Quantitative imaging of single-shot liquid distributions in sprays using broadband flash x-ray radiography

Quantitative flash x-ray imaging of sprays (abbreviated title)

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Flash x-ray radiography is used to capture quantitative, two-dimensional line-of-sight averaged, single-shot liquid distribution measurements in impinging jet sprays. The accuracy of utilizing broadband x-ray radiation from compact flash tube sources is investigated for a range of conditions by comparing the data with radiographic high-speed measurements from a narrowband, high-intensity synchrotron x-ray facility at the Advanced Photon Source (APS) of Argonne National Laboratory. The path length of the liquid jets is varied to evaluate the effects of energy dependent x-ray attenuation, also known as spectral beam hardening. The spatial liquid distributions from flash x-ray and synchrotron-based radiography are compared, along with spectral characteristics using Taylor's hypothesis. The results indicate that quantitative, single-shot imaging of liquid distributions can be achieved using broadband x-ray sources with nanosecond temporal resolution. Practical considerations for optimizing the imaging system performance are discussed, including the coupled effects of x-ray bandwidth, contrast, sensitivity, spatial resolution, temporal resolution, and spectral beam hardening.

Keywords: flash x-ray; synchrotron radiation; x-ray radiography; impinging jet; spray imaging; liquid distribution

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Introduction

Quantitative liquid distribution within multiphase flows is critical for a broad range of applications, including chemical processing, drug delivery, material synthesis, power generation, and propulsion (Lefebvre, 1989; Meyer et al., 2010). As such, a wide range of optical techniques have been successfully applied in studies of like-doublet injectors, aerated jets, supercritical injection, jets in crossflow, effervescent atomizers and air-assisted sprays. These techniques include planar laser-induced fluorescence, shadowgraphy, Mie scattering, holography, structured illumination, optical connectivity, phase Doppler interferometry, and laser diffraction (Meyer et al., 2010; Jung et al., 2003; Lin et al., 2001; Purwar et al. 2014, Sallam et al., 2006; Santangelo and Sojka, 1994; Bachalo, 1980; Dobbins et al., 1963; Wellander et al., 2011). Laser-based techniques for dense sprays include ballistic imaging, optical connectivity, and structured light illumination (Linne, 2013). Ballistic imaging relies on an optical time-gate to remove multiply scattered photons from the image, allowing visualization of spray breakup without interference from the droplet field (Linne et al., 2005). Optical connectivity illuminates only the contiguous liquid structure emanating from the injector and can be used to measure breakup length (Charalampous et al., 2009). Structured light uses a structured spatial pattern to differentiate multiply scattered photons and has been used to measure the optical attenuation in a near-field dense droplet field (Berrocal et al., 2008; Kristensson et al., 2012).

X-ray radiography is a complementary approach that may provide the only practical means for directly measuring liquid distributions that are proportional to mass in optically dense sprays (Linne, 2012; Halls et al., 2014), particularly during primary breakup when large, non-spherical liquid structures are present. Unlike visible light, which can undergo strong diffraction, refraction, and multiple scattering, the total x-ray beam attenuation can be related to the material density along the line-of-sight. This enables measurements that are proportional to the liquid mass distribution with high accuracy in the presence of strong index of refraction gradients. Even under less dense conditions in which optical techniques can acquire mass distributions using extinction and droplet sizing data, doing so requires multiple techniques and is not typically feasible on a single-shot basis. As such, a technique such as x-ray radiography that can provide single-shot mass distributions under a wide range of conditions is of practical interest.

A growing body of work in x-ray spray radiography has emerged from research conducted at the Advanced Photon Source (APS) at Argonne National Laboratory. This synchrotron source enables delivery of a tunable, monochromatic, well-collimated, high-flux beam with sufficient intensity to measure liquid path lengths with high dynamic range and excellent temporal resolution. Because the narrowband beam passes through the sprays without significant change in its spectral characteristics, the attenuation coefficient remains nearly constant along the x-ray beam path. This greatly simplifies the analysis for measurements of liquid path length along the line of sight (referred to as equivalent path length, EPL); a spatial scan can then enable spatial interrogation of the line-of-sight averaged or tomographically reconstructed liquid distribution. Work in this area has been reported in a number of publications (Cai et al., 2003; Kastengren et al., 2014; Lin et al., 2011; MacPhee et al., 2002; Poola et al., 2000; Powell et al., 2000; Qun et al., 2007; Schumaker et al., 2012; Lightfoot et al. 2012).

