Improved Method to Determine Spray Axial Velocity Using X-Ray Radiography

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Abstract

X-ray radiography is a technique that has provided important insights into the structure and behavior of diesel sprays in recent years. An analysis method has been developed to derive the mass-averaged axial velocity from the radiography data. This determination, however, was found in previous work to be subject to a significant degree of noise, limiting the usefulness of the analysis. In this work, a fitting procedure is implemented to substantially improve the results from this analysis. After demonstrating the superiority of the fitting method over the previously used method, the results of the analysis for four different sprays from light-duty diesel common rail injectors will be examined. Sprays from two different single-hole axial tip geometries (hydroground and non-hydroground) and two injection durations (400 µs and 1000 µs) have been used. The injection pressure is 250 bar, with injections into N₂ at atmospheric pressure and room temperature. The maximum velocity seen in the long-duration sprays is 20-25% less than the Bernoulli velocity, though it appears that the injectors have not yet reached steady state at the end of the data record. For the 1000 µs duration sprays, the trends of spray axial velocity with axial position are quite similar between the two nozzles. This is surprising considering that the cone angle of these sprays is quite different. Calculations of the spray momentum show that the spray from the non-hydroground nozzle has more total axial momentum than the spray from the hydroground nozzle. For the 400 µs duration injections, the hydroground nozzle has the greater momentum, possibly due to differences in the injector current histories between the non-hydroground and hydroground nozzle sprays.
Introduction

The sprays created by diesel injectors have been a subject of considerable research interest for several years. The structure of these sprays has an important impact on the emissions and performance of diesel engines [1,2]. Unfortunately, these sprays are quite difficult to measure. The droplets of the spray strongly scatter light, making optical techniques problematic, especially in the dense near-nozzle region. Most studies to date have focused on a few easily measured quantities, especially the spray cone angle, the penetration speed of the spray’s leading edge, and the maximum extent of the spray where liquid fuel can be found under evaporating conditions [3-5].

A number of numerical analyses of sprays have also been performed. Many of these studies focus on the use of Lagrangian spray breakup models in CFD models of engine flow and combustion [6-8]. A drawback of these models is that the spray properties at the injector nozzle exit, such as injection velocity and droplet size, must be either estimated or tuned to achieve agreement with experimental spray measurements. Other studies focus on the internal flow in the injector itself, modeling the flow and cavitation in the injector sac and orifice [9-12]. Both of these modeling approaches are difficult to validate with experimental data, since few measurements of dynamically important variables are available in spray flowfields, especially in the dense near-nozzle region.

X-ray radiography is a tool which allows for the internal structure of sprays to be examined, even in the near nozzle region [13,14]. This is a region which is quite difficult to probe using optical techniques. The radiography technique shows the density of the spray as a function of time and space, providing important insights into the spray dynamics. This work will describe improvements to a technique described recently [15] to measure the axial velocity of sprays using x-ray radiography. The improvements to the technique will be described and their superiority to the previously used technique will be demonstrated. Then, the improved technique will be used to analyze four sprays from nozzles of different geometries and with different commanded spray durations.

Experimental Method

Data will be shown in this paper from four different sprays, all produced by single-hole axial nozzles from a Bosch light-duty common-rail diesel injector. One of the nozzles has been extensively hydroground, with a diameter of 183 μm. The other nozzle has not been hydroground, and has a diameter of 207 μm. The steady-state flowrate for both nozzles is approximately equal, however. For each of these nozzles, two injection durations were used: 400 μs, which simulates a pilot injection, and 1000 μs, which simulates a main injection event. The ambient gas for all of these experiments was N₂ at atmospheric pressure and room temperature. For all of these sprays the injection pressure was 250 bar.

The measurements in this paper have been performed using x-ray radiography. In this technique, a narrow beam of monochromatic x-rays is passed through a specially-designed spray chamber with x-ray transparent windows. Using a simple linear absorption model, the x-ray transmission through the spray can be related to the projected density of the spray (in mass per unit area) by the following formula:

$$M(t) = \frac{\rho}{\varepsilon} \cdot \ln \left( \frac{I(z = 0, t)}{I(z = \ell, t)} \right)$$  \hspace{1cm} (1)

Here $M(t)$ is the projected density at time $t$, $\rho$ is the liquid density, $\varepsilon$ is the absorption coefficient of the liquid (in mm⁻¹), $I$ is the x-ray intensity, $z$ is the distance along the x-ray beam, measured from the upstream end of the spray chamber, and $\ell$ is the path length through the spray.

