Investigation of Vaporizing Diesel Liquid Spray Plume to Plume Penetration Variations

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Abstract
Diesel combustion and emissions formation is spray and mixing controlled. The injection event is transient and injectors consist of multiple holes and hence understanding the dynamics and variations in plume behavior is important. This includes plume-to-plume variations along with spray evolution during the injection event. In this study, an eight-hole common rail piezoelectric diesel injector was examined in an optically accessible constant volume combustion vessel under vaporizing, non-combusting 0% oxygen conditions. Charge temperatures of 800 to 1300 K at a density of 34.8 kg/m³ were investigated. The liquid phase spray penetration was characterized for all plumes via processing of images acquired from a high speed camera with images taken at 67,500 frames per second with back scattering illumination. Plume-to-plume differences in penetration were observed during both the initial transient and after the steady state liquid length had been established. Hypothesis and assessment on the basis of these plume-to-plume variations are presented and discussed.

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Introduction

Diesel engines exhibit numerous benefits including high efficiency, optimum torque and drivability, and fuel economy advantages [1-3]. However, they exhibit high emissions including NOx and particulate matter [2]. These emissions are largely governed by spray behavior as the resulting fuel-air mixing and vaporization governs the combustion processes [4-6]. Therefore understanding spray penetration and spreading as determined from cone angle and liquid and vapor spray measurements is important to provide a fundamental understanding of fuel-spray mixing for combustion and emissions. Furthermore, diesel engines utilize multi-hole injectors which can exhibit non-uniformities in spray behavior during an injection event. By better understanding the fundamentals of injection, spray processes, and spray dynamics including plume-to-plume variations, fuel injection systems and engine operating parameters can be better optimized to take full advantage of spray properties to reduce emissions and fuel consumption. These results and observations may also be used to validate and improve spray models for more reliable computer prediction.

The goals of this paper are to characterize the liquid phase of vaporizing diesel sprays from an eight-hole injector using back scatter imaging. Tests are conducted in an optically accessible constant volume combustion vessel which enables visualization of spray processes under charge conditions representative of current and advanced technology diesel engines. Tests including repeats were conducted over a charge temperature range of 800 to 1300 K. A charge density of 34.8kg/m$^3$ is selected as representative of a diesel engine under high load and boost conditions [7-10]. Liquid penetration is determined on an individual plume basis and variations between plumes are characterized and analyzed to provide insight into plume-to-plume variations and the implications.

Experimental Setup

The tests were conducted in the optically accessible constant volume chamber shown in Figure 1. The vessel has an approximately 1 liter internal volume with six face-ports housing three sapphire windows, a spark plug – dual fan port, a diesel fuel injector port (Figure 1), and one blank port. Additionally, there are eight access ports on the combustion vessel (CV) cube vertices containing a pressure transducer, inlet and exhaust valves, and blank ports. Numerous studies have detailed the operation and characteristics of the procedures used for studying vaporizing and combusting sprays in this and similar laboratories [7, 8, 11-14].

Figure 1. Michigan Tech optically accessible combustion vessel with gas panels for mixture creation (Top). Internal view of combustion chamber and external view of diesel injector window (Bottom).

The injector used in the current study is a Bosch Generation III piezoelectric common rail fuel injector (external view of mounting in CV shown in Figure 1). The injector is equipped with a sac-type nozzle, with eight holes arranged equally spaced $45^\circ$ from each other azimuthally. The included angle of these holes is $150^\circ$. Each hole is nominally $1.0 \text{ mm}$ long and $0.145 \text{ mm}$ in diameter, with a length to diameter ($L/D$) ratio of 6.9.

This injector is driven by an EFS IPoD piezoelectric injector driver in multi-peak regulation mode, which requires setting peak current, open and close voltage, and current slope levels. Drive characteristics were set to match production operation. The electronic trigger injection duration was set to 1.6 ms, and the resulting spray was 2.8 ms in duration. The fuel supply system is a high pressure system from Hydraulics International capable of injection pressures to 4140 bar, compatible with multiple fuels including diesel, biodiesel, gasoline, ethanol and others, with ultra-low sulfur diesel (ULSD) fuel used in the current study.

