Quantitative Measurement of Diesel Fuel Spray Characteristics in the Near-Nozzle Region of a Heavy Duty Multi-Hole Injector

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Abstract
A quantitative and time-resolved x-ray radiography technique has been used to determine the fuel distribution near the nozzle for the spray from a high pressure injector. This technique provides high spatial and temporal resolution without significant scattering effects, especially in the relatively dense core region. A single spray plume from a Caterpillar HEUI 315B injector with a production 6-hole nozzle was isolated and studied at engine-like densities at two different injection pressures. The steady state fuel distributions for both injection pressures are similar and show a dense spray region along the axis of the spray, with the on-axis spray density decreasing as the spray progresses downstream. The higher injection pressure case shows larger cone angle and spray broadening at the exit of the nozzle. For some time periods, the near-nozzle penetration is lower for the high injection pressure case than the low injection pressure case; this unexpected result is discussed. Optical spray imaging was conducted to evaluate the effectiveness of the shield used to isolate a single spray plume. Rate of injection testing was performed to further understand near-nozzle behavior. Comparisons of the radiography data with that from single-hole light duty injectors under similar injection conditions show several significant differences. The current data show a larger cone angle and lower penetration speed than that from the light-duty injector. Moreover, these data display a Gaussian mass distribution across the spray near the injector, whereas in previous light-duty injector measurements, the mass distribution near the injector had steeper sides and a flatter peak. These data were used to validate the spray models in STAR-CD.
Introduction

Fuel injection characteristics, in particular the atomization and penetration of the fuel droplets, are known to affect emissions and particulate formation in diesel engines. Well established measurement techniques using x-ray absorption are available to analyze the flow characteristics of the fuel spray near the exit of the injector tip. Characterizing the influence of various nozzle parameters on atomization and establishing a correlation between near nozzle flow characteristics and diesel engine performance and emissions will enhance our ability to model the spray atomization and vaporization behavior, and consequently, better predict particulate formation.

Limitations of optical diagnostics for high-speed sprays have been well established by other researchers in the past [1-3]. Small droplets of the fuel spray scatter visible light, thus limiting the capabilities of optical measurements. The main interaction between the fuel and the x-rays is absorption, hence making it an appealing alternative for spray studies. Also, x-ray absorption measurements provide information of the spray structure especially near the nozzle where the highly dense fuel region is impenetrable by optical means. This x-ray radiography technique has been used extensively to analyze the spray characteristics for single-hole research nozzles [3-10] injecting into chamber back pressure lower than typical of diesel engines. While this provides useful insight on the spray development and breakup characteristics, the impact of multi-hole nozzle geometry injecting into engine-like density gas has not been investigated in detail.

Payri et al. [11] evaluated the macroscopic behavior of diesel sprays in the first 15mm of the spray from a non-isolated 6-hole common rail injector using advanced optical visualization techniques. A major conclusion was that the spray tip penetrations in this transient region behaved differently than the steady state region. Application of x-ray radiography to multi-hole nozzles is extremely challenging simply in the context of spray isolation. Because it is desired that only a single plume of interest spray freely in the direction horizontal and normal to the x-ray beam without interference from additional spray plumes, significant design considerations must be made to do this. There have been some recent studies using 3-hole common rail, single fluid injection systems where a single plume of interest was isolated and investigated in some detail using x-ray absorption technique [12]. The present work focuses on the isolation of a single spray plume of the 6-hole injector in order to obtain high-fidelity data in the near nozzle region using x-ray radiography. Spray chamber densities employed in previous work [8,10] using x-rays have been lower than diesel engine operating pressures due to x-ray window design limitations. To the best knowledge of the authors, this presents the first detailed evaluation of a full production multi-hole nozzle under engine like ambient densities using x-ray radiography.

Improved fuel air mixing can lead to more efficient combustion and lower emissions. The mixing process is governed by injection characteristics (which in turn depends on the needle lift dynamics and nozzle flow behavior) and spray processes (influenced by aerodynamics outside the nozzle). In the present study, x-ray radiography is used to study the transient region of the spray where needle lift profile plays a significant role in fuel penetration. Needle lift effects determine the initial region of the rate of injection (ROI) profile. Hence, this ROI as obtained from the rate meter [13] is compared with the x-ray ROI. This measured ROI is also important for Computational Fluid Dynamics (CFD) modeling as it provides boundary conditions for fuel injection into the combustion chamber.

