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Evaluation of X-ray sources for quantitative two- and three-dimensional imaging of liquid mass distribution in atomizing sprays

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ABSTRACT

Quantitative measurement of liquid mass distribution is demonstrated in an impinging-jet atomizing spray using a broadband, ~80 keV X-ray tube source for 2-D radiography and 3-D computed tomography (CT). The accuracy, precision, and sensitivity of these data are evaluated using narrowband, ~10 keV, synchrotron radiation from the Argonne National Laboratory Advanced Photon Source (APS) at the same flow conditions. It is found that the broadband X-ray tube source can be used for 2-D measurement of the equivalent path length (EPL) and 3-D CT imaging of liquid mass distribution with typical error of 5–10%. Data are compared for cases with and without the use of potassium iodide (KI), which at 15% concentration by mass increases the attenuation coefficient eightfold and enables 2-D and 3-D measurement of EPL with a signal-to-noise ratio (SNR) of 5:1 down to 15 μm. At this concentration, the effects of energy-dependent attenuation (i.e., spectral beam hardening) are negligible for EPL up to 5 mm. Hence, the use of broadband X-ray tube sources is feasible for many practical engineering sprays with a dynamic range in EPL of ~330:1. The advantages and limitations of using broadband and narrowband X-ray sources are discussed, and recommendations for improving performance are presented.

1. Introduction

Optimization of liquid injection, atomization, and mass distribution is critical in a wide range of applications such as power generation, propulsion, chemical processing, material synthesis, drug delivery, and surface coatings, to name a few (Meyer et al., 2010). In the case of rocket propulsion, improper placement of the injected fuel or oxidizer can lead to combustion instability, acoustic coupling, and rapid catastrophic failures. From an engineering perspective, correlation of parameters such as injector nozzle geometry, exit velocity, and liquid properties with liquid breakup characteristics, atomization, and final mass distribution is needed to guide the development of empirical and numerical spray models.

In propulsion applications, recent studies of aerated jets, jets in crossflow, and supercritical injection have employed various optical imaging techniques, including shadowgraphy, Mie scattering, holography, laser-induced fluorescence, structured illumination, optical connectivity and ballistic imaging (e.g., Berrocal et al., 2008; Charalampous et al., 2009; Jung et al., 2003; Lin et al., 2001; Linne et al., 2005; Meyer et al., 2010; Sallam et al., 2006; Santangelo and Sojka, 1994). These techniques have been used to reveal valuable information on liquid breakup processes, although measurement of the liquid mass distribution can be impaired by the complex optical interaction with liquid structures of varying size, shape, and number density. Techniques based on phase Doppler interferometry (Bachalo, 1980) or diffraction (Dobbins et al., 1963) can provide droplet velocity and size distributions, which can then be used to infer liquid mass distributions; however, an alternative approach is required in regions dominated by a significant fraction of non-spherical liquid structures. Hence, while optical techniques provide valuable information under a wide range of spray conditions, X-ray radiography may be the only practical method of measuring the liquid mass distributions in otherwise difficult sprays (Linne, 2013).

Unlike visible light, which is strongly scattered and refracted from aerosols, droplets, and other liquid structures, the interaction of low-energy (~10 keV) X-rays with sprays is primarily through absorption and weak scattering. This greatly simplifies the analysis as the attenuation signal can be related to the liquid mass density in the path of the X-rays with minimal sensitivity to the droplet size, shape, and number density of attenuators. This gives a greater scope for absorption-based measurements of liquid mass distribution in optically complex sprays using X-ray techniques. Much of the recent work in advancing X-ray spray imaging has taken place at the Advanced Photon Source (APS) located at the Argonne

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National Laboratory. Synchrotron X-ray sources such as the APS provide a highly-collimated, tunable, low-energy X-ray beam with sufficient flux for radiography to be performed over a wide range of liquid path lengths. This has yielded time-resolved, highly accurate attenuation measurements under a variety of spray conditions (e.g., Cai et al., 2003; Kastengren and Powell, 2007; Lin et al., 2011; MacPhee et al., 2002; Poola et al., 2000; Powell et al., 2000; Qun et al., 2007; Schumaker et al., 2012). In addition to minimizing the effects of X-ray scattering through the use of low-energy X-rays, the narrowband nature of the APS X-rays allows them to propagate through liquid media without significant deviation in the attenuation coefficient.

This differs from conventional tube sources that produce X-rays with higher energies (~100 keV) which can increase scattering and reduce image contrast. In general, the scattering and absorption of X-rays scale as the inverse square and inverse cube of photon energy, respectively, leading to increased scattering contributions at higher photon energy. Furthermore, the broadband nature of X-rays from tube sources may induce the preferential attenuation of X-rays within certain photon energy ranges along the line of sight, causing so-called spectral beam hardening for long path lengths. Despite these challenges, many sprays of practical interest have path lengths of millimeters or less, and it may be possible to minimize or avoid the effects of multiple scattering and preferential attenuation of X-rays for various photon energies.

