Optical and Mechanical Patternation of an High Flow Rate Industrial Gas Turbine Nozzle

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Abstract

Many industrial gas turbine nozzles have a very high flow rate of fuel. Performing optical and mechanical characterization of these high flow rate nozzles is of interest for quality assurance and nozzle improvement programs. In particular, the objective of the study is to determine the impacts on performance of a nozzle tip redesign initiated to improve fuel injector performance. Towards this end, optical and mechanical patternation of the original and a proposed redesign are discussed. The SETscan optical pattenator that is used in this study is based on statistical deconvolution of path integrated extinction measurements obtained at six view angles and 512 parallel paths at each view angle. The local drop surface area per unit volume is obtained from the deconvolution. The drop surface areas are directly proportional to the local mass, momentum, energy, and species transfers. Although obstruction caused by the fuel drops was greater than 90% at the center of the spray, the theoretically calculated path integrated extinction based on the local surface areas reported by the pattenator agrees within 1% of the measured path integrated extinction. Therefore, the nozzles provide an efficacy test of the SETscan optical pattenator for highly obscuring sprays. Also, mechanical patternation is performed using a twenty four-sector pattenator. The angular distribution of mass fluxes obtained from both the mechanical pattenator compares reasonably well with the angular distribution of surface area densities obtained from the optical pattenator. The differences between the original and the re-designed nozzle are immediately apparent with the optical pattenator. Based on the study, the feasibility of evaluating design and development iterations of high flow rate nozzles using optical patternation is demonstrated.

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**Introduction**

Spray patternation is the spatial distribution of the mass flux or the surface area density of droplets in a plane perpendicular to spray centerline [1]. Spray patternation is important in several applications. For example, spray patternation is important in internal combustion (IC) and gas turbine engines to ensure the highest combustion efficiency while minimizing pollutant production [2]. In paint coating sprays, asymmetries in the pattern leads to poor finish quality [3]. In spray drying processes, a symmetric pattern is required to ensure product homogeneity [4]. Therefore, assuring the quality of nozzles using patternation is important in a wide variety of industrial applications [5].

There are several different types of patternators, both mechanical and optical. Mechanical patternators typically collect the mass flux of liquid in small containers [2,6] or onto papers [7] that are then weighed to provide local information. However, mechanical patternators disturb the flow to a great extent even when care is taken to sample the spray iso-kinetically. This is due to a stagnation layer that is built up when the spray impinges onto the collector. The problem is less severe in patternators that have just pie segments and evaluate only the angular uniformity of the mass flux in sprays. Radial patternation using intrusive mechanical patternators is not as accurate for quantitative purposes [4,5]. In addition, only very limited spatial resolution is available with mechanical patternators. Any attempt to improve the spatial resolution leads to unacceptable inaccuracies due to the stagnation layer.

Several types of optical patternators have been proposed to address the inaccuracies caused by the intrusive nature of mechanical patternators [8-13]. Optical patternators typically provide the distribution of drop surface areas rather than the mass flux. In many instances, this is advantageous as all local transfer phenomena, such as mass; momentum; energy and species are directly proportional to the surface area density of the droplets in the spray [5].

There are three principal types of optical patternators [1]. The most common optical patternator is based on obtaining images of Mie scattered light from the drops within the spray and analyzing the images. The second type is based on exciting a dopant (normally mixed with the working fluid) with a high-powered laser, and analyzing the fluorescent images given by the excited molecules of the dopant. Both these methods have several potential sources of errors, such as laser extinction, signal attenuation, and secondary emission [1] associated with them. Therefore, these two methods are not capable of analyzing even moderately dense sprays. The third type of optical patternation is based on extinction tomography, and has the potential to analyze highly dense sprays. The major limitation with extinction tomography is that the spatial resolution obtained is slightly lower than is possible using a laser sheet imaging patternator, although it is still much higher than a mechanical patternator’s resolution. Despite these limitations, in a wide range of applications, optical patternators are gaining acceptance as a rapid, efficient and detailed tool for nozzle development and nozzle quality assurance. This is primarily due to the ease of use and their ability to discern much smaller differences amongst similar nozzles than possible with mechanical patternation.

Successful patternation of optically dense sprays based on extinction or indeed any other optical method has not been reported in the literature. Motivated by the above discussion, the objective of the present work is to evaluate the performance of extinction tomography for analyzing optically dense sprays. In particular, the capability to discern small differences between two nozzles with the same flow rates forms the focus of the evaluation.

