Optimization of a High-Speed X-Ray Imaging System for Studying Sprays


1 Department of Physics and Engineering, Fort Lewis College, Durango, Colorado 81301, USA
2 Department of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907, USA
* Corresponding Author: mslipche@purdue.edu

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Spray-based liquid atomization and liquid mixing is critical for development of efficient combustors and drug delivery systems as well as multiple coating-related applications. While optical methods allow characterization of low density regions of sprays, the scattering of optical photons hinders the characterization of a dense core. Unlike optical photons, higher-energy X-ray photons have the capability to penetrate and image the core structure of sprays. Here we characterized temporal and spatial resolution of an X-Ray imaging system based on a commercially available tube source with an anode size of 0.6 mm. For high-speed imaging, a phosphor screen in combination with a high-speed CMOS camera equipped with a two-stage intensifier was used. Water was used as a model liquid with the addition of potassium iodide to increase the X-Ray absorption coefficient. Two-dimensional images of 0.5mm and 2 mm impinging jet sprays were taken with differing spatial resolutions and potassium iodide mass concentrations. Depending on the spray conditions, optimal imaging settings were found. The technique can be extended to three-dimensional analysis of sprays with multiple viewing angles from two or more X-ray sources along with tomographic reconstruction.

OCIS codes: (340.7440) X-ray imaging

1. INTRODUCTION

A. Significance

Contemporary technologies use sprays for many applications including but not limited to drug delivery, coaxial injectors in rocket combustion processes, and coating in manufacturing [1–3]. Aforementioned processes could be further optimized. However, limitations come with analyzing sprays. For instance, phase Doppler interferometry for spray analysis are limited to applications with spherical droplets [4]. Other techniques, such as laser diffraction, cannot be applied to imaging dense sprays due to strong scattering [5]. Broadband X-ray radiography can overcome such limitations with the addition of an absorption material for contrast enhancement [6].

Geometric characteristics that effect sprays include spray angle and nozzle size. Nozzle types include flat spray nozzles, flooding nozzles, hollow cone nozzles, etc. [7]. Flat spray nozzles create thin but wide spray patterns in a lens shape. Flooding nozzles create sprays that are elliptical in their cross-section. Hollow cone nozzles produce a hollow cone pattern of sprays. If the nozzle orifice size is decreased, the resulting exit velocity of fluid would increase. This leads to smaller droplet size [7]. An increase in flow velocity leads to breakup mechanisms that can transform Rayleigh flow to an atomized spray for plain-orifice liquid injection nozzles [8]. Each nozzle type has differing pressures and angles used that effect droplet size [7]. This in turn limits the kinds of techniques used in evaluation of each kind of spray.

B. Background

Earlier methods of analyzing the cores of sprays involved intrusive methods such as trying to split a spray open with knives or using an electrical mesh to create a conductive path to determine the length of a core [6, 9]. Since intrusive methods can significantly alter the characteristics of flow, other techniques were developed that were less invasive. These techniques include X-ray radiography, laser-ballistic imaging, planar laser imaging, laser fluorescence, etc. [9]. However, several processes occur in a spray that makes some established techniques non-applicable for certain regions. After a liquid exits the spray nozzle, droplets are formed that continue to break up via primary and secondary breakup mechanisms until possible atomization [10]. This process creates regions where there are spherical droplets, non-spherical droplets, mists, and continuous flow [9]. Because of this, there are dense and non-dense regions of a spray to evaluate.
X-ray techniques have been shown to provide three-dimensional images of sprays with reasonable spatial resolution and two-dimensional images that have reasonable spatial and temporal resolution [1, 3]. One technique called X-ray fluorescence involves introduction of an additive that is used for emitting optical radiation when excited by X-rays. This emission can be captured with appropriate equipment to produce two and three-dimensional spray images [11, 12]. Nevertheless, there is no temporal resolution if a single flash is used to produce images without a high repetition rate [12].

