Near-Nozzle Diesel Spray Imaging Using X-Rays

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Abstract

Monochromatic synchrotron x-rays are used to measure fuel mass distribution in diesel sprays. X-ray measurements are used as an alternative to optical measurements, which typically fail due to multiple scattering in high density regions of the spray. In the x-ray photon energy range used (< 8 keV), some of the photons are absorbed by doped fuel but because of the very short wavelengths, there is very little scattering. The high density region near the tip of the nozzle is studied in detail to understand details of the injection process. The spray is mapped as it develops in time allowing us to estimate different spray properties such as fuel volume fraction, spray cone angle, and spray penetration with multi-orifice injection system. Four different injector tips were characterized with the tips varying in internal angle of convergence and in orifice machining. The spray was injected into two different chamber environments: atmospheric pressure (1 bar) and pressurized N$_2$ (17 bar). The mass flow rate was compared to measurements done using a rate of injection bench system. This study provides some insight on how the near-tip liquid spray from different geometry tips compare against each other, and also how they vary from hole to hole and tip to tip.
**Introduction**

The dense region near the tip of a high-pressure diesel fuel injector presents a significant measurement challenge. It has been found that sprays with similar overall characteristics far from the nozzle can have different emission values when run under normal operating conditions in a diesel engine. Combustion characteristics are heavily influenced by the fuel-air mixing process, originating near the injector nozzle tip, which in turn will influence the emissions. A better understanding of the spray characteristics in the region near the fuel injector nozzle could help explain the emission differences observed. Optical measurement techniques have been widely used with diesel-type sprays in the past [1,2], achieving success in the downstream part of the fuel plume but failing in the near nozzle-tip region. This region is usually composed of numerous small droplets and ligaments, which make quantitative measurements difficult due to multiple scattering of visible light [3]. X-Ray measurements are used as an alternative to optical wavelength studies, since the short wavelength relative to the droplet radius of curvature makes scattering negligible. Under these conditions, x-ray absorption dominates the apparent decrease in transmission. The x-ray line of sight absorption is used to quantitatively measure the fuel mass distribution. Monochromatic x-rays are used to allow a simple mass to transmission relationship that is given by:

\[ \frac{I}{I_0} = \exp(-\mu_A M) \]  

where \( I \) is the transmitted intensity and \( I_0 \) is the incident intensity, \( M \) is the fuel mass along the line of sight of the x-ray for the cross-sectional area of the beam, and \( \mu_A M \) is the mass attenuation coefficient. The instantaneous fuel mass is determined by measuring both the incident and transmitted intensities and obtaining the mass attenuation coefficient by calibration. A small cross sectional beam is used to provide spatial resolution as high as possible. Different spray characteristics can be determined using this technique, including, mass distribution, spray cone angle, spray penetration and volumetric liquid fraction.

For the set of experiments shown, four different injector tips were used on a single injector body. The tips were defined by two characteristics: the degree of convergence and the type of orifice machining. Two different chamber back-pressure conditions were studied.

**Measurement technique**

A high pressure common rail system was used with a three-hole injector tip. The injection pressure was 950 [bar] for all the experiments presented here. The three-hole tip was intended to allow for realistic flow geometry in terms of fuel moving down the injector body and turning inside the injector to exit the injector holes. The experimental setup was composed of a high pressure equipment (950 bar) for all the experiments presented here. The three-hole tip was intended to allow for realistic flow geometry in terms of fuel moving down the injector body and turning inside the injector to exit the injector holes. The benefit of 3 holes rather than a more typical five or six was that it was easier to see one spray plume clearly in the x-ray rig and control of fuel splash from the non-imaged holes was easier. The injector was mounted in a pressure chamber to allow for pressurization of the environment into which the fuel was injected and to contain the injected fuel. The pressure chamber was specially designed so the injector was oriented with one hole aligned with the windows and the other two holes were 120° apart, azimuthally. This design allowed us to study one plume of the injector through a set of windows without interference from the other two plumes. The windows used were Kapton polymer films, which have low x-ray absorption. In order to keep the windows clean, the chamber had a draining system such that the fuel droplets and vapor were purged with \( N_2 \). The fuel supply was blended with a cerium compound to maximize the x-ray absorption at the energy of the x-ray source. The blend was approximately 4.2% cerium by weight. For safety reasons, diesel fuel was substituted with Viscor 1487, a calibration fluid with similar characteristics to diesel.

