 fps (4x4), or 60 fps (8x8)</td>
</tr>
<tr>
<td><strong>Detector B</strong> (1 unit) for superior CT imaging</td>
<td>• CsI phosphor screen with 44 cm x 44 cm (square) input region</td>
</tr>
<tr>
<td></td>
<td>• CCD camera with 3072(H) x 2044(V) active pixels</td>
</tr>
<tr>
<td></td>
<td>• Several binning options; exposure time 0.1 to 100 sec.</td>
</tr>
<tr>
<td><strong>Vertical lift system</strong></td>
<td>• 910 kg (200 lb) winch</td>
</tr>
<tr>
<td></td>
<td>• Vertical track with 2.75 m travel</td>
</tr>
<tr>
<td></td>
<td>• Approximately 4 m span in imaging region (with table extensions)</td>
</tr>
</tbody>
</table>

**X-ray Flow Visualization Capabilities**

An X-ray imaging device records a two-dimensional projection of a three-dimensional object when the object is placed between an X-ray source and detector. The recorded image is actually a map of the X-ray attenuation through the object and is called a radiograph. A medical X-ray would be one example of a radiograph. Digital radiography has seen a tremendous increase in popularity in the last 5 years due largely to improved performance of 2D sensor arrays and enhanced computer power capable of processing the large data sets generated in digital radiography. Major advantages of digital
radiography over more traditional film radiography are the speed with which images can be acquired and the flexibility in manipulating and storing the images.

If the object in the imaging region is dynamic, such as a fluid flow process, the radiographic image will be blurry unless the detector has a fast enough response and the camera connected to the detector has a fast enough shutter speed to freeze the motion. With a fast enough system, such as the two imagine intensifiers used in the XFLOViz facility (Detector A in Table 1), a 2D radiographic movie of a 3D dynamic process can be created.

The XFLOViz facility is capable of producing radiographs at a variety of temporal and spatial resolutions, depending on the CCD camera frame rate and binning options. For example, the DVC cameras used for digital radiography range from 10 frames per second (fps) with 1388(H) × 1024(V) pixels to 60 fps at 160(H) × 128(V) pixels. The resulting images can be assembled into a movie to view the process or object in motion.

The second imaging capability involves stereography. Stereographic measurement methods use information from two 2-dimensional projections to calculate the 3-dimensional location of features in an object [43]. This can be accomplished by analyzing two images of an object which are taken at different positions either due to a rotation or translation of the sample. Alternatively, with the two identical source/image intensifier pairs in the XFLOViz facility, and using appropriate software controls for the two CCD cameras, two image projections can be acquired simultaneously. As long as the point of interest is identifiable in both images, its corresponding three dimensional coordinate can be determined.

Hence, stereographic imaging can produce a three dimensional map of a feature of interest. With successive continuous images, the three dimensional location of a flow feature, such as a bubble, phase front, or particle tracer, can be determined as a function of time. Thus, X-ray stereography provides a means for three dimensional flow visualization of dynamic characteristics in opaque systems at a temporal resolution comparable to the frame rate of the digital cameras.

The third imaging capability in the XFLOViz facility is X-ray computed tomography. X-ray computed tomography (CT) imaging generates a two-dimensional cross-sectional image of an object showing internal details. In this imaging process, an X-ray source illuminates the object of interest and projects the resultant X-ray intensity onto an imaging device. Projections from several hundred orientations are collected and reconstructed with standard algorithms, such as filtered back projection [44, 45], generating an image of the object cross-section. Since it takes time to acquire several hundred projections, X-ray CT scans produce time-averaged details of the object's internal features, similar to a medical CAT scan. A single CT slice is obtained when data from a single line on the X-ray detector are collected from projections ranging from 0 to 360 degrees and reconstructed. Such slices are typically obtained when the X-ray source produces a fan beam [46]. By using an X-ray source with a cone beam, such as the sources in the XFLOViz facility, multiple slices can be simultaneously reconstructed from the 2D detector and then "stacked" to produce a three-dimensional time-averaged image of the object.

