Liquid/Vapor Penetration and Plume-Plume Interaction of Vaporizing Iso-Octane and Ethanol SIDI Sprays

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Abstract
Spark-ignition direct-injection (SIDI) engines operating in a stratified, lean-burn regime offer improved engine efficiency; however, seemingly random fluctuations in stratified combustion that result in partial-burn or misfire prevent widespread implementation. Eliminating these poor combustion events requires a detailed understanding of engine flow, fuel delivery, and ignition, but knowing the dominant cause is difficult because they occur simultaneously in an engine. In this study, the variability in fuel-air mixture linked to fuel injection hardware was addressed by experimentation in a near-quiescent pressure vessel at high-temperature and high-pressure conditions representative of late, stratified-charge injection. An 8-hole SIDI spray was interrogated using high-speed schlieren and Mie-scatter imaging from multiple, simultaneous views to acquire the vapor and liquid envelopes of the spray. 3D plume analyses combined with jet spreading angle measurements showed the sprays were attracted towards the injector axis during injection. The decreasing plume angles affected the mixing field at the end of injection, resulting in a single, central plume. Long-working distance microscopy imaging showed that droplets at the end of injection were attracted to the injector axis. These droplets persisted farther downstream in the case of ethanol. Despite the merging of plumes, which could increase total momentum and penetration, single orifice models show greater penetration than that of plumes in the multi-hole injector, leading to the conclusion that multi-hole interactions decrease penetration at these particular operating conditions.

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Introduction

Stricter on-road vehicle emission regulations and future fuel economy standards continue to push engine researchers and manufacturers toward the development of cleaner and more efficient technologies. Improvements to the spark-ignition platform have given rise to the spark-ignited direct-injection (SIDI) gasoline engine, which is becoming more prevalent worldwide due to its increased thermal efficiency over traditional port fuel-injected (PFI) gasoline engines [1]. SIDI also offers improvements in exhaust emissions compared to PFI, particularly for cold-start and overall-stoichiometric operation.

SIDI is performed with either homogenous, stoichiometric operation, by injecting early in the cycle (SIDI-E), or with more stratified combustion, by injecting late during the compression stroke (SIDI-L). Researchers have pursued stratified operation with overall lean-burn combustion for even further gains in efficiency [1, 2]. Efficiency gains are possible because late-injection SIDI can have unthrottled operation resulting in lower pumping losses. The lean mixtures are also characterized by a higher specific heat ratio, and the direct injection promotes greater charge cooling allowing the use of higher compression ratios while avoiding knock. The narrow injector cone angle leads to more centralized combustion resulting in lower wall heat transfer losses. All of these benefits lead to an increase in thermal efficiency. Despite these added benefits over PFI or SIDI-E engines, SIDI-L engines still have issues such as misfires, high carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions at light load conditions [1]. In addition, SIDI-L has a limited operating range in naturally aspirated engines, but researchers have shown that SIDI-L engines can operate with boosted intake pressures to increase the load limit [3].

Two types of SIDI-L engines have been developed since the concept was first proposed. The initial iteration, referred to as wall-guided (WG) gasoline direct-injection, directed an early-cycle injection towards the piston. The piston subsequently directed the fuel back up to the spark plug to produce a stratified charge [1, 4]. Fuel efficiency improvements were achieved with this design, but the concept of relying on wall impingement to create the fuel stratification has drawbacks, for example, UHC emissions.

The second iteration of SIDI-L, spray-guided (SG), pairs the spark plug in close proximity to the fuel spray to form a rich mixture at the spark plug. The advantages over WG include: reduction in soot emissions due to reduced piston wetting, wider stratified operating range from the closely coupled mixture preparation and ignition, and lower UHC from the more compact fuel cloud [5]. Spray-guided SIDI does not come without some disadvantages though. The close coupling of the injector and spark plug results in large gradients in equivalence ratio and velocity, which requires tight constraints on the injection and ignition event to ensure robust and consistent engine operation. Misfires, partial burns, and fouled spark plugs from liquid fuel deposits have all been observed in SG engines [5, 6]. Importantly, it has been observed that an engine could fail an emission test because of the ignition/combustion failure of only a few cycles [7, 8]. The source of these irregular combustion events must be understood in order to make SG engines more viable. In terms of the fuel preparation, the injection and atomization must be stable and repeatable.

