
Meng Tang\textsuperscript{1}, Jiongxun Zhang\textsuperscript{1}, Tyler Menucci\textsuperscript{1}, Henry Schmidt\textsuperscript{1}, Seong-Young Lee\textsuperscript{1}, Jeffrey Naber\textsuperscript{*1}, Tom Tzanetakis\textsuperscript{2}

\textsuperscript{1}Department of Mechanical Engineering – Engineering Mechanics, Michigan Technological University, Houghton, MI, 49931, USA
\textsuperscript{2}Aramco Services Company, Aramco Research Center - Detroit, 46535 Peary Court, Novi, MI, 48377, USA

Abstract
Recent trends in the transportation energy sector indicate that demand for middle distillates, such as diesel, will increase due to growing commercial traffic in emerging economies. In contrast, demand for light distillates, such as gasoline, is projected to decrease due to fuel economy regulations imposed on passenger vehicles. Therefore, market forces suggest that fuels within the gasoline property range may become an attractive alternative for the heavy-duty commercial transport sector if they can be ignited and combusted as efficiently and robustly as diesel with additional emission benefits. Prior experimental work on a production 14.9 L heavy-duty engine demonstrated that high reactivity gasoline (RON 60, CN 34) can burn in a conventional mixing-controlled combustion mode with similar brake fuel efficiency and lower soot emissions than diesel at a given engine-out NO\textsubscript{x} level. The emissions benefit was attributed to the high volatility and low aromatic content of the gasoline-like fuel. The current study is aimed at investigating the single-plume non-reacting, non-vaporizing spray characteristics of the gasoline-like fuel compared to ultra-low-sulfur-diesel (ULSD) under heavy-duty engine relevant conditions. Another companion study (Part II) focuses on the spray characteristics of non-reacting, vaporizing sprays. The measurements provided here are intended to elucidate the dominant physical and chemical processes behind previously observed engine performance differences and to provide validation data for spray models used in combustion system development. The experiments were carried out in an optically accessible constant volume combustion chamber using a production heavy-duty injector fitted with a single-hole nozzle. A wide range of charge gas densities (10.3-166.5 kg/m\textsuperscript{3}) and injection pressures (100 – 250 MPa) were considered at a fixed temperature of 323 K in order to represent heavy-duty engine relevant, non-evaporating conditions. The spray injection process was characterized using high speed videos at 25,000 frames per second (fps) to capture the entire field of view, and 100,000 fps to capture initial spray development details within the vicinity of the nozzle tip. Results show that the high reactivity gasoline produces a wider spray dispersion angle and slower spray penetration rate compared to ULSD which is consistent with enhanced air entrainment and potentially, gasoline vaporization. The observed differences were further analyzed using existing spray correlations for non-reacting, non-vaporizing sprays and related to the properties of the fuels considered.

*Corresponding author: jnaber@mtu.edu
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 10 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.

Previous studies have shown that there are benefits to using gasoline-like fuels in conventional heavy-duty (HD) diesel engines under mixing-controlled combustion conditions [4]. Compared to conventional diesel combustion, gasoline compression ignition (GCI) takes advantage of higher fuel volatility and lower aromatic content, both of which help reduce soot emissions at a given engine-out NOx level [4]. Further development of GCI into low temperature, partially premixed compression ignition (PPCI) combustion strategies can potentially lead to simultaneous reduction of soot and NOx emissions. This type of operating mode is well suited to the longer ignition delay (low cetane number) of light distillates and would help alleviate the demands placed on current compression ignition engine after-treatment systems for meeting both particulate and NOx emissions regulations. Therefore, GCI combustion provides a promising path forward to achieve high efficiency and lower emissions in the commercial transportation sector.

