Endoscopic System to Measure Fuel Spray Distribution in a Gas Turbine Augmentor

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Abstract
This paper discusses the development of an endoscopic PIV system for measuring fuel spray droplet size and velocity distributions inside gas turbine engine augmentors. The size range of interest is about 10 µm to 500 µm, while the velocity can reach 300 m/s. The size of the droplets is measured with a combination of ILIDS (small droplets) and glare points (large droplets) while the velocity is measured with PTV. A model is presented to optimize the thickness of the laser sheet with respect to the maximum droplet size. Experiments show that this thickness should be about 4 to 5 times the droplet diameter to avoid the presence of single glare points. Endoscopes with a resolution of 50 line pairs per mm were developed.

Introduction
The fuel spray distribution in a gas turbine augmentor affects both the performance and fuel efficiency of the engine. We are developing optical endoscopes to measure the spray drops size and velocity distributions. Environmental conditions inside the augmentor can reach 1900ºC and 75 psia; however, the endoscopes would only have to withstand a temperature of 90ºC, since they would be protected from the harsh environment by cooling sheaths developed at Arnold Engineering Development Center in the USA (Hiers and Hiers 2002, MacKinnon, Beitel, and Catalano 2004, Hiers and Hiers 2002). The measurement system would include two endoscopes: 1) an illumination endoscope to illuminate the spray with a pulsed laser sheet, and 2) an imaging endoscope to collect the light scattered from the droplets. Two versions of the imaging endoscope were produced. The first is 400 mm long and 25 mm diameter and is made of eight lenses for an end-to-end imaging resolution of 50 line pairs per mm. The second is about 500 mm long and 12.7 mm diameter and is made of twenty lenses for an end-to-end imaging resolution of 50 line pairs per mm. The illumination endoscope is about 500 mm long and 6 mm diameter. The two endoscopes will be mounted in cooling sheaths and traversed together across the spray field to profile it. The laser (Continuum Minilite PIV) and two cameras (LaVision Imager Pro X 2M CCD) are mounted on a common platform with the endoscopes. Figure 1 shows a conceptual design of the system. The collection angle, as discussed below, was selected as 70 degrees.

To measure the droplet size distribution in a plane, we employed a modified version of Interferometric Laser Imaging for Droplet Sizing (ILIDS) as was originally discussed by Glover, Skippon, and Boyle 2000. This modified version enables the measurement of high concentration sprays. ILIDS has been shown by numerous researchers to accurately measure droplet size and velocity in a plane. These researchers include Burke et al. 2002; Burke et al. 2003; Damaschke et al. 2005; Hess 1998; Kawaguchi, Akasaka, and Maeda 2002; and Maeda, Kawaguchi and Hishida 2000. To address the need to measure large drops and/or high-density sprays, we also measure droplet size and velocity from the glare points as discussed by van de Hulst and Wang 1991. The basic PIV system is made by LaVision as discussed by Dierksheide et al. 2001, and the endoscopes were manufactured by Zibra Corporation in the USA.
The angle of collection was selected numerically by searching for a collection angle that is characterized by two dominant and almost equal Debye scattering terms. The selection was then validated by experiments with monodisperse droplets. Figure 2 shows a semilog plot of the intensity of the three principal Debye scattering modes versus viewing angle for spherical droplets with $m=1.4$ (kerosene) illuminated by S-polarized light. Given an index of refraction of 1.4 (kerosene), there are two optimum angles: 70°, where the contribution of $p=0$ is about the same as that of $p=1$ while the contribution of $p=3$ is considerably smaller; and 115°, where the contributions of $p=0$ and $p=3$ are almost equal while $p=1$ is negligible. Contributions from other orders are negligible. At 115°, the positions on the droplet of the $p=0$ and $p=3$ are very close to each other, resulting in less spatial resolution, which limits the measurement to larger drops. We therefore selected the collection angle of 70°.

