Ultrafast X-Ray Study of Aerated-Liquid Jets in a Quiescent Environment

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ABSTRACT

The structures of pure- and aerated-liquid jets injected into a quiescent environment were investigated, using the phase contract imaging technique combined with the x-ray light source. The experiment was carried out at the 32-ID Beamline at the Argonne National Laboratory. Water and nitrogen were used as the injectant and aerating gas, respectively. Two aerated-liquid injectors with orifice diameters of 0.5 and 1.0 mm were utilized for liquid injection. Pure-liquid jets were generated by turning off the aerating gas supply. It was found that the present diagnostic technique provides the unique capability in depicting line-of-sight interfacial features on the entire periphery of the liquid column, ligament, and droplet. Highly-convoluted wrinkle structures on the column surface of a turbulent pure-liquid jet were observed. These wrinkle structures resemble turbulence eddies. The length scale of the wrinkle structures decreases as the liquid flow rate or Reynolds number increases. The near-field structures of aerated-liquid jets, which are optically dense, can be clearly depicted by the present diagnostic technique. With a modest level of liquid aeration, the liquid column can be dispersed into fine droplets and ligaments inside the injector. Increase in aeration level enhances liquid atomization. The dissolved gas inside the droplets and ligaments of aerated-liquid jets expands into bubbles, which can be clearly observed in the x-ray images. These bubbles eventually burst to generate fine droplets as the gas bubbles experience pressure relaxation at downstream locations. The surface velocity on the column of a pure-liquid jet quickly accelerates from a no-slip condition inside the injector to about 60% of the exit mean velocity within a very short distance. The surface velocity then gradually increases to 85% of the mean velocity within 10 orifice diameters.

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INTRODUCTION

For the successful design of a liquid-fueled, air-breathing propulsion system, liquid jets atomized in a high-speed air crossflow environment play an important role in establishing stable and efficient combustion within an extremely limited distance and time scale inside a combustor. In order to create deeper fuel penetration into the air stream for broader fuel spreading and to generate smaller droplets of the liquid spray for faster evaporation, a superior liquid injection scheme must be sought. Among the possible candidates, the aerated-liquid (or effervescent, or barbotage) jets have been explored extensively to illustrate its favorable characteristics, such as deep penetration, large fuel plume, small droplet size, and high droplet number density, for scramjet applications. The utilization of aerated-liquid jets also led to the successful combustion of a liquid-fueled scramjet combustor.4

While the general features of the aerated-liquid jets are very promising, detailed near-field spray structures, such as liquid disintegration process as well as distributions of droplet properties and liquid volume flux within the jets, can not be easily attained, due to instrumentation difficulties. Relatively dense spray structure along with high gas and droplet velocities make conventional diagnostics, such as shadowgraph imaging and PDPA, either inapplicable or unreliable. The holographic technique has been successfully utilized to measure droplet size and velocity at the vicinity of the near-field jet.5-6 This technique, however, has not been applied to the exploration of interior structures of near-field aerated-liquid jets. Figures 1 and 2 illustrate the appearances of pure-and aerated-liquid jets injected into a subsonic and supersonic crossflow, respectively. The extremely dense structures of the aerated-liquid jets in both the directly-illuminated photo pictures in Fig. 1 and the shadowgraph images in Fig. 2 highlight the difficulties in exploring the near-field structures, which dictate the subsequent spray structures and droplet properties. Advanced diagnostic techniques are, therefore, needed in order to further advance the understanding of the aerated-liquid jets. The candidate diagnostic technique should create a relatively small light scattering pattern for a dense spray in order to “see through” the dense structures. The x-ray facility at the Argonne National Laboratory provides the ideal light source and was, therefore, utilized for the present study.7-10

The objective of this study is to experimentally investigate the near-field structures of pure- and aerated-liquid jets injected into a quiescent environment, using the phase contrast imaging technique combined with the x-ray light source at the Argonne National Laboratory. Unique surface structures of the pure-liquid jets and the effects of liquid aeration on liquid atomization will be qualitatively discussed.

