Study of Spray Distribution and Fuel Placement from a Novel Dual Phase Airblast Injector for Gas Turbine Combustor

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Abstract

A novel airblast injector is designed for gas turbine combustors. Unlike standard pressure swirl and prefilming/non-prefilming air blast atomizers, the novel injector has a porous stainless steel tube with 7 μm porosity. The porous tube is used to inject the fuel between two air streams. The advantage of such an injector is that it can increase the surface area of contact between the fuel and air by forming a thin liquid sheet along the circumference of the tube which will enhance the distribution the fuel more effectively, and produce a fine spray at engine idle conditions. The injector can also be used to inject simultaneously both liquid and gaseous fuels. An experimental approach is adopted in the present study to characterize initially the spray and fuel placement emanating from this injector. The fuel injector consists of two streams of air, viz. through inner section of the tube and another swirling stream merging downstream of the tube. Jet-A fuel is injected through the surface of the porous tube. Due to the permeability of the tube, a thin liquid sheet is produced along the tube which is atomized by the inner airstream by surface stripping of the liquid sheet. Further, a secondary breakup occurs downstream of the tube. The swirl vane angle and air split are selected to increase the amount of air through the tube and enhance the atomization. Flow visualization studies show a hollow conical spray. Patterator tests are carried out to study the fuel distribution and symmetry of the spray. The results show a hollow cone spray with asymmetric distribution of volume flux. Spray characterization is further carried out with PDPA at selected operating conditions. The measured SMD shows that the atomization is reasonably good with wide fuel placement downstream of the atomizer at atmospheric conditions.

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Introduction

The development of next generation aero-engines is predominantly driven by NOx requirements. The current state of low NOx technology is governed by the improvements made to the conventional Rich burn, Quick quench, Lean burn (RQL) combustor design. This approach has limited potential to cope with the stringent emission standards in future. To cater for these standards, a revolutionary step has been taken towards lean combustor technology in United States. Similar approach is adopted in European Union with LowNOx programs from early 1990s.

It’s well understood that NOx formation is primarily governed by flame temperature and residence time of the species in the combustor. Lean combustor operates with excess amount of air in the primary reaction zone of the combustor at high power conditions. The excess air reduces the adiabatic flame temperature in the primary zone reducing the NOx emissions. Due to fast rate chemical kinetics, the length scales of the reaction zone are smaller thereby reducing combustor length and the residence time for thermal NOx formation. Several technologies have been developed like lean premixed (LP), lean premixed and pre-vaporized (LPP, LP (P)), dual annular staged combustion and concepts like GE TAPS combustor [1]. Though these technologies are promising, there are several issues associated with these including static and dynamic flame stability problems as well as auto ignition concerns. Atomization of fuel and fuel-air mixing plays an important role in these lean combustor designs [2-7].

One of the other promising concepts of lean burn combustion is Lean Direct Injection (LDI), developed as an ultra-low NOx combustion scheme for future aviation gas turbines that has potential to reduce NOx emissions down to ppm level. In the LDI concept, the liquid fuel is directly injected into the combustion chamber of a gas turbine enabling rapid mixing with air at lean fuel-to-air ratios. The architecture of the LDI combustor makes it compact with small residence time, low temperatures and significant size and weight reduction of the combustor with lesser requirements for liner cooling air tending towards convective cooling in the primary zone thereby increasing combustion efficiency. LDI can operate on wide range of alternate fuels such as FT process Jet Fuels, Hydropressed fuels, 100% blended fuels and biofuels. The LDI strategy facilitates rapid and uniform premixed combustion under lean operation, resulting in lower peak temperatures and low residence times. A rapid fuel evaporation process and fuel-air mixing is supposed to eliminate local hot spots in this technology, thereby producing a uniform temperature distribution within the combustion chamber. The technology improves combustor exit temperature profile which will increase the life of the turbine components. While the concept of the LDI system is comprehensive, achieving the required levels of performance can be challenging. Lean combustion systems are prone to localized extinction and re-ignition. This along with localized heat release zones can trigger axial acoustic modes in the combustor leading to combustion instabilities [8, 9]. The instabilities results in significant increase in the heat loads on the combustor liners potentially causing structural damage of the chamber. Furthermore, limitations in atomization, fuel-air mixing and evaporation will result in varied stoichiometric ratios in the reaction zone yielding higher than desired NOx levels. Accordingly, there is an ongoing need in the art to further develop LDI systems with novel injection and fuel placement concepts that can achieve enhanced atomization quality, increased fuel-air mixing rates, low levels of combustion instabilities, low pollutant and particulate formation, improved lean blow-out margins and improved turndown ratio.

