

## **Comparison of Non-Combusting Spray Fields in a Model Combustor using Shadowgraphy**

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### **Abstract**

Droplet sizes were measured using shadowgraphy in the spray issuing from the center element of the baseline configuration of the NASA 7-element lean direct injector (LDI) array. Each LDI element consisted of a 60 degree clockwise axial air swirler, converging-diverging venturi, and a pressure-swirl atomizer positioned with its tip at the venturi throat. The non-combusting measurements were conducted using water spray in a 3-inch diameter research combustor operating at pressure of 5 bar and air inlet temperature of 700 K. At these inlet conditions, three air flow rates were used, producing reference velocities of 7.6, 15.2, and 22.9 m/s. Only the center nozzle was used. At each reference velocity, water flow rates were adjusted to simulate a common equivalence. Data were collected at a frame rate of 15 Hz over a range of positions near the LDI dump plane, and downstream, along the combustor centerline. Velocity measurements were achieved by use of a dual head Nd:YAG laser and frame transfer PIV camera. Droplet size and velocity, mass and number density, and volume fraction are compared at these inlet conditions to determine the effect of nozzle pressure drop on the measured properties.

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## Introduction

Gas turbine combustors are critical technologies for energy production, especially for aircraft engines. The key to good combustor operability and durability is getting fuel and air to mix well, and in the desired locations. Good fuel-air mixing is also required for low emissions of CO, nitrogen oxides, and particulate matter. In aircraft engine gas turbine combustors, the main types of fuel injectors are pressure atomizers and airblast atomizers. Pressure atomizers have the benefit of simplicity, but since they force fuel through a small orifice to promote jet breakup, they rely on pressure drop to atomize effectively, which means a pump is needed to generate high fuel pressure [1-2]. The high fuel pressure required may be prohibitive at some engine conditions. There is also a minimum pressure drop to ensure good spray quality [2]. Airblast fuel atomizers rely on high-velocity air impinging on a thin liquid sheet to break up the sheet into droplets, so they atomize best when the air flow momentum is high [1-2]. Since pressure atomizers do not require air flow for good atomization, most aircraft engines have both types of injectors to best accommodate all parts of the flight envelope.

In the work described in this paper, we use a concept referred to as lean direct injection, or LDI. Note that aircraft gas turbine LDI is unrelated to the “direct injection” concept used in reciprocating engines. The NASA LDI is aimed at developing injection strategies that can rapidly mix fuel and air to produce a uniform vaporized mixture that, when burned, can keep combustion temperatures low to minimize NO<sub>x</sub> formation. The LDI designs also need good operability so as to minimize CO. To achieve good mixing, a single swirl cup (fuel injector) is replaced with several smaller swirlers that allow for faster overall mixing in a shorter downstream distance. There have been several studies and iterations of LDI over the last 30 years or so [3 - 22] that use pressure atomizers and/or airblast atomizers along with axial or radial air swirlers. The 7-point hardware we used in this study is based on one of the earliest designs, and termed LDI-1. LDI-1 can be considered a hybrid in that it uses a simplex pressure atomizer, but also uses high velocity air to blast the conical sheet generated by the simplex atomizer. Details are provided in the next section.

The purpose of this paper is to provide additional data that will add to the database of information for this research combustor and the baseline configuration of the 7-point LDI for researchers [19-22]. This 7-point geometry and data are largely open and has been used by both NASA and non-NASA researchers, particularly for CFD

calculations. This paper provides drop sizes, mass fluxes, and velocity information with non-reacting spray.

## Facility and Test Hardware

### Combustion and Dynamics Facility

The tests were conducted in the Combustion and Dynamics facility (Figure 1), which is capable of air flows with inlet temperature from room temperature to 811 K, pressure from 1 – 5 bar, at mass flow rates from 0.045 – 0.36 kg/s. The inside diameter of the test section is nominally 76.2 mm. Flow passes from top to bottom through the combustor section. Figure 1 shows the test rig components from the upstream air inlet flange to the fuel injector mounting flange to the optically accessible combustor.

### LDI Combustor Hardware

The 7-point swirl-venturi LDI shown in Figure 2 is mounted immediately before the optically-accessible combustor. The 7-point injector (Figure 2) mates to the bottom of its mounting flange and its dump plane is at the top of the windows. The 7-point dome is an array that has six individual LDI elements that surround a center element, and all adjacent elements are equally spaced from one another, center-to-center. Each element is nominally 25-mm in diameter. Dimensions are provided in Table 1. For these tests, all elements are identical, and each consists of a converging-diverging venturi; an axial swirler with six helical 60 degree blades that generate clockwise swirl mounted upstream of the venturi; and a simplex atomizer inserted through the swirler hub, with its tip at the venturi throat.

The low flow fuel nozzles are a custom simplex design fabricated by Woodward FST. The nozzles have a nominal  $FN_{US}$  of 0.65-0.7 ( $FN = 3.1 \times 10^{-8} \text{ m}^2$ ) and spray angle of  $65 \pm 5$  degrees. All of the air passes through the dome, but for these tests, only the center nozzle was used, flowing distilled water.

