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Abstract

Future projections in the transportation energy sector indicate that fuels within the gasoline property range may become attractive alternatives for the heavy-duty commercial market. Prior experimental work on a production heavy-duty engine demonstrated that high reactivity gasoline (RON 60, CN 34) could operate in a conventional mixing-controlled combustion mode with similar efficiency and lower soot emissions than diesel at a given engine-out NOx level due to its high volatility and low aromatic content. This study is aimed at investigating the single-plume non-reacting, vaporizing spray characteristics of high reactivity gasoline compared to ultra-low-sulfur-diesel (ULSD). A companion study (Part I) focuses on the characteristics of non-reacting, non-vaporizing sprays. The experiments were carried out in an optically accessible constant volume combustion chamber using a single-hole injector. A wide range of charge gas densities (10.3-41.7 kg/m³), temperatures (800-1200 K), and injection pressures (100-250 MPa) were tested to represent heavy-duty engine relevant conditions. A hybrid Mie scattering and shadowgraph technique was implemented using a high-speed camera to capture images at 60,000 frames per second and determine vapor dispersion angle, vapor penetration, and liquid length of the vaporizing sprays for both fuels considered. Results indicate that the high reactivity gasoline has similar vapor penetration compared to ULSD (within 5%). Although the vapor penetration of the two fuels is similar, the vapor dispersion angle is as much as 20% wider for the gasoline-like fuel in comparison to ULSD at a given operating condition. The liquid length of the gasoline-like fuel is 50% shorter than ULSD, which is consistent with the difference in volatility between fuels.

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Introduction

Due to high energy density and ease of transportation and storage, petroleum-based liquid fuels will continue to be the dominant energy source for the transportation sector, accounting for 96% of energy consumption in 2012 and a projected 88% of consumption in 2040 [1]. The US Energy Information Administration predicts that energy demand in the transportation sector will increase from 104 quadrillion BTU’s in 2012 to 155 quadrillion BTU’s in 2040 [1]. The demand for gasoline, or light distillates, is projected to peak around 2020 and then start declining, mainly due to efficiency gains expected within the passenger vehicle sector [2, 3]. On the contrary, demand for diesel and jet fuel, or middle distillates, is expected to rise through 2040, mostly due to the increasing need for additional freight and commercial transportation in developing economies [2, 3]. This energy forecast suggests that there may be an economic incentive for light distillates to become a viable alternative to diesel in future heavy-duty engine applications. The utilization of gasoline or gasoline-like fuels in the commercial transport sector could help mitigate the expected demand shift from light to heavy distillates. Furthermore, if similar fuel conversion efficiencies and additional pollutant emission benefits can be demonstrated for light distillates compared to diesel, then these fuels become attractive from an environmental perspective.

Recent investigations have shown the benefit of using gasoline-like fuels with low cetane number (CN) in conventional diesel engine architectures. These studies rely on the compression ignition of gasoline and are generally categorized as gasoline compression ignition (GCI) applications. Both mixing controlled or diffusion and partially premixed compression ignition (PPCI) combustion modes have been considered in prior work. Under mixing controlled GCI using a high compression ratio of 19, the high volatility and low aromatic content of gasoline-like fuels leads to lower soot emissions at a given engine-out NOx level and similar efficiency compared to diesel [4]. For LTC-type PPCI combustion modes, the longer ignition delay of gasoline-like fuels compared to diesel helps to promote fuel-air mixing and leads to high efficiency and simultaneously low NOx and soot emissions [5-12]. In addition to engine performance and emissions benefits, high reactivity gasoline potentially requires less energy input to manufacture at the refinery compared to current market fuels. This, along with a typically higher H/C ratio and heating value compared to diesel, may make this fuel an attractive lower carbon footprint alternative for HD applications of the future.

Several other studies have demonstrated the merits of using high reactivity gasoline (lower octane rating than market fuel) in GCI combustion applications. Akihama et al. [13] performed a computational and experimental study with two different gasoline-like fuels displayed in the last two rows of Table 1 (Research Octane Number, RON 66, CN 34, and RON 59, CN 31) in a 0.7 liter, 16:1 compression ratio, single cylinder diesel engine. They observed that engine could achieve good performance and low NOx and PM emissions at low and medium load.