To overcome the above mentioned issues with the previous art in the LDI technology, new methods are under consideration for improving the stability of the LDI combustors. One of the methods is to make the injectors smaller and inject the fuel through large number of injectors thereby improving the mixing of fuel and air. The advantage of splitting into smaller multiple swirler zones has benefit of effectively using the air for atomization. For larger swirlers, though excess air goes through the swirler, the amount of air contributing to atomization of the liquid fuel is far less and local AFR can be low. By using multiple swirlers the overall AFR is evenly distributed. The amount of swirl strength and size of the fuel injector/air-swirlers will be based on the flashback, LBO and auto ignition characteristics of the LDI combustor taking into consideration the requirements for alternative fuels. The flame lengths will be smaller and the combustors length can be reduced giving less residence time for NOx formation. However, for smaller injectors fuel injection/delivery strategy to the injector is critical. Methods have to be developed to improve the fuel-air contact surface and uniform fuel distribution in the injector. Furthing this technology for dual phase fuel injection (liquid and gas simultaneously) and alternate fuels from the same injector, fuel injection strategy is even more critical. In purview of this need, a novel injector is designed to improve the fuel injection delivery to the injector such that there is improved atomization and mixing of fuel and air.

Experimental Setup

The experiments are carried out in Combustion Research Lab (CRL), University of Cincinnati. In the present study, a novel injector is designed with porous
material for injecting fuel into the injector. The injector has two counter rotating swirlers and straight flow for air and a porous surface for fuel inlet. The isometric and cross-section views of the injector are shown in Figure 1. The injector is 3D printed by rapid prototyping from Acrylonitrile Butadiene Styrene (ABS) plastic material. The injector is made of two parts. The lower part consists of a plenum to house the porous tube from where fuel is injected. The fuel is injected through the porous tube. As the fuel emanates from the porous tube, it forms a thin liquid sheet on the inner surface of the porous tube. The air flows through the straight porous tube aids in atomization of the fuel. Downstream of the porous tube, a secondary swirling air comes in contact with the liquid sheet for further atomization. The conical angle at the end of the porous tube is set at 60°. The length of the porous tube is 20 mm. The spray and air flows through the inner venturi. The tertiary swirling out air stream merges with the flow through the venturi. In the present experiments only liquid fuel is injected. The inner surface acts like a prefilming surface. Unlike conventional injection of liquid through slit, injecting over a surface enhances fuel-air contact area and improves surface stripping of liquid sheet thereby improving atomization. Gaseous fuels or simultaneous gaseous and liquid fuel can also be injected through the porous tube at low momentum flux ratio to enhance the mixing with gaseous fuel injected on the upper section of the plenum. In the scenario of simultaneous injection of both liquid and gaseous fuels a combination of surface stripping and barbotage atomization will occur.

All experiments are carried out at ambient conditions and carried out at different equivalence ratios and pressure drops across the injector. The operating conditions are listed in Table 1. During the PDPA experiments the pressure drop (ΔP) across the injector is kept constant at 4% and equivalence ratio (φ) at 0.6 which matches fuel lean combustion in engine operation.

<table>
<thead>
<tr>
<th>ΔP</th>
<th>1%</th>
<th>2%</th>
<th>4%</th>
<th>4%</th>
</tr>
</thead>
<tbody>
<tr>
<td>equivalence ratio (φ)</td>
<td>0.6</td>
<td>0.6</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>fuel flow rate (mf) (g/s)</td>
<td>0.28</td>
<td>0.42</td>
<td>0.42</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Table 1. Experiment operating conditions

Flow Visualization
Flow visualization is carried out to measure the spray cone angle and distribution along the spray. A 450nm wavelength laser sheet is used for visualization. The laser is aligned along the center plane of the injector to illuminate the droplets. The images of the spray are taken at different exposures of 1/15s, 1/500s and 1/1000s.