In order to examine the dynamics of diesel sprays, which have durations of 1 ms or less, an ultra-fast x-ray detector is needed. Unfortunately, there are currently no ultra-fast non-intrusive x-ray detectors. Thus, Eq. 1 cannot be applied directly. The length of the data record in these experiments is 1-2 ms, during which the incident x-ray beam intensity is nearly constant. Thus, the x-ray intensity before the start of the spray can be used in place of the incident intensity in Eq. 1. With this simplification, the equation used to convert x-ray intensity to projected density becomes:

$$M(t) = \frac{\rho}{\varepsilon} \cdot \ln \left( \frac{I(t = 0)}{I(t)} \right)$$  \hspace{1cm} (2)

Here both intensity values are measured after the beam passes through the spray chamber.

The experimental setup is shown in more detail in Figure 1. The x-ray beam is produced by the 1-BM beamline of the Advanced Photon Source. The x-ray beam passes through a series of focusing optics, then two pairs of slits, which define a narrow beam. The full-width, half-maximum (FWHM) size of the beam was 200 μm axially x 30 μm transverse for the 400 μs duration injection with the hydroground nozzle. For all other cases, the beam size was 145 μm axially x 12 μm transverse. After passing through the spray chamber, the x-ray beam illuminates the detector, an EG&G avalanche photodiode (APD). The x-ray signal is measured as a function of time by the
APD and is recorded every 1 ns by a Yokogawa DL7480 500 MHz oscilloscope.

**Figure 1.** Experimental setup

Because the Advanced Photon Source is a synchrotron source, the radiation produced by the Advanced Photon Source has a pulse structure that forms a repeating pattern. For convenience, the x-ray intensity data are binned into time bins whose length equals the repetition time of the x-ray radiation, 3.68 μs. Equation 2 is then applied to convert the x-ray intensity data to projected density data. It must be stressed that the radiography technique is by its nature pathlength-integrated. Thus, the final data is the projection of the spray density onto a plane perpendicular to the x-ray beam.

The APD is a single-point detector (i.e., it has no ability to resolve spatially). To find the spatial structure of the spray, the spray chamber is rastered to a number of different positions to build up a two-dimensional map of the projected density of the spray as a function of time. Data are taken in discreet columns or slices aligned perpendicular to the injector (x) axis. For example, the measurement grid for the 1000 μs duration injection from the hydground nozzle contains 54 columns from x = 0.2 mm to x = 46 mm, with a total of 2982 individual measurement locations. Similar grids were used for the other cases.

**Results**

Figures 2 - 4 show the two-dimensional radiography data at representative times during the injection event after the start of injection (SOI). The sprays from the different nozzles exhibit similar structures, so only the sprays from the non-hydroground nozzle will be shown. The short injection events consist of a well-defined leading-edge structure connected by a jet of fluid to the nozzle. After the end of injection, this jet quickly dissipates as the leading edge structure expands and moves downstream. The long-duration spray, on the other hand, contains a much more pronounced jet connecting the leading edge structure to the nozzle. Moreover, the jet attains a nearly steady-state appearance for approximately 400 μs before the end-of-injection. This is unlike the short-duration spray, whose structure changes continuously over its lifetime.
trailing-edge speed [13,16], this work largely focuses on the determination of spray axial velocity from the radiography data. A detailed derivation of the analysis is given elsewhere [15]; the derivation will be summarized briefly here. Consider a spray flowfield with a given field-of-view in the radiography data, as shown in Fig. 5. Since the radiography technique provides the projected density of the fuel in mass per unit area, the total mass of fuel downstream of any position \( x_0 \) can be easily determined by simple summation of the projected density data so long as the entire spray is within the measurement domain. If mass only flows into this region \( x > x_0 \) through the plane \( x = x_0 \), the mass flow into the region is related to the density and velocity at \( x = x_0 \) by control volume analysis.

\[
\dot{m}_{cv}(x > x_0,t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \rho(x_0,y,z,t)V_x(x_0,y,z,t)dz\,dy
\] (3)

Next, a mass-averaged axial velocity at \( x = x_0 \) is defined with the following formula.