Many factors impact the fuel preparation process in an engine such as engine flow, fuel delivery, and the wide range of temperatures and pressures at the time of injection. The need to use alternative fuels in an engine such as gasoline and ethanol blends [9], adds to the complexity of the problem.

The current study is designed to interrogate the spray development solely as a function of the injection process, without the effect of in-cylinder flows, but at temperature and pressure conditions consistent with typical injection and spark timings in an engine operating on SIDI-L strategy. By isolating the spray event from in-cylinder phenomenon, the intention is to identify how fuels commonly used in SI engines affect spray characteristics.

Spray measurements of two fuels using an 8-hole injector were made in a near-quiescent, constant-volume vessel. The sprays were investigated using high-speed schlieren and Mie-scatter imaging from multiple, simultaneous views to acquire the vapor and liquid envelopes, including the 3D liquid-penetration position of each plume. The penetration was quantified on a shot-to-shot basis to characterize multi-hole dynamics. Additionally, long-working distance microscopy (LDM) imaging was utilized to address fuel droplet phenomena at the end of injection (EOI) in the near nozzle and downstream regions. This work aims at studying the injection process and development of SIDI-L sprays in detail to generate a dataset of measurements for two fuels. Such data are needed to evaluate the capability of forthcoming LES spray models which are used to address the problem of stochastic variability in SIDI-L engines.

Experimental Apparatus

Experiments were performed in a constant-volume combustion vessel under simulated engine conditions. Prior to and during operation, the temperature of the entire vessel is maintained at 188 °C by electric heaters. A combustible mixture of gases is spark-ignited to elevate pressure and temperature within the vessel. The fuel is injected when the desired thermodynamic conditions are achieved after a short cool-down period. Ves-
sel pressure and fine-wire thermometry measurements provided the in-vessel conditions at the time of injection. A more detailed description of the facility and its operation can be found in Ref. [10]. The combustion chamber is of cubical shape, measuring 108 mm on each side. The vessel is equipped with six ports (one for each side of the cube). The SIDI fuel injector was mounted in a side port, and two spark plugs were fitted in the top port to initiate the premixed combustion event; the last four ports were fitted with large sapphire windows to provide full optical access to the injection event.

All experiments were performed in an environment of 0% O₂ at the time of injection to avoid combustion (non-reacting spray). Table 1 shows the specifications of the ambient gas parameters that were replicated.

<table>
<thead>
<tr>
<th>Ambient Conditions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Pressure</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Oxygen (by volume)</td>
</tr>
</tbody>
</table>

Table 1. Combustion vessel ambient conditions.

The SIDI injector was operated at 200 bar injection pressure. The fuel system was statically pressurized with a N₂-balanced bladder accumulator. The valve-covered orifice (VCO) injector has 8 symmetrically spaced, 0.140 mm diameter holes (45° angle between adjacent plumes). Each hole is machined into the curved plate of the injector tip with an inner hole and a stepped counterbore. The measured dimensions/positions and other injector specifications are given in Table 2 with an accompanying sketch of the hole position in Fig. 1.