From a modeling perspective, non-evaporating spray conditions provide a more stringent test for the spray models than vaporizing spray conditions. Under evaporating conditions, injected droplets would eventually evaporate after a few time-steps. However, under non-evaporating conditions, these droplets continue to collide and break up, thus testing the spray sub-models to a greater degree. Hence, such non-evaporating sprays under engine like ambient densities provide a more effective crucible for validating the spray sub-models. In the recent past some attempts have been made to use x-ray radiography data for spray model validations. Tanner et al. [14,15] developed a Cascade atomization and droplet breakup model and matched the liquid penetration, and transverse mass distribution successfully. However the ROI was not known for injection conditions and injection velocities were determined by an iterative process to match the spray penetration. Since fuel injection rate has a strong influence on penetration, especially in the near nozzle region, this approach might be erroneous. In the present study, the ROI was accurately determined by Bosch rate meter and x-ray measurements, thus reducing uncertainties associated with injection velocities.

Experimental Setup

X-Ray Absorption

The X-ray measurements were performed at the Advanced Photon Source (APS) at Argonne National Laboratory, which generates a highly intense x-ray beam with a narrow range (2% bandwidth) of x-ray wavelengths. The x-ray radiography technique is based on the linear absorption of the monochromatic x-ray beam passing through the spray. The monochromaticity of the beam allows a straightforward application of the Beer-Lambert Law relating the measured x-ray intensities to
the mass of the fuel in the path of the beam. This relationship is given by:

\[ \frac{I}{I_0} = e^{-\mu M} \]  

(1)

Where \( \mu \) is the absorption coefficient of the fuel, \( M \) the projected density of the fuel in the beam path, and \( I \) and \( I_0 \) the x-ray intensity values during and before the spray event, respectively.

A schematic of the experimental setup is shown in Figure 1. The x-ray energy of 8 keV was selected using a double-crystal multilayer monochromator. This energy provides a good compromise between absorption and penetrating power, allowing the absorption due to the spray to be accurately measured while obtaining sufficient intensity through the spray chamber. Vertical and horizontal x-ray slits were used to limit the beam size. Full width half maximum (FWHM) values of the beam were 180 \( \mu \)m in the axial direction and 50 \( \mu \)m in the transverse direction.

![Schematic of experimental setup](image)

**Figure 1.** (a) Image of setup at APS (b) Schematic of experimental test setup

An avalanche photodiode (APD) with a time response faster than 5 ns is used to monitor the x-ray intensity. The APD output, which was proportional to the x-ray intensity, was recorded using a fast digitizing oscilloscope every 1 ns for 4 ms, which encompasses the entire spray event. At each position, the x-ray intensity from 128 successive spray events is averaged in order to improve signal to noise ratio. Equation 1 is then used to convert the x-ray intensity to projected density in the spray. More detailed descriptions of the x-ray radiography technique can be found in other work [3-12,25,27].

The spray chamber was mounted on high precision translation stages that moved it in two dimensions in the plane perpendicular to the x-ray beam. For each measurement condition, measurements were made at approximately 980 different beam positions. Figure 2 shows a typical measurement grid used in these experiments. It should be noted that these measurements contain data from different spray events. Thus, the radiography data show the persistent, ensemble average features of the spray, rather than the details of any particular spray event.