Back scattering imaging is used to visualize the liquid phase spray in the combustion vessel. Back, or Mie, scattering imaging involves capturing the spray image via scattering light off the fuel droplets and hence this diagnostic enables visualization of the liquid portion of the spray in a vaporizing (0% oxygen) environment. The imaging setup used is shown in Figure 2, along with injector orientation.
A Photron Fastcam SA1 streaming high speed digital camera was used. The camera was equipped with a 60 mm Nikon Micro-Nikkor lens with an f-stop of 2.8. Image resolution was 256 x 256 pixels to capture the spray region of interest with a 67,500 frames per second frame rate (15 µs inter-frame time) and a 1.65 µs exposure duration. The light source for scattering was a Cooke SensiFLASH flash-lamp with an 8 ms discharge duration. This light source provides illumination during the entire injection event, with the injection and imaging delayed relative to the flash-lamp to account for the warm-up time of the flash-lamp, thereby yielding a steady state illumination during the 2.8 ms liquid fuel injection. The light source as shown in the figure is directed at an angle into the CV to provide uniform illumination of the entire chamber by reflecting the light off an angled mirror. The camera and flash-lamp are remotely triggered by a pulse generator (SRS DG645) which also controls the injector to ensure synchronized fuel injection, image acquisition and illumination. This optical setup enables visualization of all eight spray plumes from the injector as shown in Figure 2 with the spray plumes oriented 15° off the plane of the injector.

**Test Procedure**

This work considers vaporizing sprays in a zero percent oxygen environment. To achieve the zero percent oxygen environment in the combustion vessel a premixed burn procedure is used [7, 8]. The procedure involves spark igniting via two electrodes (see Figure 1), a mixture of acetylene, hydrogen, oxygen and nitrogen to yield zero percent oxygen post premixed burn. The mixture is prepared via partial pressure mixing in a 10 L mixing vessel. The initial fill pressure of the CV governs the density at the time of fuel injection as determined via the ideal gas law, with the combustion vessel being electrically heated via cartridge heaters to 180°C. Fill pressure and the pressure throughout the premixed burn and injection event is monitored via a Kistler 6001 pressure transducer located in a port of the CV coupled to a Kistler 5010B charge amplifier.

The mixing fan in the top of the CV (refer to Figure 1) remains on during the premixed burn and fuel injection event to ensure uniform temperature distribution inside the chamber. See Figure 3 for a graphical description of this premixed burn process.

![Figure 2. Back scattering imaging setup (Top). Injector orientation and spray plume angles (Bottom).](image)

![Figure 3. Pressure trace showing CV premixed burn, cool down, and timing of diesel fuel injection.](image)
process is covered in numerous publications [7, 8, 12, 14].

Vaporizing ULSD spray test conditions investigated in the current work consisted of three repeat tests and a charge temperature sweep, with actual experimental conditions defined in Table 1.

<table>
<thead>
<tr>
<th>Test Set</th>
<th>ρ_{bulk} (kg/m³)</th>
<th>ρ_{core} (kg/m³)</th>
<th>T_{bulk at Inj. (K)}</th>
<th>T_{core at Inj. (K)}</th>
<th>P_{Inj.} (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeat 1</td>
<td>34.7</td>
<td>32.2</td>
<td>1100</td>
<td>1190</td>
<td>1900</td>
</tr>
<tr>
<td>Repeat 2</td>
<td>34.5</td>
<td>32.0</td>
<td>1110</td>
<td>1190</td>
<td>2000</td>
</tr>
<tr>
<td>Repeat 3</td>
<td>34.5</td>
<td>32.0</td>
<td>1110</td>
<td>1200</td>
<td>2100</td>
</tr>
<tr>
<td>Charge Temp. Sweep</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>34.5</td>
<td>32.9</td>
<td>810</td>
<td>850</td>
<td>1900</td>
</tr>
<tr>
<td>950</td>
<td>34.8</td>
<td>32.7</td>
<td>910</td>
<td>1010</td>
<td>2000</td>
</tr>
<tr>
<td>1100</td>
<td>34.7</td>
<td>32.2</td>
<td>1100</td>
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<td>32.0</td>
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<td>31.7</td>
<td>1300</td>
<td>1430</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 1. Test matrix with experimental conditions for bulk and core charge density and temperature, as well as injection pressure.

Fuel pressure was held constant at 2000±20 bar, with a targeted charge bulk density of 34.8 kg/m³. Repeat tests were at 1100 K bulk temperature, with temperature sweep conditions targeting 800, 950, 1100, 1200 and 1300 K charge bulk temperature.