![Figure 2. Semilog plot of scattering intensity vs. scattering angle for $m = 1.4$ (jet fuel).](image-url)
General optical design considerations:

Given a fringe spacing (radians) expressed by the well known equation:

$$\delta = \frac{2\lambda \left( \frac{\theta}{2} \left( m \sin \frac{\theta}{2} \sqrt{m^2 + 1 - 2m \cos \frac{\theta}{2}} \right) \right)}{d}$$

where \(\lambda\) is the wavelength, \(\theta\) is the collection angle, \(d\) the particle diameter, and \(m\) the index of refraction, we computed the following:

- To collect 2 fringes from 10 \(\mu m\) drops using a 532 nm wavelength requires a receiver with f/8.5.
- Based on requiring 4 gray levels for the smallest particles, and limiting the signal to 1024 gray levels (10 bit cameras), one could measure particles between 10 \(\mu m\) and 160 \(\mu m\) with the fringe mode. Under this condition, the 160 \(\mu m\) drops would exhibit 32 fringes.
- For an endoscopic imaging resolution of 50 lp/mm, and requiring a minimum of four resolution elements per fringe, the fringe spacing should be about 80 microns.
- The width of the halo should then be 80 microns/fringe x 32 fringes= 2.6 mm. To minimize overlap with nearby halos, the height of the halo can be compressed by using a rectangular slit. However, care must be exercised in selecting the slit height to avoid diffraction bands that can confuse the processing software if they are strong enough.
- Glare points may be used to extend the range of droplet sizes and concentrations that can be measured. For example, by requiring at least six pixels between glare points (45 \(\mu m\)), one could in principle use the glare point separation to measure all droplets larger than 50 \(\mu m\). In this case, ILIDS would be used only to measure droplets sized 50 \(\mu m\) or smaller, and the halo could be reduced to 800 \(\mu m\). This would enable measuring larger drop concentrations. The practical consideration here is that collection would have to be made at the Scheimpflug angle, or else the glare points go quickly out of focus, preventing the measurement of their separation.
- Experimental measurements, however, demonstrated that placing the cameras at the Scheimpflug angle was not practical as discussed below. We therefore placed the cameras at 90 degrees and limited the measurement with glare points to larger drops.
- The laser sheet width should be sufficiently wide to ensure the presence of the two principal glare points and the absence of the third order. As is discussed below, Gaussian sheets could result in the measurement of one, two, or three glare points if care is not exercised in the selection of the width.

Preliminary considerations of receiving optics

Test Configuration of Receiving Optics

The optimum configuration of the receiving optics is one that produces distinct, easily measurable fringe patterns on one camera and distinct glare points on the other. This is only possible at the Scheimpflug angle as discussed in a patent by Merklinger 1996. If the sensor is perpendicular to the optical axis, there can be significant variation in focus across the image, some of which can be mitigated by the fringe-forming optics. In practice, however, we ended up placing the CCD sensors perpendicular to the optical axis for the reasons given above.

Figure 3 shows a diagram of a breadboard receiving optics for testing this concept. Camera 1 records glare points, while Camera 2 records fringes. L1, L2, and L3 are \(f = +200\) mm achromatic lenses and BS is a non-polarizing cube beam splitter. The limiting aperture is a 22-mm diameter (/9) circular hole placed between L1 and BS. The following methods for producing compressed fringes on Camera 2 were tested:
• With a circular aperture, adjust L3 to make focused glare points, and then insert a cylindrical lens in front of the camera to defocus the fringes horizontally.
• Replace the circular aperture with a rectangular slit, and then move L3 toward the camera to defocus the glare points (no cylindrical lens needed).

Cylindrical lenses can also be used with a rectangular slit, an approach used by Maeda (2000). We tested all of these approaches against the IMI (LaVision) software. The IMI software requires that fringes be at least 8 pixels high and spaced at least 3 pixels apart, although in practice we’ve found that a fringe spacing of at least 6 pixels is needed for the IMI software to work reliably.

Method 1 produces thin, high-contrast fringes; unfortunately, the fringes were too thin to be recognized by the IMI software. Therefore, we defocused L3 to produce the fringe patterns shown in Figure 4. Due to the variation in focus across the image, the fringe patterns on the left are much taller than those on the right. As the fringe patterns expand, their brightness decreases (the contrast of the left-side fringes in Figure 4 are enhanced in the images presented here). The IMI software was generally able to measure the fringe patterns on the left, but often failed to recognize the patterns on the right because they were not tall enough.
Figure 5. Fringe patterns with cylindrical lens, 5 mm tall slit.