Investigating the characteristics of gasoline-range fuel sprays under HD diesel engine conditions and with high pressure injectors is a key step towards adapting combustion systems to work with these novel fuels. In limited prior works of sprays under non-vaporizing conditions, different fuel effect trends have been reported. In one set of studies, Payri et al. [5, 6] compared the injection rate, momentum flux and spray characteristics of gasoline and diesel under non-vaporizing conditions at injection pressures of 60, 90, 120, and 150 MPa, and back pressures of 2.5 and 5 MPa. No clear differences were observed between gasoline and diesel in terms of the spray penetration and momentum flux under the experimental conditions. In another set of studies, Han et al. [7] and Feng et al. [8] independently reported the effects of different blending ratios of gasoline into diesel on spray characteristics. In their investigations, diesel mixtures with 0%, 20% and 40% blended gasoline by volume were tested. The experiments from [8] were conducted at ambient conditions of 298 K, 0.1 MPa, and with injection pressures of 40 and 100 MPa. The experiments from [9] were conducted at ambient conditions of 293 K, and 2/4 MPa, with injection pressures of 60/90/120 MPa. The authors concluded that increased gasoline blending ratios lead to reduced spray penetration and increased spray dispersion angle, as well as reduced droplet sizes. These prior investigations [5-8] were carried out using diesel injectors. In another work by Wang et al. [9], fuel effects on spray characteristics were studied using an outwardly opening hollow cone injector at ambient conditions of 298 K and 0.1 MPa, with an injection pressure of 10 MPa. The time averaged spray angles were close for all four fuels considered (light naphtha, whole naphtha, toluene primary reference fuel - TPRF, and primary reference fuel - PRF). An influence of density on spray penetration was observed, although all the fuels followed similar trends. One of the key differences between [5, 6] and [7, 8] was the observable field of view, with maximum observable penetrations of less than 40 mm in [5, 6], and 90 mm in [7, 8]. A major limitation apparent from all these prior works is the charge gas conditions investigated which were not representative of those found in modern HD diesel engines. It is thus the interest of the current work to extend the charge gas density conditions to cover a larger range from 10 to 167 kg/m³ in order to further understand the fuel effects and examine the previously reported trends in the literature more closely. This work, along with two other works on vaporizing sprays [10] and combusting sprays [11], represent a combined effort to understand the potential of using high reactivity gasoline under heavy duty diesel engine conditions.

Fuels, Experimental Setup and Test Conditions

Two fuels are used in the current investigation, including a certification diesel and a high-reactivity gasoline. The results are reported in two parts: Part I, in which the two fuels are compared under non-reacting, non-vaporizing conditions; and Part II, in which
the two fuels are compared under non-reacting, vaporizing conditions [10]. Fuel properties are listed in Table 1. The certification diesel is an ultra-low sulfur diesel (ULSD), and is a heavier distillate cut than the high reactivity gasoline. This leads to a higher density and lower volatility for the diesel. ULSD has a cetane number of 44.2 and the high reactivity gasoline, which is capable of being compression-ignited in this study, has a cetane number of 33.7. The aromatics content difference between the two fuels is also large, with 28.2% aromatics in ULSD and 9.1% aromatics in the high-reactivity gasoline. This difference is partly responsible for the large differences observed in soot emissions [4] and soot luminosity levels [11] among the two fuels. H/C ratio and net heating value are higher for the high reactivity gasoline.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>ULSD</th>
<th>High Reactivity Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>848</td>
<td>705</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>44.2</td>
<td>33.7</td>
</tr>
<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>Aromatics (vol%)</td>
<td>28.2</td>
<td>9.1</td>
</tr>
<tr>
<td>IBP (°C)</td>
<td>173.3</td>
<td>32.3</td>
</tr>
<tr>
<td>10% Dist. (°C)</td>
<td>214.4</td>
<td>58.2</td>
</tr>
<tr>
<td>50% Dist. (°C)</td>
<td>267.8</td>
<td>94.4</td>
</tr>
<tr>
<td>90% Dist. (°C)</td>
<td>315.0</td>
<td>124.0</td>
</tr>
<tr>
<td>FBP (°C)</td>
<td>346.7</td>
<td>139.7</td>
</tr>
<tr>
<td>Net Heat Value (MJ/kg)</td>
<td>42.830</td>
<td>43.363</td>
</tr>
</tbody>
</table>

Table 1. Fuel properties for ULSD and high reactivity gasoline.

In this study, a constant-volume combustion vessel is used to generate the in-cylinder thermodynamic conditions representative of heavy-duty compression-ignition engines. The vessel is rated at 345 bar maximum pressure. Since the interest of the current work is non-vaporizing sprays, the temperature of the vessel is set at 323 K to prevent extensive vaporization of the high reactivity gasoline during spray injection. A comparison of the ambient vessel temperature to the distillation curves of the two fuels is shown in Figure 1. During the spray experiments, N₂ gas is used to provide the back pressure in the combustion vessel.