Other researchers studied the performance of gasoline-like fuels whose properties listed in the sixth row of Table 1 under PPCI combustion conditions in a 0.5-liter, 12:1 compression ratio, single-cylinder direct injection spark ignition (DI SI) engine [8]. The authors were able to achieve GCI combustion with these fuels at six different engine-operating points representatives of an urban driving cycle, including idle. A 19% improvement in cycle-weighted average fuel consumption compared to baseline stoichiometric spark ignition operation with optimal valve timing was also demonstrated. In a follow-up study [14], the same group successfully demonstrated that a modern diesel passenger vehicle could operate using gasoline-like fuels with a GCI combustion strategy. The investigators reported engine-out NOx emissions below the EURO6 regulation limit with lower soot emissions compared to diesel fuel and acceptable noise levels during the cold New European Driving Cycle (NEDC).

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<td>58.8</td>
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<td>94.4</td>
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<td>43.4</td>
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<td>Gasoline “B” [15]</td>
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<td>60.5</td>
<td>83</td>
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<td>44</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
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<td>Saudi Aramco</td>
<td>62</td>
<td>94</td>
<td>125</td>
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<td>12</td>
<td>45</td>
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<td>N/A</td>
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<td>Gasoline “D” [13]</td>
<td>Toyota &amp; Exxon Mobil</td>
<td>59.2</td>
<td>194</td>
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<td>335</td>
<td>17</td>
<td>43</td>
<td>761</td>
<td>31</td>
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</tbody>
</table>

Table 1. Summary of gasoline-like fuel properties from different GCI studies in the literature.
In another study, Wang et al. [15] assessed various injection strategies for gasoline-like fuels under compression ignition with exhaust gas dilution and concluded that a small pilot injection before the main injection event achieved the best overall performance.

It is evident that much of the prior work in GCI research has focused on light-duty or passenger vehicle applications with more emphasis on overall engine performance and less emphasis on spray characteristics, the latter of which plays an important role in a variety of GCI approaches. The benefits of using high reactivity, light end fuels in GCI applications has been demonstrated by the various investigations discussed herein and a summary of the actual fuels used in these studies is provided in Table 1. However, in order to further optimize the performance and control the emissions of GCI fuel-engine systems, a better understanding of gasoline-like fuel spray characteristics using modern compression ignition hardware is needed. This will lead to better fidelity on simulation-led combustion system development activities for GCI applications and the potential for adapting optimal hardware systems for light end GCI fuels. Furthermore, with the potential carbon emission and criteria pollutant emission benefits offered by the use of gasoline-like fuels in the commercial transportation sector, there is a need to study their behavior in the context of conventional HD hardware platforms.

There has been a limited amount of prior work focusing on the spray characteristics of gasoline-like fuels, even less so in the context of HD diesel engine applications. Payri et al. [16, 17] observed there were no clear differences between gasoline and diesel under non-vaporizing conditions in terms of the spray penetrations and momentum flux. The purpose of this study is to investigate the spray characteristics of high reactivity gasoline fuel in comparison to ULSD using a single-hole injector with specifications indicative of HD diesel engine hardware. The complete work is reported in two parts: Part I focuses on non-reacting, non-vaporizing conditions [18]; and this particular study, Part II, which focuses on non-reacting vaporizing conditions. The experiments were carried out in an optically accessible constant volume combustion vessel under a wide range of ambient charge gas densities (10.3–41.7 kg/m³), ambient temperatures (800–1200 K), and injection pressures (100–250 MPa). The dispersion angle, vapor penetration, and liquid length of both fuels are reported. The results are evaluated against the existing body of diesel spray literature, for which the effects of charge gas density, temperature, and vaporization behavior have been well characterized [19, 20].