<table>
<thead>
<tr>
<th>Injection:</th>
<th>Ethanol</th>
<th>Iso-octane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic inj. duration</td>
<td>0.658 ms</td>
<td>0.766 ms</td>
</tr>
<tr>
<td>Actual inj. duration</td>
<td>0.75 ms</td>
<td>0.85 ms</td>
</tr>
<tr>
<td>Injected mass</td>
<td>10.6 mg</td>
<td>10.6 mg</td>
</tr>
<tr>
<td>Nominal total spray angle</td>
<td>60°</td>
<td></td>
</tr>
<tr>
<td>Clock angle between holes</td>
<td>45°</td>
<td></td>
</tr>
<tr>
<td>Inner hole min. diameter (a)</td>
<td>0.140 mm</td>
<td></td>
</tr>
<tr>
<td>Inner hole length (b)</td>
<td>0.37 mm</td>
<td></td>
</tr>
<tr>
<td>Counterbore diameter (c)</td>
<td>0.36 mm</td>
<td></td>
</tr>
<tr>
<td>Plate thickness (d)</td>
<td>0.6 mm</td>
<td></td>
</tr>
<tr>
<td>Hole axis relative to nozzle axis (h)</td>
<td>26.5°</td>
<td></td>
</tr>
<tr>
<td>Inner hole axial origin from tip (e)</td>
<td>-0.56 mm</td>
<td></td>
</tr>
<tr>
<td>Inner hole radial origin from tip (f)</td>
<td>0.66 mm</td>
<td></td>
</tr>
<tr>
<td>Hole virtual origin dist. from tip (g)</td>
<td>1.85 mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Injector characteristics.

Injection duration has been shortened for ethanol to account for the density difference between ethanol and iso-octane with the intention of keeping total injected mass per event the same. Densities, as well as other parameters relevant to this study are listed in Table 3 for both ethanol and iso-octane.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ethanol</th>
<th>Iso-octane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³ @ 15°C)</td>
<td>786</td>
<td>690</td>
</tr>
<tr>
<td>Viscosity (mPa·s @ 20°C)</td>
<td>1.14</td>
<td>0.50</td>
</tr>
<tr>
<td>Surface tension (N/m @ 20°C)</td>
<td>0.023</td>
<td>0.022</td>
</tr>
<tr>
<td>Boiling point (°C @ 1 atm)</td>
<td>78.3</td>
<td>99.2</td>
</tr>
<tr>
<td>Enthalpy of vaporization (kJ/kg @ 25°C)</td>
<td>924.2</td>
<td>308</td>
</tr>
</tbody>
</table>

Table 3. Relevant fuel properties.

**Optical Diagnostics**

Alternative-frame schlieren/ Mie-scattering imaging was implemented at high speed to perform near-simultaneous measurements of the vapor and liquid phases of the injection from the side view of the injector axis. This was achieved by pulsing the LED sources for the respective measurements in an alternate fashion, yielding schlieren imaging for one frame of the high-speed movie and Mie-scattering for the next frame. Details of the processing technique and algorithms can be found in Refs. [11, 12]. The schlieren system was a traditional folded Z-type with a 450 nm wavelength LED source. The Mie-scattering system used a 520 nm wavelength LED array for volume illumination of the liquid phase, and a high-speed CMOS camera recorded the light scattered by the liquid region of the spray. Figure 2 details the optical setup.
Figure 2. Combined schlieren and Mie-scattering optical setup. Schlieren and Mie-scattering imaging paths are given as blue and green, respectively. Note that Mie-scattering was imaged along the schlieren path as well.

In addition to the Mie-scattering imaged along the same path as the schlieren images, a front-view (looking at the injector) of the injection process was imaged using Mie-scattering. Front-view and side-view images were recorded simultaneously. Multiple-view Mie-scattering enables three dimensionnal analyses of individual plumes in the sprays. Quantities such as the 3D pointing direction/vector of a plume and its actual liquid penetration are obtained, permitting assessment of the stochastic nature of the injection process and even hole-to-hole variations. The liquid boundaries in both front- and side-views were detected using the methodology proposed by Siebers [13], in which any pixel with a recorded intensity higher than 3% of the mean maximum intensity in the jet is considered to be part of the liquid extent of the spray. Due to the discontinuous nature of liquid plumes, multiple liquid boundaries can exist for an individual frame, whereas the vapor envelope was required to be continuous in the processing.

High-speed microscopic imaging was applied to understand the location and movement of individual liquid droplets. In particular, the technique has been applied to visualize end-of-injection atomization and droplet formation in a line-of-sight arrangement using diffused back-illumination [14]. The LDM imaging system was comprised of an ultra-fast LED as the light source, an engineered diffuser, a field lens, and a high-speed camera equipped with a long-working-distance microscope lens to acquire the images. The optical setup used to perform the microscopic measurements is shown in Fig. 3.