**Experimental and Theoretical Methods**

Two high flow rate industrial nozzles are used in this study. One, referred to as “new”, is intended as a design improvement over the other, referred to as “old”. Although both injectors have the same flow number, as a result of design improvements, their spray and patternation characteristics are slightly different.

Each nozzle is suspended above the patternator and is mounted in such a way that they spray down into the measurement interrogation region. A layer of porous media is placed below the optical patternator so that the exhaust flow does not disturb the spray. The test fluid used is MIL–PRF-7024E Type II. Three fuel flow rates of 240, 350, and 475 pounds per hour are used for the evaluation of the optical and mechanical patternators. Air assist is provided to the nozzle at 3 psi. The apex distance for the mechanical patternator is three inches. The apex distance for the optical patternator is 2.5 inches. Optical patternation of the nozzles is completed using the SETscan patternator (En’Urga Inc., Model No. OP-600). A photograph of the experimental arrangement used for the optical patternation is shown in Fig. 1.

The SETscan optical patternator [11] measures path-integrated absorptance (1 – extinction) at six view angles, and 512 parallel paths at each view angle. The maximum spray diameter that can be accommodated using the OP600 patternator is seven inches. The path-integrated absorptances are deconvoluted to estimate the local drop surface area density within the spray. The spatial resolution of the instrument is
approximately one millimeter in the radial direction and five degrees in the angular direction.

Figure 1. Photograph of experimental arrangement used for optical patterning.

Mechanical patterning is achieved using a standard twenty-four sector patternator. The mechanical patternator collects the fluid into twenty-four pie shaped compartments and weighs them to provide the mass flux distribution as a function of angle. The mechanical patternator provides an angular resolution of fifteen degrees.

Results and Discussion

The radial profiles of path integrated absorptance measured by the optical patternator for the six view angles are shown in Fig. 2.

These measurements are obtained for the new nozzle with a flow rate of 475 lbs/hr. For ease of display on the same graph, a constant has been added to the path-integrated extinction, depending on the axis number. For example, for the first axis, the constant is zero, for the second axis the constant is 0.1, and so on. The peak absorptances for the six view angles vary between 0.92 and 0.94. This confirms that the spray is extremely dense. An additional factor to note is that the spray is not perfectly axisymmetric. This is readily apparent since the radial profiles of the path-integrated measurements for the six view angles are not identical. In addition, there are clear differences between the left part and the right part of the radial profile of path-integrated absorptances obtained at a single view angle.

One test of the efficacy of the optical patternator to analyze such dense sprays is to ensure that the deconvolution algorithm provides a good convergence with the measured absorptance profiles. The measured and calculated (from the deconvoluted local spray properties) radial profile of path-integrated absorptances for one axis is shown in Fig. 3. The measurements were obtained with the new nozzle at a flow rate of 475 lbs/hr.

Figure 2. Radial profiles of path-integrated absorptance measured using the optical patternator.

Figure 3. Measured and calculated radial profile of path-integrated absorptance at the point of convergence of the deconvolution algorithm for the first axis.

The absolute differences between the calculated and measured values are less than 0.5% at all points where the path-integrated absorptances are greater than one percent. Similar agreements between the measured and calculated radial profiles of path-integrated absorptances are obtained for the other five view angles. This confirms that the MLE deconvolution algorithm [14] does provide for the optimal solution even for highly dense sprays.

The deconvoluted surface area per unit volume for the new nozzle is shown in Fig. 4. As anticipated, the spray has a hollow cone type behavior; where there is much lower drop surface area density in the center than
at the periphery. However, the drop surface area density does not fall to zero at the center of the spray. In fact, the surface area density at the center of the spray is approximately twenty-five percent of the peak value seen in the ring. This is typical of a large class of industrial nozzles that are classified as hollow cone sprays. For mechanical patternators capable of such measurements, radial distribution cannot be reliably obtained due to the stagnation layer at the center of the patternator. If radial patternation were obtained with such a mechanical patternator, the ratio of total mass flux at the center to the total mass flux near the periphery would be much lower. Since smaller drops follow the air stream, smaller drops exacerbate the effect. This is the primary reason that mechanical patternators are not recommended for radial patternation of nozzles.

All further spray characterization is based on the distribution of local surface area densities like those shown in Fig. 4. There are several potential quantitative features that can be used to assess the performance of the nozzle. The first performance characteristics used to assess nozzles is the angular uniformity of the surface area densities. The angular uniformity has been traditionally characterized by the patternation number \[ P_z \] as defined below:

$$ P_z = \frac{Z_{\text{max}} - Z_{\text{min}}}{Z_{\text{ave}}} $$

where \( Z_{\text{max}} \) is the maximum value of the mass flux or surface area density in any sector, \( Z_{\text{min}} \) is the minimum value, and \( Z_{\text{ave}} \) is the average value.