As an alternative to synchrotron radiation, polychromatic x-ray tube sources are useful for laboratory scale studies due to their small size and portability. The broadband spectrum of the tube sources includes higher energy photons (~ 100 keV), which can limit image contrast by reducing attenuation and increase the relative contribution of scattering. In general, the absorption and elastic scattering of x-rays scale as the inverse cube and inverse square of photon

energy, respectively. In addition to limiting image contrast, the broad spectrum leads to variations in the attenuation coefficient. The preferential attenuation of low energy photons leads to spectral beam hardening, which shifts the spectrum of the transmitted x-ray beam to higher x-ray energies compared to the incident beam; thus, the attenuation coefficient will depend on the path length through the spray. To minimize this effect while using broadband tube sources, it is possible to use a filter to select a narrower range of x-ray energies, often pre-hardening the beam to eliminate preferential attenuation of softer x-rays.

Application of tube sources for investigation of instantaneous and time-averaged two- or three-dimensional spray structure has been presented by a number of researchers using a single attenuation coefficient. Void fraction measurements made at kHz-rates were shown by (Char et al., 1990; Woodward et al., 1995). Time-averaged three-dimensional data by (Meyer et al., 2008; Meyer et al., 2010; Balewski et al., 2010; Eichner, 2013; Coletti et al., 2014; Marchitto et al., 2015) were collected. Multiple sources were employed to make time-resolved tomographic measurements by (Lim et al., 2013). Radiographic data collected using flash x-ray sources have been used by (Birk et al. 2003) and (Robert et al., 2010) to make single-shot images with nanosecond exposures of evaporating streams and argon gas, respectively.

In this manner, x-ray radiography utilizing broadband tube sources has been shown to be capable of capturing quantitative liquid mass distribution, despite the spectral variation of the attenuation coefficient, for path lengths that are typical of engineering sprays (Halls et al., 2014). However, spectral filtering reduces the photon flux and is not effective for single-shot flash x-ray imaging. As such, flash x-ray imaging is typically conducted without filtering to retain as much of the incident beam energy as possible for high signal to-noise ratio in the attenuation measurement. The resulting instantaneous images from a flash x-ray source require consideration of spectral beam hardening for proper interpretation of radiographic data. To the best of our knowledge, direct validation of single-shot liquid mass distributions measured using broadband flash x-ray sources has not been undertaken for sprays (Heindel, 2011).

In the current work, measurements of liquid distributions within sprays using a broadband flash x-ray tube source are compared with narrowband x-ray measurement from the APS to investigate the accuracy of the experimental approach, including corrections for beam hardening. Liquid mass distributions measured from instantaneous two-dimensional radiographs using the flash source are compared with high-speed raster-scanned profiles from the APS for different locations within the breakup and atomization regions. An impinging jet injector is used to investigate applicability to typical sprays in propulsion systems. Potential effects of spectral beam hardening for different contrast-agent concentrations in water are investigated using static cells and a model of the attenuation spectrum to provide information on the feasibility, accuracy, challenges, and potential strategies for utilizing broadband x-ray tube in quantitative single-shot spray measurements. Following Taylor's Hypothesis (Taylor, 1938), the spatial frequency is captured from the single-shot radiographs and is compared to the temporal frequencies of the APS time-traces.

Experimental Methods

Tube source x-ray emission consists of a broadband Bremsstrahlung spectrum punctuated by narrow peaks due to x-ray fluorescence of the anode material. The upper energy limit is determined by the tube voltage and the lower limit by the source window and air attenuation. Typical x-ray energies for spray imaging can range from 5 keV up to 120 keV. Previous tube-source, time-averaged studies used a metallic filter to spectrally pre-harden the beam by

attenuating low energy x-rays. This pre-hardened beam shows significantly reduced beam hardening effects, allowing for the use of a constant attenuation coefficient for the relatively short (millimeter-scale) effective path lengths that are typical in engineering sprays. Pre-hardening the beam greatly reduces the usable flux—a serious disadvantage for instantaneous measurements.

Obtaining time resolution sufficient to freeze the flow in a two-dimensional radiograph using a flash x-ray source requires maximizing the usable flux that is both readily attenuated by the spray and produces sufficient contrast on the detector. This poses challenges to the emission and collection of usable radiation. Flash x-ray pulses are produced when a bank of capacitors are discharged in rapid succession such that the full current pulse impinges upon the anode within tens of nanoseconds. The cone beam emission of x-rays passes through a thin beryllium window, through the spray, and then is partially absorbed by an image plate. The image plate is then read by a laser scanner and a digital image is formed. The cone beam emission from the source anode causes image magnification, and its finite size also leads to geometric blur due to the penumbra effect, as illustrated in Fig. 1. The unfiltered x-ray spectrum hardens as it is attenuated through the spray, resulting in a varying attenuation coefficient.