![Measurement grid](image)

**Figure 2.** Typical measurement grid showing the position of the x-ray beam in the line-of-sight coordinate system of the spray

**Injection System**

In the present experiments a Caterpillar Hydraulically actuated Electronically controlled Unit Injector (HEUI) 315 B was used. Unlike other common rail injection systems, the HEUI 315 B requires both engine oil and fuel for operation. The HEUI uses hydraulic pressure from the oil to raise the pressure of the fuel to the desired level for direct injection. This is done by an internal differential piston, which multiplies the modest oil rail pressure to a high fuel injection pressure. This injector uses an intensifier ratio of approximately 6.6 between the oil rail pressure and injection pressure. Parameters such as the injection timing, duration, and quantity are controlled by a solenoid that is connected to the engine’s electronic control unit (ECU) [16].
Figure 3 shows a schematic of the HEUI injection system that was used in this study. The HEUI injector performance bench provides the injector with both fuel and oil and also collects the return fluids. The bench is composed of four main circuits: oil circulation, oil cooling, fuel circulation, and fuel cooling. The temperatures and pressures of the supply fuel and oil are monitored and controlled in the bench. High pressure oil is supplied from the bench to the oil rail (line 2) via a Caterpillar variable delivery high-pressure oil pump. A pressure sensor and thermocouple are attached to the rail as a check of the oil conditions, along with an additional pressure sensor that is connected to the ECU. The oil is then supplied to the injector (line 4) where it builds fuel pressure for injection. The oil is then vented through the top of the injector and is cycled back to the bench (not shown). The fuel supply and return lines are shown in the diagram as lines 1 and 3. The injection system was controlled remotely using an external switch to start and stop injection. CadetWIN software was used to control and monitor parameters such as oil rail pressure, engine speed, and injection quantity.

The full-production, minisac nozzle investigated in this study is shown schematically in Figure 4(a). It has six cylindrical holes with diameter of 169 µm at a 126° angle as shown. One orifice was carefully isolated in order to study the dynamics of a single spray plume. An isolation shield, shown in Figure 4(b), was intricately designed and manufactured to deflect the remaining plumes and allow the plume of interest to spray freely through the spray chamber in the direction indicated. Figure 4(c) provides a closer view of the isolation shield and the single hole in the opening. This isolation shield was designed in such a way that it does not block the remaining plumes; rather it deflects them without restriction.

The use of a full-production six-orifice injector is definitely an advantage of this work in that it keeps the fuel dynamics inside the injector nozzle unaltered. However the introduction of the isolation shield may change the aerodynamics slightly or interact with the spray. The chamber was constructed so that the injector mounts at an angle and the plume of interest sprays horizontally and normal to the x-ray beam.
**Test Conditions**

Sprays in diesel engines encounter an environment of high pressure, temperature, and density. Unfortunately, it is not currently possible to replicate these conditions in an x-ray radiography experiment. The x-ray transparent windows used in these experiments are polyimide film and are 3mm × 22 mm in the transverse and axial directions, respectively. Nitrogen at room temperature was used as a fill gas at 30 bar pressure. No evaporation of the sprays is expected to occur at these conditions. While the temperature and pressure levels in these experiments are far from those in a diesel engine, the density is 34.13 kg/m$^3$, which is comparable to engine density. Two oil rail pressures were selected: 17 and 21 MPa, which correspond to peak injection pressures of about 1100 and 1350 bar according to the intensifier ratio (6.6) mentioned earlier. A constant injection quantity of 100 mm$^3$/stroke was chosen. These parameters were used for the present study due to their consistency with known engine test conditions. Table 1 lists other specific parameters of the experiments.

**Table 1. Test Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity</th>
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</thead>
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<tr>
<td>Injection System</td>
<td>Caterpillar HEUI 315B</td>
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<td>Number of Orifices</td>
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</tr>
<tr>
<td>Orifice Diameter [µm]</td>
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<tr>
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<tr>
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<td>Fuel Temperature [°C]</td>
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</tr>
<tr>
<td>Fuel Injection Quantity</td>
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</tbody>
</table>

**Numerical Setup**

Standard models available with STAR-CD were used to perform simulations. These included Reitz and Diwakar model for atomization and droplet breakup [17], advanced collision model [18-20], spray evaporation model [21], standard turbulent dispersion model [22], RNG $k-\varepsilon$ turbulence model, and standard drag model [23]. Post-processing codes were written to calculate the liquid penetration and radial mass distributions at a given time. The computational domain simulating the spray chamber is of 50 mm diameter and 200 mm length. An O-mesh was generated with cells near the center being a cube and therefore do not have acute angles between adjacent sides. This O-mesh is better than a radial mesh as used by previous STAR-CD users [24], since it avoids narrow wedge-shaped cells near the center of the spray chamber. A mesh with 14x14 grids in the square and 14x56 in the circle outside was generated. 110 grids were used in the direction of injection (+Z) and using a geometric distribution the grids near the injector were 1mm.