A single source and detector system is used to acquire the data for CT imaging. A single image intensifier and the associated camera system can be used for CT imaging. However, the CsI phosphor screen and a thermoelectric cooled camera that allows for low-noise, long exposure, and options to digitize the signal at either 12 or 16 bits (Detector B in Table 1), delivers superior CT images.

**X-ray Flow Visualization Data Acquisition and Image Processing Software**

Image acquisition in the XFLOViz facility is controlled by a personal computer with 4 GB of RAM and custom software developed by the Center for Nondestructive Evaluation (CNDE) at Iowa State University. The software was designed and written to integrate motion control and data acquisition for digital X-ray radiography, X-ray stereography, and X-ray computed tomography [47]. A multi-slice filtered back projection algorithm [44, 45] is used for CT reconstruction. Image reconstruction is completed on a 64-node LINUX cluster available at CNDE. Custom 3D visualization software is also provided by CNDE [48].

To compensate for imperfections in the imaging hardware, a variety of corrections are applied to the data to produce the best image. These systematic artifacts include the warping effects created by the image intensifiers and individual pixel nonuniformity. In addition, for X-ray CT imaging, corrections for a phenomenon called beam hardening must also be applied [45, 46]. To account for these effects, software algorithms were created to un warp the image, normalize the pixel response, and correct for beam hardening [47, 49]; more details can be found elsewhere [42].

**RESULTS**

The XFLOViz facility has three primary imaging capabilities: (i) digital X-ray radiography, (ii) digital X-ray stereography, and (iii) digital X-ray computed tomography (CT). Examples of each of these imaging capabilities are presented below. In all cases, selected still frames are shown; for video clips of these and other systems, please see [http://www3.me.iastate.edu/heindel-research/XfV.html](http://www3.me.iastate.edu/heindel-research/XfV.html).

**X-ray Radiography Imaging**

**Multiphase Bubble Column**

Figure 3 shows a radiographic sequence of five images taken of different air-liquid systems with a single image intensifier with a camera frame rate of 20 fps. Hence, the time between each image in the respective sequence is 50 ms. For each system, a single air sparger is centrally located in the bottom of an 8 cm diameter column, and the gas flow rate is set to a superficial gas velocity (defined as the volumetric gas flow rate divided by the column cross sectional area) of $U_g = 2$ cm/s.
The dark region on the bottom of each image is the sparger connector. Note that details in Fig. 3 (and in the images that follow) can be difficult to distinguish when presented in 8-bit grayscale (and even worse when printed on paper); however, the current DVC cameras attached to the image intensifiers actually provide 12-bit grayscale data. Additional information can be determined. In this particular example, the 12-bit data was linearly mapped to 8-bits.

An air-water system is used in Fig. 3a. Gas bubbles appear in each radiograph as lighter grayscale regions because the gassed regions attenuate less X-ray energy than the water-only regions. Individual gas bubbles are difficult to identify at a frame rate of 20 fps. Thus, in Fig. 3a, gas bubbles appear as light grayscale streaks. Assembling a long sequence of radiographs into a movie reveals that the gas stream oscillates in a serpentine pattern in the 2D projection; in the actual 3D cylindrical bubble column, the gas plume moves more in a helical pattern.

Figure 3b shows air being injected into a mixture of water and 10% by weight polyethylene glycol (PEG). PEG is a water-soluble polymer that makes the Newtonian fluid more viscous, with the viscosity increasing as the PEG concentration increases [50]. Although viscosity was not measured in this study, Gonzalez-Tello et al. [50] indicate the viscosity of a solution of 10% PEG with an average molecular mass of 8000 and water at 25°C is $\mu = 8.9 \text{ mPa-s}$. By increasing the fluid viscosity by a factor of 9, the serpentine gas flow pattern was suppressed (determined from the radiographic video) and several individual bubbles could be identified.