Fig. 1. Flash x-ray source experimental schematic showing the relevant source and geometrical imaging parameters, including the effects of magnification and penumbra.

In this work, a modeling and calibration approach is used to determine the effective attenuation coefficient for quantitative measurements, maximize signal-to-noise ratio, and optimize spatial resolution. Relevant imaging parameters shown, in part, in Fig. 1 include the source voltage, source anode size and material, source window material, anode-spray distance, spray-plate distance, image plate (detector) sensitivity, and laser scanner resolution.

The x-ray photon energy is fixed by selecting the number of capacitors used in the voltage source. Starting with a 150 keV commercial system (L-3 Communications), half of the capacitors were removed to produce a 75 keV system resulting in a larger fraction of lower energy photons for increased attenuation. The tubes in a flash source are readily interchangeable, and a 1 mm tungsten anode was chosen to balance anode longevity with the need to have a small focal spot size for reducing the effect of penumbra and improving spatial resolution. Anodes of lower atomic number materials than tungsten can produce increased levels of lower energy photons, but these degrade faster with each pulse. This leads to less consistent imaging behavior and increases the frequency and expense of anode replacement, especially for smaller anodes. A window consisting of beryllium was chosen over other materials, such as steel, to maximize the

output of lower energy photons and maximize attenuation (i.e., image contrast) through the spray.

The locations of the anode, spray, and detector affect the total measured flux, the influence of penumbra, and the geometric magnification. The source is placed as near the image plate as possible (225 mm) to maximize the photon flux on the detector. As shown in Fig. 1, both the penumbra and magnification increase if the spray is moved closer to the anode. These are offsetting effects with regard to image resolution, but the penumbra will increase at a greater rate than the magnification. When using a relatively large, millimeter-sized source, the penumbra may dominate over any benefit of magnification; therefore the spray was placed nominally 200 mm away from the anode and within 25 mm of the image plate, resulting in a penumbra of 125 μm . The expanding beam induces an error due to the angle at which the rays transmit the spray. The largest included angle from the x-ray source to the spray was 2 degrees, resulting in a maximum error of +3% in equivalent path length at the edges of the spray. The corresponding error in spatial location amounts to $\pm 100 \mu\text{m}$, which is less than the reported spatial resolution and can be accounted for when comparing to a computational model. The short (25 mm) distance from the spray to the imaging plate minimized the phase effects to $< 1 \mu\text{m}$.

A Kodak GP image plate was chosen for its relatively high sensitivity and to ensure high image contrast. The thickness of the plate determines the absorbance and spatial resolution. A thinner plate increases the spatial resolution, because of scatter inside the scintillator material. However, a thinner plate also preferentially transmits higher energy x-rays, effectively softening the spectrum of recorded x-rays and reducing the total amount of visible light emitted. A laser scanner with 50 μm focal spot size (ScanX HC) was used to read the imaging plates in post-processing. The focal spot size of the scanner affects the resolution and contrast of the image, with a smaller focal spot yielding higher resolution and lower contrast. During post-processing, it was found that the background collected without the spray was inconsistent, and flat-field normalization was required on a shot-to-shot basis. Hence, the shape of the background was determined in a number of steps and approximated by a third-order polynomial. Each horizontal array was linearly normalized, and pixels with significantly greater attenuation than the standard deviation were eliminated from the array as they carried attenuation signals that potentially originated within the spray. The background signal was then fit with a polynomial and used to normalize the original data array. This procedure reduced the transmission measurement error, which was 12% of the maximum signal, by one-half or better.

Once the imaging system was in place, calibration images were collected using steady liquid jets of known diameters, and the system was modeled to determine the attenuation coefficient as a function of the equivalent path length of liquid. The photon-energy dependent attenuation coefficients were taken from NIST tables (Hubbell & Seltzer, 2004), the imaging plate properties were provided by the manufacturer (Kodak, 2006), and the laser scanner was assumed to be independent of photon energy (Kodak, 2006). The attenuation coefficient was then modeled using known or estimated values for the source spectrum, spray path length, and detector spectral sensitivity. Several models exist to predict the spectral output of tube sources, and it was found that a linear correction can be applied to estimate a lower voltage source given the known output of a higher voltage source. Hence, the 75 keV source spectrum, needed to predict the general behavior of the attenuation coefficient, was approximated from the shape of the 150 keV spectrum obtained empirically by the tube manufacturer with a linear correction factor, as shown Eq. 1 and plotted in Fig. 2. The linear correction is incapable of estimating the changes in

characteristic peaks, but the difference in overall intensity does not appreciably change the attenuation coefficient.