**Results and Discussion**

To further understand the initial dynamics of the fuel spray, rate of injection (ROI) studies were conducted using a Bosch rate of injection indicator [13]. Rate profiles were obtained for a range of oil rail pressures and injection deliveries. The ROI profiles as a function of time for the oil rail pressures of 17 and 21 MPa are shown in Figure 6.

**Figure 6. Rate of Injection profiles for 17 and 21 MPa oil rail pressures, 30 bar ambient pressure, 100 mm$^3$ per stroke fuel delivery. The transition period of rapid increase to quasi-steady injection is marked.**

For both conditions the commanded fuel delivery was set to 100 mm$^3$ per stroke. The injection back pressure was maintained constant at 30 bar to simulate the x-ray test conditions. The pressure signal from the ROI meter was low-pass filtered at 30 kHz and was ensemble averaged over 512 traces. Both cases show similar delay
between commanded start of injection (SOI) and apparent SOI with the higher rail pressure slightly ahead, and have comparable rate shapes. As expected the higher rail pressure yields higher peak value of ROI with a slightly quicker initial rise than the 17 MPa case. A notable feature of both rate profiles is the slower rise to the steady state injection period than with single-fluid common rail injection systems. It should be mentioned that the rate profiles shown are for a combination of all six orifices. Considerations were taken when using the ROI profiles for numerical modeling of a single spray plume to match the x-ray experiments.

Using the ROI profile, for the early transition region (t<0.2ms), shown in Figure 6, yields gross underprediction in penetration lengths (not shown here). Further investigation revealed that directly scaling the injection rate from six-sprays to a single spray in the transition region might cause this under prediction. Therefore further investigation of this critical area was performed to gain more understanding of the initial period of ROI for a single spray.

Examination of the x-ray data itself provided insight regarding the initial ROI for a single hole of the nozzle. Total mass injected versus time was calculated. According to the control volume analysis conducted by Kastengren et al. [3], the initial rise in mass can be used as the ROI until the spray has reached the end of the measurement domain. Figure 7 plots the ROI obtained from the x-ray data up to 0.2ms at the first measurement location (0.283mm). The lines represent a linear fit to the data.

For the STAR-CD simulations presented here, the initial ROI was obtained from x-ray data and was combined with the steady state ROI obtained from the Bosch meter to construct an injection rate for the duration of injection. It was ensured that the mass injected through the single hole of the nozzle was 1/6th of the total mass injected.

The data obtained from the x-ray experiments were analyzed for further understanding of the spray characteristics. Penetration was obtained by determining the time at which the amount of fuel seen at a particular axial location rises above a threshold value. The calculation is repeated for all axial measurement positions. Figure 8 presents the measured and predicted variation in penetration with time for oil rail pressures of 17 and 21 MPa.

There are several observations from the penetration data presented in Figure 8. For both rail pressures, a slow penetration region up to 0.1ms is followed by a faster penetration region (where penetration linearly scales with time) up to 0.2ms. The last measured point for the 17 MPa case suggests that the spray may be entering a region where penetration scales with square root of time; however, more measurements would be necessary to verify this trend. These spray penetration characteristics are consistent with the observations of Naber and Siebers [26]. Validation of STAR-CD simulations against penetration data is also presented in Figure 8. In general the match is excellent for both cases after 0.1ms; small differences are observed earlier.

A polynomial fit is taken of the penetration data shown in figure 8 and the penetration speed is then calculated as shown in Figure 9. The 17 MPa oil rail pressure spray shows a rapid initial increase in penetration speed followed by a slow decrease. For the higher oil rail pressure, the penetration speed increases more

![Figure 7. Rate of Injection as measured from x-ray data at 0.283mm from Injector nozzle for different rail pressures along with the respective linear fits.](image)

![Figure 8. Validation of spray models in STAR-CD against x-ray penetration data for oil rail pressures of 17 and 21 MPa, 30 bar ambient pressure, 100 mm³/stroke fuel delivery](image)
gradually and continues increasing throughout the measurements. The maximum speeds achieved are notably lower than those achieved at similar conditions with a single-hole injector [25]. Further investigation indicated that the single-hole injector with the single-fluid common rail injection system used in the cited study shows a much steeper rise in mass flow rate during the initial stages of injection than the HEUI system. This slower ramp in ROI for the HEUI injector may account for the slower penetration speeds observed in the present experiments.