\[
V_{ma}(x_0,t) = \frac{\int_{-\infty}^{\infty} \rho(x_0,y,z,t)dz\,dy}{\int_{-\infty}^{\infty} \rho(x_0,y,z,t)dz\,dy}
\] (4)

The denominator of this expression is simply the integral of the projected density across the plane \( x = x_0 \). As described in previous work [15], this quantity is determined by performing Gaussian fits to the projected density distribution across the spray, and is termed the transverse-integrated mass (TIM). The numerator of Eq. 4 is the same as the right-hand side of Eq. 3. Thus, the mass-averaged axial velocity can be determined by:

\[
V_{ma}(x_0,t) = \frac{\dot{m}_{cv}(x > x_0,t)}{TIM(x_0,t)}
\] (5)

A few observations should be made regarding this technique. This analysis can be performed for any axial position \( x_0 \). This, if this analysis is performed for every axial measurement location, a measurement of the trend in spray axial velocity with downstream distance can be shown. Moreover, this analysis can be performed at every time step of the measurement. Thus, the time history of the spray velocity at any axial location can also be determined. Combining these two features, the spray velocity can be determined as a function of axial position and time across the entire spray flowfield.

There are a few important limitations of this technique. The data obtained by this technique are mass-averaged across the plane \( x = x_0 \) at a particular time step; thus, no data regarding the transverse variation in velocity is available from this analysis. Moreover, only the axial component of velocity is measured. Finally, this analysis is only valid if mass flows into region \( x > x_0 \) only through the plane \( x > x_0 \). Thus, once the spray reaches the edge of the measurement domain, the analysis is no longer valid.

As demonstrated previously [15], the success of this analysis depends critically on the determination of the mass flux through \( x = x_0 \). The record of mass in the region \( x > x_0 \) is experimental data subject to noise. An example of such a record is shown in Fig. 6a. While the curve appears smooth, a direct derivative of this curve is quite rough, even when filtering and averaging is used, as shown in Figure 7. Such a large amount of noise limits the usefulness of the final data, since this noise is directly reflected in the spray velocity results.
To improve upon the previous technique, a polynomial has been fitted to the downstream mass data shown in Fig. 6a. An eighth-order polynomial has been fit to the data to smooth the data while retaining the detailed features of the curve shown in Fig. 6a. While such a high order fit is unnecessary to fit a curve like that shown in Fig. 6a, this curve can take a wide variety of shapes at different axial positions and for different sprays. The domain of the polynomial fit ranges from the time mass first appears at \( x = x_0 \) to the point where mass first appears at the downstream edge of the measurement domain (1000 \( \mu s \) duration sprays) or when the injection appears to end (400 \( \mu s \) duration sprays). As shown in Figure 6b, the fitted curve retains the same general shape as the original data. While these results are for a single case, the agreement shown in Figure 6 is typical for other axial locations and the other spray cases.

A distinct advantage of using the polynomial fitting is that the derivative of the fitted curve can be found analytically, rather than by numerical differentiation of the raw data, as was done previously [15]. This yields a much smoother mass flow curve, as shown in Fig. 7. The mass flow curve based on the polynomial fits shows the same general features as the data using the direct method, but the reduced level of noise allows one to observe that the mass flow levels off near the end of the data record.

Figure 8 shows the axial velocity near the injector nozzle (\( x = 0.2 \) mm) for the 1000 \( \mu s \) spray from the hydroground nozzle using the direct mass flow determination and the fitted method described above. While both curves show the same general trends, the curve using the fitted data is much smoother, and the trends in the data near the end of the data record are much clearer. This demonstrates the superiority of the fitting method over a direct determination of the mass flow, even with filtering and local averaging.
Figure 8. Comparison of the spray axial velocity as determined with the previous direct method and the current fitting method.

Figure 9 shows the axial velocity of the spray near the nozzle exit \((x = 0.2 \text{ mm})\) as a function of time for the 1000 \(\mu\text{s}\) sprays from both the hydroground and non-hydroground nozzles. Several features are evident. The spray velocity is less than 75 m/s near the start of injection. The spray velocity rises over a time period of approximately 400 \(\mu\text{s}\), with a distinct decrease in slope at 200 \(\mu\text{s}\) after SOI. Both sprays reach a maximum axial velocity of 175-180 m/s 400 \(\mu\text{s}\) after the start of injection. The spray from the hydroground nozzle moves more quickly immediately after the start of injection. This difference in spray velocity persists until the sprays near their peak velocity 400 \(\mu\text{s}\) after the start of injection.