To “freeze” the spray during the camera exposure, an ultra-fast LED driver capable of producing 50 ns pulses at high repetition rate was developed. The light from the LED is passed through the diffuser and field lens to produce a uniform background while avoiding severe beam-steering. The long-distance microscope lens is configured to a 2x magnification for the experiments, providing an optical resolution of approximately 12 µm per pixel.
Results

A wide range of ambient conditions were explored for the two tested fuels, as described in Table 1. For brevity, exemplary conditions and the associated results are presented and analyzed in this study, namely 900 K, 3 kg/m$^3$ and 900 K, 9 kg/m$^3$. All reported times are given after the start of injection (aSOI) as measured through high-speed imaging.

Figure 4 shows the 3D vapor and liquid penetration for ethanol and iso-octane at the condition of 900 K, 9 kg/m$^3$. The individual injection events were averaged across all 8 holes and repeated experiments. The actual ends of injection (see Table 2) are indicated by the solid vertical lines for reference. The 3D liquid penetration was readily calculated from the side- and front-view Mie-scattering using the detected liquid boundaries. As previously explained, the 3D measurements provide the actual distance from the orifice outlet to the tip of the spray. These quantities are important as they may deviate from the angle-corrected axial measurements; this aspect will be addressed later in the analysis section.

The detected vapor boundary, in conjunction with the 3D plume vector, was used to extrapolate the vapor penetration into the third dimension as well. Because the vapor penetration was calculated along the plume vector, it corresponds to a point where vapor is guaranteed to exist, thereby not overestimating the calculation.

The liquid penetration of ethanol is higher than iso-octane, consistent with previous observations [15]. This is likely attributable to ethanol’s greater heat of vaporization and density (see Table 3). A higher heat of vaporization requires more energy transfer (mixing) in the vessel to vaporize the same amount of fuel (when compared to iso-octane), therefore allowing the liquid to penetrate farther. As a result, the iso-octane injections reached a quasi-steady liquid length quickly, whereas the ethanol appears to not reach a quasi-steady state during the injection.

Additional fuel property effects are evident in the liquid length tails after the end of injection. Despite ethanol’s injection ending before that of iso-octane, liquid-phase ethanol persisted until after all of the iso-octane vaporized. The head of the liquid iso-octane jet retreated to the injector after the end of injection while the fuel stream stayed attached to the injector. That is, after EOI, vaporization proceeded from the head of the liquid jet back toward the injector tip such that liquid nearest to the injector was the last to vaporize at around 1 ms aSOI. This is shown by the black dashed curve in Fig. 4. For ethanol, the head of the liquid jet and the “tail” (i.e., the liquid closest to the injector tip) merged to a location approximately 11 mm downstream of the injector tip just after 1 ms aSOI. More specifically, the liquid ethanol stream detached from the injector tip resulting in an upstream liquid boundary that moved downstream to meet the retreating, vaporizing liquid head. This is illustrated in Fig. 4 by showing a second dashed curve corresponding to the tail of the ethanol liquid jet. As the head and tail of the liquid merge, the rate at which the head retreats decreases. Diesel experiments have shown similar behavior in which the fuel detached from the injector after EOI and met the retreating head downstream [16].
Despite the difference in fuel properties and liquid penetration, the 3D vapor penetration curves were similar. Although fuel density is higher for ethanol compared to iso-octane, this does not necessarily translate into increased penetration for isolated sprays because spray penetration is driven by momentum flow rate rather than mass flow rate [16-19]. The momentum flux is preserved because low density fuels have higher injection velocities [17]. Previous research has shown that fuel density has no direct impact on spray momentum as proven with a wide range of fuels including gasoline, diesel and bio-diesel [16-19]. This ultimately means that differences in spray penetration must be associated with other parameters such as spreading angle. Comparisons using a single-jet model approach to simulate plume penetration are available in the analysis section. It is important to note that spray momentum can be impacted by fluid properties indirectly through the hydraulic coefficients of the flow at the injector’s nozzle exit.