**Experiment Setup, Fuels and Test Conditions**

The experiments were carried out in an optically accessible constant-volume (1 liter) combustion vessel (CV). The vessel has a maximum rated pressure and temperature of 34.5 MPa and 2000 K, and is similar to the vessel at Sandia National Laboratories [19,21,22]. Vaporizing conditions are achieved by a pre-burn combustion process that uses an acetylene-hydrogen mixture as fuel. The mixture composition is designed so that the products and end-state of the pre-burn combustion process simulate in-cylinder engine conditions. Before the pre-burn mixture is ignited by a spark discharge, a fan stirs the gas mixture to obtain a uniform ambient temperature profile within the CV. Liquid fuel injection is triggered when the desired temperature and pressure conditions are reached within the chamber. This occurs during the cool-down phase after pre-burn when heat is transferred to the CV walls. Additional details about the CV apparatus and the pre-burn process are provided in [19,23].

The two fuels, high reactivity gasoline and ULSD, are injected by a central axis, single hole HD injector whose specifications are provided in Table 2. The properties of the liquid test fuels are given in Table 1 and Table 3. The high reactivity gasoline has a RON of 58.8 and a CN of 33.7. The ULSD has a higher CN and aromatics content than the gasoline-like fuel. As the initial ambient temperature of the vessel is heated to 453K to achieve the appropriate charge conditions at injection, a cooling system located at the injector tip is employed so that the fuel temperature is maintained at a set-point of 358K.

### Table 2. Single-hole injector specifications.

<table>
<thead>
<tr>
<th>Outlet Diameter (D_{out}, \mu m)</th>
<th>176</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-factor</td>
<td>1.8</td>
</tr>
<tr>
<td>Ca (Re ~ 12,000)</td>
<td>0.94</td>
</tr>
</tbody>
</table>

| Description | Central axis, single-hole, solenoid driven, hydraulically lifted needle |

### Table 3. Supplement fuel properties for ULSD and high reactivity gasoline.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>ULSD</th>
<th>High Reactivity Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (wt%)</td>
<td>86.80</td>
<td>84.87</td>
</tr>
<tr>
<td>Hydrogen (wt%)</td>
<td>13.20</td>
<td>15.13</td>
</tr>
<tr>
<td>IBP (°C)</td>
<td>173.3</td>
<td>32.3</td>
</tr>
<tr>
<td>FBP (°C)</td>
<td>346.7</td>
<td>139.7</td>
</tr>
</tbody>
</table>

To study the non-reacting, vaporizing spray characteristics, both the liquid and vapor penetration are captured using a high-speed camera (FASTCAM SA1.1) outfitted with a Nikon 85mm lens. The diagnostics configuration used in this study is a near-simultaneous shadowgraph \ Mie scattering optical setup [24] as shown in Figure 1. A Z-type shadowgraph system with two light emitting diodes (LEDs) is applied. One LED provides
the light source for the shadowgraph image. The second LED provides a light source for the Mie scattering image. The LEDs are set to flash separately in time and are synchronized with the camera shutter at 60,000 frames per second (fps). With this frame rate, the time in between each frame is 16.7 μs. As shown in the time sequence of Figure 1, when LED1 is off, LED2 provides the light that scatters from the liquid portion of the spray producing the Mie scattering images. After the Mie scattering image is taken, LED 1 turns on and LED2 turns off. LED1 is the light source for the subsequent shadowgraph imaging technique. The switching between LED1 and LED2 is repeated throughout the time duration of an injection event. An aperture size of f/1.4 on the camera lens is applied. The focus plane of the image is across the central axis of the single plume for which both liquid and vapor phase images are captured.

<table>
<thead>
<tr>
<th>Fuels</th>
<th>ULSD</th>
<th>High Reactivity Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Temperature (K)</td>
<td>800</td>
<td>900</td>
</tr>
<tr>
<td>Charge Pressure (MPa)</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Charge Density (kg/m³)</td>
<td>10.3, 12.8, 17, 18.5, 20.3, 22.5, 25.4, 28, 33.4, 41.7</td>
<td></td>
</tr>
<tr>
<td>Injection Pressure (MPa)</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 4. Experimental conditions.

