Spray Diagnostics of a Low NOx Air Blast Atomizer for NASA ERA N+2 Program

United Technologies Aerospace Systems
Engine Components Division
West Des Moines, IA 50265 USA

Abstract
Spray Diagnostics Measurements of an air blast atomizer at ambient pressure conditions are presented. The atomizer was developed by United Technologies Aerospace Systems as part of a combustor design for NASA’s Environmentally Responsible Aviation (ERA) N+2 advanced, low NOx combustor technologies program. The goals of this combustor design is to meet or exceed the N+2 LTO NOx goal of 75% reduction from the ICAO standard adopted by CAEP 6 in an engine in the 70,000 lb. thrust class with an engine pressure ratio of at least 55:1. The combustor was developed to include three independent fuel circuits (pilot, intermediate, and outer) which are radially staged to improve performance and stability. The main objective of the presented research is to probe the performance of the outer air blast atomizer design utilized in this combustion system. The atomizer design was developed extensively by utilizing CFD with the intent of rapidly and thoroughly mixing fuel and air to minimize NOx predictions. It is the intent of the currently presented research to confirm that the actual atomizers created behave as predicted. This paper provides comparisons of the air flow field predicted by CFD to that measured by Particle Image Velocimetry (PIV) at ambient air-only test conditions for a 5% ΔP pressure drop through the atomizer. Additionally, the atomizer’s behavior with both air and fuel was investigated using Laser Induced Fluorescence (LIF). In these tests, a laser dye (Pyromethene 597) was added to MIL-PRF-7024 Type II test fluid and excited by a laser sheet to produce the LIF results. These air and liquid PIV/LIF results are presented and compared to air-only PIV results at the same pressure drop. Mass flux measurements calculated for the fuel by performing liquid PIV measurements and utilizing the LIF signal are also presented.

*Corresponding author: spencer.pack@utas.utc.com
Introduction

As part of NASA’s “Environmentally Responsible Aircraft” (ERA) N+2 initiative, United Technologies Aerospace Systems (UTAS) is working to develop combustion technologies for a low-NOx combustor [1]-[2]. This program builds on UTAS’s history of Multipoint Lean Direct Injection (MLDI) concepts [3] which have been shown to have very low NOx emissions index (EI). Recent developments from UTAS [4] include radial staging of injectors, converging combustor geometries, and the use of air-blast fuel injectors in addition to the traditional air-assist fuel injectors which were solely used in previous MLDI concepts. It is the intent of these recent developments to advance the practicality of the combustion technologies by increasing the operating range of the combustor, reducing the number of nozzles, as well as improving low-NOx emissions to a goal of 75% reduction from the ICAO standard adopted by CAEP 6 at engine pressure ratios of at least 55. UTAS is working with NASA and the University of Cincinnati to demonstrate concepts with these capabilities [9-11].

In the effort to design the current MLDI combustor array and constituent fuel injectors, CFD was heavily used to predict the NOx emissions associated with a number of injector concepts. One limitation of this approach is that assumptions were made in terms of how the fuel was distributed by the fuel injectors. In an air-blast atomizer, the distribution of fuel is heavily influenced by the momentum of the air. Due to the nature of the environment in which the fuel nozzles operate, it is extremely difficult to experimentally measure the droplet size and distribution of fuel. Therefore, it is the intent of the present work to experimentally measure the flow field and fuel distribution at atmospheric conditions to be used to correlate to CFD predictions. With this correlation established, it is the hope that future CFD predictions will be more able to predict the fuel and air distributions more accurately.

Nomenclature

| AC_D | Effective Flow Area |
| CAEP | Committee on Aviation |
| CFD | Computational Fluid Dynamics |
| EI | Emissions Index (grams of constituent/kilogram of fuel) |
| EINOx | Emissions Index of NOx |
| ERA | Environmentally Responsible Aircraft |
| ICAO | International Civil Aviation Organization |
| MLDI | Multipoint Direct Lean Injection |
| N+2 | Technology available for next generation or for the 2020 time-frame |
| NOx | Oxides of Nitrogen |
| OPR | Overall Pressure Ratio |
| UTAS | United Technologies Aerospace Systems |

Physical Description

Although the current research program is focused on how an entire MLDI combustor array operates, it is advantageous to focus solely on a single fuel injector to reduce the uncontrolled variables associated with multi-nozzle interactions. Therefore, in the current work, a single air-blast injector is examined (see Figure 1 below). The present air-blast concept is unique over other traditional air-blast atomizers because of the placement of the fuel between a high swirl inner air circuit and a low-swirl outer air circuit (Patents Pending US 13/664,785, US 13/665,497, US 13/665,568). Additionally, the percent of air that flows through the center channel is greater than other traditional air-blast atomizers. The intent of these features is to promote rapid mixing of fuel and air in close proximity to the fuel injector, prior to any interaction with neighboring fuel injectors in an MLDI array.