$$[Spectra_{75}(hv)] = [Spectra_{150}(hv)] \times \left[-\left(\frac{1}{75}\right)hv + 1 \right] \quad (1)$$

Using the modeled 75 keV spectrum, three spectra are computed as shown in Fig. 3(a) to estimate the effects of beam hardening. These include an incident spectrum after passing through the beryllium window and air, a spectrum after the x-rays pass through 2 mm of water, and a spectrum after the x-rays pass through 2 mm of water with 15% by mass of potassium iodide (KI), a contrast-enhancing agent. NIST attenuation values were used to model the attenuation by the tube source window, the air, and the water or KI solution (Hubbell and Seltzer, 2004).

Fig. 2. 75 keV x-ray source spectrum estimated from a 150 keV source spectrum with a linear correction.

Figure 3(a) shows that the incident spectrum is highly attenuated by the window and air, especially at low photon energies. This is most noticeable in the case of pure water, where the x-ray intensities at lower energies are greatly attenuated, while the intensities at higher energies show very little attenuation. For the case of 15% KI, there is greater attenuation for low energy x-rays, but there is also noticeable attenuation at higher x-rays. These effects can be understood by analyzing the energy dependent attenuation of water, iodine, and potassium, as shown in a plot of photon energy vs. attenuation coefficient in Fig. 3(b). The increased attenuation coefficient at lower x-ray energies leads to spectral beam hardening for water and water with a contrast-enhancing agent, meaning that the x-ray energy spectrum shifts toward higher energies and changes the attenuation coefficient through the remainder of the spray after passing through 2 mm of liquid.

Fig. 3. (a) Modeled spectra, showing energy shift after passing through water and 15% KI, and (b) attenuation coefficients of water, potassium, and iodine vs. photon energy.

The APS 7BM beamline was used to verify the accuracy of the flash x-ray images and compare the temporal and spatial frequencies of the time traces and radiographs, respectively. The x-ray source was a synchrotron bending magnet, providing a nearly collimated, polychromatic x-ray beam. The first beamline enclosure (7BM-A) contains slits to condition the beam size and a double multilayer monochromator to create a monochromatic beam. The second enclosure (7BM-B) houses a pair of Kirkpatrick-Baez focusing mirrors (Eng et al., 1998), the experimental spray setup, and the x-ray detector. Further details regarding the beamline are given by Kastengren et al. (2012). The APS experiments used a focused x-ray beam with full width at half maximum (FWHM) dimensions of 5 μm (vertical) $\times$ 6 μm (horizontal) at 9 keV photon energy with 1.6×10^{10} photons per second flux at the detector. The detector was an unbiased, 300- μm thick silicon PIN diode with 89% of the x-ray photons absorbed by the detector. The PIN diode output was amplified with a transimpedance amplifier, recorded on an oscilloscope, and normalized by a diamond transmission photodiode positioned upstream of the spray to correct for modulations in beam intensity. Data were collected as path averaged local time-traces at 2.5 MHz for a period of 5 s, and data collected from the raster-scanned spray were mapped to a two-dimensional grid. The dark current was subtracted from all data points, and points far from the spray were used as background for flat-field normalization. The signal was converted to an equivalent path length (EPL) of liquid along the line of sight. Because of the relatively small focal spot size, the spatial resolution of the images was limited by the raster scan spacing, which was a minimum of 50 μm .

Table 1 compares each of the sources and techniques. The APS has very high spatial resolution with a monochromatic beam. These features greatly reduce the potential measurement error at the APS. The flash technique can produce single-shot, two-dimensional images using a compact source, but with trade-offs in image resolution and signal-to-noise ratio.

Table 1. Measurement parameters for the flash and synchrotron x-ray techniques.