**Fuel Injector Tips**

The tips used have three holes, with “K” and “KS” tips. The “K” values indicate the amount of convergence of the passage inside the tip. As defined by manufacturer,

\[ K = \frac{ID - OD}{10} \]

where ID is the internal diameter and OD is the external diameter in microns. The difference between K and KS tips is that the KS holes have been machined by hydraulic grinding whereas the K holes are in their as-formed state. It is suggested by manufacturer that the hydraulic grinding allows smoother passage of the fuel through the spray hole. A total of four different tips were used, and one tip was tested for hole-to-hole variation and tip-to-tip variation.

Two different chamber pressures were used: 1 bar and 17 bar. Ideal experimental conditions would reproduce those of an engine with high temperature and pressure, but due to safety concerns the temperature was maintained at ambient conditions 298 K. Since our goal was to simulate engine conditions we used a back
The injection was controlled using a GENOTEC driver. The spray consisted of a main event followed by a dwell and a second event; the shape of the driving signal for each event can be seen in Fig 1.

Figure 1. Spray event: Main event lasts 580 μs, dwell 400 μs followed by a second event 250 μs

The experiments were done using 8 keV focused synchrotron x-rays from the Advanced Photon Source (APS) at Argonne National Laboratory (ANL). The APS system allows a high photon flux for a narrow energy band of x-rays after the x-rays pass through a monochromator. Measurements using x-ray attenuation have been presented for diesel sprays with single hole tips [3,4,5,6] and for gasoline injectors [7]. Extensive details of the measurement system used at ANL are provided in [3,4,5,6]. The measurements shown in this paper are somewhat different in that they use a multi-hole nozzle and some are at elevated back pressure to better simulate cylinder pressure at injection time for diesel injectors.

The detection system consisted of an avalanche photodiode detector with a response time of 5 ns, a high-speed oscilloscope, and a computer data acquisition system. The x-ray beam was focused and its area was defined by a pair of slits. The slits have two dimensions: horizontal (X) and vertical (Y), which varied from experiment to experiment as seen in Table 2. As a reference, the spray plume was parallel to the x direction, the y direction was perpendicular to the spray flow. The y slit size was smaller than x in order to improve the resolution across the nozzle exit which had a diameter of 140 μm. Figure 2 shows a sketch of the system used in these experiments. The ion chambers shown in fig. 2 measure the overall x-ray intensity to monitor any variation in beam intensity with time. In order to reproduce the entire spray field, an ensemble of measurements was made at different locations throughout the spray field. Normally, 50 to 100 x-ray energy measurements were made at one location in the field, thus averaging a single point measurement over 50 to 100 injection events. The spray chamber would then be moved incrementally to allow a different location in the spray field to be sampled, and another 50 to 100 samples were recorded. The overall set of sample locations is shown in fig.3.

Figure 2. Schematic of experimental setup

Figure 3: Experimental grid: Each marker represents a measured location with its respective beam area.

Since our interest is the mechanics of the flow near the injector tip, there was a high concentration of measuring points close to the tip and a sparser grid further downstream; the grid is shown in fig. 3. The

### Table 1. Experimental Conditions

<table>
<thead>
<tr>
<th>Tip</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>K 1.0</td>
<td>1 bar</td>
</tr>
<tr>
<td>K 1.5</td>
<td>1 bar</td>
</tr>
<tr>
<td>KS 1.0</td>
<td>1 bar</td>
</tr>
<tr>
<td>KS 1.0</td>
<td>17 bar</td>
</tr>
<tr>
<td>KS 1.5</td>
<td>1 bar</td>
</tr>
<tr>
<td>KS 1.5</td>
<td>17 bar</td>
</tr>
</tbody>
</table>
chamber windows were 15 mm long (in the “x” direction) and 3 mm high for the high chamber pressure cases. Some low (1 bar) chamber cases were run with larger windows. For the smaller windows, the entire spray plume was only visible for about 100 μs after start of injection. Near injector tip measurements are possible after that, but the spray tip itself and much of the spray plume was well out of the field of view.