![Graph showing penetration speed vs. time after SOI](image)

Figure 9. (a) Penetration Speed (b) Full field spray projected density vs. position at 0.122 ms after SOI for 17 and 21 MPa oil rail pressures, 30 bar ambient pressure, 100 mm$^3$ per stroke fuel delivery.

Probably the most remarkable observation is that the higher oil rail pressure shows lower penetration speeds than the lower oil rail pressure case for some parts of the spray. This is unexpected, since other studies have observed that higher injection pressure yields faster penetration under similar conditions [11,25]. Also, the existing penetration correlations in the literature show that penetration scales with the difference in the injection and ambient pressures [11,26]. The ROI profiles measured with the Bosch rate meter also indicate a faster rise in mass flow for the higher oil rail pressure. Figure 9(b) shows the projected density versus position of both sprays at 0.122 ms after SOI. Here it can clearly be seen that the penetration for the 21 MPa oil rail pressure case is smaller than for the lower pressure during this transient period.

One interesting thing to note is that simulations also show this same trend in terms of penetration, i.e., the 17MPa rail pressure case yields higher penetration velocities compared to the 21MPa rail pressure case. As noted earlier, the ROI for the early transition region is taken from x-ray data. In the region this close to the nozzle, only the upstream conditions effect spray penetration rather than the details of the spray models. As seen in Figure 7, clearly the 17 MPa rail pressure case sees higher injection rates and thus yields higher injection velocities. This is apparently the reason as to why the 17 MPa rail pressure case has faster penetration than the 21 MPa rail pressure case in both experiments and simulations.

Previous researchers have measured diesel spray penetration, and provided correlations for penetration behavior. Payri et. al. [11] obtained the following penetration correlation in the transition region:

$$S = (0.018)(\rho_a)^{-0.256}(\Delta P)^{0.516}(t)^{1.044}$$  \hspace{1cm} (2)

These curve-fit coefficients were obtained to specifically match penetration in the first 15 mm region of the spray. In the short-time limit Naber and Siebers [26] obtained:

$$S = C_v(t)\sqrt{\frac{2*(P_f - P_a)}{\rho_f}}$$ \hspace{1cm} (3)

Figure 10 plots the x-ray data obtained for rail pressure of 17 MPa and the above penetration correlations. For our case $C_v$ was not measured. Extensive cavitation modeling (not presented here), however, revealed a value close to 0.75, which is comparable to typical $C_v$ values for diesel injection nozzles. Even if the $C_v$ were much lower than 0.75, the qualitative result remains that the Naber and Siebers correlations [26] predict much higher spray penetrations than the current data. This is attributed to the fact that the initial gradient in the injection rate for the experiments upon which the Naber and Siebers correlation is based is much higher than that in the current experiments. This yields high injection velocities earlier in the spray event, and hence faster penetration. The correlation of Payri et. al. [11] was much closer to the x-ray data obtained. A closer comparison of injection rates between Payri et. al. and those presented in Figure 6 shows that the injection
rates are close to each other. Indeed, the gradient in the rate of injection for Payri et. al. [11] was higher than in the current experiments. This results in over prediction of penetration by Payri’s correlation.