![Figure 1. Air-blast atomizer studied in the present work.](image)

Experimental Setup

In this experiment, a laser based stereo PIV measurement technique is applied to spray field produced from the MLDI atomizer. The atomizer is contained within a metal chamber that is pressurized with air. A pressurized liquid line is fed directly into the atomizer. The spray is created inside an open test chamber that is at ambient conditions of room temperature and pressure. A photo of the experimental setup and test rig is shown in Figure 25 at the end of this paper. The incoming flow rates are then varied and the pressure and temperature of the supply air and liquid are measured.

The advanced air-blast atomizer was mounted in an air box that was pressurized at 2%, 3%, 4%, and 5% ΔP across the atomizer tip. Only the 5% ΔP air pressure...
test points are presented in this paper. The air delta pressure was the difference between the pressure measured via a pressure tap just upstream of the nozzle tip and the ambient pressure in the lab. See Figure 2 for test atomizer air box layout. There were two different setups used for this testing. The first was PIV measurements of scatter laser light off of small seeded particles in the air stream. The second was liquid PIV measurements using laser induced fluorescence (LIF). These two setups will be discussed separately in the following two subsections.

Figure 2. Air box layout for atomizer testing.

The PIV system used to take the measurements was a complete adaptive PIV system for standard planar 2D- and Stereo-PIV from LaVision. This system included a 532 nm double-pulsed Nd:YAG laser, nanopiv Litron laser (1200 mJ / 4 ns), with optics to produce about a one millimeter thick light sheet on the central axis of the flow. The delay between the two laser pulses depended on the flow conditions that were being tested. As the incoming flow conditions are changed, the velocity of the spray flow changes. Thus, the time delay Δ$t$, needs to be changed to maintain the accuracy of the PIV measurements. The timing of the system is controlled by a programmable timing unit (PTU9). Two CCD cameras (Imager Pro X 4M) each with a Nikon AF Micro Nikkor 105 mm lens with a double shutter feature is used to capture two images per camera for each sample. The images are then stored on a computer for further processing. LaVision PIV software, DaVis v8.1, is used to construct the velocity vector fields. The interrogation window is circular 32 x 32 pixels with a 50% overlap. The velocity vectors are analyzed by the DaVis post-processing program that detects and deletes erroneous vectors; masks shadow regions; computes the vorticity, turbulent kinetic energy, and Reynolds' stress; and computes the ensemble averages. Only the velocity vectors and contours are presented in this paper. The ensemble average is comprised of the average of 500 to 750 instantaneous velocity vector fields.

**PIV Air Only Measurements**

PIV is an optical method of flow visualization used in education and research. It is used to obtain instantaneous velocity measurements and related properties in fluids. The fluid is seeded with tracer particles which, for sufficiently small particles, are assumed to faithfully follow the flow dynamics. In these measurements, only the gas flow from the nozzle is measured by a standard stereo PIV technique. The liquid circuit is turned off, so there are no liquid droplets in the flow. The compressed air supplied to the air box is seeded using Bis(2-ethylhexyl)sebacate (DEHS) via a LaVision Aerosol Generator (PN1108926). The sizes of these DEHS droplets are less than one micron.

The air only measurements used a stereo PIV technique to measure the air flow field. The PIV setup is as mentioned and the CCD cameras utilize a band pass filter (BP-532-10, #1108560) from LaVision that allows the scattered laser light to pass thru while limiting background emissions.

The cameras are setup approximately 45° apart facing the laser sheet. A Scheimpflug mount is utilized to allow the two cameras to focus on the laser sheet through the entire measurement area. This mount uses the Scheimpflug Principle to allow the measurement plane to be in focus even though the cameras are at different angles to the laser measurement plane [5].

**PIV Liquid Spray Measurements**

The liquid PIV experiments used a stereo PIV technique to measure the spray flow of MIL-PRF-7024 type II (fuel substitute), mixed with Exciton laser dye Pyromethene 597 (P597). P597 readily absorbs into the fuel substitute [6], [7].

