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

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ABSTRACT

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.

1. 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.

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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 and Powell, 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), and Woodward et al. (1995). Time-averaged three-dimensional data by Meyer et al. (2008, 2010), Balewski et al. (2010), Eichner (2013), Coletti et al. (2014) and 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. (1995) 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.

2. 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.

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