One source of error in estimating the angular uniformity is the potential misalignment of the nozzle center with the patternator center during the measurement. If the nozzle is grossly misaligned with the center of the mechanical patternator, it is easy to discern. The mass flux distribution will have a marked bow in the angular pattern [5]. This is because half of the sectors on one side of the mechanical patternator will have higher mass flux value than the other side. This can be explained best with the aid of the small cartoon shown in Fig. 5.

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**Figure 4.** Contour plot of local surface area density within the highly dense spray.

**Figure 5.** Cartoon showing the effects of misalignment on the results obtained using a mechanical patternator.

In Fig. 5, the spray nozzle is shown misaligned with the center of the nozzle. The center of the spray nozzle is inside the sector labeled one of a twelve-sector patternator. The mass flux with an ideal nozzle will be the highest in sector one and the lowest in sector seven. There will a systematic decrease in the mass flux from the highest value in sector one to the lowest value in sector seven. This profile will be symmetric around sector seven, leading to a bowed profile. In addition, the patternation number obtained will be higher.

The optical patternator provides a means of testing the sensitivity of the patternation number to the placement of the nozzle center. The center of the optical patternator can be placed at any location in the domain and the patternation number can be calculated. The variation in the patternation number calculated with the assumed center of the nozzle varying by about 3 mm in the x-y plane is shown in Fig. 6. The results shown are for the new nozzle with a fuel flow rate of 240 lbs/hr. The patternation number varies from a low value 0.138 (at x = -0.74 mm, y = 0.59 mm) to a high value of 0.340 (at x = 1.0 mm, y = -1.0 mm).
The results therefore indicate that the patternation number can vary by as much as 250% when the center is shifted by less than 2.5 mm. This implies that to obtain patternation numbers with a +/-20% accuracy, the nozzle will have to be positioned within half a millimeter of the actual center of the patternator. This was possibly achieved for the mechanical patternator, but not for the optical patternator. In addition, the lowest value for the patternation number is obtained, when the deconvolution is performed with the center of the nozzle being assumed to be at the absorption weighted center of the spray.

The change in the angular distribution of surface area densities when the assumed center is changed from the absorption-weighted center to the geometric center for the new nozzle is shown in Fig. 7.

It is clear that significant variation can occur in the angular distribution of the surface area densities with a small change in the alignment of the nozzle to the center of the patternator.

The angular distributions of the mass flux (mechanical patternation) and surface area density (optical patternation) for the two nozzles at a fuel flow rate of 240 lbs/hr are shown in Fig. 8.

The angular distributions of the mass flux and surface area density for the two nozzles at the other two flow rates are shown in Figs. 9 and 10.

For the sake of consistency, all results shown in Figs. 8 to 10 are calculated with the center of the nozzle assumed to be at the center of the patternator.
In general, it is preferable to calculate all values based on the geometric center, since patternation numbers calculated using the absorption weighted center can show very low values even when a visual examination of the contour show a high degree of asymmetry in the nozzle.

No attempt was made to match the orientation of the two nozzles to the two instruments during the measurements. Therefore, the results for the mechanical patternator have been rotated to provide for the highest correlation between the mass flux measurements and the surface area density measurements obtained with the optical patternator. A line is also drawn in the figure that shows the theoretical angular distribution that would be obtained from a perfectly symmetric nozzle. The angular profiles obtained by both the mechanical and optical patternator are very similar. Both instruments show some asymmetry for both fuel nozzles, old and new.

It is difficult to rank the quality of the nozzles from purely looking at the results shown in Figs. 8 to 10. There are two possible methods of ranking the performance of nozzles based on their angular distribution. The first is to use the patternation number, defined by Eq. 1. Another potential method is to assess the overall deviation from the theoretically perfect (shown by the solid line) nozzle. The L2 norm, defined as the distance between two lines, can be calculated as:

$$L_2 = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Z_i - Z_{ave})^2}$$

where N is the number of discrete locations where the surface area density $Z_i$ are estimated. The results obtained for the two nozzles using both these methods are shown in Table 1.