The liquid flow rate was tested at several different mass flow rates with 5% air Δ$P$. In this technique, only the velocity of the liquid is measured as the liquid droplets form the “seeding” particles that are tracked in the PIV algorithm. The laser pulse excites the P597 in the water, and it begins to phosphoresce. The CCD cameras are both filtered to capture P597’s phosphorescent frequency, 582 nm. The lens filter used on each camera was an assembly of two filters from Midwest Optical Systems (band pass filter BP635-52 and long pass filter LP550-52). The Mie scattering of the laser light is filtered out of the image and only the phosphorescent light is recorded. Thus, the position of the droplets can be more accurately determined. The flow meter used to measure the fuel substitute is a Max 120 Flow Computer utilizing a positive displacement flow meter model 214410. As with air only measurements, the laser pulse time delay varies with the air flow rate.
The air box and atomizer were mounted in two different directions. The atomizer could face in the downward direction of face horizontal (facing the cameras). This allowed measurements of the flow field at multiple planes. In addition, a traverse was utilized to move the measurement plane. In the downward direction, only the atomizer center line plane was measured. In the horizontal plane, the measurement plane started at 12.5 mm from the atomizer face and was moved at increments of 12.5 up to 37.5 mm.

**Experimental Results**

The first measurements completed were air only velocity measurements at 5% air $\Delta P$. The air box was oriented face down with the center line of the two CCD cameras perpendicular to the measurement plane. 500 image pairs (2 images per camera) were collected for these test points at a sample frequency of 5Hz. The test area is vented in the downward direction. This downward velocity was not measured but is expected to be less than .5 m/s. The $\Delta t$ between laser pulses was 7 $\mu$s which corresponds to a droplet displacement of 8 to 10 pixels. Figures 3 through 5 show the resulting velocity contours. The atomizer face is within 1 mm of the top of each contour.

As seen in Figure 3, the peak total velocity is approximately 70 m/s. As expected the peak velocity is near the atomizer face. In addition, there appears to be small wakes present from the air swirler. This is apparent from the peak velocity zones that appear, recede, and then reappear as one examines the flow proceeding from the nozzle face.

**Figure 3. Total air velocity contour 5% $\Delta P$**

It is important to note that the velocity vectors shown in all figures in this paper are total velocity vectors. For example, in Figure 4 the contour shown is the tangential velocity profile and the vectors shown are total velocity vectors to help aid in visualizing the flow field. The red color indicates that the velocity is out of the page whereas the magenta color indicates velocities that are into the page. The maximum tangential velocity is approximately 40 m/s in and out of the page.

**Figure 4. Tangential air velocity contour 5% $\Delta P$**

Figure 5 provides the axial velocity contour of the 5% $\Delta P$ air only test point. The peak axial velocity is approximately 60 m/s in the downward direction. There is a recirculation zone present at the atomizer center line with a peak upward velocity of almost 12 m/s. This recirculation zone disappears within 35 mm of the atomizer face.

**Figure 5. Axial air velocity contour 5% $\Delta P$.**

Figure 6 was created using the technique discussed previously where P597 laser dye is added to the test fluid and PIV is measured from the liquid LIF signal. As seen in Figure 6 there is a significant difference between air only total velocities (Figure 2) and combined fuel and air total liquid velocities (Figure 6). For this contour, 750 image pairs were collected. It is important to note that the contour shown is the fuel velocities not fuel location or fuel distribution. The $\Delta t$ between each laser pulse was change to 10$\mu$s owing to the velocity reduction.
As seen in Figure 6, the peak velocity is closer to 30 m/s. This is expected since a pure air-blast atomizer utilizes the air velocity and air pressure to cause fuel droplet breakup, not fuel pressure and velocity. Thus, the velocity of the liquid is very low as it leaves the atomizer tip and quickly increases to the peak velocity approximately 35 mm downstream from the atomizer face.

Figure 6. Total liquid velocity contour, 5% air ΔP, 27.2 kg/hr fuel.

Figure 7 shows the standard deviation or RMS of the average total air velocity contours. This plot can be useful in finding areas of high variability. As shown, the highest variability is shown near the atomizer tip where the air circuits first meet and combine. What this figure doesn’t show is how much uncertainty there is in the average total velocity measurement. It was unclear if 500 image pairs were enough measurement points to ensure that the average total velocity uncertainty was less than 3 to 5 percent.