An essential aspect of the experiments is determining the mass attenuation coefficient. This is done using capillary tubes successively filled with water, air, and doped fuel. The mass attenuation of water and air are well known so these two are used to determine the attenuation of the capillary tube and its inner diameter. Since the beam size and the density of the fuel are known, the path length determines the mass of fuel illuminated by the x-ray beam. The attenuation and the mass can then be used to determine the mass attenuation coefficient according to Equation 1. The mass attenuation coefficient depended greatly on two factors: the fuel composition and the beam size. The fuel was nearly identical for all the experiments but the beam size varied as seen in Table 2.

<table>
<thead>
<tr>
<th>Date of experiment</th>
<th>Mass attenuation coefficient (1/g)</th>
<th>Beam Area size (μm)</th>
</tr>
</thead>
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<tr>
<td>April 2004</td>
<td>380071</td>
<td>200 x 60</td>
</tr>
<tr>
<td>December 2004</td>
<td>607544</td>
<td>155 x 30</td>
</tr>
<tr>
<td>June 2005</td>
<td>600773</td>
<td>145 x 35</td>
</tr>
</tbody>
</table>

Table 2: Mass Attenuation coefficients

Experimental Result:

The fuel mass distribution was calculated for all cases from the transmitted intensity. For each measurement point, there is a time interval between the start of the measurement and the start of injection. The measurements from this time were used as our reference value for the transmission of ambient gas with no fuel present.

Figure 4, shows the line of sight mass distribution 280 μs after the start of injection. The centerline mass decreases with distance downstream. Combining all the measured points allows an estimate of the total mass of the spray in the field of view, and creation of 2-D contour images of the mass of the spray at any specific time after start of injection (SOI). These images reveal both qualitative and quantitative features of the liquid spray. From the images we can clearly identify the boundaries of the spray and even see some interesting features of the developing stage of the spray.
Figure 5. Spray Injection Sequence (Mass in \( \mu g \)):
A) 22 \( \mu s \) after SOI. B) 33 \( \mu s \) after SOI. C) 44 \( \mu s \) after SOI.
D) 55 \( \mu s \) after SOI. E) 66 \( \mu s \) after SOI. F) 77 \( \mu s \) after SOI.

Figure 5 shows contour plots for total line-of-sight mass of fuel at various times after SOI. The color scale is in \( \mu g \) of fuel. The data for this figure is from a KS 1.5 tip, operated with 1 bar chamber pressure. This figure shows several interesting features typical of these sprays. For example, in fig. 5, we can see a very good example of a spray feature made evident with the x-ray method. At 44 \( \mu s \) after start of injection (fig 5b) the spray approaches 4 mm downstream, after which a bulge of mass separates from the original plume and then moves ahead of the main plume until it leaves the field of view at 77 \( \mu s \) at figure 5e. There is fuel between the large mass and the main plume, but the line of sight average mass is clearly much smaller than in either the plume or the leading edge fuel mass. For these experiments with a limited field of view, we can’t show whether the main body of the spray will catch this separated fuel mass or not.

Mass Calculations:
The total spray mass can be estimated by adding all the measured points for a given time. The measurements were compared with measurements done with a rate of injection bench. The bench provides an estimate of the mass flow rate as a function of time from transient pressure data as the injector operates in a long column of pressurized fuel [8]. Comparison of the injection rate bench data and the total fuel mass observed here can help confirm the ability of this method to capture all the fuel mass.
The injection rate data for fuel injection rate are shown in fig. 6. The total mass at any given time is estimated by integrating the injection rate for the desired time period. The x-ray data will provide the total mass in the field of view at any given time but the mass that has already left the field of view is not accounted for. This will limit the comparison to a very small time span, about 75 μs after SOI. This is a small part of the total injection event that is about 1200 μs long.

The mass comparison results can be seen in Table 3. It is seen that the x-ray and bench data agree to within about 10%.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Pressure (bar)</th>
<th>X-Ray (mg)</th>
<th>Injection Rate Bench (mg)</th>
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</thead>
<tbody>
<tr>
<td>K 1.5</td>
<td>1</td>
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<td>0.137</td>
</tr>
<tr>
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<td>1</td>
<td>0.180</td>
<td>0.207</td>
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<tr>
<td>KS 1.5</td>
<td>17</td>
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<td>0.207</td>
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<tr>
<td>K 1.5</td>
<td>17</td>
<td>0.105</td>
<td>0.106</td>
</tr>
<tr>
<td>K 1.0</td>
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<td>0.172</td>
</tr>
<tr>
<td>KS 1.0</td>
<td>1</td>
<td>0.095</td>
<td>0.122</td>
</tr>
<tr>
<td>KS 1.0</td>
<td>17</td>
<td>0.084</td>
<td>0.097</td>
</tr>
</tbody>
</table>