The fringe patterns in Figure 5 were produced with a cylindrical lens and a 22 mm wide by 5 mm high rectangular slit behind the main f= 200-mm collection lens. The variation in fringe height across the image is not as drastic. The IMI software was able to measure the droplet size from the fringe patterns on the left; however, the patterns on the right were not always tall enough. Defocusing the glare points more helps make the right-side fringe patterns easier to measure, but degrades the contrast of the left side fringes so much that they are no longer usable. One disadvantage of using a rectangular slit is that horizontal diffraction bands appear in the fringe pattern; the IMI software has trouble calculating the droplet size when these bands are strong relative to the vertical fringe pattern.

Figure 6. Fringe patterns with 5-mm rectangular slit.

Figure 6 shows fringes collected using method 2 (rectangular slit, defocused glare points, no cylindrical lens). The quality of the fringes still varies across the image; however, the IMI software is able to utilize fringe patterns from either side of the image to measure droplet size.

Figure 7. Fringe patterns with 3-mm slit.

Figure 7 shows fringe patterns collected with a 22-mm wide x 3-mm high rectangular slit. The IMI software had a harder time calculating the droplet size from the fringe patterns than with the 5-mm slit, probably because of the prominent diffraction bands running horizontally through the fringe pattern.

We concluded that for this configuration the optimum configuration of the receiving optics is one with a 5-mm tall slit in front of the first collection lens, spherical lenses only in both legs of the receiving optics, and the last lens in front of the fringe pattern camera slightly out of focus. One other advantage of not using cylindrical optics is that the position of the glare points in Camera 1 matches the position of the fringe patterns on Camera 2, which makes it easier to correlate droplet size with velocity. With a cylindrical lens in front of Camera 2, the FOV for Camera 2 is less wide than that of Camera 1.
One issue that needs to be examined is scaling the optimum slit height with lens diameter. Our preliminary consideration of diffraction effects suggests that the optimum slit height does not scale linearly (see Optics Ch. 10 by Hecht 2002).

**Preliminary considerations of transmitting optics**

*Evaluation of $M^2$ factor for PIV lasers.*

The $M^2$ factors of the Wave Optics Solo III and Continuum Minilite lasers were estimated by measuring the laser sheet thickness for a given set of transmitting optics. $M^2$ is a measure of the departure from single longitudinal mode TEM00. A perfect Gaussian beam has an $M^2 = 1$. Since the evaluation of the $M^2$ factor hinges on the precise measurement of the laser beam after it is focused by a known lens, great care was placed in 1) characterizing the focusing lens and 2) measuring the laser waist dimension. To avoid excessive energy density, a cylindrical lens was placed to spread the laser waist into a sheet. The sheet forming optics are shown schematically in Figure 8. It consisted of two lenses: a spherical lens $L_1$ of focal length $f_1 = 125$ mm to focus the beam, and a negative cylindrical lens $L_2$ of focal length $f_2 = -13$ mm to spread the beam into a sheet.

![Sheet forming optics](image)

The sheet waist was measured in two different ways: 1) placing a CCD sensor right at the waist (the energy level was reduced several orders of magnitude to prevent damage to the sensor), and 2) projecting the sheet onto a far wall with the aid of an imaging lens and then capturing the image with a CCD camera. The magnification of the imaging lens was verified by imaging a known-size object (plastic ruler with mm scale) and was also computed with the thin lens equation given the focal length, object distance, and image distance. We estimated that the error in the measurement of $M^2$ could be as much as 10%. The waist dimension was measured to the $1/e^2$ intensity.

Both the Continuum MiniLite PIV and the Solo III PIV contain two lasers (A and B), each of which can be pumped at high or low intensity flashlamp. The $M^2$ factors for high and low energies for each laser are given in Table 1. The $M^2$ factors of two different Minilite lasers are reported below.

<table>
<thead>
<tr>
<th></th>
<th>Minilite demo</th>
<th>Minilite final</th>
<th>Solo III</th>
</tr>
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<tr>
<td>Laser A, low</td>
<td>6</td>
<td>4.6</td>
<td>6.8</td>
</tr>
<tr>
<td>Laser B, low</td>
<td>5.7</td>
<td>8.5</td>
<td>16</td>
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<td>Laser A, high</td>
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<td>7.2</td>
<td>13.3</td>
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<tr>
<td>Laser B, high</td>
<td>8.1</td>
<td>8.8</td>
<td>20.5</td>
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</tbody>
</table>

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Given the limited beam diameter in the illumination endoscope and the desire to form a thin sheet, we selected the Minilite, although the Solo was attractive due to its compact size.