By increasing the PEG concentration (Figs. 3c-3d), the fluid viscosity increases and bubble motion is slowed. In Fig. 3d, the PEG concentration is 50% by weight and the fluid viscosity is approximately $\mu = 325 \text{ mPa-s}$ [50]. This makes the fluid like thick syrup and large bubbles form near the sparger head. These bubbles form a slow oscillating flow pattern near the center region of the column and large bubble coalescence is readily observed. Due to continuity considerations, there is also a region near the column walls of fluid downflow which also carries small bubbles (~1-2 mm in diameter) toward the column base; these bubbles are difficult to identify in the individual radiographs but are clearly observed in the radiographic movies.

**Fluidized Bed**

Figure 4 shows a radiographic sequence of nine images during the operation of a 9.5 cm diameter fluidized bed consisting of 500-600 µm glass beads. A single image intensifier was used with a CCD camera frame rate of 20 fps (50 ms between each image). The superficial gas velocity was $U_g = 18.2 \text{ cm/s}$ with a minimum fluidization velocity of ~15 cm/s. Additionally, 10 tracer particles consisting of 9.5 mm diameter polypropylene spheres with imbedded small metallic rods (~1.6 mm diameter x ~4.8 mm long) have also been added to the bed material; these tracer particles are also shown in Fig. 4.

The radiographic sequence starts at “a” with a large air bubble just beginning to break the bed surface. Several tracer particles are found near the bed surface. In “b”, the large air bubble pushes a large amount of bed material above the bed surface. A tracer particle is also caught in this flow. Images “c” through “f” show the large air bubble breaking the bed surface and ejecting a single tracer particle and some bed material above the freeboard region. The remaining images show the
bed collapsing in the air bubble void and the formation of another large air bubble. The brightness and contrast in image “h” was adjusted to show the large void and several tracer particles located near the bed surface.

These and other images (200 total) have been assembled into a radiographic movie where the tracer particles are observed moving from the top of the bed towards the bottom and then rising rapidly to the bed surface to repeat the process. The tracer particles appear to move as a group or cluster. When 500-600 μm sand particles are used as the bed material (not shown), the tracer particle movement is less clustered.

Wave Motion

Radiography can also be used to visualize wave dynamics or tank sloshing, which is important to the transportation of liquefied natural gas. This process is simulated by partitioning a common fish tank into a thin “sloshing” region (Fig. 5a). A single image intensifier system is used to view the 2D wave that is generated with an agitation bar. Silver-painted polypropylene spheres (3.2 mm diameter) were also used as liquid tracer particles in this demonstration.

Figure 5b shows four frames of the wave motion generated within the tank schematically shown in Fig. 5a. These images were taken at 20 fps (50 ms between frames). The air that is entrained in the breaking wave is clearly visible in frame 1. The entrained air dissipates with time, and the radiographic movies of this process show the gas-liquid interface in the tank eventually flattening out. The tracer particles in this sequence were not sufficiently entrained in the liquid because they were slightly more dense than water so they are preferentially found near the tank bottom. Further research is needed to develop ideal tracer particles to enhance the X-ray flow visualization system.

By properly calibrating the grayscale variation, the amount of gas entrained by the wave may be estimated, and its dissipation as a function of time could be tracked. Further research is needed in this area.
X-ray Stereography Imaging

Water Flowing Through a Packed bed

Figure 6 shows one example of stereographic imaging from the XFloViz facility. This figure shows a sequence of images of water trickling through a packed (initially dry) rice bed within a 4.8 cm graduated cylinder. Each camera is synchronized so the images from camera 1 and 2 correspond to the same instant in time, but are offset by 90°. The frame rate for these images was 20 fps, but the time between each image pair in Fig. 6 is 1.0 sec so the reader can clearly see differences with time. The fill line is shown in the top of each image and the demonstration was initiated with an initial water level in the bottom of the graduated cylinder.