For the 17MPa case, downstream of x = 12mm simulations clearly show the long-time limit behavior [26] with the penetration scaling with square root of time. However, for the 21MPa case this transition appears at approximately x = 14mm. Naber and Siebers [26] used a characteristic length (x’’) to mark the transition between penetration being proportional to time versus square root of time. The equation for the characteristic length is:

\[ x'' = \frac{d}{\alpha \tan\left(\frac{\theta}{2}\right) \sqrt{\frac{\rho_f}{\rho_a}}} \]  

The nozzle effective diameter was assumed to be 160 \( \mu m \) for the current 169 \( \mu m \) orifice and \( \alpha \) was assumed to be 0.66 [26]. Optical cone angle was calculated as:

\[ \tan\left(\frac{\theta}{2}\right) = 0.31 \left(\frac{\rho_a}{\rho_f}\right)^{0.19} \]  

A value of about 13mm was obtained for both pressures. Clearly, the simulations match this value with close proximity.

Figure 11 presents the variation of projected spray density with respect to position. As seen in Figure 11(a), both the sprays exhibit similar structures initially (i.e., 0.7 ms after SOI). The 21 MPa oil rail pressure case shows interesting behavior near the nozzle starting around 0.9 ms after SOI. A broadened region of the spray appears during this time lasting approximately 0.73 ms (cf. Figure 11(b)).

**Figure 10.** Comparison of X-ray data at 17MPa rail pressure with penetration correlations available in literature

**Figure 11.** (a) Full field spray projected density vs. position at 0.7 ms after SOI for oil rail pressures of 17 and 21 MPa. (b) Near nozzle region of spray projected density vs. position at 1.15 ms after SOI for oil rail pressure of 21 MPa. (c) Transverse mass distributions at an axial position of 0.283 mm from the nozzle for various times after SOI for case of 21 MPa oil rail pressure.

Taking a closer look at the transverse mass distributions at the first measurement location (0.283 mm from the nozzle) at various times after SOI, a shift in mass is
observed as shown in Figure 11(c). At 0.7 ms after SOI (before the broadening is observed) the mass distribution is fairly even from one side to another. It then proceeds to increase towards the top of the spray at 0.9 mm/stroke. Although some accumulation of mass was observed, however due to limitations imposed by the windows used for optical access, lower back pressure in the spray chamber was necessary. Figure 12 presents an image of an injection event at 17 MPa oil rail pressure, 2 bar chamber pressure, and a fuel delivery of 100 mm³/ stroke. Although some accumulation of mass was observed on the slanted surface of the shield below the spray, no errant interference with the spray was observed. Improvements to the shield design would include a more drastic slope on the angled surface.

An example of the transverse projected mass distribution profiles obtained from the x-ray data for the 21 MPa oil rail pressure case is shown in Figure 13. This profile is taken at an axial position of 0.283 mm away from the nozzle and 0.1 ms after SOI. The black rectangle at the bottom of the figure is provided to indicate the injector nozzle size (169 μm diameter). The projected mass density profile shows a Gaussian distribution even at this early stage of injection. Previous studies on sprays from single-hole common rail injectors have observed that close to the nozzle the mass distribution has a more square shape and develops to Gaussian distributions at further downstream locations [27].

**Figure 12.** Optical image of injection event at 17 MPa oil rail pressure, 2 bar chamber pressure, fuel delivery of 100 mm³/ stroke.

**Figure 13.** Transverse mass distribution profile for 21 MPa oil rail pressure at 0.283 mm axial position and 0.1 ms after SOI.

**Figure 14.** Validation of spray models in STAR-CD against x-ray data obtained for transverse distributions of projected density at 2.883mm from the nozzle 1.05ms after SOI.
Figure 14 presents x-ray data and simulation results in terms of the transverse distributions of projected density after 1.05ms from SOI at 2.883mm from nozzle tip for 17 and 21 MPa rail pressures. Simulations also predict Gaussian distributions for both cases. The match is satisfactory at the tails for 17 MPa rail pressure case. While simulations can fairly reproduce the x-ray data qualitatively, the spray density is overpredicted for both the cases. This over-prediction yields a difference of peak mass value of about 40% and a 50% over-prediction of the transverse integrated mass (TIM) at the 2.883mm axial location. Similar trends are observed for the 21 MPa rail pressure case. While the experimental Gaussian profiles are nearly symmetrical about the y-axis, simulation results indicate skewness towards positive transverse position. This could be due to a statistical error as a sufficient number of droplets may not be residing in the domain of interest. In general, the comparison clearly indicates the need for additional work to further improve the spray models.