EXPERIMENTAL METHODS

The experiment was conducted at the XOR 32-ID beamline of the Advanced Photon Source (APS) at the Argonne National Laboratory. The undulator source provides the high x-ray brilliance necessary for the white-beam ultra-fast imaging technique. With the undulator gap set to 31 mm, most of the intensity was located within the first harmonic at 13.3 keV, with a peak irradiance of 10^14 ph/s/mm²/0.1%bw and a natural 5 bandwidth of 0.3 keV at FWHM. For imaging of the liquid jet, the higher order harmonic was used and the lower energy was filtered with a 10 mm thick silicon slab. A fast scintillator crystal (LYSO:Ce, with a 40 ns decay time) converted the transmitted x-rays into visible light (434 nm). The images were captured with a fast CCD camera (Sensicam HS-SVGA, 1024×1280 pixels, from Cooke Corp.) coupled to the scintillator via a microscope objective (5x, NA = 0.14) and a 45° mirror. The field of view of the imaging system (1.3 × 1.7 mm²) matched the full usable x-ray beam size. The ultrafast imaging capability of the present setup provides an exposure time of 170 ps for each image. For double exposure operation to catch liquid movement within a single image, the time delay between two exposures was set as short as 3.68 µs, the transit time for electrons within the synchrotron circuit.

Water and nitrogen with desired flowrates were supplied into the aerated-liquid injector to form a two-phase mixture prior to discharging into a quiescent environment. Two aerated-liquid injectors with discharge orifices of 0.5 and 1.0 mm were utilized for the present study. The aerated-liquid jet was vertically discharged into a collecting bucket with a small opening on the cap to prevent drifted droplets getting into the beam path. In addition, the distance between the nozzle exit and the bucket cap was kept at 10 mm, in order to avoid water splashing. Originally, the structures of aerated-liquid jets both inside the injector and immediately after injection would be probed by the x-ray. Attempts to image the structure of the two-phase mixture inside the injector, however, were unsuccessful. The instantaneous image of the fast-moving two-phase mixture inside the injector could not be captured by the 5-µs exposure time, which is required for a higher energy x-ray to penetrate the injector metal walls. Therefore, the present study focuses on the structures of liquid jets immediately downstream the injector orifice. Both the aerated-liquid injector and the collecting bucket were rigidly mounted on a traversing table, which provides desired movement normal to the x-ray beam.

RESULTS AND DISCUSSION

Pure-Liquid Jets:

Figure 3 shows the x-ray images of pure-liquid jets injected from a 1.0-mm aerated-liquid injector at
various liquid flow rates. The Reynolds number ranges from $1.64 \times 10^4$ to $6.00 \times 10^4$ for those four jets. The injected flows in Fig. 3 are all turbulent since the Re number is greater than 4,000. Also, the emerging flows are fully-developed pipe flows. The physical dimension of the jet is 9.4 mm in the injection direction in Fig. 3. These images show that the highly-convoluted surface structures along the periphery of the liquid jet can be clearly depicted by the line-of-sight x-ray. These surface features have never been seen before. The combination of the phase contrast imaging technique and the unique properties of x-ray provides the capability to depict subtle variation in surface continuity throughout the entire periphery of the liquid jet. For conventional shadowgraph images using visible light sources, the surface structures can only be captured along the surfaces tangential to the parallel light. Other surface areas appear as dark shadows, as shown in Fig. 2(a). Consequently, only structures on surfaces tangential to the parallel to the light beam can be utilized from shadow images to reach scientific conclusions. The directly-illuminated images in Fig. 1(a) can capture some surface structures along the jet periphery close to the injector orifice. Reflection and refraction of the incoming light beam from the wrinkle surfaces eventually render the surface structures un-discernible at further downstream locations.

It is believed that the wrinkle structure is related to the combined effect of turbulence eddies within the liquid jet and the shear force interaction between high-speed liquid and quiescent air. Please note that the x-ray image is line of sight. The actual density of the wrinkle structure on the jet surface is one half of the observed density in Fig. 3. If conventional shadowgraph images were used for the study, the wrinkle structures at the surfaces tangential to the parallel light highly resemble surface waves. The length scale of the wrinkle structure is a mainly a function of the jet Re number. The length scale decreases as the liquid flow rate or Reynolds number increases from Fig. 3(a) to Fig. 3(d). Unlike the liquid jets studied by Marmottant and Villermaux, the no well-organized wave structure distributed azimuthally along the column surface can be clearly depicted in those four jets. The present observations on the surface structures of those four turbulent jets suggest that the three-dimensional surface structures may be highly related to the turbulence eddies inside the liquid jets.

Figure 3(a) also shows that the initial length scale of the wrinkle structure increases with the streamwise distance, probably due to the dissipation of the small wrinkle structures, similar to the dissipation of small turbulence eddies, or due to the growth of surface waves. The same phenomena can be observed for the jet in Fig. 3(b). For the high Re jet in Fig. 3(d), there are high-density small turbulence eddies on the jet surface. Some intrusive ligaments and stripped drops can be seen along the jet edges. The high-density wrinkle structures do not dissipate within the probing area for this jet.