There exist boundary layers in the CV and hence temperature gradients which leads to the definition of core and bulk temperatures. The mixing fan in the CV helps to provide temperature uniformity with there being optimum uniformity in the core region of the vessel. This corresponds to the location of the gases that mix with the spray during injection where the mean temperatures are uniform but there does still exist temperature fluctuations [7]. The core temperature is higher than the bulk temperature due to cooler, higher density gases which exist in CV boundary layers, and can be calculated from bulk gas conditions via equation (1) [7, 8].

\[
\frac{T_{core}}{T_{wall}} = 1 + a \times \left(1 - \frac{T_{wall}}{T_{wall0}}\right) + b \times \left(\frac{T_{bulk}}{T_{wall0}} - 1\right)
\]  

(1)

The second and third terms on the right hand side consider gases in the boundary layers and crevices, with constant a corresponding to the boundary layer thickness (and is a function of density), and constant b representing the ratio of chamber crevice volume to chamber volume [7, 8]. The CV fill pressure measurement enables calculation of bulk gas density, which is used to determine the bulk temperature at injection as bulk density is constant during the test. Bulk temperature is used to calculate core temperature per the above equation, which is subsequently used in the core density calculation again using measured CV pressure at the time of injection.

**Image Processing**

Image sets acquired at each test condition were processed in Mathworks Matlab™ to determine penetration for each spray of the eight-plume injector, as a function of time after start of injection (ASOI), which corresponds to the start of liquid fuel. Plume labeling is provided in Figure 4.

Image sets were read into arrays with frame 1 prior to injection used as the background image. The center injector tip location is determined, which enables calculation of the injector hole locations which are offset from the center of the nozzle based on injector configuration (Figure 4). Penetration is referenced relative to the individual injector hole locations.

The image processing of each movie frame is composed of the following steps. First, the background image was subtracted from the spray image to avoid interference from the injector tip in image processing. To process each plume in a given image frame the image was rotated in 45° increments such that each plume was aligned exiting the injector tip from left to right. The spray region of interest was isolated along a line from the injector tip to the image edge along the spray centerline, and perpendicularly relative to this line to visualize the entire width of the spray plume. Masking was applied to the adjacent spray plumes to avoid interference. The image was normalized by the maximum intensity in the image to yield an intensity scale from 0 to 1.

With the spray plume isolated from the background, injector tip, and adjacent spray plumes, the image is thresholded to black and white. The threshold is determined for each spray plume based on Matlab’s™ “graythresh” operator which relies on Otsu’s method, choosing a threshold to separate the two classes of pixels in the image, in this case spray and background, by minimizing their intraclass variance [15]. The spray is further isolated from noise in the black and white image by finding the largest connected region of the spray via blob analysis. The black and
white spray image next has its boundary traced, and the leading edge of the boundary along either the spray axis or at an angle from the axis is defined as the tip penetration, relative to the injector nozzle hole. This penetration is defined as the maximum length of the continuous portion of the spray as observed from the back scattering imaging as defined in Figure 5.

**Figure 5. Liquid penetration definition.**

Penetration is converted to millimeters using the known image scaling of 0.18 mm/pixel, and is also scaled by the cosine of 15° to account for the angled spray based on injector orientation, refer to Figure 2.

**Results & Discussion**

This section will be broken up into two parts. First, results from three repeat tests at 1100 K will be analyzed to determine the variation in individual spray plumes. Next, results will be presented on the plume-to-plume variation for the bulk charge temperature sweep from 800 to 1300 K.

**Repeatability Tests**

Three repeat tests were undertaken for vaporizing sprays (0% oxygen), at a bulk charge density of 34.8 kg/m³, 1100 K bulk charge gas temperature, and 2000 bar injection pressure with a 1.6 ms electronic injector drive duration (2.8 ms liquid fuel injection event). Actual test conditions were provided in Table 1, with the mean injection pressure being 2000 bar (10 bar standard deviation), mean bulk charge gas temperature of 1110 K (6 K standard deviation), and mean bulk charge gas density of 34.6 kg/m³ (0.1 kg/m³ standard deviation). By characterizing the plume-to-plume trends over the repeat tests it can be determined if plume-to-plume variations are a result of system repeatability or if they are an inherent phenomenon of the injector and spray.

Background subtracted images for these test conditions are shown in Figure 6. There are plume to plume variations at each time ASOI, as well as fluctuations in liquid length of a single plume as time ASOI progresses. This paper focuses on the plume-to-plume variations including potential causes and implications, not on the fluctuations of a single plume.

The median penetration for the eight plumes is plotted in Figure 7 as a function of time ASOI for the three tests. The median value is used as this does not weight outliers in the data and therefore provides a representative value of the combined spray characteristics.