**Optimum laser sheet thickness**

The selection of sheet thickness is predicated by two opposing criteria:

1. *The number density of particles in the flow.* High number density calls for a thin sheet.
2. *The maximum droplet size of interest.* It is shown below that if the droplet diameter is equal to or larger than the Gaussian beam, glare points may be detected from the 0, 1, and/or 3 modes, even though the only modes of interest are 0 and 1. If the laser sheet is larger than the drops, this problem is avoided and only the 0 and 1 modes are detected.

We have developed a model to optimize the selection of laser sheet thickness relative to the droplet diameter. The model follows these conditions:

- Only three Debye terms are visible at 70 degree collection for either jet fuel (*m* = 1.4) or water (*m* = 1.33). The objective is to measure only two of these terms (*p* = 0 and *p* = 1).
- The laser sheet impinging upon the drops is assumed to have a Gaussian intensity distribution.

Throughout the model, we follow the convention and nomenclature established by van de Hulst 1981. The angle between each ray and the tangent to the droplet is τₚ, where *p* = 0, 1, or 3. The angle of refraction measured from the tangent as the ray penetrates the droplet is τ'ₚ, and it is given by Snell’s law. The model concludes that the sheet thickness should be more than two times the largest droplet diameter. Experiments showed that to avoid single glare points, the sheet thickness had to be larger than four times the droplet diameter.

<table>
<thead>
<tr>
<th>θ</th>
<th><em>m</em></th>
<th><em>p</em></th>
<th>τᵢ</th>
<th>τ'ᵢ</th>
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<tr>
<td>70</td>
<td>1.33</td>
<td>3</td>
<td>61</td>
<td>68.7</td>
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<tr>
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<td>1.33</td>
<td>1</td>
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<td>1.4</td>
<td>3</td>
<td>57.7</td>
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<tr>
<td>70</td>
<td>1.4</td>
<td>1</td>
<td>10.36</td>
<td>45.36</td>
</tr>
</tbody>
</table>

The reflection angle is τ₀ = 35°.

The position where the respective rays impinge upon the droplet is given by: rₚ = d/2 cos τₚ. For kerosene (*m* = 1.4) at 70°, the values are r₀ = 0.41 d, r₁ = -0.492 d, and r₃ = 0.267 d. The model then finds the relative scattering intensity of these three discrete points due to a Gaussian input. For kerosene at 70°, the intensity of *p* = 0 is approximately equal to the intensity of *p* = 1 while the intensity of *p* = 3 is about 1/83 that of *p* = 0.

In the model, a droplet of diameter *d* is illuminated by a Gaussian beam with 1/e² half width = *b*. The center of the droplet may be offset from the center of the beam by some value Δ; see Figure 9 for details. The intensity that impinges upon the droplet is then:

\[
\frac{I}{I₀} = \exp \left[ -\frac{2(r-Δ)^2}{b^2} \right], \text{ where } I₀ \text{ is the intensity in the center of the Gaussian.}
\]

The intensity which is scattered by the droplet is divided into three terms (for *p* = 0, 1, and 3). This intensity is expressed as follows:
\[ \frac{I_{0,1}}{I_{\text{max}}} = \left( \frac{d}{d_{\text{max}}} \right)^2 \exp \left[ -2 \frac{(xd-\Delta)^2}{b^2} \right] \], where it is assumed that the scattered intensity scales with the square of the droplet diameter and that the intensity of the p=0 and p=1 modes are equal. For p=3 the scattered intensity is about:

\[ \frac{I_3}{I_{\text{max}}} = \frac{1}{83} \frac{I_0}{I_{\text{max}}} \]. If we define \( b = K_1 d \), \( \Delta = K_3 d \), and \( K_{\text{ref}} = b/d_{\text{max}} \), then:

\[ \frac{I_{0,1}}{I_{\text{max}}} = \left( \frac{K_{\text{ref}}}{K_1} \right)^2 \exp \left[ -2 \left( \frac{x-K_1}{K_1^2} \right)^2 \right] \] defines the sheet thickness in terms of the maximum droplet size.

\[ \frac{I}{I_0} = e^{-2(r-\Delta)^2} \]

Figure 9. Schematic of droplet interacting with Gaussian beam.