To answer this question an uncertainty analysis was performed on the 500 image pairs using a program developed in MATLAB R2012a. This program calculated the confidence interval (CI) of the velocity contour using the standard CI equation with confidence 95% [8]. The goal was to ensure that enough images had been collected to provide a CI of less than 3%. This 3% limit was arbitrarily chosen. As a side note, the RMS used in this CI calculation was computed for each vector (Vx, Vy, and Vz) and then totaled instead of calculating the RMS from just the total velocity vector.

Figure 7. Total air velocity RMS 5% ΔP

Figure 8 shows the uncertainty of the total velocity if only 50 image pairs (2 per camera) were used for these measurements. As seen the uncertainty of the velocity profile is well above the 3% target. Figure 9 shows the uncertainty if 150 image pairs had been used. At this point, a majority of the flow field under examination is under the 3% target. However, near the atomizer face there are areas where the uncertainty is more than desired. Figure 10 shows the uncertainty when 500 images pairs are used. The result is significantly improved over the previous two. The entire area of interest is below the 3% target. As seen areas outside the flow field still have very high uncertainty. This is expected since very few droplets or seeded particles are present in this area. Thus, DaVis predicts extremely high velocity fluctuations only because there is very little signal in these areas. These areas were cropped (removed) from the results contours shown in this paper.

Figure 8. Avg. air velocity uncertainty (50 images).
The next step in analyzing the flow was to mount the air box with the atomizer’s facing the laser sheet. This allowed for better examination of the wakes and was required for collecting the mass flux measurement. The downdraft mentioned previously was considered negligible because it was less than 0.5 m/s.

Figure 11 shows the average total air velocity 12.5 mm from the atomizer face with 5% air ΔP. Again, this is 500 image pairs with 7µs Δt between laser pulses. As shown, the peak velocity is very near 70m/s with 8 distinct wake zones. These zones corresponded to the number of vanes on the inner air swirler which suggested that the inner air swirler was an area of focus if wake reduction was needed. The vectors shown in this figure clearly show the rotational component of this air flow field which was described in the tangential velocity contour Figure 4.

For added clarity, Figure 12 shows the tangential average velocity contours. The contour is the velocity in and out of the page. As seen there is a somewhat large recirculation zone down the center of this flow field. The wakes are still present. It is interesting to note the total velocity vectors. The rotational vectors are largest between the outer and inner zones. The outer swirler has almost no rotational air velocity, whereas the inner swirler is has much larger rotation velocity. This was the intent of this atomizer and is readily apparent in this PIV velocity measurement.

In preparation for the mass flux measurement, liquid PIV using the LIF signal was next accomplished. Figure 13 shows the result of this measurement. The phosphorescing reflections off of the atomizer and air box were minimized by moving the measurement plane in Figure 13 downstream to the 37.5mm plane. 5% air ΔP was applied with 4.54 kg/hr of test fluid. As expected, the resulting contour was significantly different than the air only measurement.
As seen in Figure 13, the total velocity max of the liquid droplets is near 30 m/s. This corresponds with Figure 7. It is interesting to note that the recirculation zone is more visible in this planar measurement than in Figure 7. The recirculation zone is significantly reduced from the air only recirculation zone (Figure 12).

As a reminder, Figure 13 is comprised of 750 image pairs. It is important to note that the contour shown is the fuel velocities not fuel location or fuel distribution. In addition, the  \( \Delta t \) between each laser pulse was changed to 10µs owing to the velocity reduction.

Figure 13. Tangential liquid velocity contour, 5% air \( \Delta P \), off axis plane, 37.5 mm from atomizer face, 4.54 kg/hr fuel.

To obtain fuel distribution or mass flux, a 3 step process was utilized as discussed in [12] by correlating the measured flow rate from the test stand to the velocity calculated from the PIV/LIF measurements and the superimposed intensity images. The resulting mass flux can be seen in Figure 14. As seen, the resulting liquid mass distribution is slightly non-uniform. The spray is heavier on the right side of the spray compared to the left. It was first thought that this was because of laser light absorption. The further the beam has to travel through the liquid medium the more the light is absorbed and thus less LIF signal generated. This is not the case since the laser beam entered from the left side of the image. The slight mass distribution non-uniformity is possibly due to gravity effects. The atomizer may allow the fuel to collect more towards the bottom of the atomizer. As the fuel enters the air stream it is rotated in a clockwise direction. This clockwise spinning could result in a heavy region 37.5 mm downstream of the nozzle.