Figure 3 shows water spray issuing into still air from the center injector over a range of nozzle pressure drops that span the current experiment. The spray was illuminated using a laser sheet to reveal the overall pattern. The images are the RMS for 50 images collected at a frame rate of 500 Hz. At a fuel injector pressure drop of 3.8 bar, the spray is not fully developed. The spray angle has not fully opened to its maximum value of nominally 65°. At 10.3 bar, the spray angle is nearly at its full width. At higher pressures, the spray angle is similar. The primary difference one can see is that the region in the center appears to get brighter as the pressure drop increases. This is a qualitative indication that more droplets are present to scatter the light from the laser sheet.

**Table 1. Physical details of NASA 7-point LDI injector.**

| Description                      | Dimensions<br>mm |
|----------------------------------|------------------|
| Combustor diameter               | 76.2             |
| Element center-to-center spacing | 23.8             |
| Element axial length             | 20.83            |
| Element radial length            | 22.17            |
| Venturi throat diameter          | 13.0             |
| Venturi throat length            | 1.55             |
| Diffuser length                  | 4.37             |
| Diffuser diameter at dump plane  | 20.32            |

Water was used instead of jet fuel because the facility does not have an afterburner or a way to recycle any fuel sprayed into the test rig. To maintain safety at air temperatures of 700K, the long data acquisition times necessary for these tests prevent us from using combustible liquids. We flow the inlet air in order to avoid water condensation on the windows. We use the same air inlet flow rates and temperatures as when conducting our combusting tests, but the water flow rates were set so as to be similar to a local Jet-A/air equivalence ratio of 0.35 at the pilot. Pressure was set to 5 bar for all test points. The matrix of flow rates used, and nozzle pressure drop is shown in Table 2. Note that point 500L had greater uncertainty in the water flow rate; there seemed to be an unsteadiness affecting both flowmeters and the pressure drop across the nozzle.

The liquid physical properties of density, viscosity, and surface tension are different for water compared to Jet-A. Of these, the largest difference between water and Jet-A is the surface tension. At 293 K, Jet-A has about one-third the surface tension of water; therefore, Jet-A fuel is more likely to break up into droplets than is water at room temperature. Studies done to determine correlations for SMD, such as [2, 23-24] have shown that water drops will be larger than Jet-A drops under similar conditions.

**Table 2. Test Matrix**

| test point  | Reference velocity, uref<br>m/s | Air flow rate<br>kg/s | water flow rate<br>kg/h | water/air ratio | ALR        | line + nozzle $\Delta P$<br>bar |
|-------------|---------------------------------|-----------------------|-------------------------|-----------------|------------|---------------------------------|
| 300L        | 7.6                             | 0.089                 | 1.6                     | 0.0050          | 202        | 2.1                             |
| <b>300N</b> | <b>7.6</b>                      | <b>0.089</b>          | <b>2.1</b>              | <b>0.0066</b>   | <b>150</b> | <b>3.7</b>                      |
| 300H        | 7.6                             | 0.089                 | 2.7                     | 0.0086          | 117        | 6.1                             |
| 500L        | 15.2                            | 0.179                 | 2.5                     | 0.0039          | 254        | 5.2                             |
| <b>500N</b> | <b>15.2</b>                     | <b>0.179</b>          | <b>2.9</b>              | <b>0.0044</b>   | <b>225</b> | <b>6.6</b>                      |
| 500H        | 15.2                            | 0.179                 | 3.5                     | 0.0054          | 184        | 10.3                            |
| 700L        | 22.8                            | 0.269                 | 2.8                     | 0.0029          | 342        | 6.4                             |
| <b>700N</b> | <b>22.9</b>                     | <b>0.269</b>          | <b>4.0</b>              | <b>0.0041</b>   | <b>241</b> | <b>12.8</b>                     |
| 700H        | 22.9                            | 0.269                 | 5.1                     | 0.0053          | 190        | 20.3                            |

## Optical Setup

Figure 4 illustrates the arrangement used for acquiring shadowgraph images. We used a 15-Hz, frequency-doubled, dual head Nd:YAG laser as the light source to obtain double-frame images for velocimetry. The time between frames was 2  $\mu$ s. The laser beam was expanded to approximately 50-mm diameter and collimated before striking a fluorescent plate and diffuser on one side of the combustor. On the opposite side, an interline transfer CCD camera with array size of 1600 x 1200 pixels (LaVision Imager Pro 2M) recorded the images. The receiving optics were a Navitar 12x zoom system that consisted of a 12mm F.F. (fine focus) zoom lens, a 2x standard adapter, and 0.5x lens attachment. Using these optics, we obtained images with magnification factor of 1.32  $\mu$ m/pixel resulting in images with area 2.1-mm wide x 1.58-mm high (width y, height z, in our coordinate system). We used a calibrated plate with sizes from 10  $\mu$ m to 200  $\mu$ m to determine the system for depth-of-field via DaVis ParticleMaster Shadow v8.4 control software. The calibration determined a depth of field of 1.5 mm for a 100- $\mu$ m particle, and 0.5 mm for a 40- $\mu$ m particle. Most of the drops measured had equivalent diameters below 40  $\mu$ m. The minimum drop size recordable using this system setup is 5  $\mu$ m.