An alternate method of spray imaging involves using a synchrotron source of X-rays. Advantages of synchrotron X-Ray sources are high brightness, high spatial resolution, and capability to emit X-Ray photons in a narrow range of energies [9]. The brightness, measured in photons/\(s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%\text{bandwidth}\), of a tube source is about \(10^{13}\) times lower than that of third generation synchrotron sources. Some synchrotrons have a brightness of approximately \(10^{20}\) [13]. Synchrotron sources can also resolve an image down to micrometers [10]. Furthermore, synchrotron sources can have multiple beamlines with varying photon energy ranges for various applications. Some beamlines emit photons with energies as low as 5 kV and as high as 150 kV for the Advanced Photon Source (APS) at the Argonne National Laboratory [14].

The APS was successfully used to image sprays in two dimensions at multi-kHz rates [9]. Although synchrotron sources of X-rays yield temporally and spatially accurate two-dimensional representations of sprays, implementation of synchrotron sources in average laboratories is unfeasible due to their high cost.

C. Beer-Lambert Law

Beer’s Law is used to compare the intensity of photons emitted by the tube source and viewed by the camera system. The following is Beer-Lambert law [3]:

\[
I = I_0 e^{-\mu l}
\]  

(1)

In Equation 1, \(I\) is the final intensity, \(I_0\) is the emitted intensity, \(\mu\) is the attenuation coefficient, and \(l\) is the equivalent path length. Beer-Lambert Law enables reconstruction of images for the future experimental setup by finding an equivalent path length when intensities and attenuation coefficients are known. The law was used to find attenuation values for the two dimensional setup.

D. Purpose

The study at Zucrow Laboratories aims to provide three-dimensional spray images that have good spatial and temporal resolution. This will be done by continuously radiating X-rays in two or more directions. Multiple images in multiple directions could then be compiled to give a three dimensional images at several moments in time. The important aspects of this project are the capability of imaging sprays with a more portable source than a synchrotron and to image sprays in three dimensions with sufficient temporal and spatial resolution to view flow characteristics. However, this report only examines two-dimensional aspects of the proposed, future experimental setup.

With this method, X-rays are emitted towards a spray which absorb some of the X-rays [3]. This works in a similar fashion as X-ray tomography [5]. However, some problems arise with this method. Because of the low intrinsic absorption of water, an additive is needed to be introduced in sprays to enable better absorption of higher energy X-rays photons. Furthermore, depending on how broad the wavelengths of the X-rays emitted, the attenuation coefficient through the spray may not be linear [3]. In other words, the lower energy X-rays would be absorbed while higher energy X-rays pass through. This is called beam hardening which could skew density readings of spray regions [3, 4]. Fortunately, the short distances traveled through sprays make the attenuation coefficient act linearly with respect to concentration of potassium iodide, the contrast additive, up until a certain concentration [3, 4].

2. METHODS

A. Experimental Setup

The experimental setup consists of an X-ray tube source, HighSpeed IRO, FASTCAM SA-Z high-speed camera, reflective prism, phosphor plate, 20mm camera extension, 50mm lens, and spray source. X-ray tube sources emit photons at 40, 60, 80, 100, and 120 kV towards a spray. Some of the x-rays produced pass completely through the spray onto a phosphorous plate that produces light within the range of 190 to 800 nanometers the HighSpeed IRO can image. The HighSpeed IRO intensifies images received which enables the FASTCAM SA-Z to record images in grayscale. The camera system was shielded with led to preserve image quality. The experimental setup is shown in Figure 1.

Sprays imaged were created from impinging jets consisting of two 0.5 mm and two 2 mm diameter nozzles. The angle of impact between streams was 60 degrees. Images where taken at volume flow rates of 0.016 and 0.030 gallons per minute for the setup consisting of the 0.5 mm nozzles and 0.13 gallons per minute for the 2 mm nozzles. All sprays are imaged 2.5 inches
from the face of a Varian tube type A-272 with B-130H housing. The f-stop was set at 1.2.