The \( I_{0,1} \) and \( I_3 \) intensities can now be solved. Below we show solutions for two cases. In the first case, the laser sheet thickness is twice the maximum droplet diameter (Figure 10, Figure 11, and Figure 12) and in the second case, the laser sheet thickness is equal to the maximum droplet diameter (Figure 13). The threshold in all cases is assumed to be 1/83, which is the relative intensity of p=3 to p=0.

Figure 10. p=0, 1, and 3 intensity of \( d_{\text{max}} \) for laser sheet = 2 \( d_{\text{max}} \).

Figure 11. p=0, 1, and 3 intensity of \( d_{\text{max}}/2 \) for laser sheet = 2 \( d_{\text{max}} \).
The endoscopes

The first imaging endoscope (with a diameter of 25 mm and length of about 400 mm) was single ended; it mounts to a CCD camera using a C-mount connection. The black knob on the end of the endoscope moves the camera back and forth, which changes the focus to enable collection of glare points or fringes. **Figure 14** shows a photograph of this initial test endoscope. The endoscope was designed and built using only singlet lenses and with no adhesives to hold the lenses in place. It is actually capable of withstanding a temperature of 428° C.

![Figure 14. Photograph of first imaging endoscope.](image)

The initial system evaluation was done using water droplets (70° is also a suitable angle for m = 1.33). **Figure 15** shows some sample data of glare points and fringes from 89.5 µm diameter water droplets collected by the endoscope with a viewing angle of 70° and a working distance of 158 mm. The measured separation between the glare points was 80 ± 7 µm. This indeed corresponds to the produced droplet diameter since the separation between glare points is 90.6% of the droplet diameter for the stated conditions of 70° and m = 1.33. The fringe pattern was used to confirm the effective F/# of the endoscope: 18 fringes were observed, which corresponds to a F/# between 8.0 and 8.5.
Measurements were also made at 120°. In this case, the fringes are produced by interference between the p=3 and p=0 scattering modes, which originate from glare points that are much closer together. **Figure 16** shows fringes from 90 µm water droplets collected with the endoscope at a viewing angle of 120°. We observed 5 fringes from 89.5 µm diameter droplets. Given that a minimum of 2 fringes are needed to accurately determine drop size, the minimum size drop that can be measured at a viewing angle of 120° is about 36 µm. This strategy may be well suited for measuring larger drops.

**Figure 16.** Fringes from 90 µm water droplets, collected with endoscope at θ = 120°.

The second imaging endoscope is dual ended: one leg focuses the glare points and the other produces out-of-focus images with fringes. The leg that focuses the glare points is shown below in **Figure 17**.

**Figure 17.** Optical layout of imaging endoscope.
The imaging endoscope is 12.7 mm diameter and 442 mm long. There is a separate larger piece that houses the beamsplitter, filter, etc. to enable the simultaneous measurement of fringes and glare points. This piece would stay outside the cooling sheath. The endoscope also includes a bandpass filter to block unwanted light.

The illumination endoscope measures 5.88 mm in diameter and 596 mm in length. It is terminated with a reflecting element that sends the laser sheet at 70 degrees. A photograph of the imaging and illumination endoscopes is shown on Figure 18. The rod to the right of the illumination endoscope adds rigidity.

In principle, it would be advantageous to position the receiving cameras as close as possible to the Scheimpflug angle to optimize the focus of the glare points throughout the entire collection area (Figure 19 shows a schematic of this configuration). Two cameras, one at the focal plane (glare points) and the other out of focus (fringes) are shown in this tilted position. We learned, however, that it was not practical to tilt the cameras; 1) the tilted cameras experienced a significant reduction in signal intensity and 2) the camera that collects the images of the glare points must be very close to the endoscope and there is very little room for tilting. The intensity drop-off may be a consequence of using fast optics in combination with an interline CCD sensor with microlenses. We therefore kept the cameras along the optical axis of the receiving optics as shown in Figure 18.

![Figure 18. PIV breadboard with illumination and imaging endoscopes.](image1)

![Figure 19. Schematic of receiving endoscope showing two cameras at close to the Scheimpflug angle.](image2)

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**References:**


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