Source	Flash Tube Source	APS Synchrotron
Imaging Method	Radiograph of 15% KI in Water	Raster Scan of Water
Beam Shape	Cone	Collimated
Spectrum	Polychromatic	Monochromatic
Energy [keV]	5–75	9 ± 0.13
Detector	Image Plate	PIN Diode
Temporal Response	Single Shot at 20 ns	5 s at 2.5 MHz
Nominal Resolution [μm^2]	44×44 (pixel size)	5×6 (focal spot)

The spray used in this study is a like-doublet impinging-jet injector with an enclosed angle of 60 degrees, as shown in Fig. 4(a). The injector orifices have matching diameters of $D = 510 \mu\text{m}$ and length-to-diameter ratios of 46 with chamfered inlets. A gear pump drives the liquid at impinging jet exit velocities of 3.5 m/s and 8 m/s, as shown by the visible-light, backlit images in Figs. 4(b) and 4(c), respectively. The two jets approach the impingement zone in the plane perpendicular to the plane of the image. The jets meet roughly 3 mm below the injector tips. The 3.5 m/s spray forms a semi-stable liquid sheet with most of the liquid occurring in the rim. In contrast, the unstable 8 m/s spray forms a wavy sheet with a disintegrating rim. The 15% KI used to increase contrast introduced a change in fluid properties, but the kinematic viscosity, ν , for 15% KI ($0.98 \times 10^{-6} \text{ m}^2/\text{s}$) is nearly the same as that for pure water ($1.00 \times 10^{-6} \text{ m}^2/\text{s}$). This allows for a near match of both the jet velocity, V , and the Reynolds number based on jet diameter, $Re_D = VD/\nu$. For jet velocities of 3.5–8 m/s, the Reynolds numbers are 1800–4200 for 15% KI in water and similarly are 1800–4100 for pure water.

Fig. 4. (a) Schematic of impinging-jet injector shown rotated ninety degrees from the plane of the qualitative visible-light, backlit spray images with jet exit velocities of (b) 3.5 m/s and (c) 8 m/s. Vertical span of the images is ~ 15 mm.

In the following discussion, the accuracy of the single-shot flash radiograph approach is estimated through comparison with time-resolved APS measurements. The mass distribution within the spray is presented as a line-of-sight averaged equivalent path length (EPL) of liquid. This is determined through the normalized measurement of the transmitted x-ray intensity and is a function of the attenuation coefficients specific to the source energy and detection method. The signals from the time traces at the APS and the radiographs produced from the flash x-ray source

are processed to compare the behavior of the spray in the spatio-temporal domain and frequency domain.

Results and Discussion

Due to the monochromatic x-ray beam and point detector of the synchrotron x-ray source at the APS, the EPL could be determined through a simplified version of the Beer-Lambert Law, as shown in Eq. 2, where α is the attenuation coefficient determined from calibration with samples of known liquid path length. The normalized transmission, τ , is computed from the measured intensity transmitted through the spray, I , normalized by the measured intensity transmitted without the spray, I_0 .

$$\frac{I(y, z)}{I_0(y, z)} = \tau = e^{-\alpha EPL} \quad (2)$$

Values of the EPL were measured at specific locations in the spray, with the results presented here being taken from the centerline starting just below the injector tips and moving down through the breakup of the liquid sheet. The time traces are used to calculate the time-averaged statistics and the power spectral density (PSD). The PSD was determined through a discrete fast Fourier analysis employing a Hann window to reduce aliasing from edge discontinuities. The 2.5 MHz, 5 s duration time traces of the transmission signals from the PIN diode are partitioned into 0.1 s duration periods, and the 50 individual time traces are used to produce an ensemble averaged PSD. The 0.1 s time traces have a minimum resolvable frequency of 10 Hz. A second-order Butterworth filter with 250 kHz cutoff frequency conditions the signal resulting in a maximum Nyquist frequency of 125 kHz. This bandwidth produces a dynamic range of 12,500 and encompasses the temporal behavior of the spray.

When collecting radiographs using a flash tube source, the dependence of the attenuation coefficient on photon energy, $h\nu$, becomes relevant. Unlike the narrowband synchrotron source, the relationship between the transmission and the EPL for a broadband tube source is dependent on the convolution of energy dispersion and the detector response function, ψ , as shown in Eq. 3. To simplify Eq. 3, which contains parameters that are difficult to measure in practice, a simple model with an attenuation coefficient linearly dependent upon transmission is used, as shown in Eq. 4.

$$\tau = \frac{\int e^{-\int \alpha(h\nu, x, y, z) dx} \psi(h\nu) dh\nu}{\int \psi(h\nu) dh\nu} \quad (3)$$

$$\tau = e^{-[m\tau + b]EPL} \quad (4)$$

Determining the variable attenuation coefficient is crucial for measurement accuracy. To capture the variation in the coefficient over a range of path lengths and thus transmission levels, a transmission vs. coefficient study was conducted. Sixteen steady liquid jets of varying diameter were imaged, and the transmission and path length of each jet allowed for determination of the attenuation coefficient. As shown in Fig. 5 lower transmissions corresponding to longer path lengths lead to beam hardening and an effective reduction in the attenuation coefficient. Conversely, the attenuation for higher transmissions or shorter path lengths is dominated by softer x-rays, which have a higher attenuation coefficient. Hence, the effect of beam hardening is

to allow imaging over a wider range of path lengths. A linear fit of the points is used as the path-length-dependent attenuation coefficient to calculate the unknown EPL in sprays of interest.