To understand the spray injection processes, a Z-type shadowgraph image setup, as shown in Figure 2, is used. A high-speed camera FASTCAM SA 1.1 is used with a Nikon 85 mm lens at f/1.4, and the lens is focused on the injector axis. Two frame rates are used in the experiments, including 25,000 frames per second (fps) to capture the spray evolution towards the boundary of the vessel, and 100,000 fps to capture the initial spray development with higher temporal resolution.

Test conditions are listed in Table 2. The spray injections are triggered under five charge gas densities, covering a range from mid-load HD engine operation to beyond typically expected conditions. Three injection pressures are used, including 100, 150, and 250 MPa. Table 3 provides details on the central axis, single-hole injector.

<table>
<thead>
<tr>
<th>Injection Pressure (MPa)</th>
<th>100</th>
<th>150</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Gas Temperature (K)</td>
<td>323</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge Gas Density (kg/m³)</td>
<td>10.3</td>
<td>22.8</td>
<td>31.3</td>
</tr>
<tr>
<td>Charge Gas</td>
<td>Nitrogen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuels</td>
<td>ULSD</td>
<td>High Reactivity Gasoline</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Experimental conditions.
Outlet Diameter (µm) | 176  
K-factor | 1.8  
Cd (Re = 12,000) | 0.94  
Description | Central axis, single-hole, solenoid driven, hydraulically lifted needle

| Table 3. Injector specifications. |

**Data Processing Methods**

Experimentally obtained images were analyzed to obtain the spray characteristics that include spray penetration and spray dispersion angle. The processing methods are shown in Figure 3, which includes the following procedures:

1. Reading in image data from an 8 bit gray scale uncompressed file.
2. Performing background subtractions.
3. Applying thresholds to grayscale images to obtain binary images. The threshold is selected as 5% of the upper limit of pixel intensity (255).
4. Performing boundary tracking and identifying the spray penetration. The spray penetration corresponds to a distance downstream of the injector tip where the area between accounts for 99% of the total spray envelope area.
5. Identifying the spray dispersion angle by performing a linear fit on either side of the spray plume boundary from the injector tip to 60% of the spray penetration distance. The spray dispersion angle is defined by the arc enclosed by the two linear fits.

These procedures are implemented in a MathWorks® MATLAB® program. Spray penetrations and dispersion angles are obtained for each frame and are plotted against time after start of injection. Sensitivity of the spray penetration and dispersion angle to the thresholds used are tested by increasing and decreasing the threshold value by 20%, the results of which are shown in Figure 4. The sensitivity analyses show that the processing methods used are threshold-insensitive.

During testing, three repeats are performed under each test condition and ensemble averaged results are acquired. Note that when the spray penetration is plotted against the time after start of injection, as shown in Figure 5(a), the data acquired from the two distinct frame rates used is not aligned because of the finite time difference between the first captured images in each case. In addition, the high speed camera cannot capture the exact start of injection which occurs between frames. Thus, alignment is required not only to match the results from the two frame rates used, but also to enable comparison between different conditions. The alignment is done via the following two procedures as shown in Figure 5(b) and (c):

1. Fit the original penetration curves in Figure 5(a) to equation $y = a \sqrt{b \cdot (t - c)}$. The 25,000 fps curve is shifted to the left by the fitted $c$ term.
2. Fit the linear portion of the 100,000 fps curve to equation $y = d \cdot (t - e)$. Both penetration curves are shifted to the left by the fitted $e$ term. A zero point is added to both penetration curves.

The two equations in steps 1 and 2 above are based on the square root and linear dependence of spray penetration at different times after start of injection as shown by Naber and Siebers [12]. The shifted penetration curves in Figure 5(c) are compared in the results and discussion.

![Figure 3. Illustration of the image processing methods.](image)
results and discussions

spray dispersion

fuel effects on spray dispersion angles are compared in figure 6 using ensemble-averaged data. the average values and error bars are calculated as the mean and standard deviation of the spray dispersion angles from 0.4 ms after start of injection (aso) to 0.2 ms before end of injection for the three repeat tests, respectively. the error bars therefore indicate overall test repeatability.

the main observation from figure 6 with respect to fuel effects is that the high reactivity gasoline exhibits an equal or larger mean spray dispersion angle under most of the test conditions. all gasoline cases with 250 mpA injection pressure show larger dispersion angle than ULSD, three points of which have error bars smaller than the differences observed. under 100 and 150 mpA injection pressures, the general trend of equal or larger gasoline dispersion angle versus ULSD is maintained except for the highest charge gas density cases under both injection pressures, where there is significant overlap in the error bars.
Figure 6. Spray dispersion angle vs. charge gas density at injection pressures of: (a) 100 MPa, (b) 150 MPa, and (c) 250 MPa.