**Table 3**: Total injected mass for injection rate bench and x-ray measurements

### Liquid Volume Fraction

An important characteristic of a spray is the local liquid volumetric fraction. The liquid volumetric fraction is calculated by estimating the spray density at any given location and comparing it with the liquid fuel density. To estimate liquid volumetric fraction from the line of sight mass data produced in the x-ray experiments requires several assumptions. A first step is to identify the edges of the spray and determine the estimated diameter of the spray as a function of axial location. This measurement is the equivalent to the width of the spray from fig 5. We assume axisymmetry, and the length of the local line-of-sight can thus be calculated from the local geometry. The liquid mass distribution along any line of sight is assumed to have a Gaussian profile, with a width as outlined above. Deconvolving the mass distribution along the line of sight allows an estimate of the local spray density.

The liquid volumetric fraction will be the ratio between the calculated spray density and the pure liquid fuel density.
Figure 8. Liquid volume fraction profile for K 1.0 well into the first injection

Figure 8 shows the liquid volume fraction of one of the K 1.0 nozzle plotted as a function of the distance from the center of the spray, for a number of axial positions. The maximum liquid volume fraction value was about 0.65 at 0.1 mm from the tip and decayed quickly.

The relatively dense region of fuel near the leading edge of the spray, as seen in fig. 5, can also be quantified in terms of liquid volume fraction. Contour plots comparing the liquid volume fraction and the line-of-sight mass distribution are seen in fig. 9. These allow a different perspective into some of the features that form the line of sight mass plots. Figure 9a shows the liquid volume fraction for the K=1.0 tip at 58 μs after SOI, fig. 9b shows the same data in terms of line-of-sight mass. The concentrated region near the leading edge of the spray contains a substantial amount of fuel and appears to be relatively dense, but because it has a large geometric extent the estimated liquid volume fraction is relatively small (0.1–0.25).

Spray Cone Angles

The spray cone angle was determined using two different approaches: the first used four specific fixed locations in the spray; a second estimated the location of the spray edges continuously as a function of the axial position. Both approaches rely on identifying the edge of the spray which was assumed to be the location were the spray mass falls below 10% of the maximum measured for that axial distance from the nozzle at a particular time after SOI. The results are presented in Table 4. Given the transient nature of the spray, the cone angle will depend on when the cone angle is measured. For these data, the angle was measured at approximately 200 μs after start of injection. At this time the spray is well into the first event. The cone angles were also measured for each time step for the first event (50–500 μs after SOI). If we average the results we obtain a similar result as at 200 μs after start of injection with standard deviation between 1 and 3 degrees.
These results suggest that the most significant factor in determining the spray cone angle was the ambient pressure as cone angles at 17 bar were less than half the values at 1 bar. The shape of the nozzle exit also played a significant role. At 1 bar pressure, both KS nozzles had larger spray cone angles than their K counterparts. The hydro machined tips were expected to provide a smoother fluid exit from the sac region of the injector tip into the orifice hole, and probably less fluid turbulence in the hole. There was no observable difference by varying the convergence magnitude.

Comparing the lower chamber pressure (1 bar) results with the higher-pressure results (17 bar) shows a substantial decrease in spray cone angle at higher pressures. This is opposite to the results commonly observed for optical measurement systems. For example Hirayosu [9] found that spray cone angles increase with increased pressure difference. The cone angle as measured here is based on the mass distribution of the central region of the spray rather than scattering by the outermost droplets of the spray as in optical measurements. Since small droplets will have low x-ray absorption but will scatter light, the spray edges will be defined differently thus producing different results for similar nozzles.

**Spray Penetration**

Since we can clearly define the liquid-gas boundary we can quantitatively measure the spray penetration. As seen in figure 4, the maximum mass values occur typically at the centerline. We defined the boundary as 10% of the maximum mass along the centerline of the spray. The results are shown in figure 10 and 11. It is important to clearly define when the spray starts. Even though the injection driver signal was identical, the start of injection as determined by visible fuel changed slightly from tip to tip. The start of injection was defined as one time step prior to the first appearance of fuel mass at the tip the nozzle. Each time step is equal to 3.6825 μs. Within this time resolution all the time values will be referenced to a zero time or start of injection.