The measurement of the spray’s full spreading angle containing all eight plumes can help highlight the potential variations in spray shape when using different fuels. The jet spreading angles were calculated using the vapor envelope at an axial distance of 11 mm. Because the angle was calculated at a certain distance from the outlet, no angle was computed before the vapor reached 11 mm axially; therefore the spreading angles presented in Fig. 5 do not start at 0 ms aSOI. As a result, the lower density case has a calculated spreading angle before the higher density case due to the greater penetration rate in lower density environments [20]. The figure compares the sprays injected into a fixed ambient temperature to highlight fuel and ambient density effects only. The spreading angle results reveal transient behavior as reductions up to 15% occur during the injection event. After injection, the angle continues to decrease as the vapor cloud moved downstream. The transient behavior results in the formation of a single central jet that affects the mixing field, particularly at the end of injection, as will be seen in later results.

In general, iso-octane shows a larger spreading angle at early times in the injection event. This difference was significantly greater under higher ambient density conditions. The larger spreading angle can be attributed to iso-octane vaporizing faster than ethanol. Specifically, as vaporization proceeds, the jet stream loses axial momentum (in the direction of the jet) as it mixes with the ambient. This results in the fuel moving transverse to the injection direction (radially) causing the vapor cloud to swell.

For a given fuel, the higher ambient density resulted in a larger spreading angle. This phenomenon has been observed for single-jets [20] and is attributed to increased mixing at higher ambient density. Increased mixing causes the jet to grow more in the radial direction resulting in a larger spreading angle. Towards the end of injection, the four curves approached each other and decreased at similar rates. Characterizing the transient spreading angle is necessary because spark timings can range from during the injection period until as much as two milliseconds after the end of injection [5]. The close coupling of the injector and spark plug in a SG SIDI-L engine requires detailed knowledge of the spreading angle to ensure proper spark and flame kernel growth in the spark gap, making these measurements valuable across the range of possible engine conditions.

**Figure 5.** Jet total spreading angles for all 8 plumes for 3 and 9 kg/m³ densities. Note the decreasing angle during the injection event.

Figure 6 is a time sequence of a 900 K, 3 kg/m³ iso-octane injection event using the schlieren images as the background to provide visual support for the previous figure (Fig. 5). The injector was orientated such that only four plumes of the 8 hole injector were visible, therefore each plume is really a pair of plumes. The vapor and liquid envelopes are distinguished by the green and blue outlines, respectively. The averaged (for a pair of plumes) drill angles (dimension “h”, Fig. 1) are shown in yellow, and the averaged plume vectors are given by the red lines.

At the early timing (Fig. 6a), the liquid boundary had a similar penetration to the vapor boundary as little vaporization has occurred; the difference in timings between schlieren and Mie-scattering images are accountable for the liquid boundary not being at the tip of the plumes. The plume vectors aligned with the drill angles indicates a lack of multi-hole dynamics and hole-to-hole interactions during the early part of the injection event.
During the middle of injection (Fig. 6b), the bottom and top plume vectors deviated from the drill angles. They are observed to move towards the injector centerline. The middle plume vectors also moved towards the injector axis, but due to the viewing angle, they moved more into the page so the change is not as evident. At the end of injection (Fig. 6c), all plumes have been noticeably attracted to the injector axis.

Figure 7 shows the angle between the plumes and the injector axis as derived from the 3D pointing vector for the single injection event presented in Fig. 6. After 200 µs, the measured plume angles are all approximately equivalent, oscillating roughly between 20° and 26° during the main sequence of the injection. The amount of variability from hole to hole appears random and does not indicate any biases in the orifices or optical setup, even when ensemble averaged; consequently, the remaining data presented in this work are given as averages of the eight holes and ten repeated injections, as seen in Figs. 4 and 5.

Figure 8 shows the averaged plume angles for two cases of interest. It should be noted the average angle is not calculated unless a plume vector (and plume angle) exists for all eight holes and ten injections at a specific point in time. This enforces the average to only exist during repeatable periods of the injection event. The end of the plume angle measurement’s time discrepancy between the 3 and 9 kg/m³ ethanol cases is a result of this processing method.