Image Processing

Shadowgraph and Mie scattering images captured by the high-speed camera require post processing to obtain quantitative penetration, dispersion angle, and liquid length data. Figure 2 shows an example of the processing steps for the shadowgraph image. These steps are also applied to the Mie scattering images, however, the dispersion angle of the liquid spray is not acquired during Mie scattering image processing.

Figure 1. Near-simultaneous shadowgraph \ Mie scattering optical setup and time sequence.

The steps are as follows:
1. Read in raw image data from 8 bit gray scale uncompressed files.
2. Perform image background subtraction. For shadowgraph, subtract the previous frame from the current frame (\(I_{n} - I_{n-1}\)) to obtain a vapor boundary. For Mie scattering, subtract the background only.
3. Apply a threshold using the MATLAB® “graythresh” function to obtain binary images. This process uses Ostu’s method to find the global image threshold [25].

Figure 2. Illustration of shadowgraph image processing methods.
4. Implement boundary tracking and define the vapor penetration that is the distance from the injector tip to a point in the downstream vapor envelope covering 99% of the total envelope. This compensates for fluctuations in the leading edge of the vapor envelope caused by test-to-test variations in the spray structure.

5. Find the region of the spray where 60% of the spray penetration occurs.

6. Define the vapor dispersion angle as the angle enclosed by the two linearly fitted lines from the boundary identified in Step 5.

7. Dispersion angle linear fits overlaid on shadowgraph vapor envelope.

8. Vapor penetration tracking line as 99% of the shadowgraph vapor envelope

Since boundary tracking of the images depends on the pixel light intensity threshold value, a sweep of threshold values is conducted to determine the vapor penetration sensitivity to this parameter. Figure 3 shows results from a sweep completed between ± 50% of the original threshold value and indicates the small differences observed in vapor penetration. The actual difference in penetration is less than 3% across the wide range of threshold values used.

The actual start of liquid injection (SOI) from the orifice needs to be calculated via post-processing techniques because it occurs before the first frame in which Mie scattering data is captured given the temporal resolution of the optical setup. A linear fit is applied to the first five points of the spray penetration versus time curve and extrapolated to zero-penetration in order to determine the true SOI. A time shift is then applied to the ensemble-averaged vapor penetration curves accounting for the real SOI. The details of this process are illustrated in the accompanying non-vaporizing paper, or Part I of this study [18].

![Figure 3. Sensitivity of the vapor penetration measurement to thresholds used during image processing.](image)

**Results and Discussions**

The results for both fuels are presented in three separate sections: vapor dispersion angle, vapor penetration, and liquid length. The influence of charge gas conditions and injection pressure are also discussed in each section. Figure 4 shows an example of the post-processed shadowgraph (top four rows) and Mie scattering (bottom row) images of ULSD and high reactivity gasoline at various times between 0.1 to 0.8 ms after the start of injection (ASOI). The shadowgraph images in Figure 4 demonstrate the boundary tracking and dispersion angle fitting to the vapor envelope identified. The Mie scattering images displayed in the last row represent the steady-state liquid length of the sprays. The major differences between ULSD and gasoline are apparent from the figures and include the following observations: (1) the dispersion angle of gasoline is larger than ULSD; (2) the vapor penetration of the two fuels is similar; (3) the liquid length of gasoline is significantly lower than ULSD.

![Figure 4. Sample of processed vapor (top four rows) and liquid (bottom row) spray images comparing ULSD and high reactivity gasoline.](image)

**Vapor Dispersion Angle**

Vapor dispersion angle indicates the extent of fuel-air mixing in diesel sprays and is an important macroscopic characteristic. A large dispersion angle denotes higher rates of ambient air entrainment that promotes the liquid fuel vaporization process. There are two realizations for each test condition and only the ensemble-average dispersion angles are plotted in the following figures. Within each individual test realization, a single mean value for the dispersion angle is calculated from the steady-state portion of the spray injection event.