Figure 4 shows blown-up x-ray images for those four pure-liquid jets in Fig. 3 within 0.5 mm from the nozzle exit. Careful examinations of Fig. 4 show that there exist elongated surface structures adjacent to the nozzle exit. These structures are orientated with the jet injection direction. Both length and width of the elongated structure decrease as the jet Re number increases. These elongated structures transform into small three-dimensional wrinkle structures, which gradually grow into the bigger structures at downstream locations. Root causes of the observed elongated structures and the subsequent transition into three-dimensional structures merit further investigation in the future. Elongated regions of uniform momentum with a length greater than 8 times the boundary layer thickness were recently observed inside a supersonic turbulent boundary layer over a flat plate. The orientation of these elongated structures is also aligned with the freestream flow. The potential relationship between both elongated structures merits further exploration.

Aerated-Liquid Jets:

The effect of liquid aeration on the destruction of liquid column can be easily seen by comparing both pure- and aerated-liquid jets in Fig. 5. The same liquid flow rate was injected from a 0.5-mm injector. For the pure-liquid jet in Fig. 5(a), the liquid column is still intact within the field of view. The general feature of the pure-liquid jet is similar to those observed in Fig. 3. Please note that gas bubbles, which may come from the residue gas inside the aerating gas chamber, are embedded inside the liquid column and can be clearly seen from the x-ray images. Once again, the combination of phase contrast imaging technique and the x-ray provides the capability to depict the interface of the gas bubble inside the liquid column. The gas bubble grows in size toward downstream stream locations as it experiences pressure relaxation.

For the aerated-liquid jet in Fig. 5(b), which has a gas-to-liquid mass ratio (GLR) of 1.41%, the injected liquid is already disintegrated into small droplets and fine ligaments immediately after injection. No intact liquid core can be observed at this aeration level. The advantage of liquid aeration on enhancing the liquid atomization processes is quite obvious. The two-phase mixture generated from the internal mixing of water and nitrogen is close to a homogeneous mixture. With a slightly higher injection pressure, the injected two-phase mixture exhibits a larger spreading angle. The advantage of using the x-ray technique can also be seen between Figs. 2(b) and 5(b). For the image in Fig. 2(b), the jet appears opaque with the internal structure
entirely indistinguishable. For the image in Fig 5(b), the small droplet and fine ligaments are discernible. The droplets and ligaments, however, are highly cluttered at the central region of the jet close to the jet exit, due to the high number density at this axial location and the line-of-sight feature of the x-ray image.

With the present diagnostic technique, it is interesting to observe tiny bubbles embedded inside some droplets and ligaments at the downstream locations of the aerated-liquid jet. Apparently, some aerating gas gets dissolved into the liquid during the mixing process inside the aerated-liquid injector and expands into bubbles as the dissolved gas experiences pressure relaxation at the downstream locations. That is also the reason why some bigger droplets, which actually have hollow structures, can be observed at the downstream locations. Eventually, these gas bubbles burst as illustrated in the x-ray images in Fig. 6. The entire bubble growth and burst process is similar to the working principles of the flash atomization. Therefore, the aerating gas can not only significantly disintegrate the liquid column by forming homogeneous-like two-phase mixtures but can also generate fine droplets through bubble burst. Probing at further downstream locations for the aerated-liquid jets should be carried out with the present diagnostic technique to measure the evolution of the droplet size and fuel plume structures.

Figures 7 and 8 further illustrate the effects of liquid aeration on atomization processes. The liquid flow rate was kept the same in these injection conditions. For the case with GLR=1.16% in Fig. 7(a), the plume width is smallest among those three jets, due to a low injection pressure. Consequently, the dissolved gas quickly expands into a large gas bubble within a short distance from the nozzle exit. The x-ray image in Fig. 7(a) shows that streams of the gas bubbles are mainly embedded inside ligaments. To further demonstrate this observation, blown-up images for the same jet at selected streamwise locations are shown in Fig. 9. Please note the existence of smaller droplets surrounding the bubble-embedded ligaments at x=6 and 9 mm locations. These droplets contain no dissolved gas and may potentially collide with the expanded ligaments. The degree of liquid atomization is the lowest among those three conditions.