As observed for the total spreading angle of the fuel stream (Fig. 5), the average plume angles are seen to decrease during injection in all cases. The multi-hole effects are likely a consequence of the narrow cone angle of the plumes yielding a low pressure zone in the core of the cone formed by the plumes during injection. A low pressure zone would result in the plumes being attracted towards the injector axis. Regardless of fuel or condition, the plume angles were rarely seen to match the drill angles except in the very beginning of the injection.

Fuel effects had minimal impact on the plume angle, though it can be noted that at the beginning and middle of injection, iso-octane had a slightly lower angle, which is in opposition to the full spreading angle results shown in Fig. 5. The spreading angles plotted in Fig. 5, however, were measurements done on the vapor boundary, while the pointing vectors were measured combining both side and front Mie-scatter imaging. Therefore, different vaporization characteristics, as expected when comparing iso-octane and ethanol (see Table 3), are likely to cause differences in the sprays whether the analysis is focused on vapor or liquid phases. Knowing this, the observations made for Fig. 8 are logical as ethanol plumes retain angles closer to the drilling angle (around 26°) for a longer period of time due to a lower vaporization rate. This is consistent with the argument made earlier that the momentum distribu-
tion is likely to be more axial (i.e., following each plume) for ethanol than for iso-octane, making ethanol plumes deviate less from their initial direction (drilling vector).

Density/pressure effects had a greater impact on the spray angle. The higher density condition gave a smaller angle, offering additional proof of a low pressure zone in the cone between sprays; the higher pressure of the 9 kg/m$^3$ condition would drive the sprays closer to the centerline as the potential pressure difference is greater at higher ambient pressures.

Effects of the decreasing spreading angle and plume pointing angles were also observed with long-working distance microscopy. The experiments allow the identification of individual droplets generated at the end of injection. Figure 9 depicts a time sequence of near-nozzle LDM images after the end of injection for a 900 K, 9 kg/m$^3$ ethanol experiment. The injector tip and vessel wall are marked by the black region, and the origin is located at the injector tip. For reference, a blue dashed line shows the injector axis.

Figure 9. Averaged plume angle for different density conditions and fuels. Note the decreasing angle during injection.

The high-speed, high-resolution imaging allows individual droplets to be tracked. A group of droplets originating from the upper holes was identified with the red ellipses on the three images of this sequence. The droplets demonstrate typical behavior after the end of injection in which they move towards the injector axis while heading downstream. The decreasing spreading angle and spray angles create a more centralized momentum distribution. The centralized momentum combined with an air entrainment wave at the end of injection drive the droplets towards the centerline. These droplets were carried in an entrainment-wave resulting in a fuel-droplet-dense central plume far downstream (10-20 mm), as observed on the high-speed movies used to measure the liquid penetration. Although these relatively large droplets were generated with both fuels at the end of injection, the liquid penetration measurements suggest that the impact is somewhat greater with ethanol, as shown by the mass of fuel continuing to move downstream (“tail” observed in Fig. 4).

Figure 9. Near-nozzle LDM images of a 900 K, 9 kg/m$^3$ ethanol injection. Note the tracked fuel droplets circled in red move towards the injector axis as do the entrainment waves after the end of injection.

Figure 10 shows two downstream LDM images in the region of 17-19 mm from the injector tip for 900 K, 9 kg/m$^3$ tests using iso-octane and ethanol. The corresponding times are more than 1.5 ms after the end of injection, yet for the ethanol case many droplets persist. This highlights a difference in fuel properties between ethanol and iso-octane, as the latter and its lower enthalpy of vaporization shows no presence of liquid droplets that far downstream or that late after the end of injection. It is worth mentioning that the two images shown in Fig. 10 are on the same intensity scale after each image was normalized by its respective initial intensity (frames taken before injection). Backgrounds with similar intensities give further proof of the presence of droplets for ethanol sprays compared to iso-octane.
Figure 10. Downstream LDM images of ethanol and iso-octane at 900 K, 9 kg/m$^3$.