## Experimental procedure

The optics were set up on traversing stages that provided access to the rig in three coordinates. We typically traversed across radially in y in increments of 2 mm, from y = -22 to y = +22; and in x increments of 4 mm, from x = -20 to x = +20. For the axial direction, z, we had three ranges. Along the centerline, we moved from 0 (dome exit) to 50 mm in increments of 2 mm. In coordination with x or y traverses, we collected images at z = 5, 10, 20, 30, and 40 mm from the dome. The traverse system has positional accuracy of  $\pm 6$   $\mu$ m and bi-direction repeatability of  $\pm 1$   $\mu$ m. However, the test rig and traverse system are not coupled and the test rig shifts depending on the air inlet conditions, so we estimate our position may be off by  $\pm 1$  mm in y and  $\pm 2$  mm in x at each inlet condition. We can set z = 0 by using the blockage at top of the dome, so the estimate of the true z position is up to +0.5 mm. After getting to the air flow conditions, we wait a couple of minutes to allow the rig position to equilibrate before beginning image acquisition. Five hundred image pairs were collected per position at a rate of 15 Hz, so each acquisition took about 33.3 seconds.

The air flow was supplied by the nominally 10-bar building shop air system. After filtering and a slight pressure reduction, the air flow rate was measured by turbine and Coriolis flow meters; values from the more-precise Coriolis meter are reported here. Downstream of the flow meters, the air flow rate was set using a flow control valve and the air was heated using an electric heater. The

air temperature was measured using a type K thermocouple inserted into the center of air path approximately 15.7 cm upstream of the dome. Reference velocity,  $u_{ref}$ , is determined based on the inlet air flow rate and density through the 76.2 mm inlet pipe. After the test section, the gas was cooled to below 480 K using a quench water spray before going through a second control valve that was used to set the backpressure.

The water flow was supplied to the center injector only. A bladder accumulator pressurized the water with pressurized nitrogen, and a hand-operated needle valve set the water flow rate. Coriolis and turbine flow meters measured the water flow. The water pressure was measured downstream of the flow meters but relatively far upstream of the fuel injector. There were multiple bends and area changes between the pressure transducer and the fuel injector. This means the measured drop includes not only the pressure drop across the injector but also the pressure drop across the bends and area changes, resulting in an approximately 7% decrease in the reported flow number.

## Results and Discussion

Figures 5 – 8 present overview results for the three nominal flow conditions, 300N, 500N, and 700N.

Figure 5 shows 3D plots of the mass of all particles per unit volume (reported as  $g/cm^3$ ) and referred to as mass volume fraction (MVF) in the ParticleMaster software. MVF is plotted as a function of position in the test section, providing a nice spatial map of where we acquired the data. The color and size of the points indicates the relative mass of water that passed through the spatial location. As expected, for each reference velocity, the MVF is highest at the dump plane and near the centerline and reduces moving downstream. The MVF are similar for the two higher reference velocities, but the 300N condition has nearly three times the relative mass near the dome and twice the relative mass at  $z = 40$  mm.

Figure 6 shows scatter plots in the  $x=0$  plane that provide the following at each position scanned: the number of drops by symbol size; Sauter Mean Diameter (SMD) represented by color; and average velocity vector. The overall range of particles counted is also indicated in each graph. The highest particle count is axially within the first 5 mm downstream of the dome and radially within the diameter of the venturi exit, roughly  $\pm 10$  mm.

As one might expect, as water flow rate and nozzle pressure drop increase, the total number of drops increases, and the overall size of the droplets decreases, both in magnitude and in range. In terms of velocity, drops from the lowest flow case, point 300N, have the least overall radial ( $y$ ) velocity component, which is also expected. Furthermore, although the axial velocity component reduces in magnitude in the area where a central

recirculation zone (CRZ) is expected, no reverse flow is seen. Points 500N and 700N both show small regions of recirculation, between 5- and 12-mm downstream.

These cases demonstrate that the drop sizes are not small enough to follow the air flow. On the other hand, they likely show a more realistic behavior when fuel is injected into the combustor.

Figure 7 shows the absolute mass flux (axial and radial), along with the average droplet diameter, as a function of distance along the centerline. The right y-axis is mapped with the average linear diameter,  $D_{10}$ . At the dome exit, the axial mass flux increases by an order of magnitude when going from the lowest reference velocity (7.6 m/s, top graph) to the highest reference velocity (22.9 m/s, bottom graph). As also seen in Figure 6, there is no reverse flow for the lowest reference velocity; the axial flux is always a positive value, indicating no reverse flow. Along with the comparatively large values of  $D_{10}$ , this points to the droplets of point 300N following a ballistic trajectory from the nozzle and are not much affected by the swirling air.