Patteranator Test
Spray patternator is used to investigate spray characteristics such as spray angle, fuel distribution along the cross section of the spray and a quantifiable symmetry. SetScan patternator, Model OP-600, is used in

Figure 1. Schematic of the pre-mixer
The test setup for investigating the spray is shown in Figure 2. The air is supplied to the test rig from a compressor at 10 bar and at temperature of 25°C. The maximum mass flow rate that can be supplied is 0.5 Kg/s. The air is fed to the air-plenum of the test setup to which the injector is attached. In these experiments, the air plenum is mounted on the traverse system. The air flow rate is controlled by a dome pressure regulator and a gate valve. In the experiments, Jet- A fuel is supplied to the injector plenum from a fuel tank. The fuel is injected using fuel pump and the mass flow rate is controlled using a needle valve. The fuel mass flow rate is measured with a micro-motion mass flow meter, CMF10.
these experiments. The patternator is a laser extinction tomography system that provides the drop surface areas density (number of drops per unit volume at a specific location multiplied by the surface area of the drops). The local transfer phenomena such as mass, momentum, energy and species are directly proportional to the surface area density of droplets in the spray. It has six lasers which are used to form laser sheets as shown in Figure 3. Linear photodiode array detectors are placed on the other end of the sheet. As the spray is illuminated by the laser sheet, the light extinction of the sheet is measured by the detector. Initially, calibration of the local extinction coefficients is carried out. The path integrated extinction of laser sheets is linearly proportional to drop surface areas density for liquid sprays, can be obtained. The data obtained from the detectors is used to reconstruct the distribution of the spray in the cross section plane.

![Figure 3. SETScan Patternator](image)

**Figure 3. SETScan Patternator [10]**

**PDA Measurements**

A 2-D standard PDA setup, Artium PDI-200, is used for the spray measurements. The PDA transmitted and receiving optics is mounted on a fixed frame. A green, $\lambda = 532$ nm, and a blue beam, $\lambda = 473$ nm are used for measuring size and two velocity components of the droplets. Figure 4 shows the schematic of the PDA setup and the coordinate system. A lens of 500 mm focal length is used on the transmitting optics to converge the beams to form a measurement volume. A lens of 1000 mm focal length is used on the receiving optics. The beam separation is 60 mm. The slit width is 200 $\mu$m, and the fringe spacing is 4.4 $\mu$m for green beams. Due to the presence of obstructions around the test setup, the receiving optics is positioned at $\alpha = 30^\circ$. A total of 30,000 samples are acquired at each measurement point with 45 s maximum for acquisition. The PDA system is FFT based. The sampling rate, mixer and analog filters are set such that the validation rates are 80% in the regions of maximum volume flux.

Measurements are also carried out in a square grid of 25×25 points from $x = -40$ to 40 mm and $y = -40$ to 40 mm for characterization of the final SMD and the dispersion of the spray. The measurements are carried out at 25 mm downstream of the injector. Usually, the flame front is around 25 mm in gas turbine combustors. At these length scales, the reliability of PDA measurements is affected by the resolution of the measurements and spray density. As the measurements are carried out at atmospheric conditions, the maximum data rates observed are around 10 KHz giving high validation rates not significantly affected by spray density.

![Figure 4. Schematic of the PDPA technique](image)

**Results**

The images obtained from the laser sheet visualization of spray along the direction of flow are shown in Figure 5. The images are taken at pressure drop of 4%. Figure 5(a) and (c) are time averaged images while Figure 5(b) and (d) are instantaneous images. The images are at two equivalence ratios of $\phi = 0.4, 0.6$. Figure 5(a) at $\phi = 0.4$ shows that the spray spreads downstream of the injector. The fuel concentration is low in the center and at outer edges of the spray with maximum concentration reaching half way between the outer edge and the center. This suggests that the spray is hollow cone. It can also be observed that the spray has asymmetry with higher fuel concentrations on the right side of the injector. Similar observations can be made at $\phi = 0.8$, Figure 5(c).

Spray angle is another important parameter to analyze the quality of the atomizer. The spray angle is measured by marking the outer edge of the spray. The spray included angle is ~100$^\circ$ in both cases. The instantaneous images Figure 5(a) and (c) shows that the fuel concentration varies with pockets of high concentrations along the axis of the spray. Large droplets can be observed on the outer edges of the spray. This suggests that the spray has instabilities and the fuel concentrations fluctuate around the circumference of the injector probably due to the asymmetry of the spray. This is also observed visually.