Analysis

If only image projection data along a line of sight is available, the actual plume penetration (3D) for multi-hole injectors is calculated using the axial penetration and specified drill angle, or by default, the specified included spray angle. The dual view Mie-scattering arrangement used in this study increases the complexity and cost of the diagnostic suite, so it is of interest to access the necessity of such a setup to measure the 3D penetration. Figure 11 shows the axial, measured 3D and calculated 3D liquid penetration for 900 K, 9 kg/m$^3$ ambient conditions. The calculated 3D penetration has been obtained using the axial penetration measured from the side view divided by the cosine of the drill angle.

From the figure, the calculated 3D penetration values are slightly larger (3-5\%) than the measured penetration during the steady injection period. When a drill angle of 23$^\circ$ was used to calculate the true penetration, the calculated values agreed very well with the measured penetration. Referring to Fig. 8, it is expected that a value of 22-23$^\circ$ would yield the correct result. The overestimation can be accredited to the actual plume angles being less than the specified drill angle.

The ethanol case displays more transient behavior when considering the difference between the calculated and measured penetrations. It appears that the difference between measured and calculated values grows as the plumes penetrate in the chamber. Similar behavior was observed with the plume angles in Fig. 8 in which the angle continually decreased for ethanol while iso-octane reached a quasi-steady value. This is additional evidence that the bending of the plumes toward the injector axis starts later for ethanol relative to iso-octane and continues until the end of injection. The fuel properties of ethanol prohibit the spray from reaching a quasi-steady form, even at the high-temperature and high-pressure conditions. (See the liquid length in Figs. 4, 11.) This means that a variable drill angle would be needed to replicate the 3D penetration based on the axial penetration for ethanol; using a fixed angle would overestimate the liquid penetration (by up to 5\% under these conditions).

Figure 11. Axial, measured 3D and calculated 3D liquid penetration for 900 K, 9 kg/m$^3$ conditions. The calculated values using the drill angle are overestimated during the steady injection period.

To understand the influence of the bending of the plumes toward the injector axis on vapor and liquid penetration in a more quantitative fashion, modeling predictions have been compared to the measurements. The predictions have been obtained using a 1D/2D diesel jet model developed by Musculus and Kattke [21]. The model was used to simulate vapor and liquid penetration as a function of the measured rate of injection (ROI), orifice diameter and discharge coefficient, ambient and fuel densities, and plume spreading angle. Except for the spreading angle for a single jet, all the input parameters needed for the model were selected based on the multiple experiments performed for this work. As the objective is to study the influence of the deviation of the plumes from the initial pointing direction (drill angles), and more generally, multi-hole effects,
the spreading angle was obtained by matching the penetration rate up until the steady liquid length for the iso-octane experiment.

While the model has been shown to reveal the fluid mechanics of mixing after the end of injection for diesel jets, its application to the current study comes with a caveat: the interaction between plumes is not included in this model. In fact, it is simpler to model a single orifice injector and then apply the results to multi-hole injection applications. However, the validity of such a process comes into question when the plumes are closely positioned like the narrow cone angle injector used in the current study. Deviations between the model and experimental results will occur due to violation of the non-interaction assumption, consequently revealing information about multi-hole interactions.

Figure 12 shows measured and modeled results for the 900 K, 9 kg/m³ ethanol and iso-octane conditions. The modeled iso-octane vapor penetration is underneath the modeled ethanol vapor penetration, which shows that the model captured the density-independent vapor penetration as observed in Fig. 4. It is clear that the modeled values exceed the actual vapor penetrations for both the fuels. This was not necessarily expected as it has been observed that collapsed sprays have increased penetration from the combined momentum of the plumes [15]. Collapsed sprays have small spray spreading angles resulting in momentum mainly along the injector axis leading to the increased penetration. In this study, the measured spray spreading angles during injection were large and individual plumes were still identifiable indicating the spray did not fully collapse despite the decreasing spreading angle. The momentum exchange with gas at the centerline, accompanied by strong growth and spreading of each individual plume, likely results in a decrease in penetration.