Figure 5 provides the dispersion angle over the entire range of charge gas densities from 10.3 to 41.7 kg/m³. For both fuels, the dispersion angle becomes larger as charge gas density is increased. This result agrees with prior studies; it is attributed to the higher rates of air mass...
entrainment due to higher density air [19]. In addition, the dispersion angle of high reactivity gasoline is notably larger than the ULSD under most of the operating conditions. At 10.3 kg/m³ charge density and 150 MPa of injection pressure, the high reactivity gasoline has 20% larger dispersion angle. At a higher injection pressure of 250 MPa, the difference in dispersion angle between fuels falls to within 5%. The overall trends in dispersion angle for both fuels with respect to charge gas density and injection pressure are quite consistent.

![Figure 5](image5.png)

**Figure 5.** Steady-state dispersion angle vs. charge gas density at different injection pressures.

![Figure 6](image6.png)

**Figure 6.** Vapor dispersion angle versus charge to fuel density ratio.

The dispersion half angle tangent versus the ratio of charge gas to fuel density is fitted to equation (1) [19].

\[ \tan \left( \frac{\theta}{2} \right) = a \cdot \left( \frac{\rho_c}{\rho_f} \right)^b \]  

(1)

The data for both fuels fitted using equation (1) and plotted on a log-log scale are shown in Figure 6. The coefficients of the fitted curves for ULSD and high reactivity gasoline are also provided in Table 5. The observations from non-vaporizing tests [18] indicate that ULSD and high reactivity gasoline exhibit similar trends in spray dispersion and could be represented by a single fit to equation (1). Based on that work, it was concluded that the differences in spray dispersion angles were primarily due to differences in the fuel density. However, the fitted lines in Figure 6 clearly show distinctive slopes for the ULSD and high reactivity gasoline. In addition to the influence that viscosity and orifice flow coefficients may have on the minor differences observed in dispersion angle between fuels under non-vaporizing conditions, it is quite likely that the overall higher volatility of gasoline plays a significant role in the differences observed under vaporizing conditions.

<table>
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<th></th>
<th>a</th>
<th>b</th>
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<tbody>
<tr>
<td>Gasoline</td>
<td>0.30</td>
<td>0.18</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.34</td>
<td>0.22</td>
</tr>
</tbody>
</table>

**Table 5.** Dispersion angle fit coefficients

**Vapor Penetration**

Vapor penetration represents the axial momentum of the spray after the start of injection and is related to the dispersion angle because of the ambient air continually being entrained within the plume [19].

![Figure 7](image7.png)

**Figure 7.** Vapor penetration vs. time for high reactivity gasoline at various charge gas densities under 6 MPa ambient pressure and 150 MPa injection pressure.

In Figure 7, the vapor penetration of high reactivity gasoline is plotted for charge gas densities between 17 to 25.4 kg/m³ at 6 MPa ambient pressure and for an injection pressure of 150 MPa. It is observed that the penetration exhibits a linear dependence during the initial stage of the spray (< 0.3 ms). During this period, there is no apparent impact of charge gas density on penetration rate because the spray is dominated by liquid injection. After 0.3 ms, the penetration slows down and follows a square root dependence that is consistent with prior work and due to the influence of ambient air entrainment into the spray envelope [19]. As charge gas density is increased, the vapor dispersion angle becomes larger. This is caused by more air entrainment that results in reduced...
fuel momentum and vapor penetration. From charge gas densities of 17 to 25.4 kg/m$^3$, the maximum difference between the penetrations for gasoline is 14%.

From charge gas densities of 17 to 25.4 kg/m$^3$, the maximum difference between the penetrations for gasoline is 14%.

The vapor penetration of ULSD and high reactivity gasoline at charge gas pressures of 3, 6 and 10 MPa, charge gas temperatures of 800, 1000 and 1200 K, and an injection pressure of 150 MPa are shown in Figure 8. The differences between fuels at all conditions are relatively small (within 5%).

The influence of injection pressure between 100 to 250 MPa on vapor penetration for gasoline is shown in Figure 9. Penetration rate increases with higher injection pressure due to the higher velocity and momentum of the fuel spray. Vapor penetration increases by a maximum of 40% when the injection pressure is increased from 100 to 250 MPa. In general, the trends of vapor penetration vs. charge gas density, temperature, and injection pressure for the high reactivity gasoline are consistent with expectations based on prior work with diesel [19]. It was also found that for the conditions discussed herein, there was no significant difference in vapor penetration between ULSD and high reactivity gasoline.