Fig. 5. Comparison of the empirical and modeled attenuation coefficients vs. transmission for water with and without 15% KI. Trend lines are used to extract parameters for the attenuation coefficient in Eq. 4.

Note that the model captures the measured trends in the attenuation coefficient due to beam hardening for transmissions of 0.5 and greater, which is typical of most spray applications. The modeled attenuation coefficient agrees to the linear fit to within 12% and 13% on average for path lengths less than 2 mm for pure water and 15% KI in water, respectively. This provides confidence that the linear fits to the calibration data will capture the path length-dependent attenuation coefficients for the flash radiograph measurements. The linear fits had root mean squared values of 10% and 13% for pure water and 15% KI in water, respectively. Differences between the experimental and modeled attenuation coefficients can be caused by source and detector noise, with the largest systematic error in the model likely being due to the approximated input spectrum, as shown in Fig. 3(a). The varying thickness and path-length-dependent attenuation through the cylindrical jet also leads to an overestimate in the experimental spectrum of $\sim 1.5\%$ for path lengths under 2 mm.

Radiographs of the impinging jets using the flash x-ray source are converted to EPL using linear fits to the attenuation coefficients in Fig. 5 and are shown in Fig. 6 for the low and high Reynolds number conditions. Two instantaneous flash x-ray images of each condition are shown to illustrate the typical behavior. The lower Re_D condition (3.5 m/s) shown in Fig. 6(a) is characterized by stable liquid jets impinging at about 3 mm below the jet exit and forming a quasi-stable liquid sheet encompassed by a pronounced rim. The higher intensity regions of the image, as indicated in the color scale, represent the thicker regions of the spray; these occur in the impingement region, in the rims, and during the formation of rim instabilities. Attenuation levels in the thinnest regions of the liquid sheet along the centerline are sufficient to detect impact waves with varying amplitude that perturb the liquid sheet and lead to variations in the EPL. Further downstream, the liquid sheet collapses as the rim breaks into larger droplets at around 10 mm below the jet exit. Increasing the velocity to the high Reynolds number condition (8 m/s) changes the spray characteristics substantially, as shown in Fig. 6(b). In this case, turbulent primary breakup occurs very near the point of jet impingement, resulting in a wider unstable liquid sheet with no pronounced rim structure. Here the impact waves generate much

larger perturbations of the liquid sheet thickness, as well as the early onset of breakup into smaller droplets. Further downstream at about 10 mm, the sheet does not coalesce, but rather breaks into ligaments and subsequent droplets as the impact waves spread radially outward. The attenuation is sufficient to capture liquid core structures of varying shape and size, including long connected ligaments, droplets, and thin sheets between the instability waves. The flow conditions shown in Fig. 6 provide a wide range of spatio-temporal features for comparison between the flash and APS x-ray source measurements.

Fig. 6. Sample flash x-ray radiographs converted to EPL maps at jet-exit velocities of (a) 3.5 m/s and (b) 8 m/s. Color map saturates above 500 μm to highlight low-EPL features.

Figure 7 compares the centerline vertical profiles of EPL from the flash x-ray images with vertical spatial scans obtained using the APS x-ray source. The flash x-ray images are instantaneous while the APS data are time-averaged based on point-wise raster scanning. The centerline profiles from the flash x-ray data include sharp peaks due to the impact waves generated by the merging of liquid jets, which highlights the ability of this approach to freeze the flow and capture the instantaneous spatial distribution within the spray. Of course it is not possible to compare the instantaneous spray structure with the time-averaged, point-wise synchrotron x-ray measurements; however, as discussed further below, it is possible to detect corresponding sharp peaks in the APS time traces due to the passage of the instability waves through the probe location. Furthermore, the spatial trends of the flash radiographs are very well matched with the time-averaged raster-scan trends from the APS. For example, the EPL along the centerline decays more quickly for the case of 3.5 m/s as compared to 8 m/s because much of the liquid in the case of 3.5 m/s is contained within the outer rim and is not intersected by the x-ray beam. In contrast, the rim structure at 8 m/s is non-existent and more of the liquid is contained within the central, very turbulent region. Based on the very thin liquid sheet for the

case of 3.5 m/s in the 10 mm region, as shown in Fig. 7(a), it is possible to ascertain that the flash x-ray radiographs can capture sheet liquid features with EPL down to about 50 microns.