B. Sharpness

The best imaging distance from the face of the X-ray tube source was determined using a 0.3 mm anode of the same tube to image a carbon steel edge of 0.95 mm thickness. The 10-90% rise distance was determined for different distances from the tube source. A total of 101 images for each distance were averaged together to reduce the effect of noise. Flat and dark images were not taken as this was a comparison to determine if the optimal imaging distance was closer to the tube source or farther away. The 10-90% rise distance was initially attained in a length of pixels. These were converted according to how many pixels the nozzle occupied. The position yielding the lowest rise distance was used for spray imaging with the 0.6 mm anode. At this position, the 10-90% rise distance was attained with the 0.6 mm anode of the same 0.95 mm steel. Each of the 101 images for each energy setting was normalized with flats and dark images.

C. Imaging Conditions

Each energy used in imaging had a set of conditions. The values in Table 1 depict conditions used for each respective energy for the report. This was done to attain similar non-normalized signal levels throughout imaging.

Table 1. Conditions used for each respective energy are shown.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Current</th>
<th>Gate</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kV</td>
<td>250 mA</td>
<td>20 µ</td>
<td>59%</td>
</tr>
<tr>
<td>60 kV</td>
<td>250 mA</td>
<td>20 µ</td>
<td>52%</td>
</tr>
<tr>
<td>80 kV</td>
<td>200 mA</td>
<td>20 µ</td>
<td>50%</td>
</tr>
<tr>
<td>100 kV</td>
<td>160 mA</td>
<td>20 µ</td>
<td>47%</td>
</tr>
<tr>
<td>120 kV</td>
<td>160 mA</td>
<td>20 µ</td>
<td>45%</td>
</tr>
</tbody>
</table>

D. Noise

For 30% KI concentration spray at the energies of 40, 60, 80, 100, and 120 kV, standard deviations of the signal peak and background before and after a signal were taken. The signal was found as well. Signal to noise ratios were then calculated.

E. Attenuation

In this experiment, a mixture of 10, 20, 30, 40, and 50% KI and water by mass was made. This was done because X-rays used in the experiment can have high energies that pass through regular water without significant absorption. With the aforementioned mixtures, the absorption coefficient of the flow can be compared with different mass concentrations using the flow of the 2 mm impinging jet before impact. Background photon intensities were compared with intensities after permeating the flows. Given the known diameters of nozzles and ratio of initial and final intensities, Beer-Lambert Law can be used to calculate the attenuation coefficient for KI mixtures. This was done at a constant 80 and 120 kV photon energy for different KI concentrations.

3. RESULTS

An imaging distance of 2.5 inches from the face of the tube source was found to be the optimal imaging distance for two reasons. As the distance from the tube source increased, the 10-90% rise distance increased as well. In other words, the sharpness decreased. Additionally, 2.5 inches was the closest position the impinging jet could be to the tube source without contact. Figure 2 depicts the aforementioned trend with the 0.3 mm anode.

![Rise vs. Tube Face Distance](image)

**Fig. 2.** The 10-90% rise distance increases with increased object distance from X-ray source.

The 10-90% rise distances, taken from 2.5 inches away from the face of the tube source, were attained at different conditions with the 0.6 mm anode. These conditions correspond to the energy used in other spray images. Figure 3 display rise distances.

From a distance of 2.5 inches, sprays of 10, 20, 30, 40, and 50% KI were taken of the 2 mm impinging jet. Each concentration of KI was imaged with 40 to 120 kV at increments of 20 kV. Aforementioned criteria are imaged with a flow rate of 0.13 gallons per minute. Figures 4-8 show images collected.

For 30% KI and energies of 40, 60, 80, 100, and 120 kV the signal and signal to noise ratios (SNR) were attained. Table 2 contains attained values.

For 30% KI and energies of 40, 60, 80, 100, and 120 kV the signal and signal to noise ratios (SNR) were attained. Table 2 contains attained values.