Spray dispersion angle is related to ambient gas entrainment during injection, as well as possible fuel vaporization. Dimensional analysis on spray dispersion angles often relates the data to charge gas densities, injection pressures, hydraulic diameters and times after start of injection [13]. Non-dimensional analysis of spray dispersion angles relates the half-angle tangent to the ratio of densities between ambient charge gas and fuel as expressed in equation (1) [12].

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

(1)

Non-dimensional analysis of the spray dispersion angles for gasoline and ULSD are shown in Figure 7. Data from all three injection pressures are plotted on a log-log scale. It is observed that gasoline and ULSD follow a similar trend. Upon fitting all data to equation (1), \( a_{\text{gasoline}} = 0.26, b_{\text{gasoline}} = 0.14 \) and \( a_{\text{ULSD}} = 0.26, b_{\text{ULSD}} = 0.16 \). The three fitted lines are plotted in Figure 7. These results confirm that the trends in the two data sets are very close and can thus be effectively collapsed onto a single correlation. The difference in dispersion angle between gasoline and ULSD is therefore mainly explained by the difference in fuel density. There may also likely be some vaporization for the gasoline. The results also suggest that some other minor factors might be responsible for the difference in fitted power used between the fuels. Relevant physical properties that could affect dispersion angle include boiling point and viscosity [4]. Also plotted in Figure 7 is a dispersion angle band of +1° based on the gasoline fit and -1° based on ULSD fit. The majority of data is scattered between the upper and lower bands.
with respect to injection pressure is observed. This result is consistent with a number of prior research studies [12-15].

\[ S = \sqrt{\frac{C_v \cdot 2 \cdot C_a}{\alpha \cdot \tan(\theta/2)} \cdot \sqrt{\frac{(P_f - P_a)}{\rho_a}} \cdot d_o \cdot t} \]  

\[ (2) \]

**Figure 8.** Spray dispersion angle vs. injection pressure for all five charge gas densities.

**Spray Penetration**

Fuel effects on the spray penetration are shown in Figure 9 for all charge gas densities and injection pressures. The main observation from Figure 9 is that ULSD has faster penetration compared to gasoline under the same injection pressure and charge gas conditions. A correlation for spray penetration by Naber and Siebers [12] is given by equation (2) in its dimensional form. In this equation, \( S \) is the spray penetration, \( C_v \) is the velocity coefficient, \( C_a \) is the area contraction coefficient, \( a \) is a term set to 0.66 [12], \( P_f \) is the fuel pressure, \( P_a \) is the ambient charge gas pressure, \( \rho_a \) is the ambient charge gas density, \( d_o \) is the orifice diameter, and \( t \) is the time.
From this correlation, it is evident that fuel properties have no direct influence on the spray penetration. The second term remains the same regardless of the fuel, thus any differences in spray penetration due to fuel properties are attributed to the first term. A larger first term is expected for ULSD compared to gasoline. As previously discussed, gasoline exhibits a larger dispersion angle than ULSD under most conditions. This leads to a smaller first term, assuming that the flow coefficients are independent of the fuel. Therefore, the spray penetration rate for gasoline is expected to be slower than ULSD.

Evidence from non-dimensional spray penetration analyses also supports this observation. Spray penetrations can be non-dimensionalized by using a length scale as given by equation (3) and a time scale as given by equation (4). The non-dimensional form of the Naber and Sieber’s spray penetration correlation [12] is therefore given by equation (5).

In this equation, $x^+$ is the length scale to normalize the spray penetration, $t^+$ is the time scale to normalize the time vector, $\bar{t}$ is the non-dimensional time, $S$ is the non-dimensional spray penetration, $\rho_f$ is the fuel density.

$$x^+ = \frac{\sqrt{C_a} \cdot d_0 \cdot \sqrt{\rho_f / \rho_a}}{a \cdot \tan(\theta / 2)}$$ (3)

$$t^+ = \frac{\sqrt{C_a} \cdot d_0 \cdot \sqrt{\rho_f / \rho_a}}{a \cdot \tan(\theta / 2) \cdot C_v \cdot \sqrt{2 \cdot (P_f - P_a) / \rho_f}}$$ (4)

$$\bar{t} = \frac{S}{\bar{S}} + \frac{\frac{S}{2} \sqrt{1 + 16\bar{S}^2}}{4} + \ln\left(\frac{4\bar{S} + \sqrt{1 + 16\bar{S}^2}}{16}\right)$$ (5)

**Figure 9.** Spray penetration vs. time ASOI under charge gas densities of (a) 10.3 kg/m$^3$, (b) 22.8 kg/m$^3$, (c) 31.3 kg/m$^3$, (d) 52.5 kg/m$^3$, and (e) 166.5 kg/m$^3$.