It is of interest, therefore, to determine if under certain conditions a broadband, high-energy X-ray tube source can reproduce quantitative data on liquid mass distributions as determined from a narrowband, low-energy X-ray source. Tube sources can be more readily employed in various laboratories for studying propulsion and other industrial applications of sprays because they are relatively compact and require a much smaller capital investment. They are also readily employed for time-averaged, two-dimensional radiography and three-dimensional computed tomography (CT) (Meyer et al., 2010). Meyer et al. (2008, 2010), for example, showed that the broadband X-ray attenuation coefficient through water seeded with potassium iodide (KI) as a contrast enhancing agent increases linearly up to a certain KI concentration with minimal influence from the effects of beam hardening. To the best of the author's knowledge, however, a direct validation of liquid mass distributions (2-D or 3-D) measured using broadband X-ray sources has not yet been presented for atomizing sprays (Heindel, 2011). Application of polychromatic sources for investigation of instantaneous or time-averaged spray structure has been presented by a number of researchers, including Char et al. (1989), Woodward et al. (1995), Birk et al. (2003), Meyer et al. (2008, 2010), Balewski et al. (2010), Robert et al. (2010), Halls et al. (2012, 2013) and Lim et al. (2013), but only for qualitative imaging and without comprehensive comparison with narrowband sources.

In the current work, we evaluate the differences in liquid mass distributions measured within atomizing jet sprays using broadband X-rays from a tube source and measurements using narrowband X-rays from the APS synchrotron facility. We compare the liquid mass distributions measured from two-dimensional radiographs and three-dimensional CT scans using the tube source with raster-scanned profiles from the APS for different locations within the breakup and atomization regions. Because the APS can utilize lower energy X-rays, which are attenuated more readily by the spray, a comparison is also made with attenuation data from the tube source with and without KI as a contrast enhancing agent. An impinging jet injector is used to investigate applicability to a typical spray used in rocket propulsion, as well as to test the validity of the mass distribution measurements under challenging conditions, which in the case of broadband X-rays are under conditions of both low attenuation (contrast) and high spatial frequencies. Static measurements using cuvette samples are used to measure the attenuation coefficient to investigate the potential effects of beam hardening for different KI concentrations in water (Meyer et al., 2008, 2010). These data provide information on the feasibility, accuracy, challenges, and potential strategies for utilizing broadband X-ray tube sources for quantifying liquid mass distributions in atomizing sprays.

2. Experimental methods

The X-ray source for the APS 7-BM beamline employed in this work is a synchrotron bending magnet, which provides a nearly collimated, polychromatic X-ray beam. This beamline consists of two enclosures. The first enclosure (7BM-A) contains slits to condition the beam size and a double multilayer monochromator ($\Delta E/E = 1.4\%$) to create a monochromatic beam. The energy range of the monochromator is 5.1–12 keV. The second enclosure (7BM-B) houses a pair of Kirkpatrick–Baez focusing mirrors (Eng et al., 1998), the experimental spray equipment, and the X-ray detector. Further details regarding the beamline setup are given by Kastengren et al. (2012).

The current APS experiments use a focused X-ray beam with full width at half maximum (FWHM) dimensions of 5 μm (vertical) × 6 μm (horizontal) at 10 keV photon energy. The X-ray flux without the spray is 6×10^{10} photons per second. The detector is an unbiased, 300-μm thick silicon PIN diode with 89% of the X-ray photons being absorbed in the detector. The PIN diode output was amplified with a transimpedance amplifier and time-averaged over a 1 s integration time for each point. Data points collected from the raster-scanned spray were mapped to a two-dimensional grid that was slightly larger than the spray to allow for background normalization. The point measurements were dark-current subtracted and flat-field normalized. The signal was converted to an equivalent path length (EPL) of liquid along the line of sight and compiled into two-dimensional, interpolated images via MATLAB. Because of the relatively small focal spot size, the spatial resolution of the interpolated images was limited by the raster scan spacing, which was a minimum of 50 μm near the jet centerline.

The Iowa State University (ISU) X-ray Flow Visualization Laboratory is capable of 16-bit radiography, stereography, and computed tomography (CT), as described in previous publications (Heindel et al., 2007, 2008). Twin LORAD LPX200 portable sealed tube sources produce cone beams and are positioned ninety degrees apart on a movable rotation ring, as shown in Fig. 1. The supply voltage and current can be varied from 10 to 200 kV and 0.1 to 10.0 mA, respectively, with 900 W maximum electrical output per source from a copper anode. Opposite of one source is a cesium-iodide phosphor screen coupled to an Apogee Alta U9 camera via a

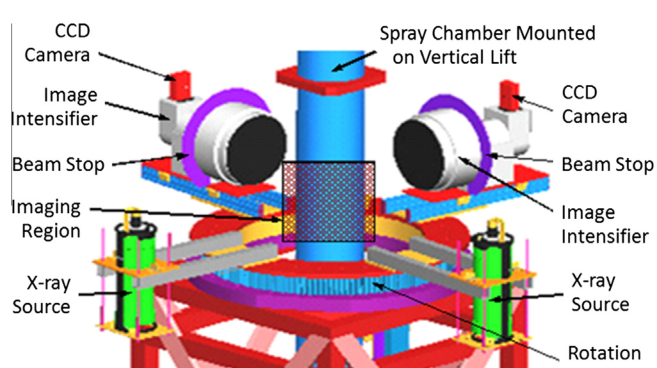

Fig. 1. Set-up for X-ray radiography and 3-D computed tomography using broadband tube sources and planar imaging systems (Heindel et al., 2007).