![Figure 8. Vapor penetration vs. time for ULSD and high reactivity gasoline at an injection pressure of 150 MPa for a range of ambient pressures and temperatures.](image)

![Figure 9. Vapor penetrations versus time for high reactivity gasoline with 6 MPa charge gas pressure and 900K charge gas temperature.](image)

Liquid Length

The liquid lengths of ULSD and high reactivity gasoline between charge gas temperatures of 800-1200 K and for injection pressures of 100-150 MPa are plotted in Figure 10 and Figure 11 respectively. Similar to the vapor penetration, the liquid length values are obtained from the Mie scattering image boundaries that contain 99% of the total liquid envelope area from the injector tip. The charge gas density in these experiments is controlled by changing the charge gas temperature while keeping the charge gas pressure constant per Table 4. Therefore, at a specific charge gas temperature, increasing the charge gas pressure corresponds to a higher charge gas density.

Figure 10 displays that the liquid length of high reactivity gasoline is more than 50% shorter than the ULSD under the corresponding conditions. This is due to the higher volatility of high reactivity gasoline (T50 of ULSD is 267 °C and of the high reactivity gasoline is 94.4 °C). Further it is seen that the liquid length decreases with an increasing back pressure. From Figure 11, the injection pressure is seen to have no significant impact on liquid length. These observations are consistent with those observed in Siebers’ and others work on liquid penetrations [20, 26].

Interestingly, the liquid length of ULSD in Figure 10 decreases by 33% from 36 to 24 mm at a constant charge pressure of 6 MPa and across a charge temperature range from 800 to 1200 K. The liquid length of ULSD under 3 and 10 MPa have the same trends, which is consistent with prior observations. However, the liquid length of
high reactivity gasoline is insensitive (less than 5% reduction from 13.9 to 13.3 mm at 6 MPa) to changes in ambient temperature over the same range which does not follow the expected trend in Siebers’ studies [20, 26].

\[
\frac{\hat{S}}{\hat{c}} = \frac{S}{c} \sqrt{1 + 16 \Delta^2} + \frac{\ln \left( 4S + \sqrt{1 + 16 \Delta^2} \right)}{16} \quad (2)
\]

\[
t^+ = \frac{\sqrt{\frac{C_o}{a}} \cdot d_o \cdot \sqrt{\rho_f / \rho_a}}{a \cdot \tan (\theta / 2) \cdot C_v \cdot 2 \cdot (P_f - P_a) / \rho_f} \quad (3)
\]

\[
x^+ = \frac{\sqrt{\frac{C_o}{a}} \cdot d_o \cdot \sqrt{\rho_f / \rho_a}}{a \cdot \tan (\theta / 2)} \quad (4)
\]

Figure 10. Liquid length vs. charge temperature at an injection pressure of 150 MPa.

Figure 11. Liquid length vs. injection pressure at a charge gas pressure and temperature of 6 MPa and 900 K, respectively.

According to the correlations of Naber and Siebers [19] and Siebers [20,26], there are two regimes of these types of sprays where the spray transitions from one dominated by the initial velocity and the other dominated by gas entrainment. In the velocity dominated regime, primary atomization, momentum, mass, and energy transport processes control the spray evolution. This corresponds to a regime in the normalized spray penetration \( \hat{S} \) defined in equation (2) and normalized times \( \hat{t} = t / t^+ \) in equation (3) less than 1 as shown in Figure 12. The transition in transport versus entrainment controlled is shown with the short and long time limits with linear and square root dependence on time. At normalized times \( \hat{t} \) greater than 1, the momentum, mass and energy exchange between the fuel (liquid or gas) can be considered to be in equilibrium, and the fuel reaches its saturation temperature. This is the regime in which the liquid length is predicted by the Siebers’ scaling law [20].