Absorption in a Porous Medium

In addition to multiphase flows, X-ray imaging can be used to visualize other flows that have limited optical access. For example, liquid absorption in porous media posses a similar phase front tracking problem that is very difficult to visualize. Stereographic imaging was used to view this process by using a child’s doll that “wets” to generate a saturation front in a preemie diaper. Although images were acquired at 20 fps, Fig. 7 shows four representative frames from each camera system. Again, each camera is synchronized so the images from camera 1 and 2 correspond to the same instant in time, but are offset by 90°.
Initially \((t = 0)\), the diaper is not visible because it has similar X-ray attenuation characteristics as the surrounding air. The fill tube and internal “feeding tube” are clearly seen in each image. As water is injected into the doll and passes to the diaper, the wet region becomes visible because water has significantly higher X-ray attenuation than air. After 2.5 seconds of “feeding”, water is observed in the diaper and 50 ms later, the phase front has moved a little. This movement is very visible when each image is assembled into a movie.

At the end of the demonstration (52.5 seconds), the diaper is completely saturated with water and the diaper is fully visible in the mutually perpendicular images because water has permeated all absorbent regions. At some point prior to the end of the demonstration, leaks appear around the doll’s mouth and diaper.

\section*{X-ray Computed Tomography Imaging}

\subsection*{Multiphase Bubble Column}

The 8 cm diameter sparged column used in Fig. 3 was also used to obtain X-ray CT images of an air-water and air-50\% PEG-water system operating at a superficial gas velocity of 2 cm/s (Fig. 8). The images in Fig. 8 are contour maps of the local CT value, which can be related to the local gas holdup \cite{49}. The blue regions correspond to all air and the orangeryellow regions are nearly all water. Note that the time required to gather the CT data results in the CT images being a time-average of the local gas fraction within this gas-liquid system.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig8}
\caption{CT images of air sparged in an 8 cm diameter column filled with water (left) and 50\% PEG-water (right).}
\end{figure}

The left images in Fig. 8 are horizontal and vertical CT slices of the air-water system. The air inlet is clearly visible by the blue region centrally located in the column. The region near the column walls and in the same plane as the sparger is almost 100\% water. As air bubbles leave the sparger, visible observations reveal a serpentine pattern where, on average, the entire upper portion of the column is exposed to gas bubbles. This is shown by the uniform light green color in the upper region of the column. The bubbles rise to the surface where the light blue region represents an average of the gas-liquid interface.

The right images in Fig. 8 are vertical and horizontal CT slices of the air-50\% PEG-water system operating under identical conditions. In this case, the 50\% PEG solution is very viscous, causing large bubbles to form and rise in a slow oscillating fashion near the central region of the column (see Fig. 3d). When time-averaged, the central column region has a gas channel that forms, as shown by the light blue region. The large rising bubbles break the surface, on average, near the central part of the column, revealing what appears to be a hole.
in the fluid, but is just a region of high local time-averaged gas fraction. There also appears to be a meniscus near the column walls; this is due to fluid splashing when the large bubbles breach the gas-liquid interface. The splashed fluid hits the column walls and then falls back into the bulk fluid. The splashing at the surface also generates small bubbles which are entrained in the liquid. Since the liquid is very viscous, the entrained small bubbles (~1–2 mm in diameter, based on visual observations) are dispersed throughout the column. This is the reason for the light green color through the majority of the column. Note also that this increases the time-average overall gas fraction within the system when compared to the air-water system (i.e., the time-averaged gas-liquid interface is higher in the 50% PEG solution than in air-water system where both started at the same level).

CONCLUSIONS
X-rays can be used to visualize fluid flows where optical access may be limited. X-ray radiography produces a two-dimensional density map of a two- or three-dimensional flow system. Gas-liquid and gas-solid systems were visualized with this technique. X-ray stereography results from simultaneous X-ray imaging from two different directions. This technique was demonstrated by trickling water through a packed bed and tracking the liquid phase front in a porous medium. Finally, X-ray computed tomography produces time-averaged density (phase) maps of a multiphase system. This imaging technique was used to show differences in two different gas-liquid systems.

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REFERENCES