In order to confirm the flow asymmetry and instantaneous fluctuations, spray patternator tests are carried out. Fuel concentration distribution, surface area densi-
Symmetry of the spray and spray angle calculation are obtained from spray patternator tests.

![Patternator Images](image)

**Figure 5.** Flow visualization of spray ($\Delta P = 4\%$)

Spray patternator tests are carried out at two equivalence ratios, two pressure drop conditions and at 12.7 mm and 19.05 mm downstream of the atomizer. Table 2 shows the operating conditions and the spray angle measured from the patternator experiments. In Case d, spray angle measured from patternator matches with the calculation result from spray visualization.

<table>
<thead>
<tr>
<th>Case</th>
<th>Pressure Drop</th>
<th>$\phi$</th>
<th>h (mm)</th>
<th>Spray Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2%</td>
<td>0.6</td>
<td>19.05</td>
<td>115.8</td>
</tr>
<tr>
<td>b</td>
<td>2%</td>
<td>0.8</td>
<td>19.05</td>
<td>111.54</td>
</tr>
<tr>
<td>c</td>
<td>2%</td>
<td>0.6</td>
<td>12.7</td>
<td>118.8</td>
</tr>
<tr>
<td>d</td>
<td>4%</td>
<td>0.6</td>
<td>12.7</td>
<td>120.7</td>
</tr>
</tbody>
</table>

**Table 2.** Results of spray angle calculation

Figure 6 (a) and (b) represent droplets surface area density distribution at 19.05 mm downstream of atomizer. Figure 6 (c) and (d) represents droplets surface area density distribution at 12.7 mm downstream of the atomizer. The droplets surface area density is the product of the droplets surface area and the counts of droplets per unit volume. The surface area density is a significant parameter in combustion application due to the high correlation to local evaporation rate. Fuel concentration distribution is also proportional to droplets surface area density which is represented in Figure 6. Figure 6 (a) and 6 (b) are at pressure drop of 2% and at equivalence ratio $\phi = 0.6$ and $\phi = 0.8$. As it is evident, the droplets spray surface area density increases with equivalence ratio. This is primary due to the increase in fuel flow rates. An increase in fuel rates leads to higher volume flux and higher droplet density. Figure 6 (c) and 6 (d) exemplifies that at same equivalence ratio condition, higher droplet surface area density and fuel concentration distribution can be obtained by increasing pressure drop. As the pressure drop across the injector is increasing, the velocity of air is increasing leading to increase in surface stripping of liquid sheet on the porous tube. The increased surface stripping improves atomization and much finer droplets are formed. The smaller droplets have higher surface to volume ratio there by increasing the droplets surface area even when the mass flow rate of fuel is kept constant. Figure 6 (a) and 6 (c) shows that as downstream distance increases from the injector, the spray expands.

In all of the four cases discussed above, a hollow cone spray is observed, as evident from the contour plots, with lower fuel concentration in the center of the spray shown by green color, and higher concentration distribution in the form of an inner ring shown by red color. This is due to the atomization of the liquid sheet which is produced along the inner circumference of the porous tube. The liquid sheet is atomized by air entering through the porous tube through surface stripping phenomena [11].

Similar to the observations made in Figure 5, the spray is asymmetric with higher concentrations on upper right side of the spray. It is observed that some of the gaps between the vanes of the inner swirler are blocked during 3d printing of the injector causing non-uniform distribution of air leading to higher spray concentrations on the right side of the atomizer.
Figure 6. Droplet surface area density distribution

Spray angle is calculated from the patternator data. It is defined from the distance from the atomizer to the location of spray pattern and the radius of spray pattern which is calculated from 95% surface area of pattern. The calculation is given in Equation 1 and shown in Figure 7.

$$\theta = 2\tan^{-1}\left(\frac{r}{h}\right)$$ (1)

The results of spray angle are listed in Table 2. Under same operation condition, spray angle remains same as downstream distance changes. Also as pressure drop stays same, higher equivalence ratio results in smaller spray angle.