For the case with GLR=2.50% in Fig. 7(b), the plume width increases with a high injection pressure. More fine droplets and small ligaments can be observed within this plume. The bubble size is smaller except for those bubbles at the plume edges, where bubbles experience a quicker pressure relaxation. The plume width is the largest and the size of droplet and ligament is the smallest for the case with GLR=4.13% in Fig. 8. To achieve this aeration level, a higher injection pressure is required, which helps to further widen the plume width. The blown-up x-ray images at selected streamwise locations along the jet axis of this jet are shown in Fig. 10. The comparison between Figs. 9 and 10 clearly shows there are more fine droplets and less bubble-embedded ligaments for the GLR=4.13% jet. Apparently, the degree of liquid dispersion increases with liquid aeration.

**Surface Velocities:**

Double-pulsed x-ray images for pure-liquid jets were used for the measurement of surface velocities along the liquid column. Figure 11 illustrates the typical double-pulsed x-ray images for the present study. The additional features from the wrinkle structures on the liquid column, which can be clearly depicted by the present diagnostic technique, provide more references for the direct measurement of surface velocity. With the conventional shadowgraph images, only a limited number of distinguishable features on surfaces tangential to the parallel beam can be utilized for measurement. With more features in the x-ray images, autocorrelation can also be used to obtain the surface velocity.\(^7\) The direct measurement of the displacement of the flow features, however, was used in the present study.

Figure 12 shows the distribution profile of the measured surface velocity at various streamwise locations for a pure-liquid jet injected from a 1.0-mm injector. For the present study, the average velocity within each image, which covers 1.0 mm distance in the streamwise direction, is plotted as the velocity at the mid point. At the x=0.5 mm location, the liquid surface just exits from the no-slip boundary condition inside the injector and quickly accelerates to reach about 60% of the top-hat velocity profile. The actual difference between the surface velocity and the liquid core velocity can be even bigger since the flow is a fully-developed turbulent pipe flow at the nozzle exit. The measured surface velocity gradually increases due to the action of the viscous force within the liquid jet. The surface velocity eventually reaches a value of about 85% of the top-hat velocity near the end of the probing area.

**CONCLUSIONS**

The structures of pure- and aerated-liquid jets injected into a quiescent environment were explored, using the phase contract imaging technique combined with the x-ray light source. The experiment was carried out at the 32-ID Beamline at the Argonne National Laboratory. Water and nitrogen were used as the injectant and aerating gas, respectively. Two aerated-liquid injectors with orifice diameters of 0.5 and 1.0 mm were utilized for liquid injection. Never-been-seen features on the liquid column surface of the pure-liquid jets were qualitatively described. In addition, near-field structures of the aerated-liquid jets and the advantages
of liquid aeration were discussed. The major conclusions of the present study are as follows:

1. The present diagnostic technique provides the unique capability in depicting interfacial features on the entire periphery of the liquid column, ligament, and droplets.

2. With the present diagnostic technique, the observed highly-convoluted wrinkle structures on the column surface of a turbulent liquid jet resemble turbulence eddies.

3. The length scale of the wrinkle structures decreases as the liquid flow rate or Reynolds number increases.

4. The near-field structures of aerated-liquid jets, which are optically dense, can be clearly depicted by the present diagnostic technique.

5. With a modest level of liquid aeration, the liquid column can be dispersed into fine droplets and ligaments, which can contain dissolved gas. Increase in aeration level enhances liquid atomization.

6. The dissolved gas inside the droplets and ligaments of aerated-liquid jets expands into bubbles and eventually bursts to generate fine droplets as the gas bubbles experience pressure relaxation at downstream locations.

7. The surface velocity on the column of a pure-liquid jet quickly accelerates from a no-slip boundary condition inside the injector to about 60% of the mean exit velocity within a very short distance.

Size and velocity of droplets and ligaments can be measured within the near field of an aerated-liquid jet, using the double-pulse x-ray images. In addition, the fundamental breakup processes of a pure-liquid jet, whether it is due to turbulence eddies or linear wave growth, should be further explored with the present diagnostic techniques.

ACKNOWLEDGEMENT
This work was sponsored by the AFRL/Propulsion Directorate under contract number F33615-03-D-2326 (Contract monitor: Robert Behdadnia). The use of the APS was supported by the US Department of Energy, Office of Science, Office of Basic Energy Sciences and the Argonne National Laboratory. Also, the authors would like thank Matt Streby and Steve Enneking (Taitech, Inc.) for their assistance in hardware design, setup, and data acquisition.