**Table 1: Patternation numbers obtained with the mechanical and optical patternators.**

<table>
<thead>
<tr>
<th>Flow rate (lbs/hr)</th>
<th>Patternation number</th>
<th>L2 Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New</td>
<td>Old</td>
</tr>
<tr>
<td>240 (Opt.)</td>
<td>0.207</td>
<td>0.218</td>
</tr>
<tr>
<td>350 (Opt.)</td>
<td>0.142</td>
<td>0.188</td>
</tr>
<tr>
<td>475 (Opt.)</td>
<td>0.210</td>
<td>0.211</td>
</tr>
<tr>
<td>240 (Mech.)</td>
<td>0.129</td>
<td>0.212</td>
</tr>
<tr>
<td>350 (Mech.)</td>
<td>0.147</td>
<td>0.208</td>
</tr>
<tr>
<td>475 (Mech.)</td>
<td>0.234</td>
<td>0.152</td>
</tr>
</tbody>
</table>

It can be seen that, except for the highest flow rate as measured by the mechanical patternator, the design change improved the patternation. Given the differences that can arise from misalignment of nozzle centers, the agreement in the patternation numbers and L2 norm between the two patternators are reasonable. Over the three flow rates, the optical patternation data show a similar trend: Both injectors display a minimum in patternation number at the moderate flow condition (350 pph). The mechanical patternation data does not show this trend. In fact the mechanical data show opposite trends. The old nozzle performs at a higher patternation level at the lower flow rates and then drops approximately 28% at the high flow rate whereas the new nozzle performs at a lower patternation level at the two low fuel flow rates and then jumps 70% at the high flow rate. This phenomenon is not well understood.

In addition to the angular pattern, the radial pattern of the drop surface area densities can also be obtained using the optical patternator. No attempt was made to perform radial patternation with mechanical devices since the one used is incapable of making such measurements. The radial distributions of drop surface area densities for the two nozzles are shown in Fig. 11.

The radial distributions for the new nozzle are shown as a solid line, while that for the old nozzle are shown as solid symbols. Two observations can be made from the radial distribution. In general, the peak value in the radial distribution increases with flow rate, while the value at the center of nozzles remains constant. This implies a greater hollow cone type behavior with flow rate. The new nozzle has a narrower profile than the old nozzle. This implies that the spray angle (defined as the angle that includes ninety-five percent of the surface area densities [5]) has decreased due to the design alteration. This can be confirmed by looking at the variation in spray angles with flow rates for the two nozzles.
The radial distributions of drop surface area densities for the two nozzles are shown in Fig. 11. The spray angles obtained at the three flow rates for the two nozzles are shown in Fig. 12.

![Figure 11](image1.png)

**Figure 11.** The radial distributions of drop surface area densities for the two nozzles.

The spray angles obtained at the three flow rates for the two nozzles are shown in Fig. 12.

![Figure 12](image2.png)

**Figure 12.** The variation in spray angles obtained using the optical patternator for the two nozzles.

Two angles are shown in Fig. 12. The one on the top shown with the solid lines and symbol is the spray angle. The spray angles decrease by approximately five to ten degrees due to the design change. The angle shown in the bottom of the Fig. 12 is the deviation angle. The deviation angle is the angle subtended by the center of mass of the surface area densities with a vertical line drawn through the center of the nozzle. It is a measure of the skewness of the spray. The results show that the spray from the old nozzle is slightly more askew than the new nozzle. This is either a result of inconsistencies in the mounting of the nozzle with respect to the patternator, a result of manufacturing variations or, far less likely, design differences.

By design, for both the old and the new nozzle, the total mass flow rates are the same. However, the total surface area density can vary either due to a difference in the number of droplets in the measurement plane or a variation in the drop sizes. The average and RMS of surface area densities at an apex distance of 2.5 inches for the two nozzles are shown in Fig. 13.

![Figure 13](image3.png)

**Figure 13.** The mean and RMS of surface areas for the two nozzles as a function of the fuel flow rate.

There is a slight decrease in both the mean and RMS surface area densities with the design change. This is expected since the radial spread of the drop surface areas have decreased substantially. Based on the results of the radial spread, it was anticipated that the surface area density would increase significantly. In fact, it has decreased. This implies that potentially, atomization is poorer due to reduced drop/atomizing air interaction. This needs to be confirmed with additional experiments.

**Conclusions**

The following conclusions were obtained from the present study.

1. Extinction tomography can be used to obtain local information in sprays even when the obscuration exceeds 90%.
2. Alignment of the nozzle center with the patternator is very critical for the mechanical patternator.
3. Angular patternation using the optical patternator can be performed with the axis being in an off-center location without any degradation in the results obtained.
4. Results obtained with the optical patternator are in general more consistent than the ones obtained with the mechanical patternator.
Acknowledgement

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References