Velocity and Size Measurements of Aerated Spray using Digital Holographic Microscopy

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Abstract

Aerated liquid jets are of interest due to their applications in ramjet and scramjet engines. Probing the dense spray region near the injector is optically challenging for traditional spray diagnostics like Phase Doppler Particle Analyzer (PDPA). In the present work the use of digital inline holographic microscopy (DIHM) for probing this dense spray region is investigated. When individual droplets are brought in focus during the reconstruction process, the sizes and locations can be measured. Moreover, it is possible to get the velocity measurements for each droplet by using a two laser pulses to store double-pulsed holograms on a double exposure CCD sensor. The flow field in three-dimensions is easily expressed by several two-dimensional slices. The technique proved to be successful in measuring droplet sizes and velocities in three dimensions. The small field view associated with the method was overcome by constructing a map the spray field by patching several reconstructed holograms. A three dimensional map of the droplets’ locations, sizes, and velocities can be obtained using this technique.

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**Introduction**

To achieve good atomization, atomizers require high injection pressures and small exit orifices which unfortunately can be easily clogged. Aerated (effervescent) atomizers [1] are superior in that they provide fine spray with low injection pressures and with relatively large orifices. Moreover, this atomization quality is not sensitive to the liquid viscosity and it is possible to atomize very viscous liquids. Aerated liquid jets have been proven to be particularly successful in air breathing propulsion applications [2]. Unfortunately, investigating the resulting dense spray in the near-injector region is very challenging. The majority of the research conducted on aerated spray in crossflow was performed further downstream of the injector (x/d>50) [e.g. 3] where the droplets are all spherical so that spray diagnostics; such as, Phase Doppler Particle Analyzers (PDPA) can function properly, or was performed immediately at the jet surface [4] using film-based off-axis-holography. The optically-challenging near-injector region extending from x/d= 0 to 25, however, is very important because it is the place where secondary breakup processes that affect spray size and velocity distribution occur.

Traditional inline holography [5-9] has been used to study the sprays. Traditional film-based techniques are nowadays being replaced by digital holographic techniques that can avoid the expensive, time consuming, and hazardous film development process [10, 11]. In-line digital holography was used successfully by the authors to investigate the spray structure in the near-injector region of aerated injector [12]. The spatial resolution was limited to 18 μm, however.

To increase the spatial resolution, digital inline holographic microscopy (DIHM) will be investigated in the present work. DIHM is the simplest method of the holographic techniques. It also reduces the spatial resolution requirements on the CCD sensor, which typically has a much lower resolution than traditional holographic film [13]. The objective of the present study is to explore the potential of digital inline holographic microscopy in probing the near-injector region (x/d=0-25) of an aerated jet injected into a subsonic cross flow typical of experimental conditions in ramjet engines to obtain size and velocity information.

**Experimental Method**

An aerated injector with exit diameter (d) of 1.0 mm was installed at the ceiling of 0.3m×0.3m×0.6m test section of a subsonic wind tunnel capable of generating velocities up to 65 m/s. The intake of the wind tunnel had a contraction ratio of 16:1 and the velocity inside the test section had a variation of ± 1%. The air velocity in the test section, was measured by a Pitot-static tube (United Sensors Model PDC-18-G-16-KL) installed at the end of the test section. The Pitot-static tube was connected to an inclined tube manometer (Dwyer Model No. 400-10-Kit) through two clear plastic tubes. Air velocities in the wind tunnel could be measured within +/- 2%. The test liquid (tap water) was supplied from a cylindrical chamber having a diameter of 100 mm and a height of 300 mm, and the aerating gas (air) was provided from a pressure tank with a volume of 0.18 m$^3$ kept at a pressure of 160 psi. The aerating gas traveled through the inner tube of the injector to pass through 100μm holes located near the end of the injector, as shown in Fig. 1. The jet, at large gas to liquid mass flow rate ratio (GLR), forms an annular-type two-phase flow composed of a gas core surrounded by a thin liquid sheet. The mass flow rate of the liquid and the aerating gas was controlled by a rotameter type flow meter (air flow meter: OMEGA model # 044-40NCA, water flow meter: OMEGA model # N034-39G). The air flow meter could read flow rates +/- 3 cc/s and the water flow meter could read flow rates +/- 0.02 cc/s. Air pressurized at 160 psi was used as the aerating gas, and water, also pressurized to 160 psi, was used as the test liquid. The present test conditions included GLR of 8% (water flow rate of 87mL/min and an air flow rate of 6181mL/min) and jet-to-freestream momentum flux ratio of 0.74 (gaseous crossflow with a speed of $u_\infty=61$m/s).

The instrumentation consisted of double-pulsed digital holographic microscopy as shown in Fig. 2. Two frequency doubled Nd:YAG lasers (Spectra Physics model# LAB-150, 532nm, 7ns pulse duration, 300mJ/pulse) could be fired independently using a delay generator (Quantum model# LAB-150, 10 ns resolution). The time interval designated by the pulse generator is somewhat incorrect because of the different Q-switch delay-time of two lasers. To find the exact time interval between the double pulses, a photo detector and an oscilloscope (Lecroy model 9314L, 300Hz) were used to measure the time between the two pulses within 0.5 us resolution. The sensor was installed behind a polarized cube to detect weak laser light through it.