These data indicate that the flash x-ray spatial profiles closely track the variations in EPL with high signal-to-noise ratio, even though these variations may appear to be quite subtle in the images shown previously in Fig. 6. In the case of 3.5 m/s, for example, fluctuations of up to 200 μm in EPL occur primarily further upstream near the jet impingement region at ~ 2 mm and further downstream where the sheet coalesces at ~ 10 mm. This is in contrast to the case of 8 m/s, in which the largest fluctuations of up to 400 μm in EPL occur in the central part of the sheet from 4–8 mm. The larger fluctuations in sheet thickness for the case of 8 m/s are also evident in the larger mean range of the APS data in Fig. 7(b).

Fig. 7. EPL along the centerline comparing flash and APS x-ray data for jet-exit velocities of (a) 3.5 m/s and (b) 8 m/s. The triangles in the APS data are the upper and lower mean range at each point, which quantify the temporal fluctuations in the EPL.

To compare the fluctuations of the EPL in time, Fig. 8 shows sample time traces of the APS data at the 3.5 m/s and 8 m/s conditions. Note that the time traces in Fig. 8 are samples of the much longer signal traces that are used later in the spectral analysis. The durations of the time traces in Figs. 8(a) and (b) are 3.3 ms and 1.45 ms, respectively, which were selected to correspond to an approximate convective length of about 10 mm based on the vertical component of the jet-exit velocities (Dombrowski & Hooper, 1964). As it happens, 10 mm also corresponds to the approximate length of the contiguous liquid sheets shown previously in the flash x-ray images. This region of contiguous liquid sheets begins at approximately 2 mm downstream and ends at approximately 10 mm downstream, as marked on the plots in Fig. 6. Hence the spatial characteristics in the flash x-ray images and the APS time traces should have similar characteristics based on Taylor's hypothesis. Of course, the spatial frequencies from 2 mm to 10 mm downstream are varying in space, and this cannot be captured by the time traces as they are collected at a fixed location 8 mm downstream. However, it is possible to discern based on Taylor's Hypothesis and the spatial profiles close to 8 mm in Fig. 7 that the EPL time traces for the case of 3.5 m/s should vary by up to ~ 200 μm and the EPL time traces for the case of 8 m/s should vary by up to ~ 400 μm . This is well captured in the APS time traces shown in Fig. 8,

although the actual magnitudes of the variations can vary from one time sample to the next. Note also that the spatial extent and magnitude of the fluctuations in EPL from the flash radiographs may not agree precisely with the APS data due to spatial blur in the images..

Fig. 8. Sample APS time traces 8 mm below the injector exit for jet-exit velocities of (a) 3.5 m/s and (b) 8 m/s.

Because of the periodic nature of the fluctuations in EPL generated by the jet impact process, it is of interest to evaluate the frequency content of the time traces from the APL data along with the spatial frequencies from the flash x-ray images. The centerline data from five radiographs of the full spray are analyzed, and the impact-wave amplitudes and frequency information are shown in Fig. 9. The range of resolvable frequencies is determined by the Nyquist criterion and the length of the signal. The centerline spatial data arrays have a pixel size of $44 \mu\text{m}$ or sampling frequency of 22.7 mm^{-1} , resulting in a Nyquist frequency of 11.3 mm^{-1} , or approximately 34 kHz at 3.5 m/s and 78 kHz at 8 m/s. The length of the centerline data at 8 mm results in a lowest resolvable frequency of 0.125 mm^{-1} , or approximately 380 Hz at 3.5 m/s and 860 Hz at 8 m/s. This gives a dynamic range of 90 in the detection of spatial frequencies for the flash x-ray data. The higher frequency behavior seen in the backlit images is not fully resolved, while the lowest resolvable frequencies are sufficient because the spray is of finite length.

Data from five spatial PSDs were computed using a Hann window and are compared with the APS time-domain frequencies in Fig. 9. The spectra for the case of 3.5 m/s compare well, as shown in Fig. 9(a). The low frequency components are likely perturbed by limitations on signal length; however, there is consistent behavior in the region around 1.7 mm^{-1} and 5 kHz, providing credence to the measurement technique and analysis. The high frequency component tapers off around 4 mm^{-1} and 12 kHz.