Along the centerline for point 300N we observe a relatively large increase in  $D_{10}$  from the dump plane to about  $z = 8$  mm before the droplet size decreases. The increase is about  $8 \mu m$ , which is about 47% larger than the average drop size at  $z = 0$ . Similarly, this  $D_{10}$  size increase occurs at point 500N, but the percent size increase is just 13%. At point 700N, the drop size appears to stay relatively constant. We attribute these differences to droplet recombination in the region where the droplet axial velocity slows down (point 300N) or reverses flow (points 500N and 700N). That is, it is due to the interaction of the air-swirl-generated CRZ with the fuel injector spray. In the case of point 300N, the fuel spray angle is small, and the droplet axial velocity is high near the dome (Figure 6), and the drops are too large to follow the air flow. The higher velocity droplets entering the system are slowed as they approach the CRZ and the slower-moving droplets within. There, the drops can collide and coalesce to become larger drops. For point 500N, the droplets start out from the fuel injector with smaller diameter, a larger spray angle, and lower axial velocity. Droplet coalescence still occurs, but growth is smaller because the droplets start out smaller. For point 700N, the droplets are even smaller, and more likely to vaporize. These factors, along with the higher turbulence levels, are likely why there is limited or no droplet coalescence. Another factor that distinguishes point 300N from 500N and 700N is that the former has a higher liquid to air ratio.

Farther downstream, such as between  $z = 30$  mm to  $z = 40$  mm, is another region in which the droplet sizes increase for all three test points. These might be regions in which some droplets that were in the main conical stream have migrated into the CRZ.

Figure 8 plots the SMD vs. the x-location at various downstream distances  $z$ . The graphs indicate a fairly symmetric distribution of droplet size for all axial locations. We typically observe a decrease in  $D_{32}$  as we move downstream. However, for point 300N, SMD is larger at  $z=10\text{mm}$  than at  $z=0\text{ mm}$ ; this we attribute to droplet recombination, as noted earlier.

The region in  $x$  between  $\pm 10\text{ mm}$  corresponds approximately to the element diameter at the dump plane—the venturi diffuser exit diameter (Table 1), so we would expect near  $z = 0$  for the drop sizes within the element diameter to be larger than those outside the diffuser region of  $x < -10\text{ mm}$  and  $x > +10\text{ mm}$ . We find this to be the case. Droplets in the outer region may come from the spray cone periphery or droplets downstream mixing with the outer swirler CRZs, or both.

Beyond the dump plane, there are differences. Moving downstream for the 500N and 700N conditions, the distributions flatten such that all drops from  $z \geq 20\text{ mm}$  are roughly the same size, but for the 300N condition, size uniformity is observed only at  $40\text{ mm}$  downstream. This suggests that no further significant droplet breakup beyond  $20\text{ mm}$  and that further droplet-air mixing relies more on evaporation than atomization. For point 300N, as previously noted, the combination of small spray angle and large initial droplet size requires more time for evaporation and mixing, so the radial distribution becomes near-uniform farther downstream, at about  $z = 30\text{ mm}$ .

We next explore differences within each reference velocity for small excursions above and below the nominal water flow rate. For these flow excursions, we used data from three positions  $(x, y, z)$ :  $(0, 0, 0)$ ,  $(0, 0, 5)$ , and  $(0, 0, 10)$ . For Figures 9 and 10, these data are bundled. For Figures 11-12, positional differences are briefly discussed. The excursions were roughly  $\pm 27\%$  about the nominal flow rate, with the exception of point 500L, which was about  $-11\%$  /  $+23\%$  about the nominal flow.

Figures 9 and 10 show  $D_{32}$  and the number of drops for each group as a function of reference velocity. We expect SMD to reduce across reference velocities, and they do. The excursion at  $7.62\text{ m/s}$  shows that SMD decreases as the water flow rate (thus injector pressure drop) increases. Considering the 500 series, at first glance, point 500L seems anomalous; however, the flow rate and pressure drop through the nozzle lie between points 300N and 300H, and the SMD at point 500L is comparable to point 300N. Note that despite point 500L having twice the air momentum of the 300 series to help contribute to liquid breakup,  $\Delta P$  is a much larger factor in determining drop size.

Also recall the spray patterns shown in Figure 1. The spray at a  $\Delta P$  of  $3.8\text{ bar}$  is not full, but the spray with

pressure drop of  $6.9\text{ bar}$ , though not completely fully developed, has better uniformity in the middle and is not as streaky. Based on the drop sizes at the 500 and 700 series, a pressure drop  $\geq 6.4\text{ bar}$  seems to generate smaller drops with this nozzle and might be thought of as a critical pressure drop. Within the 500 and 700 test groups, once this critical  $\Delta P$  has been met, SMD does not change much. However,  $\Delta P$  still affects the number of drops generated by promoting droplet breakup, as shown in Figure 10.