It is interesting to note that once the model has been adjusted to match the initial penetration of the sprays, the predictions obtained for the liquid penetration captured certain characteristics observed in the experiments. The simulations for iso-octane reached a quasi-steady liquid length like the experiments and with a comparable value. The liquid also quickly retreats to the injector after the end of injection. The ethanol liquid penetration follows the vapor penetration for a duration that is similar to the experiments, but as a result, the liquid penetration is overestimated due to the greater model vapor penetration. It appears the modeled ethanol reached a quasi-steady liquid length just before the end of injection unlike the experiments. After the end of injection, the model shows a “knee” at approximately 1 ms aS01. Equivalence ratio contours showed a mass of upstream liquid traveled downstream towards the head of the plume (as observed in the experiments), resulting in the “knee.” Unlike experimental results, though, the model predicted that liquid ethanol stayed attached to the injector instead of a tail moving downstream. In addition, the fuel property trends were correctly captured in the model, as ethanol gave greater penetration.

![Figure 12. Measured and modeled 3D liquid and vapor penetrations for 900 K, 9 kg/m³ ethanol and iso-octane injections.](image)

All of the experimental test conditions were modeled, and they all showed the experimental penetrations to be less than that of the modeled single orifice injection. Truly collapsed sprays have resulted in increased penetration as the individual sprays combine to give greater momentum. Despite the decreasing spreading angle during injection, the spray didn’t collapse, so increases in penetration were not observed. Instead, the multi-hole interactions of the closely coupled sprays resulted in increased mixing and thus decreased penetration.

**Conclusions**

In this study, a suite of optical measurements addressed fuel and ambient condition effects on the fuel injection process of ethanol and iso-octane sprays injected in a high-pressure, high-temperature vessel. High-speed schlieren and Mie-scatter imaging from multiple and near-simultaneous views identified the vapor and liquid envelopes of an 8-hole SIDI spray. Pointing vectors and penetration values were measured in 3D with the multi-view Mie-scattering imaging. Long-working distance microscopy imaging identified liquid fuel droplets in the near-nozzle and downstream regions of the spray. The study’s major contributions are as follows:

1. Liquid penetration lengths are significantly longer for ethanol compared to iso-octane as a result of the higher heat of vaporization of the former, while similar vapor penetration rates have been observed.
2. During and after injection, the individual plume angles decrease as the spray is attracted towards the injector axis, resulting in a global spray becoming more compact and axially-oriented.
3. Microscopic measurements showed liquid droplets being attracted to the injector centerline and carried downstream along the central axis.
4. Consistent with the longer liquid length and ethanol’s fuel properties, liquid droplets were observed far downstream several milliseconds after injection for ethanol.
5. 3D liquid penetration values can be calculated from the axial penetration using the specified drill angle with minor error coming from the plumes deviating from the initial pointing direction. The over-predicted projection angle results in an overestimation of the calculated liquid penetration.
6. Single-jet model predictions provided higher values for vapor penetration compared to the measurements for individual plumes indicating a loss of momentum along the injection axis as the sprays moved towards the injector axis.
7. The observation in conclusion 6 lead to the conclusion that multi-hole dynamics of the narrow cone SIDI injector resulted in increased mixing as the individual plumes interact with each other.
8. Simulated liquid penetrations agree with the measurements and indicate the mixing-controlled aspect of vaporizing liquid sprays.

Nomenclature

- \( aSOI \) After the Start of Injection
- \( CO \) Carbon Monoxide
- \( DI \) Direct-Injection
- \( EOI \) End of Injection
- \( LDM \) Long-Working Distance Microscopic Imaging
- \( LES \) Large Eddy Simulation
- \( KOI \) Rate of Injection
- \( PFI \) Port Fuel-Injection
- \( SG \) Spray-Guided
- \( SIDI \) Spark-Ignited Direct-Injection
- \( SIDI-E \) Spark-Ignited Direct-Injection Early-Timing
- \( SIDI-L \) Spark-Ignited Direct-Injection Late-Timing
- \( UHC \) Unburned Hydrocarbon
- \( VCO \) Valve-Covered Orifice
- \( WG \) Wall-Guided

References

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