Exploration of Aerated-Liquid Jets Using X-Ray Phase Contrast Imaging and X-Ray Radiography

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Abstract

Liquid jet atomization plays an important role in establishing stable and efficient combustion inside the combustor of a liquid-fueled air-breathing propulsion system. For applications requiring both deep fuel penetration into high-speed crossflows for broader fuel spreading and smaller droplets in the liquid spray for faster evaporation, a superior liquid injection scheme is sought. Among the possible candidates, aerated-liquid (or effervescent, or barbotage) jets have been explored extensively. It has been shown that the liquid aeration technique can generate a spray that penetrates well into the flow and produces a large fuel plume containing a large number of small droplets. The required amount of aerating gas and delivery pressure are practically obtainable in a high-speed air-breathing propulsion system. The utilization of aerated-liquid jets has led to successful combustion in a liquid-fueled high-speed air-breathing combustor. While macroscopic and far-field features of the aerated-liquid jets have been extensively examined, detailed near-field spray structures cannot easily be explored.

In the present study, two X-ray diagnostics, one is the X-ray phase contrast imaging (PCI) technique and the other one is the X-ray radiography, available at the Advanced Photon Source (APS) of the Argonne National Laboratory, were successfully utilized to characterize the dense near field of aerated-liquid jets injected into a quiescent environment. Water and nitrogen were used as the injectant and aerating gas, respectively. An axisymmetric aerated-liquid injector equipped with an exit adaptor was utilized for the investigation of external spray structures. A total of three adaptors with various internal configurations and a throat diameter of 1.0 mm were selected for testing. The major motivation of this study was to obtain a better understanding of the near-field structures of aerated-liquid jets discharged from the contoured adaptors.

It was found that the measurements from the X-ray PCI technique give both a qualitative understanding of microscopic structures, such the existence of small droplets, ligaments, and even bubbles, and also quantitative size distributions of the disintegrated small objects within the peripheries of aerated-liquid jets. The phase contrast images were captured with a CCD camera by converting the transmitted X-rays into visible light via a fast scintillator crystal. Each image has a field of view of 1.5×1.9 mm^2. The actual exposure time, determined by the X-ray pulse, is 150 ps (FWHM). Size measurement of microscopic structures was achieved, using an in-house code to remove the undesirable background noise with an enhanced contrast ratio for each X-ray image and then to identify objects of interest, such as droplets or gas bubbles, for measurement. The measured Sauter mean diameter (SMD), bubble SMD and bubble film thickness are on the order of 20, 40 and 10 μm, respectively in the present study. This technique, however, cannot depict either the spray structure within the core region of the spray or the liquid mass distribution within the plume, due to the line-of-sight feature of the X-ray PCI.

The X-ray radiography was utilized by the present study to supplement X-ray PCI technique. Notably, X-ray radiography provides quantitative liquid mass distribution profiles or even contours within the dense near-field region of an aerated-liquid jet. This was achieved by converting the measured X-ray extinction to the equivalent path length (EPL) via the Beer's law. The EPL is the thickness of pure water required for the transmitting X-ray to generate the same amount of extinction as that generated from the dispersed spray at the same X-ray energy level. The value of the EPL can, therefore, be related to the local density of the liquid/air mixture or local liquid mass fraction. For the present study, only the two-dimensional line-of-sight EPL is presented to depict the spray structure. The focused X-ray beam is approximately 5 (V) × 6 (H) µm FWHM. The utilization of X-ray radiography also helps to illuminate the two-phase structures inside the injector and within the near field of the spray plume. For the present injector design and operating conditions, it was found that an annular-like liquid distribution exists inside the injector and within the discharged near-field jet at low liquid flow rates, even at high aeration levels. The present study demonstrates that a combination of both X-ray diagnostics provides valuable insights into the understanding of aerated-liquid jets or potentially other optically dense sprays.

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