Figures 11 and 12 compare the three reference velocities at roughly the same water-to-air ratio—points 300L, 500N, and 700N, so  $\Delta P$  and reference velocity are the factors that explains the differences. As we have seen above, these results are consistent with what was earlier presented. These figures show the number of drops counted (Figure 11) and SMD (Figure 12) moving downstream along the centerline. There generally appears to be a monotonic falloff of drops counted as the liquid drops break up and begin vaporizing. A large number of droplets were counted at the dump plane compared to the most downstream location, and SMD decreases with increasing water flow and  $\Delta P$ .

## Summary

We have presented non-combusting water spray droplet data using shadowgraph. The data were collected using the NASA 7-point LDI baseline injector configuration, which consists of 7 identical swirler elements that use  $60^\circ$  clockwise axial swirlers and simplex pressure atomizing nozzles. The inlet temperature and pressure were  $700\text{ K}$  and  $5\text{ bar}$ . Three cold-flow air reference velocities were used, and at each reference velocity, three water flow rates were used: one nominal, one low, and one high. Data were collected at different positions within the location, providing a map of information that included average diameter statistics of linear and Sauter Mean diameter ( $D_{10}$ , and  $D_{32}$ ), absolute mass flux, and droplet velocity. For pressure atomizers, flow rate and nozzle pressure drop are positively coupled. The data are consistent with the pressure atomizer theory in that higher flow rates and pressure drops result in a greater number of droplets having smaller diameter; and that for low flows relatively poor atomization is achieved.

## Nomenclature

|          |                                                   |
|----------|---------------------------------------------------|
| ALR      | Air-liquid ratio                                  |
| CRZ      | Central Recirculation Zone                        |
| $D_{10}$ | Average linear drop diameter                      |
| $D_{32}$ | Sauter Mean diameter, volume/surface drop average |
| MVF      | mass volume fraction                              |
| RMS      | root mean square                                  |
| SMD      | Sauter Mean diameter                              |
| uref     | cold flow reference velocity                      |

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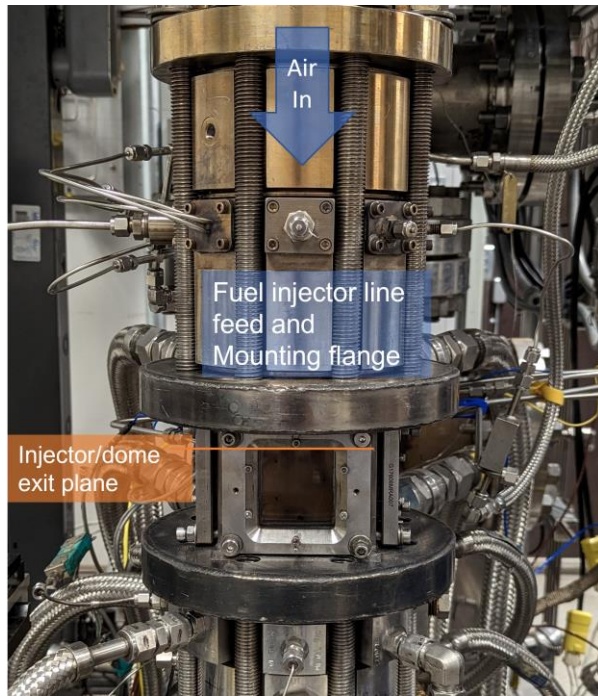


Figure 1. Test rig picture, showing inlet and combustor

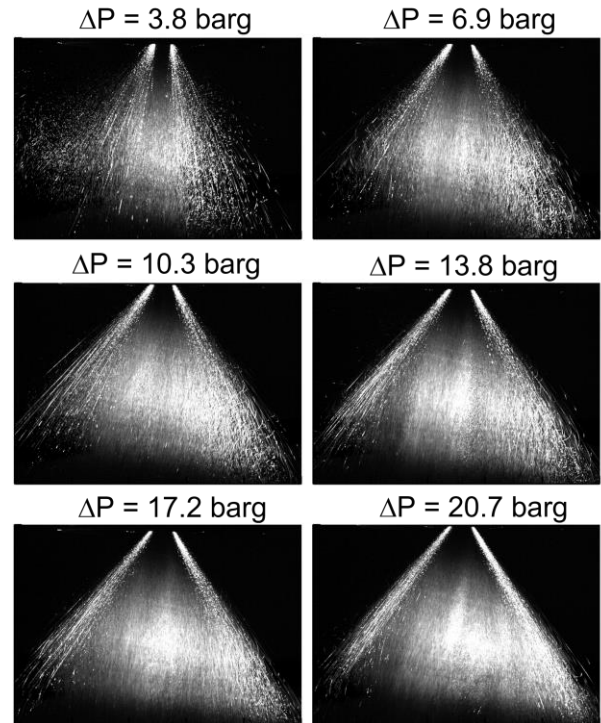


Figure 3. RMS images of center nozzle water spray into quiescent room air at various injector pressure drops. Spray illuminated by a laser sheet.