Note that the location in the spray where mass, momentum and energy equilibrium may not occur at the same location \( \hat{S} \); however, this transition still occurs near \( \hat{t} = 1 \). Also shown in Figure 12 are the normalized liquid lengths of ULSD and high reactivity gasoline, marked as the red and blue dots for the test cases shown in Figure 10, respectively. These are obtained by normalizing the liquid length using the length scale shown in equation (4), in which \( x^+ \) is the length scale to normalize the spray penetration, \( C_o \) is the area contraction coefficient, assuming to be 1 in this study, \( d_o \) is the orifice diameter, \( \rho_f \) is the fuel density, \( \rho_a \) is the ambient charge gas density, \( a \) is a term set to 0.66, \( \theta \) is the spray dispersion angle [19].

Figure 12. The normalized penetration correlation with short and long time limits of correlation.

In Figure 12, it is observed that the ULSD normalized liquid lengths are larger than those of the high reactivity gasoline. It is also observed that gasoline data approaches the transition regime from entrainment limited to rate limited. This is hypothesized to be the reason for the unexpected trend of gasoline liquid lengths with respect to charge gas temperature.

To further illustrate this, shown in Figure 13, are the normalized liquid lengths of ULSD and gasoline compared to the normalized penetration at a normalized time of 1 for the three charge gas pressures. The trends here further highlight the observation and hypothesis for rate limited conditions for the high reactivity gasoline with
respect to vaporization. As the temperature increases the normalized liquid lengths of the three charge gas pressures are approaching the transition between the regimes and trend to the same value.

![Figure 13. The normalized liquid length versus charge temperature.](image)

Summary

This work, which focuses on non-reacting, vaporizing sprays, is part of a broader study investigating the single-plume injection characteristics of high reactivity gasoline compared to ULSD under heavy-duty engine relevant conditions in an optically accessible, constant volume chamber. In a companion study (Part I), non-reacting, non-vaporizing sprays for both fuels were also characterized in detail [18].

For the current vaporizing study, spray measurements include vapor dispersion angle, vapor penetration, and liquid length. Data were acquired using near-simultaneous shadowgraph and Mie scattering imaging techniques. Operating conditions were designed to cover a wide range of charge gas densities (10.3 - 41.7 kg/m³), temperatures (800-1200 K), and injection pressures (100-250 MPa) that are typical of heavy-duty engine cylinder conditions.

In general, the characteristics of high reactivity gasoline sprays are in good agreement with previous literature. The vapor dispersion angle increases with higher charge gas density (30% increase from 10.3 to 41.7 kg/m³) but exhibits only minor differences with increasing injection pressure (less than 5%). The vapor penetration increases (by a maximum of 40%) with increasing injection pressure (100 to 250 MPa) and a 14% increase in penetration is observed when lowering the charge gas density (from 25.4 to 17 kg/m³). The liquid length decreases with higher charge gas density while changing the injection pressure has only a minor impact on this parameter (2% reduction from 100 to 250 MPa).

High reactivity gasoline has a vapor dispersion angle up to 20% larger than ULSD at a charge density of 10kg/m³ and injection pressure of 150 MPa, although both fuels exhibit very similar vapor penetration (within 5%). The gasoline also has significantly shorter liquid length (by 50%) compared to ULSD. Although high reactivity gasoline and ULSD liquid length share a similar insensitivity to injection pressure, there is an interesting difference observed with respect to charge gas temperature. ULSD shows decreasing liquid length with increasing charge gas temperature, which is the expected trend based on previous work. However, gasoline liquid length remains insensitive to charge gas temperature between 800-1200 K for the injection pressures investigated in this work. This may be due to the influence of local transport of mass, momentum and energy. More analysis is needed to understand this behavior with specific attention to the large differences in fuel properties between ULSD and high reactivity gasoline.

This study provides a framework and starting point for understanding the spray characteristics of high reactivity gasoline under vaporizing conditions in heavy-duty engine applications. In the future, the experimental data presented here will be further analyzed using existing spray correlations developed for diesel sprays and with consideration of important fuel property differences between gasoline and ULSD, including volatility characteristics, viscosity, and other fuel effects on the flow coefficients of orifices.

Acknowledgements

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References