It is interesting to note that the peak velocity for both nozzles is only about 75% of the Bernoulli speed of 236 m/s for this injection pressure. For the hydroground nozzle spray, the authors believe that the needle has not reached full lift, since the 2-D spray density data show that the spray undergoes a significant transition in behavior after the end of the data record. It is clear from these data, however, that the Bernoulli speed is a relatively poor estimate for the mass-averaged velocity for a significant time period during the opening of the injector.

Figure 9 also demonstrates some limitations of the technique, even with the use of polynomial fitting to determine the mass flow past each column. There are artifacts near the beginning and end of both curves. The authors believe that this is the cause for the decline in both curves near the end of the data records. While the information shown in these plots is quite valuable, the authors do not believe that the sprays have reached steady state; steady-state measurements would be desirable to discuss the influence of different nozzle geometries on the spray axial velocity without the confounding effects of throttling from the flow passage along the needle seat.

Figure 10 shows the spray axial velocity for the 400 \(\mu\text{s}\) duration sprays from both nozzles near the nozzle exit \((x = 0.2 \text{ mm})\). When comparing these two sprays, it should be noted that while the total commanded injection duration was 400 \(\mu\text{s}\) for both sprays, in initial pulse of high current used to help the injector begin to open (the “breaking current”) was applied for 250 \(\mu\text{s}\) for the spray from the hydroground nozzle, as opposed to 150 \(\mu\text{s}\) for the spray from the non-hydroground nozzle and the 1000 \(\mu\text{s}\) duration sprays. There are significant differences in the spray axial velocity in these sprays. In the non-hydroground nozzle spray, the spray axial velocity gradually increases to a peak value of 88 m/s 215 \(\mu\text{s}\) after SOI. The spray velocity then rapidly decreases. In contrast, the spray from the hydroground nozzle rapidly rises to a peak value of 93 m/s 105 \(\mu\text{s}\) after SOI and gradually decreases for the next 150 \(\mu\text{s}\). It is possible that these differences are due to inherent differences in the flow development in these nozzles. This seems unlikely, however, given that the flow developed similarly in both nozzles for the 1000 \(\mu\text{s}\) spray. A more likely explanation is that the longer breaking current duration caused the injector to open more quickly for the hydroground nozzle.

An interesting aspect of the short-duration sprays is that the delay between the commanded and actual start of injection is actually longer than the commanded injection duration. It is especially interesting that the detailed history of the injection current supplied to the injector seems to influence the spray velocity behavior even though the current to the injector has ended before any fuel is emitted.
Figure 10. Spray axial velocity at $x = 0.2$ mm as a function of time for the 400 $\mu$s duration sprays.

Table 1. Delay between the commanded and actual start-of-injection

<table>
<thead>
<tr>
<th>Spray Event</th>
<th>Delay, $\mu$s</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 $\mu$s, Hydroground</td>
<td>483</td>
</tr>
<tr>
<td>400 $\mu$s, Non-hydroground</td>
<td>447</td>
</tr>
<tr>
<td>1000 $\mu$s, Hydroground</td>
<td>425</td>
</tr>
<tr>
<td>1000 $\mu$s, Non-hydroground</td>
<td>473</td>
</tr>
</tbody>
</table>

As mentioned in previous work regarding spray axial velocity [15], the main source of noise in the mass flow and spray velocity determinations was the spray behavior near the spray’s leading edge. Since this fluid is downstream of most of the flowfield, noise and errors in the spray density measurements near the spray leading edge influence the mass flow and spray velocity measurements for much of the flowfield. These errors influence all of the downstream measurement positions equally. Thus, it was hypothesized that if one examined the spray velocity as a function of $x$, the noise in the spray velocity would be less noticeable, since the noise would affect most of the axial positions in the same way.

Figure 12 shows a comparison of the spray axial velocity vs. $x$ at 438 $\mu$s after SOI for the 1000 $\mu$s spray from the hydroground nozzle using both the current method and the previous mass flow determination [15]. There is an offset between the curves, but as discussed in Ref. 15, this offset is an effect of the noise in the underlying mass flow determination. The curves are more or less parallel to each other, with similar levels of noise. For example, both curves show a spurious peak at $x = 12$ mm.