Comparison of the non-dimensional spray penetration of ULSD and gasoline for a charge gas density of 22.8 kg/m$^3$ and an injection pressure of 100 MPa is shown in Figure 10. The non-dimensional spray penetration of ULSD and gasoline collapse onto the same line representing the correlation. Data below a normalized time of 1 is limited by the charge gas densities considered in this work which do not go below 10 kg/m$^3$. Since the length and time scales used to non-dimensionalize the spray penetration both include fuel density, any differences caused by this property are cancelled out. Note that the analysis is performed assuming the same area contraction and velocity coefficients between the two fuels.

When examining individual test sets in Figure 6, some cases show a deviation from the general trend of larger ULSD penetration rate, including the following cases exhibiting equal or faster penetration for gasoline compared to ULSD:

1. Penetrations prior to 0.1 ms, under a charge gas density of 10.3 kg/m$^3$ and an injection pressure of 150 MPa.
2. Penetrations prior to 0.6 ms, under a charge gas density of 22.8 kg/m$^3$ and an injection pressure of 250 MPa.
3. Penetrations prior to 0.8 ms, under a charge gas density of 52.5 kg/m$^3$ and an injection pressure of 150 MPa.
4. Penetrations after 1.0 ms, under a charge gas density of 52.5 kg/m$^3$ and an injection pressure of 250 MPa.
5. Penetrations after 2.0 ms, under a charge gas density of 166.5 kg/m$^3$ and an injection pressure of 100 MPa.

A direct comparison of spray dispersion angles at all these cases is shown in Table 4. For the cases where
gasoline has equal or faster penetration than ULSD, the spray dispersion angles are very close to each other, except for case 2.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion: Gasoline (°)</td>
<td>14.8</td>
<td>18.0</td>
<td>20.5</td>
<td>19.9</td>
<td>24.1</td>
</tr>
<tr>
<td>Dispersion: ULSD (°)</td>
<td>15.0</td>
<td>16.5</td>
<td>20.3</td>
<td>19.4</td>
<td>24.2</td>
</tr>
</tbody>
</table>

Table 4. Spray dispersion angle comparisons for equal or larger gasoline spray penetrations than ULSD.

The above analysis shows that fuel effects impact spray penetration mainly through the difference in spray dispersion angle. This is based on both the general trends of faster ULSD spray penetration compared to gasoline and results from the special cases of equal or slower ULSD spray penetration.

Summary

This work is part of a larger effort to understand high reactivity gasoline’s potential in heavy-duty engine applications. In this work (Part I), non-vaporizing gasoline and ULSD sprays are compared using a single-hole, heavy-duty injector. A second paper (Part II) examines sprays under vaporizing conditions. Experimental conditions for the current work cover a wide range of charge gas densities between 10.3 kg/m³ and 166.5 kg/m³, and injection pressures of 100, 150 and 250 MPa. A high-speed shadowgraph imaging technique was employed to understand the spray injection characteristics. Dispersion angle and jet penetration were characterized from the captured images.

As a general trend, it was observed that high reactivity gasoline exhibits larger spray dispersion angles and slower spray penetration than ULSD, although several cases exist that do deviate from this behavior. It was found that fuel effects on spray dispersion and spray penetration are mainly reflected in the difference in fuel density. Vaporization might also play a role for high reactivity gasoline injections under these conditions because of its high volatility. It is also believed that other fuel parameters, including viscosity, likely play a minor role compared to fuel density in influencing spray injection characteristics under these conditions. However, further analyses considering the effect of fuel properties on the velocity and area contraction coefficients will be needed to understand these influences in greater detail.

Acknowledgements

The authors would like to acknowledge the support of Saudi Aramco and King Abdullah University of Science and Technology (KAUST) for funding this work through the FUELCOM 2 Research Program. The authors would also like to thank Cummins for their support in providing the single-hole nozzle and integrating the injector with the experimental hardware at Michigan Tech University.

References