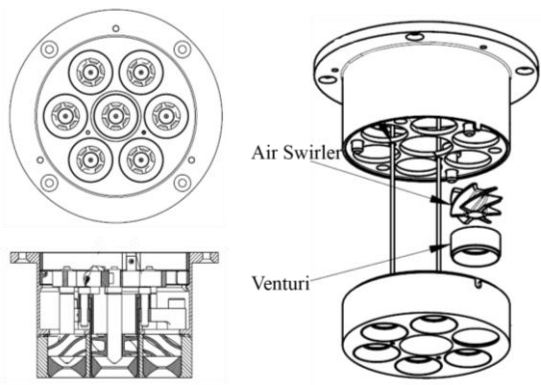


Figure 2. Schema of the NASA 7-point LDI injector.

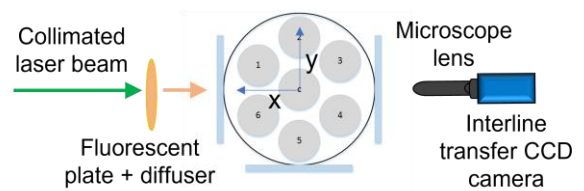
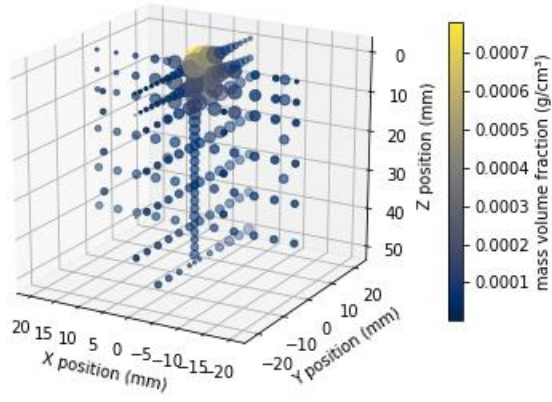
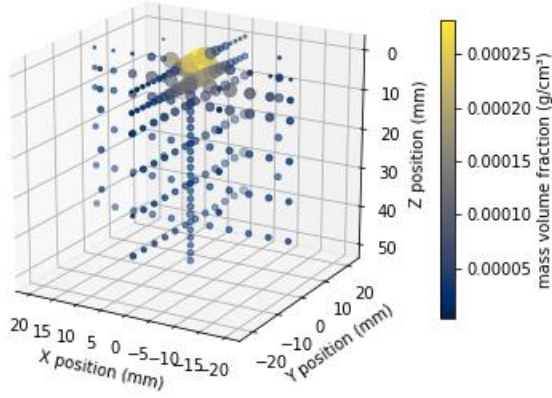


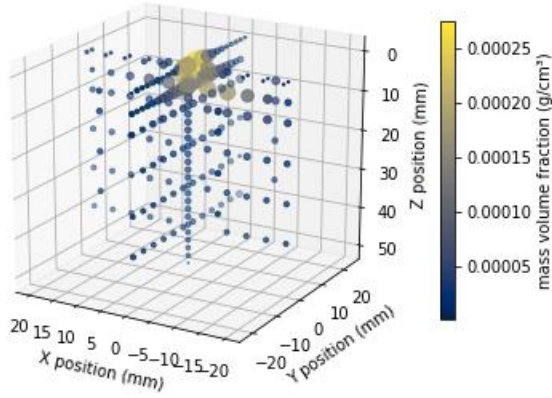
Figure 4. Instrumentation layout used for shadowgraphy