![Figure 10: Spray penetration for ambient pressure cases](image)

![Figure 11: Comparison between pressurized and ambient pressure cases.](image)

![Figure 12: Comparison between calculated spray penetration and Hiroyasu model](image)

The spray penetration was similar for all the cases with an ambient pressure of 1 bar. Note that these penetrations are only for very early injection times since after about 75 μs, the spray tip is out of the field of view of the experiment. Penetration was also

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Pressure</th>
<th>Cone angle (degrees)</th>
</tr>
</thead>
<tbody>
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<td>KS 1.0</td>
<td>1 bar</td>
<td>16</td>
</tr>
<tr>
<td>K 1.0</td>
<td>1 bar</td>
<td>12</td>
</tr>
<tr>
<td>KS 1.5</td>
<td>1 bar</td>
<td>17</td>
</tr>
<tr>
<td>K 1.5</td>
<td>1 bar</td>
<td>11</td>
</tr>
<tr>
<td>KS 1.0</td>
<td>17 bar</td>
<td>5</td>
</tr>
<tr>
<td>KS 1.5</td>
<td>17 bar</td>
<td>6.5</td>
</tr>
</tbody>
</table>

*Table 4: Spray cone angle for different tips and pressures*
studied for pressurized cases in which it increased slightly for the KS 1.5 nozzle but was similar for the KS 1.0 nozzle, when we increased the ambient pressure. This measurement agrees with the spray cone angle for pressurized KS 1.5 case, which was found to be smaller than the cases with 1 bar pressure.

The results were compared to Hiroyasu’s [6] model for the KS 1.5 case in fig. 12. The penetration predicted by Hiroyasu’s model and measured in these experiments are similar. The KS 1.0 (fig 12) has a slightly lower slope than that predicted by Hiroyasu’s model. The pressurized cases (fig. 11) show rapid penetration early, then settle into penetration increase (slope) similar to that of the 1 bar cases and the Hiroyasu model.

**X-Ray vs. Optics**

The x-ray mass measurements provide useful tool that allows characterization of the spray in the near-nozzle region of the spray. In fig. 13 we can see optical and x-ray mass images side by side of the KS 1.0 nozzle at room temperature and pressure at 200 $\mu$s after SOI. The scale on both axes is in mm. The optical image was taken using backlit NdYAG laser at 532nm, the camera used was Phantom v.7 by Vision Research Inc. at 10000 fps.

**Figure 13:** A) Optical spray Imaging B) X-Ray Mass Imaging

Using x-ray techniques we can see details of the near tip region, where absorption is high. These details provide the basis for our volume fraction calculations, which are difficult to estimate using optical measurements. Other spray parameters such as cone angle and penetration can be also estimated and compared to their counterpart measurements using optical techniques. Further downstream the fuel mass was spread out and the absorption was reduced. In this region, optical techniques provide more details than the x-ray measurements.

**Conclusions**

A series of three-hole nozzles were characterized using x-rays at the APS. Different spray characteristics were estimated using line-of-sight x-ray absorption mass measurements: spray mass, liquid volume fraction, spray cone angle, and spray penetration. The spray mass was compared with experiments done with a rate-of-injection bench and the two showed consistency for the small part of the spray event where comparison was possible.

Liquid volume fractions were estimated and they show a very rapid decrease as the sprays moved...
downstream. Even in the near tip region ( < 0.5 mm) the maximum fraction was between 0.6 and 0.7, which suggests liquid breakup and subsequent air entrainment in the fluid very early in the spray development. In the pressurized cases the liquid volume fraction was further reduced very early in the event with maximum values of 0.5.

For cases at 1 bar pressure, a well-defined bulge of fuel broke from the spray core and moved until it left the field of view. In pressurized cases, the stream is more compact and even though there was break-up, there was no defined structure as was the case with 1 bar pressure cases.

Spray cone angles were studied and an interesting trend was found: at near tip region: the cone angles were smaller for higher-pressure cases than for 1 bar pressure cases. A consistent similar trend was found for spray penetration in the KS 1.5 case. The spray cone angle was higher for hydro-machined holes, while no significant change was observed for changes in convergence.

The x-ray experiments showed interesting details for the transient nature of the spray in the near-tip region. Further experiments will help to correlate the characteristics shown by this experiment to other spray features such as needle movement and fluid behavior inside the nozzle.

Acknowledgements

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