NOMENCLATURE

d = injector orifice diameter
GLR = aerating gas-to-liquid mass ratio
M∞ = freestream Mach number
Ql = liquid volumetric flow rate
q0 = jet-to-air momentum flux ratio at GLR=0
Re = Reynolds number
u = velocity component in the x direction
u_mean = mean exit velocity of the liquid jet
x = axial position downstream of the injector exit centerline

REFERENCES


Figure 1   Photographs of near-field structures of liquid jets injected from the top of the image into a subsonic environment at various aeration levels: (a) Pure-liquid jet, (b) Aerated-liquid jets. $M_\infty=0.3$, $d=1.0$ mm, $q_0=10.4$. The jets were illuminated with 7-ns pulse laser beam from an Nd-YAG laser.

Figure 2   Shadowgraph images of aerated-liquid jets injected from the top of the image into a supersonic environment at various aeration levels: (a) GLR=0%, (b) GLR=8.0%, (c) GLR=4%. $M_\infty=2.0$, $d=1.0$ mm, $q_0=2$. 
Figure 3  Composite x-ray images of pure-liquid jets injected into a quiescent environment at various liquid flow rates. $d=1.0$ mm. The physical dimension in the vertical direction is $9.4$ mm. (a) $Q_L=0.79$ l/min ($Re=1.64 \times 10^4$), (b) $Q_L=1.32$ l/min ($Re=2.73 \times 10^4$), (c) $Q_L=1.85$ l/min ($Re=3.82 \times 10^4$), (d) $Q_L=2.91$ l/min ($Re=6.00 \times 10^4$).
Figure 4   X-ray images of pure-liquid jets adjacent to the nozzle exit. d=1.0 mm. The physical dimension in the vertical direction is 0.5 mm. (a) \( Q_L = 0.79 \text{ l/min} \) (Re=1.64×\( 10^4 \)), (b) \( Q_L = 1.32 \text{ l/min} \) (Re=2.73×\( 10^4 \)), (c) \( Q_L = 1.85 \text{ l/min} \) (Re=3.82×\( 10^4 \)), (d) \( Q_L = 2.91 \text{ l/min} \) (Re=6.00×\( 10^4 \)).

Figure 6   X-ray images of aerated-liquid jets to illustrate bubble burst.
Figure 5  Composite x-ray images of pure- and aerated-liquid jets injected into a quiescent environment. d=0.5 mm, \( Q_l=0.53 \text{ l/min} \) (Re=2.18×10^4). The physical dimension for the liquid jet in the vertical direction is 6.1 mm. (a) GLR=0 (b) GLR=1.41%.
Figure 7 Composite x-ray images of aerated-liquid jets injected into a quiescent environment at various GLRs. $d=1.0\ \text{mm}, \ Q_L=0.64\ \text{l/min}$. The physical dimension of the liquid jet in the vertical direction is 9.3 mm. (a) GLR=1.16\% (b) GLR=2.50\%.
Figure 8  Composite x-ray images of the aerated-liquid jet injected into a quiescent environment. \( d=1.0 \text{ mm}, \ Q_L=0.64 \text{ l/min}, \ \text{GLR}=4.13\%. \) The physical dimension of the liquid jet in the vertical direction is 9.3 mm.
Figure 9  X-ray images of an aerated-liquid jet injected into a quiescent environment at various downstream locations. \( d=1.0 \text{ mm}, Q_L=0.64 \text{ l/min}, \text{GLR}=1.16\%. \) (a) \( x=0 \), (b) \( x=3 \text{ mm} \), (c) \( x=6 \text{ mm} \), (d) \( x=9 \text{ mm} \).

Figure 10  X-ray images of an aerated-liquid jet injected into a quiescent environment at various downstream locations. \( d=1.0 \text{ mm}, Q_L=0.64 \text{ l/min}, \text{GLR}=4.13\%. \) (a) \( x=0 \), (b) \( x=3 \text{ mm} \), (c) \( x=6 \text{ mm} \), (d) \( x=9 \text{ mm} \).
Figure 11  Double-pulsed x-ray images of a pure-liquid jet injected into a quiescent environment at various downstream locations. $d=1.0$ mm, $Q_L=1.32$ l/min ($Re=2.73 \times 10^4$), GLR=0. (a) $x=3$ mm (b) $x=6$ mm.

Figure 12  Surface velocities at various streamwise locations for a pure-liquid jet injected into a quiescent environment. $d=1.0$ mm, $Q_L=1.32$ l/min ($Re=2.73 \times 10^4$), GLR=0.