From Figure 7 it is observed that the liquid penetration is consistent between tests, with the largest deviation of 2.1 mm in early times ASOI for test 1 relative to test 2 and 3. This is the transient state of the spray during development and hence deviations are more prevalent when compared to the steady state spray in the longer times ASOI. The penetration increases until 0.75 ms ASOI at which a steady state value is reached, termed the liquid length. After this time the penetration fluctuates around this value until the end of injection when penetration falls off following similar observations from reference 7. Comparing the average median liquid length over the steady state period (0.75 through 2 ms ASOI), the steady state liquid length for all three tests are within 0.2 mm of each other when using the average value over steady state, but the instantaneous variation during the same steady state period can exceed 1 mm.
Polar plots of liquid penetration for each test are given in Figure 8 to compare plume behavior as a function of time ASOI. The eight individual spray plume penetrations are shown in the polar plots in 45° increments, with plume 1 at 0°, plume 2 at 45°, etc., (as was defined in Figure 2). The 0.2 ms ASOI condition represents transient spray development, but the remaining times (1.0 to 2.0 ms) correspond to steady state spray conditions when the liquid length has been established (refer to Figure 7). Considering the standard deviation of the penetration as a function of time ASOI, it decreases from SOI to 1.0 ms ASOI where it reaches a minimum until 2.0 ms ASOI at which the standard deviation increases due to end of injection transients. Hence the 1.0 to 2.0 ms region is chosen to represent steady state due to the decreased variation in standard deviation. Also included in the polar plots is the mean steady state liquid length (mean SS LL) over all eight plumes during steady state.

Considering each polar plot in Figure 8 for a given test, the variation in plume-to-plume penetration is evidenced by different radial extensions of the plume along each spoke, at various times ASOI during steady state and looking at the circular radii created for each time ASOI which represent the liquid length. The plume-to-plume variation is most prominent at 0.2 ms ASOI, as expected as this is the transient start of injection and spray development.

To further compare plume-to-plume variations and trends over the three repeat tests, the mean liquid length was determined from 1 to 2 ms ASOI for each test (which consists of 68 data points) and compared to the mean steady state liquid length (mean SS LL) for all plumes over the three repeat tests as shown in Figure 9.

Considering each plume independently and looking at the liquid length for each test, the results are similar showing there is minimal test to test variation and high repeatability. There is however plume-to-plume variation in liquid length, with certain plumes consistently having longer, or shorter, liquid lengths. Plumes 1, 4, 5, 6, and 7 are typically shorter than the mean, with plumes 2, 3, and 8 being longer than the mean, with the mean liquid length being 10.8 mm. The trends for the repeats are as follows; plume 5 has the shortest liquid length being almost 11% less than the mean, followed by plume 7 which is over 3% less than the mean, and then plume 1 which is more than 2% shorter than the mean. Plume 4 and 6 have similar liquid lengths being around 0.5% shorter than the mean, with plume 8 being almost 5% larger than the mean.
and plumes 2 and 3 having similar liquid lengths and the largest of all plumes, over 6% larger than the mean.

**Charge Temperature Sweep**

A charge bulk-gas temperature sweep was undertaken from 800 to 1300 K to understand its influence on plume-to-plume liquid length variations. Conditions were vaporizing sprays at 34.8 kg/m³ bulk charge density, 2000 bar injection pressure, 2.8 ms liquid injection duration. Background subtracted images during steady state are compared for temperatures investigated, as shown in Figure 10.

Considering each temperature case independently, over a range of times ASOI, there is evidence of plume-to-plume variations in liquid length amongst all temperatures. These plume-to-plume variations are quantified to understand plume trends and characteristics. As temperature increases, plume penetration (liquid length) decreases as expected due to increased vaporization, with the sensitivity of liquid length to temperature decreasing at higher temperatures [8].

The penetration change with temperature is further understood by considering the mean liquid length during steady state as a function of gas temperature, as shown in Figure 12. Error bars represent the average standard deviation of the mean liquid length during steady state over all eight plumes. The gas temperature at the location of the liquid spray varies between the vessel wall temperature of 453K to the core temperature (Table 1) due to temperature gradients near the wall. Here the liquid penetration is plotted versus the bulk temperature. The experimental mean liquid length data is compared to the expected temperature dependence, temperature to the -1.73 power, as proposed by Payri et al. 2008 [16] and interpolated from experimental data [17]. This data is also compared to experimental data from Siebers and Sandia Engine Combustion Network (ECN) [8, 17] for a bulk gas density of 31.1 kg/m³, injection pressure of 140 MPa, hole diameter of 0.246 mm, using Heptamethylnonane (HMN) fuel to compare bulk gas temperature trends.