Figure 7. Spray angle Calculation

PDA Measurements
Droplet size measurements are carried out to access the spray distribution downstream of the injector. The measurement grid is rectangular. The data obtained is further processed and interpolated into a circular grid. The data is filtered such that there is minimum of 5 Hz data rates at any given measurement point. The data is processed with Artium software. PDA measurements are carried out at $\Delta P = 4\%$ and $\phi = 0.6$ condition. Figure 8 shows the contour plot of mean diameter $D_{10}$. The contour plot shows a uniform distribution of mean diameter with higher droplet diameters on the outer periphery of the spray. Further the mean diameter is higher on the right side. This is, as explained in the earlier sections, due to the higher volume flux on the side of the spray. This is also evident from the volume flux data obtained from PDA measurements. Figure 9 shows volume flux distribution obtained from the PDA measurements. As can be observed the volume flux is higher on the right side of the spray. The reason for higher volume flux is already explained in the earlier section. A low volume flux region is observed on the periphery of the spray which is expected. Further a concentric ring of low volume flux around the higher volume flux region is observed which is not observed in the patternator data. This is not clear from the PDA data acquired. Further PDA data analysis needs to carried out to explain the difference between volume flux distribution between PDA and Patternator.

Figure 10, shows the contour plot of SMD (Sauter Mean Diameter) $D_{32}$. Similar to $D_{10}$, the $D_{32}$ shows a uniform distribution in the spray with marginally higher diameter on the right side of the spray. Also, higher droplet diameters are observed on the outer periphery of the spray which is expected. The uniformity in the distribution is mainly to the process of the atomization. The atomization occurs due to the surface stripping of the liquid sheet [11]. In the present scenario, as the liquid emanates from the micro porous, the fuel is spread uniformly on the inner walls of the porous tube (in comparison the liquid sheet from a slit of any standard airblast atomizer depends on the manufacturing tolerances of the slit). SMD is important
parameter in the applications for combustion as it determines the surface area available for evaporation of fuel for a given volume of the droplet. The average mean diameter and SMD is calculated based on the weighted volume flux distribution as shown below.

\[ \bar{D}_{10} = \frac{\sum V_i D_{10i}}{\sum V_i} \]  \hspace{1cm} (2)

\[ \bar{D}_{32} = \frac{\sum V_i D_{32i}}{\sum V_i} \]  \hspace{1cm} (3)

where \( \bar{D}_{10}, \bar{D}_{32} \), is the weighted average diameters of the spray, \( V_i \) is the local volume flux and \( D_{10i} \) is the local mean diameter, \( D_{32i} \) is the local SMD. The average mean diameter, \( D_{10} \), of the spray calculated is \( \sim 23 \) \( \mu \)m and the average SMD, \( D_{32} \), is 49.2 \( \mu \)m. Further data analysis is underway to characterize the spray at different operating conditions.

Conclusions

Spray visualization, patternation and PDA tests are carried out on a novel airblast injector with porous stainless steel tube to increase the surface area of contact between the fuel and air to enhance atomization. Experiments are carried out at lean fuel air ratios. A hollow cone spray is observed downstream of the injector with lower concentrations in the center of the spray, and higher in the inner ring.

Droplets surface area density distribution and spray angle are investigated by spray patternation tests. Surface area density increases with equivalence ratio due to higher volume flux. Surface area density of droplets also increases with higher pressure drop across the injector. This is due to the smaller droplet size. Spray angle is calculated from 95% surface area of pattern, and the results match with the calculation from spray visual images. The spray angle is \( \sim 100^\circ \).

Volume flux distribution and droplet size measurements are analyzed by PDA measurements. A uniform distribution of mean diameter with bigger droplets on the outer periphery of the spray is observed. A low volume flux region on the periphery of the spray is observed. The weighted mean diameter is \( \sim 23 \) \( \mu \)m and weighted SMD is \( \sim 49.2 \) \( \mu \)m.

Acknowledgements

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Nomenclature

- \( \Delta P \): pressure drop
- \( \varphi \): equivalence ratio
- \( m \): mass flow rate
- \( \lambda \): wavelength
- \( \alpha \): receiving optics position
- \( x \): axis
y axis
h atomizer height
θ spray angle
r radius of spray pattern
D diameter
V volume flux

Subscripts
f fuel
i local
D_{10} mean
D_{32} SMD

Superscripts
- average

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