The two laser beams were aligned with a polarized beam splitter cube. The laser beam energy was controlled by a half wave plate installed before the polarized beam cube. An aluminum breadboard was installed under the wind tunnel test section for easy routing of the two laser beams from the optical table where the lasers were seated to the wind tunnel test section. This breadboard could be moved horizontally on a rail with an accuracy of 0.5 mm. The breadboard was used to transverse the CCD camera (Cooke model# PCO.2000, 2048×2048 pixels, double exposure with inter-frame time down to 400ns) and objective lens/spatial filter combination in the crossflow direction. Mounting posts of 1.5” were used to transverse...
the CCD sensor and the objective lens vertically (in the direction of the jet injection) with a resolution of 0.5 mm. The two laser pulses were synchronized with a CCD camera operating in the double-exposure mode in order to record two pulsed hologram. The double-pulsed hologram was recorded on the CCD had a field of view of 8mm×8mm.

Once the holograms have been recorded, they are reconstructed numerically [14] to form multiple 2D slices of the 3D spray volume. These 2D slices were searched for the best plane of focus of each droplet. Once the plane of focus is determined, the droplet cross sectional area, minor and major axis, and the coordinates of the droplet center of geometry were measured and recorded. The same measurements were conducted for the same droplet in the second pulsed hologram to yield droplets velocities.

Results and Discussion

Flow visualization:

A pulsed Shadowgraph of aerated jet is subsonic cross flow (d=1 mm, GLR=8%, q=0.74) is shown in Fig. 3. The shadowgraph was taken using 4"x5" Polaroid film. The resolution achieved by using large format films is estimated to be equivalent to using a CCD sensor with 120 MPixels, which is beyond the capabilities of commercially available double-exposure CCD sensors nowadays (4 MPixels). A drawback, however, of using shadowgraphs is the limited depth of field especially at large magnification. The limited depth of field renders the shadowgraphs useless when measuring the spray flux. Digital inline holographic microscopy (DIHM) is a true three-dimensional diagnostics and can easily detect all the droplets in the measuring volume regardless of their spanwise direction. To overcome the limited spatial resolution, the near-injector region was divided into multiple investigation windows (8mm×8mm each) and double-pulsed holograms were recorded for each window with a 2048 × 2048 CCD double exposure sensor. The entire flow field can then be obtained at any spanwise distance by reconstructing these holograms at this particular spanwise distance as shown in Fig. 4.

Droplets sizes and velocities:

On the expense of the limited field of view, the spatial resolution of the current setup can reach 5 μm which allows the size measurements of the majority of the droplets in the spray. The droplet velocities in the streamwise and the cross stream directions could be obtained by observing the displacements of the center of geometry of each droplet between the two pulsed holograms. The spanwise velocity could be measured by observing the change in the plane of focus of the droplet between the two holograms. The time between the two pulsed holograms was controlled by a pulse generator.

A typical double pulsed hologram for GLR=8% and q=0.74 is shown in Fig. 5. The hologram was reconstructed at the center plane of the injector and at stream wise and cross stream distances of x/d = 12-20 and y/d = 48-56, respectively. The time interval between two reconstructed holograms measured was 20 μs. The three droplets (marked with “A,” “B,” and “C”) on the images have different displacements in the x and y directions. At the center plane of the injector (z/d=0) the droplets did not have a velocity in the spanwise direction since there was no change in the plane of focus for individual droplets as shown in Figs. 5(a) and 5(b). This is plausible because of the symmetry across the center plane of the injector. Measuring the velocities of these droplets is straightforward, although it is currently time consuming. Automating the search for each droplet plane of focus is a crucial needed step that will allow the full automation of the spray measurements.

Conclusions

The spray produced by an aerated-liquid injector in a subsonic crossflow was investigated using digital inline holographic microscopy (DIHM) to provide spray visualization and droplets size and velocity measurements. The conclusions of the present research are as follows:

- The present optical setup is relatively simple and does not require a collimating lens or relay lens unlike the digital in-line holography [Miller et al., 2006].
- Large field of view measurements can be obtained by patching several high resolution holograms reconstructed in the same spanwise distance.
- Droplets velocities in three-dimensions are measured by tracking their displacements during the time interval between the double-pulses.

Finally, when the process of finding the droplets plan of focus is automated, double-pulsed DIHM technique will provide a powerful tool for velocity measurements of fine droplets in the dense spray region near the injector.

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Nomenclature

GLR aerating gas-to-liquid mass ratio
injector orifice diameter

$\frac{\rho_1 v_j^2}{\rho_s u_x^2}$

velocity component in the crossflow direction

crossstream distance

References

Figure 1. Schematic of the injector assembly.

Figure 2. Optical setup of Digital Inline Holographic Microscopy (DIHM).

Figure 3. Pulsed Shadowgraph of aerated jet is subsonic cross flow (d=1 mm, GLR=8%, q=0.74).
Figure 4. Composed image of six holograms reconstructed at the plane of symmetry of the aerated injector. Test conditions: $d = 1$ mm, GLR = 8%, $q = 0.74$, crossflow from left to right.
Figure 5. Double-pulsed reconstructed hologram at (a) $t = 0$ and (b) $t = 20\mu s$. Test conditions are: GLR=8%, $q=0.74$ at $x/d=16$, $y/d=52$, and $z/d=0$. The field of view is $9 \text{ mm} \times 9 \text{ mm}$ and the letters “A,” “B,” and “C” refer to distinct droplets that are tacked between the two pulses to yield velocity information.