a) uref = 7.6 m/s

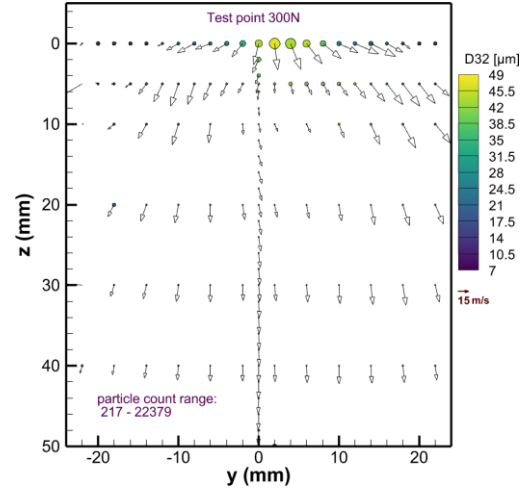


b) uref = 15.2 m/s

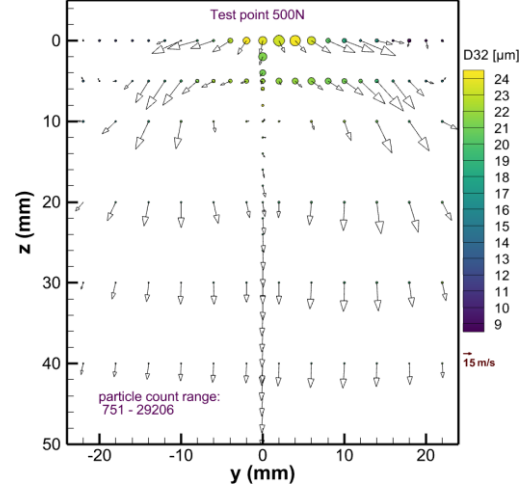


c) uref = 22.9 m/s

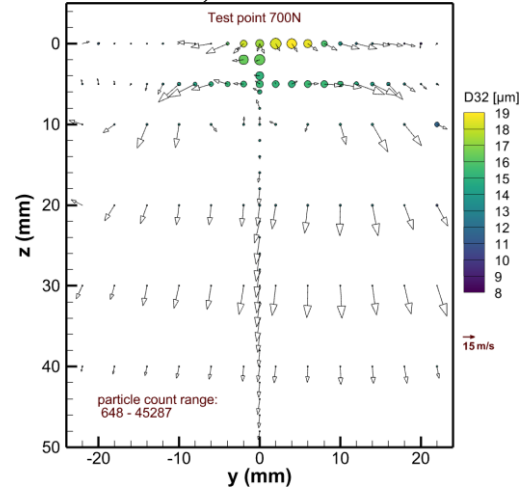
**Figure 5. Mass volume fractions measured for the three nominal flow points. a) 300N; b) 500N; c) 700N**



a) uref = 7.6 m/s

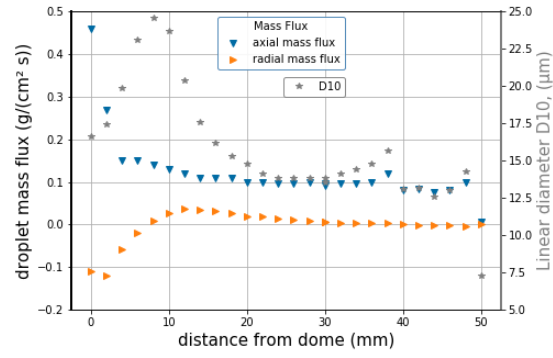


b) uref = 15.2 m/s

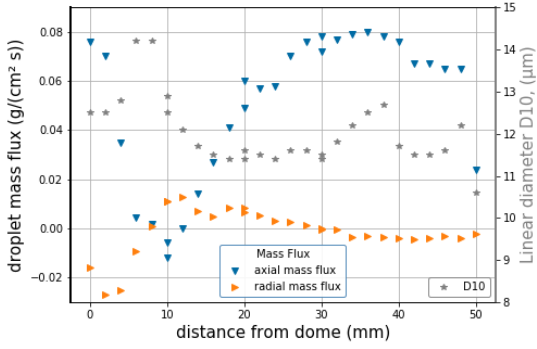


c) uref = 22.9 m/s

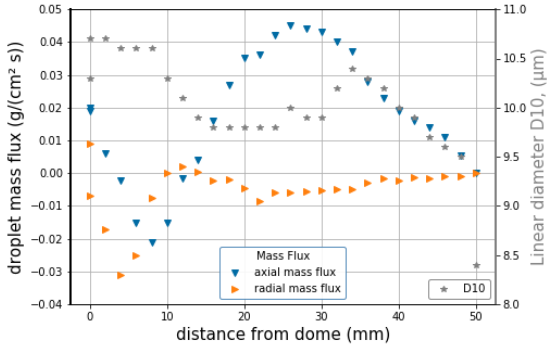
**Figure 6. Plots showing SMD (color), number of drops (by size), and 2D velocity in the x=0 plane. a) 300N ; b) 500N; c) 700N**