X-ray cone angle is computed by marking the location of the FWHM of the Gaussian fits to the transverse mass distributions at each axial location for each moment in time. The cone angle is then calculated from a linear fit to the FWHM locations, and is plotted as a function of time in Figure 15(a). If the transverse mass distributions are perfectly axisymmetric and Gaussian, this cone angle value indicates a volume containing half the total mass in the spray. Since x-ray radiography focuses on the core of the spray while optical techniques focus on the spray periphery, the x-ray cone angle is expected to be significantly smaller than the optical cone angle [8].

Although there is not a large difference in cone angle values between the two cases, the cone angle tends to be higher for the 21 MPa oil rail pressure case than for the 17 MPa oil rail pressure case, with average quasi-steady state values of 10.5° and 9.9° respectively. Figure 15(b) presents the cone angle versus time in the initial transient part of the spray along with a polynomial fit to the data. The spray cone angle for the 21 MPa oil rail pressure case is consistently larger compared to that of the lower pressure case in this transient region as well. This is consistent with the projected density results discussed earlier in the context of Figure 9(b) where the projected density for both sprays is shown during the transient period of injection. These cone angle values are larger than those observed for single-hole common rail injectors under similar conditions [25].

Conclusions
A full production, six-hole tip of a HEUI 315B injector has been investigated at engine-like ambient densities. Rate of injection studies have been performed to further understand the fuel flow dynamics in the injector nozzle. For the x-ray radiography experiments, particular attention was given to isolate a single spray plume. The amount of fuel injected and ambient conditions were kept constant while varying the oil rail pressure, which scales with peak injection pressure. The
experiment parameters were selected to correspond with known engine test conditions. A detailed analysis of the acquired data was performed and used for validating the sub-models available in Star-CD software.

Special considerations were taken when constructing an ROI profile for numerical simulation of the spray. The x-ray data was used to obtain the initial part of the transient rise in the rate shape and was combined with the measured ROI profile to account for one-sixth of the total mass injected. Good agreement was found between the measured data and the simulated penetration curves, including the unusual penetration behavior at higher pressures. This is a direct result of the numerical ROI profile construction from the x-ray data. However, a closer match is achieved in this manner than simply scaling down from the measured rate shapes, indicating that x-ray data can give closer insight to the initial behavior of flow through a single hole in a multi-hole nozzle. Moreover, the CFD simulations captured penetration well. Providing more detailed spray characteristics, such as the transverse mass distribution, requires significant improvements to the spray models, especially in the area near the injector nozzle.

The rate profiles obtained from ROI experiments indicate that the higher oil rail pressure case has a slightly more rapid rise in ROI during the initial transient period compared to the lower pressure case. This suggests that penetration should be quicker for the higher pressure case. However, the x-ray data indicates slower penetration speeds for portions of the spray for the higher pressure case. Because this uncharacteristic behavior is not observed in the ROI testing where the injector nozzle is unobstructed, it may be an effect of interference of the isolation hardware with the nozzle and the spray during x-ray experiments. The isolation shield was evaluated for effectiveness and possible improvements were identified.

Although direct comparisons cannot be made between the performance of the HEUI dual-fluid multi-hole injection system and common rail single-fluid, single-hole injection system; on a bulk level they show several differences. Naturally, the vast differences in fluid dynamics of a single and multi-hole injector contribute to these differences. In addition, some of these could be attributed to fairly significant dissimilarities in the trends of initial transient rise in ROI between the two systems.

\[ I \] Intensity of x-ray beam during spray event
\[ I_0 \] Intensity of x-ray beam before spray event
\[ M \] Projected density, \( \mu g/mm^2 \)
\[ \Delta P \] (Injection – Back) Pressure, N/m\(^2\)
\[ S \] Spray tip penetration, mm
\[ t \] Time, s
\[ x^+ \] Characteristic length, m
\[ \alpha \] Nozzle constant
\[ \rho \] Density, kg/m\(^3\)
\[ \mu \] Absorption coefficient of the fuel, mm\(^2/\mu g\)
\[ \theta \] Optical cone angle

Subscripts
\[ a \] Ambient
\[ f \] Fuel

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