From a distance of 2.5 inches, sprays of 50% KI were taken of the 0.5 mm impinging jet. The concentration of KI was imaged with 40 to 120 kV at increments of 20 kV. Figures 9-10 show the images collected at flow rates of 0.016 and 0.030 gallons per minute.

The attenuation coefficient for 10, 20, 30, 40, and 50% KI by mass with water were taken from Figures 4-8. Table 3 tabulates the attained values.
Varying 10-90% rise distances were taken for a 0.95 mm thick carbon steel strip at energies ranging from 40 to 120 kV at increments of 20 kV. For energies of 40, 60, 80, 100, and 120 kV the respective rise distances were 1.56, 1.52, 1.61, 1.63, and 1.61 mm.

Fig. 3. Varying 10-90% rise distances were taken for a 0.95 mm thick carbon steel strip at energies ranging from 40 to 120 kV at increments of 20 kV. For energies of 40, 60, 80, 100, and 120 kV the respective rise distances were 1.56, 1.52, 1.61, 1.63, and 1.61 mm.
Table 2. Signal and SNR values of Figure 6 were taken as percentages of transmission.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Signal</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 6a</td>
<td>0.887</td>
<td>72.5</td>
</tr>
<tr>
<td>Figure 6b</td>
<td>0.883</td>
<td>74.0</td>
</tr>
<tr>
<td>Figure 6c</td>
<td>0.965</td>
<td>128</td>
</tr>
<tr>
<td>Figure 6d</td>
<td>0.933</td>
<td>113</td>
</tr>
<tr>
<td>Figure 6e</td>
<td>0.948</td>
<td>122</td>
</tr>
</tbody>
</table>

Table 3. Attenuation coefficients for 10-50% KI at increments of 10% for 80 and 120 kV energies and corresponding conditions.

<table>
<thead>
<tr>
<th>KI Concentration</th>
<th>80 kV Attenuation Coefficient [g/cm³]</th>
<th>120 kV Attenuation Coefficient [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% KI</td>
<td>0.200</td>
<td>0.473</td>
</tr>
<tr>
<td>20% KI</td>
<td>0.574</td>
<td>0.928</td>
</tr>
<tr>
<td>30% KI</td>
<td>1.07</td>
<td>1.46</td>
</tr>
<tr>
<td>40% KI</td>
<td>1.65</td>
<td>2.11</td>
</tr>
<tr>
<td>50% KI</td>
<td>1.49</td>
<td>1.82</td>
</tr>
</tbody>
</table>

4. DISCUSSION

A. Penumbra

A criterion used to determine image quality is the size of the penumbra or geometric unsharpness. Several factors influence the geometric unsharpness such as photon source size, size of the imaged object, the distance from the photon source to the object imaged, and the distance from the imaging sensor to the object imaged [15]. Decreasing the photon source size and increasing the distance between the source and the imaged object decreases the penumbra size. However, a sensor may not receive enough photons for imaging at a certain point. The trend depicted on Figure 2 demonstrates that penumbra is not the controlling factor for sharpness. One possible reason for this is that the magnification of the object provides more details than the blurriness provided by the penumbra.

B. 10-90% Rise Distances

The imaged carbon steel object does not have a constant thickness throughout. The edges of the object are tapered by an unknown amount. A possible increase in rise distance from 40 kV and 60 kV compared to 80, 100, and 120 kV is that more photons travel through the tapered edges of the material if their energy is higher. Future examination without a tapering object is needed.

C. Noise

The SNR increased drastically changed from Figures 6a-6b compared to Figures 6c-6e. This can be explained by using lower gain settings in imaging by using higher energy photons.

D. Area

Images can be further optimized depending on the kind of spray imaged. For instance, sprays which are wide may require more imaging area to the sides. Imaged area can be changed through the FASTCAM SA-Z settings. The frames per second (fps) that the camera captures can be increased or decreased. Increasing the fps may require a decrease of the highest resolution of the camera. With a decrease in the number of imaging pixels used comes a decrease in imaging area. Different kinds of sprays may require this area to image more distant features of a spray.