a)  $u_{ref} = 7.6$  m/s

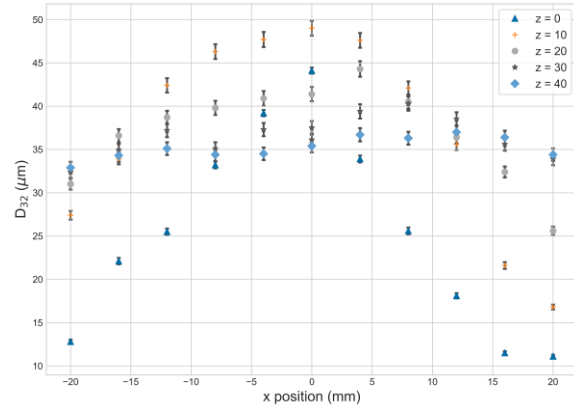


b)  $u_{ref} = 15.2$  m/s

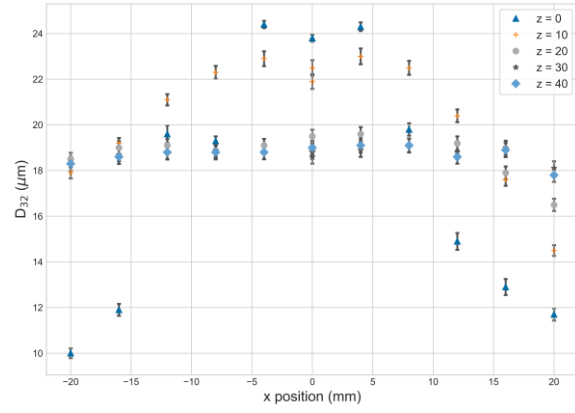


c)  $u_{ref} = 22.9$  m/s

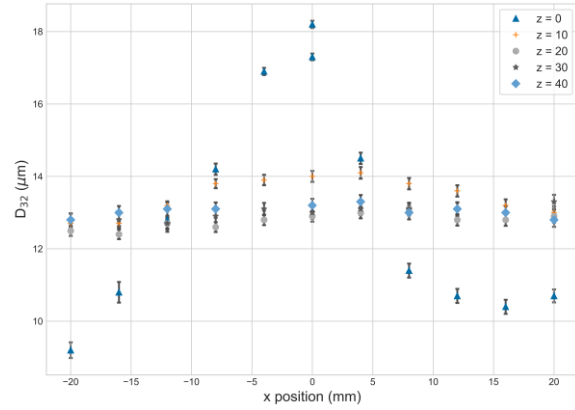
**Figure 7. Axial and radial mass flux, and average linear diameter along the centerline as a function of distance from dome,  $z$ .**



a)  $u_{ref} = 7.6$  m/s



b)  $u_{ref} = 15.2$  m/s



c)  $u_{ref} = 22.9$  m/s

**Figure 8. SMD at  $y=0$  for various downstream positions,  $z$ , at the three nominal flow conditions.**

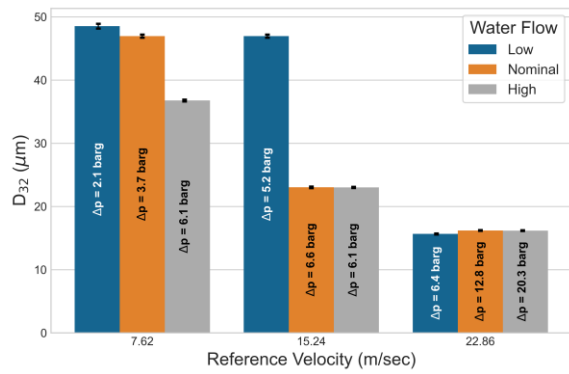


Figure 9. Effect of water flow rate ( $\Delta P$ ) on drop-let size for the three reference velocities.

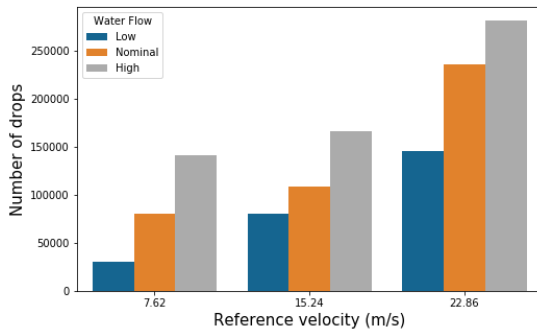


Figure 10. Effect of water flow rate ( $\Delta P$ ) on the number of drops for the three reference velocities.

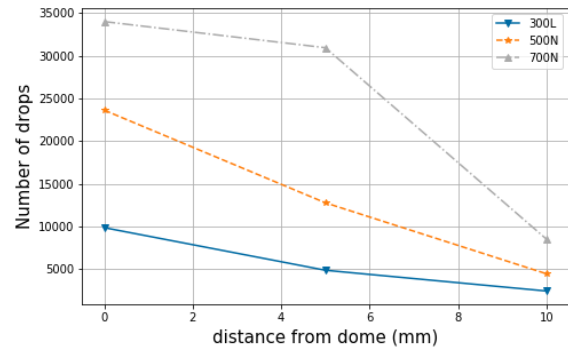


Figure 11. Comparing raw droplet count for roughly the same ALR with distance from dome along centerline.

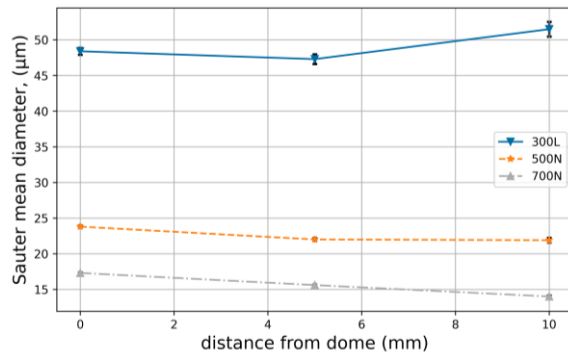


Figure 12. Comparison of SMD with distance from dome at roughly the same ALR for the three reference velocities.