The curve from the direct mass flow determination decreases more rapidly near the spray leading edge than the curve found using the current method. Unfortunately, the spray tip is the region where both methods perform the most poorly. The direct method performs poorly because the axial resolution and signal-to-noise ratio are both relatively poor in this re-
The current method performs poorly because
the fitting procedure tends to contain spurious fea-
tures near the beginning and end of the data record
for each column as discussed earlier. While the cur-
rent method does not substantially improve the
amount of noise in the spray velocity vs. time curve
vs. the direct mass flow method, it has the advantage
of removing the offset in the curve, making compari-
sions between different sprays simpler, as shown in
Fig. 11.

Figure 12. Comparison of the spray velocity vs. \( x \)
using the current method versus previously published
data \cite{15} using a direct determination of the mass
flow through the individual axial positions.

As mentioned in Ref. 15, the spray axial velocity
values can be integrated to determine the total axial
momentum of the liquid injected into the spray. Such
a determination would be quite valuable, since cur-
cent methods to measure spray momentum rely on
intrusive techniques \cite{17}. With the previous method,
the degree of noise in the data was such that such
calculations would have been of little value. How-
ever, with the current fitting procedure, such calcula-
tions are more reasonable.

Figure 13 shows the total axial momentum of the
spray fuel as a function of time for the 1000 \( \mu \)s duration
sprays from both nozzles. While these data are
quite noisy, especially near the end of the data
record, it is clear that the total spray momentum in-
creases as the spray develops, with the rate of in-
crease tending to increase. This behavior makes
sense, since the axial velocity at which fluid is in-
jected into the flowfield steadily increases as the flow
develops, leading to an increasing slope of the mo-
mentum vs. time curve. It is also clear that the mo-
mentum of the spray from the non-hydroground noz-
zie is greater than that from the hydroground nozzle.
This is again logical, since the axial velocity at the
nozzle exit was greater for the non-hydroground noz-
zie than for the hydroground nozzle in Fig. 9.

The liquid momentum for the 400 \( \mu \)s duration
sprays from both nozzles is shown in Figure 14. In
this case, the momentum of the spray from the hy-
droground nozzle is greater than that from the non-
hydroground nozzle. The authors believe that this
may be due to the difference in the breaking current
duration between these two sprays. It is interesting to
note that the rate at which the momentum rises near
the beginning of the spray event is significantly lower
for the 400 \( \mu \)s duration sprays than for the 1000 \( \mu \)s
duration sprays. For example, 200 \( \mu \)s after SOI, the
momentum of the 400 \( \mu \)s spray from the hydroground
nozzle is 25-30\% less than that for the 1000 \( \mu \)s spray;
for the non-hydroground nozzle, the momentum of
the 400 \( \mu \)s duration spray is 55\% lower than the mo-
mentum of the 1000 \( \mu \)s duration spray. As demon-
strated above, the behavior of the spray even in its
earliest stages is significantly influenced by the
commanded injection duration.

Future Work

While the spray velocity data shown in this work
show great potential, there are further improvements
that can be made to this method. Since the radiogra-
phy data are built from a series of measurements at
different locations in the spray, any systematic shifts
in the data will cause errors in the calculation of axial
velocity. The spray velocity determination requires
higher data quality than other analyses of the x-ray radiography data to examine spray behavior. Thus, reducing such errors is especially important for this analysis.

These refinements allow meaningful comparisons to be made between different sprays. Sprays from two axial single-hole nozzles (hydroground and non-hydroground) have been measured with two different injection durations (400 µs and 1000 µs). The axial velocity data show that for the 1000 µs duration injections, the spray from the non-hydroground nozzle moves more quickly than that from the hydroground nozzle for the first few hundred microseconds after SOI. The spray velocity gradually increased in both cases over a time period of several hundred microseconds. The peak spray velocity is 20-25% lower than the Bernoulli velocity, though it does not appear that the injector has reached full needle lift at the end of the data record. For the 400 µs duration injections, the hydroground nozzle spray moves more quickly than the non-hydroground nozzle spray, though this may be due to differences in the details of the injector current history rather than fundamental differences in the flowfields. For the 1000 µs spray, both nozzles show virtually identical trends in spray velocity with x. Given that the cone angles of these sprays are quite different, this similarity is somewhat surprising. The spray momentum follows the same trends as the spray velocity at the exit plane, with higher momentum for the non-hydroground nozzle spray for the 1000 µs injections and for the hydroground nozzle spray for the 400 µs injections.

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