Figure 14. Mass flux contour, 5% air \( \Delta P \), off axis plane, 37.5 mm from atomizer face, 4.54 kg/hr fuel.

### CFD Setup

The intent of this of this work is to validate the CFD models compared to experimental results. The CFD code used was OpenFOAM® using a compressible solver, rhoPimpleFoam. The envelope for the CFD simulation included the entire air box upstream of the nozzle, all of the air passages within the nozzle, and a downstream region which extended approximately 2 nozzle diameters from the tip of the nozzle. Two Reynolds-Averaged 2-equation turbulence models were used: the RNG k-\( \varepsilon \), and the k-\( \omega \)-SST model. The mesh used consisted of approximately 16 million cells comprised of both tetrahedral and hexahedral cells. Atmospheric conditions similar to the experimental test conditions were employed. The 5% air \( \Delta P \) was used for comparison between CFD and PIV.

### CFD Results

The air-only results of the CFD analysis using the RNG k-\( \varepsilon \) turbulence model are shown in Figures 15-19. This model compared very well in predicting the AC\(_D\) of the nozzle in comparison with experimental measurements. This model appears to be less dissipative than other turbulence models, and the peak velocity zones may be overpredicted. Figure 15 shows the intense shearing forces in that the velocity is well dissipated within 1 nozzle diameter of the nozzle tip. Figure 16 shows the high swirl velocity in the centerline of the nozzle corresponding to the large inner air swirler of the nozzle. Figure 17 shows the large recirculation zone down the centerline of the nozzle. This recirculation zone is more evident in the perpendicular plane located 12.5mm from the tip of the nozzle, as shown in Figures 18 and 19. The structure of the wakes is more pronounced in these CFD models than what was measured within the PIV setup, possibly due to the reduced dissipation of the turbulence model.
In addition to the RNG k-ε, the kω-SST turbulence model was also utilized (see Figures 20-24). This model also compared very well with the measured AC_D of the nozzle. The velocity contours were slightly improved over the RNG k-ε model when compared to the PIV measurements, however, some discrepancies still exist. Specifically, the high-velocity zone is still somewhat longer than the PIV measurements indicated.

Overall, the comparison with PIV is promising. The use of these 2-equation RANS models is beneficial in terms of reducing computation requirements compared with more accurate CFD simulations, which is necessary for expedient development of fuel nozzles. Additionally, OpenFOAM® has proven to be a very useful CFD code and the results are good in comparison with PIV. Currently, we are looking at other turbulence models as well as LES simulations of this injector for comparison to PIV. Additionally, multiphase (VOF)
analysis of the injector is also planned for future comparisons.

Figure 20. CFD Prediction of Total Air Velocity Contours at 5% ΔP using kω-SST

Figure 21. CFD prediction of total air velocity contours at 5% ΔP using kω-SST

Figure 22. CFD prediction of axial air velocity contours at 5% ΔP using kω-SST

Figure 23. CFD prediction of total air velocity contours at a perpendicular plane located 12.5mm from the tip at 5% ΔP using kω-SST

Figure 24. CFD prediction of tangential velocity contours at a perpendicular plane located 12.5mm from the tip at 5% ΔP using kω-SST

Conclusions

The atomizer design presented in this paper was developed extensively by utilizing CFD with the intent of rapidly and thoroughly mixing fuel and air to minimize NOx predictions. The currently presented research confirms that the actual atomizers created behave as predicted. Although not an exact match, the provided comparisons of the air flow field predictions by CFD matched fairly well to those measured by PIV at ambient air-only test conditions. Additionally, the atomizer’s behavior with both air and fuel was investigated using LIF. For these purposes, a laser dye (Pyromethene 597) was added to MIL-PRF-7024 Type II test fluid to produce the LIF results presented in this work. The air and liquid PIV/LIF results presented were compared to air-only PIV results at similar pressure drops and significant differences were noted in the flow fields due to the added momentum of liquid. Mass flux measurements calculated for the fuel by performing liquid
PIV measurements and utilizing the LIF signal were also presented. These mass flux measurements were not compared to mechanical patternation results, which is planned for future work.

References
Figure 25. Representative PIV setup for liquid LIF and seeded air PIV measurements.