The mean liquid length during steady state decreases 49% as temperature increases from 800 to 1300 K. This variation in liquid length is nonlinear with temperature in agreement with literature [14]. As
temperature increases from 800 to 950 K, liquid length decreases 24%, for 950 to 1100 K temperature increase liquid length decreases 19%, for a temperature increase of 1100 to 1200 K liquid length decreases 13%, and for a temperature increase from 1200 to 1300 K liquid length decreases 4%. The experimental and published temperature trends agree within one standard deviation of the experimental mean liquid length data. The experimental data does not agree with Siebers Sandia ECN data due to the different conditions, injector geometry and fuel type, however, the temperature trends for liquid length are preserved in the current experimental data relative to that shown by Siebers.

Figure 13 shows the liquid penetration for each plume from the injector for each of the bulk charge gas temperatures investigated. These polar plots consider transient spray development (0.2 ms ASOI) as well as steady state spray penetration (liquid length). Also included is the mean steady state liquid length (mean SS LL) over all eight plumes during steady state. The variation in plume-to-plume penetration is evidenced by different radial extensions of the plume along each spoke at various times during steady state. During steady state (1 to 2 ms ASOI) plume penetration should be identical as the liquid length has been established, however, not only are there fluctuations in penetration (refer to Figure 11), there are plume-to-plume variations in penetration for a given time ASOI. Again, plume-to-plume variation is most prominent at 0.2 ms ASOI, as expected as this is the transient start of injection and spray development.

To examine if there are plumes that consistently have longer or shorter liquid penetration over this range of charge temperatures the individual plume liquid lengths for each charge temperature are normalized by the mean value over all eight plumes. The results are shown in Figure 14.

Figure 13. Polar plots of plume penetration for various times ASOI (for spray development and steady state), charge temperatures 800 to 1300 K.

Figure 14. Mean steady state liquid length (over 1 to 2 ms ASOI) for the charge temperature sweep, normalized by the mean liquid length to isolate plume influences from temperature effects.
As the figure shows, plume-to-plume variations are evident as was the case for repeat tests. These plume-to-plume variations exhibit similar trends to those observed in the repeat tests, with plume 5 having the shortest liquid length on average almost 7% shorter than the mean, followed by plumes 1, 4, 6, and 7 which are up to 3% shorter than the mean. Plumes 2, 3, and 8 are almost 4% longer than the mean value, considering the average temperature trends.

Discussions on Plume-to-Plume Variations

The plume-to-plume variations in liquid length can yield differences in fuel air mixing and emissions, and therefore understanding their causes is essential. There are various potential explanations for the plume-to-plume variations. These include nozzle configuration, eccentric needle movement, nozzle manufacturing smoothness, and variations in nozzle dimensions as discussed in the literature [18-21]. There is the potential for eccentric needle movement, which could cause uneven needle lift and hence yield plume-to-plume variations. There is uneven needle lift evidenced in early times ASOI images as shown in Figure 15 which includes background subtracted images from repeat tests, during the start of injection (SOI) where certain holes start injecting fuel before others.

As shown in Figure 15, plumes 1, 7 and 8 consistently inject 0.019 ms after the other plumes. However, this change in SOI proposed as a result of uneven needle lift does not translate to variations observed during steady state when plume 8 has one of the largest liquid lengths, with plumes 1 and 7 having shorter liquid lengths. Hence the eccentric needle motion only impacts the plume dynamics during the transient state. The needle lift, even though it is double-guided, is likely dependent on the exerted pressure from the fuel, which could vary due to differences in internal nozzle geometry. During steady state the needle is relatively far away from the nozzle hole entrance as it is fully lifted, and therefore it is no longer an influencing factor on the fuel flow, and thus is likely not the cause of the observed plume-to-plume variations during steady state.