The same EPL and spectral analyses were performed for the case of 8 m/s, as shown in Fig. 9(b). The spectra become more difficult to compare in this condition because the spectrum from the APS data is surprisingly broad. This indicates that the fluctuations in EPL are not purely periodic and have a wide variation in frequency. Hence, difference between the spatial and temporal frequencies may result from differences in sample size. As such, there is agreement in the fundamental frequency around 1 mm^{-1} and 6 kHz, but a larger sample size is needed for more accurate comparisons.

Fig. 9. EPL spectral content caused by instability waves in the liquid sheet for jet-exit velocities of (a) 3.5 m/s and (b) 8 m/s.

Table 2 summarizes the measurement characteristics of the x-ray sources. The APS data display higher contrast, spatial resolution, and accuracy in point-wise time-resolved measurements, while the portable flash x-ray source with 15% KI by mass in water is capable of providing quantitative single-shot two-dimensional imaging. The spatial resolution of the flash x-ray images was dictated by the geometry of the source, the spray location, and detector characteristics. Upstream of the jet impingement point, the flash radiographs did not capture the exact shape of the jets due to limited spatial resolution. Nonetheless, the spatial resolution in the image plane was estimated to be $\sim 350 \mu\text{m}$ at a 10-90% rise criterion for the flash x-ray images, which was sufficient to capture instability waves, liquid sheets, ligaments tearing from the sheet, and larger spray droplets. In contrast the spatial resolution of the visible light images was $\sim 150 \mu\text{m}$ at a 10-90% rise criterion.

Table 2. Measurement characteristics of the APS and flash x-ray sources.

Source	APS Synchrotron	Flash Tube Source
Imaging Method	Point-Wise Raster Scan	2D Flash Radiograph
Temporal Resolution	700 ns	10 ns
Attenuation Coefficient [cm^{-1}]	5.33	$7.32 \times \tau$
Theoretical Penumbra [μm]	0	125
10-90% Rise [μm]	40	350
EPL Standard Deviation [μm]	0.3	25
Dynamic Range of PSD	12500	110

Concluding Remarks

The current work examined the applicability of flash x-ray radiography for quantifying the single-shot, two-dimensional line-of-sight averaged liquid distribution in sprays. Data are

collected in terms of the instantaneous equivalent path length (EPL) in an impinging-jet spray geometry. Comparisons with data from a high-photon-flux, narrowband synchrotron source show that this approach is capable of quantitative measurements of EPL down to 50 μm . However, to achieve this one needs to maximize photon flux, ensuring sufficient x-ray attenuation for low EPL, and calibrate for a transmission dependent attenuation coefficient at high EPL. High photon flux was achieved by removing filters normally used to narrow the source spectrum in spectral pre-hardening. This resulted in transmission-dependent attenuation coefficients, which were addressed through proper calibration and post-processing. Sufficient attenuation was achieved through proper selection of source spectrum and use of a contrast-enhancing agent.

With these considerations, it was shown that the flash x-ray radiographs using a broadband source are capable of measuring the instantaneous two-dimensional EPL data, while the APS data provides temporal statistics. When a downstream line plot along the spray central axis is compared, the spatial profiles of time-averaged EPL values from the APS data agreed quite well with the single-shot flash x-ray images. The fluctuations in EPL, which were induced by impact waves generated during jet impingement, showed very good agreement between the APS time-trace data and the flash x-ray spatial profiles, but the spatial extent and the magnitude of the fluctuations for the flash x-ray data were moderated by limited spatial resolution and sample size.

Future measurements with broadband x-ray (tube or synchrotron) sources could be enhanced using high-speed imaging to capture two-dimensional temporal dynamics. With the use of multiple flash x-ray sources, it should be possible to acquire three-dimensional spatial distributions. Careful attention must be paid to the fluid properties when using contrast-enhancing agents. The spectroscopic effects of contrast-enhancing agents must be determined as well. The preferential attenuation of lower energy x-rays led to spectral beam hardening that must be taken into account through calibration and spectral modeling. In future experiments, greater precision can be achieved by collecting a larger number of calibration images, and calibration should be conducted for each source and detector. Simultaneous calibration would allow for minor changes in the attenuation coefficient to be determined on a shot-to-shot basis, and normalization may also be improved by acquiring a larger number of background images and determining a general trend to help decrease the associated error. More accurate determination of the x-ray source spectrum would also increase the accuracy of the model and aid in the calibration and determination of the variable attenuation coefficient. The choice of source size, material, and imaging geometry should also be determined to optimize the contrast and spatial resolution based on the experimental objectives.

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