E. Attenuation

Visual inspection of Figures 4-8 display less brightness as the KI concentration increases. This is because the KI in solution aids in absorption of X-rays. This was done to attain contrasts at higher energy photons. However, the increased KI concentration may alter flow characteristics of water.

Values in Table 3 are largely inconsistent. Factors effecting this are misalignment of impinging jets and the varying cross-sectional length throughout the nozzle (nozzles are cylindrical). Data used to gather attenuation coefficients were at the center of the spray before impacting to create a flap. However, this value is not exact and does not have a wider area to average results to reduce error. A way to measure the attenuation could be to place different concentrations of KI into capillary tubes made of quarts and imaging them. This would provide a more controlled fluid to image.

For Figures 9-10, an increase in flow rate through the 0.5 mm nozzles leads to less visible features. This is due to atomization. In other words, a shorter path length leads to less photons being absorbed by the fluid. This decreases the contrast available. Figures 9-10 contain a low number of high index values for pixels resulting in more blue coloration displayed by MATLAB when using imagesc. Hence, a general difference in appearance between Figures 9-10 and Figures 4-8 resulted.

5. CONCLUSION

Techniques that do not use X-rays for imaging sprays provide information about certain regions. However, they fail to provide an overall picture of a spray regime [9]. The current experimental setup has the capacity to image whole sprays with 10-90% rise distances of 1.56, 1.52, 1.61, 1.63, and 1.62 mm with their respective used photon energies. The used gate of 20 μs on the intensifier is our temporal resolution. Three-dimensional X-ray produced images of sprays with good temporal resolution can be accomplished with cross-firing multiple X-ray tube sources in the future. Additionally, the tube source this technique utilizes can be implemented in laboratories easier than a synchrotron source [3]. If the proposed experimental setup for three dimensional imaging is successful, knowledge could be gained of nozzle types and the spray patterns they produce. This knowledge, in turn, could contribute to the overall efficiency of operations that require sprays.
REFERENCES


A. SPRAY FIGURES

Spray figures are displayed in subsequent pages.
Fig. 4. Images for water and 10% KI by mass spray with a flow rate of 0.13 gallons per minute through 2 mm nozzles were taken for photon energies of 40, 60, 80, 100, and 120 kV shown in 4a, 4b, 4c, 4d, and 4e respectively.
Fig. 5. Images for water and 20% KI by mass spray with a flow rate of 0.13 gallons per minute through 2 mm nozzles were taken for photon energies of 40, 60, 80, 100, and 120 kV shown in 5a, 5b, 5c, 5d, and 5e respectively.
Fig. 6. Images for water and 30% KI by mass spray with a flow rate of 0.13 gallons per minute through 2 mm nozzles were taken for photon energies of 40, 60, 80, 100, and 120 kV shown in 6a, 6b, 6c, 6d, and 6e respectively.
Fig. 7. Images for water and 40% KI by mass spray with a flow rate of 0.13 gallons per minute through 2 mm nozzles were taken for photon energies of 40, 60, 80, 100, and 120 kV shown in 7a, 7b, 7c, 7d, and 7e respectively.
Fig. 8. Images for water and 50% KI by mass spray with a flow rate of 0.13 gallons per minute through 2 mm nozzles were taken for photon energies of 40, 60, 80, 100, and 120 kV shown in 8a, 8b, 8c, 8d, and 8e respectively.
Fig. 9. Images for water and 50% KI by mass spray with a flow rate of 0.016 gallons per minute through 0.5 mm nozzles were taken for photon energies of 40, 60, 80, 100, and 120 kV shown in 9a, 9b, 9c, 9d, and 9e respectively.
Fig. 10. Images for water and 50% KI by mass spray with a flow rate of 0.030 gallons per minute through 0.5 mm nozzles were taken for photon energies of 40, 60, 80, 100, and 120 kV shown in 10a, 10b, 10c, 10d, and 10e respectively.