Hole-to-hole differences introduced during nozzle manufacturing could potentially explain the plume-to-plume variation trends. The nozzle was hydro-ground but there could be differences in the smoothness of each hole which would cause turbulence or cavitation differences, and this could translate into downstream spray characteristics [19]. As fluid flows through the nozzle, the flow can be two-phase and cavitating both in the sac volume and holes, which changes flow characteristics and hence hole-to-hole variations in spray characteristics [22]. Furthermore, there could be differences in hole diameters relative to manufacturer specifications [21]. Observations of liquid length have shown it increases linearly with orifice diameter [14], and therefore the 1.8 mm (19%) increase in liquid length observed between plume 5 and plumes 2 and 3 would require a 19% increase in orifice diameter. To examine this, diameters of all eight holes were measured using a scanning electron microscope (SEM, model JEOL JSM-6400). The test results showed a mean hole diameter of 145.1 µm, with a standard deviation of 1.2 µm (with this standard deviation being less than the measurement repeatability). The maximum hole diameter of 146.5 µm was observed for hole 3, with a minimum hole diameter of 143.5 µm for hole 7. Hence this variation in hole diameter is not of large enough or of significant magnitude to explain the liquid length hole-to-hole variations.

Instead it is hypothesized that internal flow geometry and conditions in the injector are a contributing factor to the observed differences in steady state liquid penetration. In this injector design it is known that the internal injector geometry results in the fuel filling the sac from one side of the injector. This geometry can increase fuel pressure to certain injector holes which could change internal nozzle flow characteristics and translate to spray variations as seen currently. Based on the orientation of fuel filling, holes one and five are symmetric about the fuel filling location and hence the reduction in liquid length as seen with these plumes could be attributed to the internal flow geometry.

Future Work

Hypothesis on the causes of the differences in plume to plume variation have been proposed. Future work is proposed to evaluate a set of injectors to see whether trends support the proposed hypothesis. Additionally, detailed studies using CFD or advanced diagnostics to study the flow in the injector would.
provide insight to the causes. With respect to spray studies, future work will include the characterization of plume-to-plume variations as a function of injection pressure, gas density, and fuel temperature. Similar analyses will be undertaken on non-vaporizing sprays and on combusting sprays to understand consistencies and trends in plume behavior and determine impacts on ignition and soot formation. The time varying fluctuations in vaporizing sprays liquid penetration will also be characterized including frequency analyses to understand the phenomenon and causes.

Conclusions

Diesel combustion and emissions formation is largely spray and mixing controlled and hence understanding liquid phase spray characteristics is important to determine methods to enhance and optimize combustion while minimizing emissions. The current work aimed to understand and characterize plume-to-plume variations of the eight spray plumes from a multi-hole injector under repeat test conditions and for a charge temperature sweep. Using an optically accessible constant volume combustion vessel with Mie back scattering diagnostics liquid penetration and mean steady state liquid lengths were characterized. Key conclusions are as follows:

- Liquid penetration increases as time ASOI increases before reaching a steady state value where the liquid phase reaches a steady state. Under the conditions of this test this takes 0.75 ms.
- As charge gas temperature increases from 800 to 1300 K mean liquid length of all plumes decreases by 49% due to increased vaporization. This decrease in liquid length is nonlinear with ambient temperature agreeing with previous published studies in the literature.
- Liquid penetration is initially shorter for plumes 1, 7 and 8 as injection starts; however, this difference diminishes over time and is not observed in steady state measurements.
- Under steady state, results show that plumes 2, 3, and 8 consistently have larger liquid lengths then plumes 1, 4, 6, and 7, followed by the smallest liquid length of plume 5, both under repeat test conditions and over the charge temperature sweep. For repeat test conditions, the span in liquid length from shortest to longest is in excess of 18%. For the temperature sweep tests, the largest span in liquid length from shortest to longest considering all temperature tests is 15%.
- Measurements of the individual hole diameters indicate that this is not the primary factor in the differences in liquid penetration.
- Differences in the initial versus steady state liquid penetrations indicate that there are two factors controlling the differences in liquid length. It is hypothesized that the initial differences are driven by eccentric needle movement. Additionally it is hypothesized that the steady state differences are the result of internal flows and geometry in the injector.

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Nomenclature

- \( a \) : Empirical Constant
- \( ASOI \) : After start of injection of liquid fuel
- \( b \) : Empirical Constant
- \( D \) : Nozzle hole diameter
- \( L \) : Nozzle hole length
- \( P \) : Pressure
- \( T \) : Temperature
- \( \rho \) : Density

Subscripts

- \( Bulk \) : Bulk gas conditions
- \( Core \) : Core gas conditions
- \( i \) : Nozzle inlet
- \( inj \) : Injection conditions
- \( o \) : Nozzle outlet
- \( Wall \) : CV wall conditions

References