Spray and atomization of diesel and biofuels using a single-hole nozzle

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Abstract
Fuel spray and atomization characteristics play an important role in the performance of internal combustion engines. Generally, small droplet size and large spread area of fuel sprays are considered as important factors to enhance the combustion efficiency. As petroleum fuel is expected to be depleted in a few decades, finding alternative fuels that are competitive to replace the petroleum fuel has attracted much research attention. In this work, the spray and atomization characteristics were investigated for commercial No. 2 diesel fuel, biodiesel derived from waste cooking oil (B100), 20% biodiesel blended diesel fuel (B20), renewable diesel produced by university laboratory and civil aircraft jet fuel (Jet-A). Droplet diameters and particle size distributions were measured by a laser diffraction particle analyzing system and the spray tip penetrations and cone angles were acquired using a high speed imaging technique. All experiments were conducted by employing a common rail high pressure fuel injection system with a single-hole nozzle under room temperature and pressure. The experimental results showed that Biodiesel and Jet fuel had different features compared with diesel. Longer spray tip penetration and larger droplet diameters were observed for B100. Smaller droplet size of Jet-A were believed caused by its relatively lower viscosity and surface tension. B20 showed similar characteristics to diesel but with slightly larger droplet sizes and shorter tip penetration. The properties of refined green biofuel were closer to Jet-A than diesel. Furthermore, we also observed that the smallest droplets are within a region near the injector nozzle tip and grew larger along the axial and radial direction. The variation of their diameters becomes smaller while increasing the injection pressure.

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The combustion of fossil fuels increased with ambient pressure. The faster vaporization of injection duration and ambient pressure on diesel showed the effect of injector driver energizing duration. The spray angle was slightly influenced by injection pressure and remained nearly constant during the whole injection process. Suh et al. studied the effect of injector driver energizing duration (injection duration) and ambient pressure on diesel spray characteristics. Study of the fuel spray behavior can be classified into two categories: macroscopic parameters, such as spray tip penetration and cone angle can be measured by direct visualization methods; microscopic parameters, such as velocity, droplet size and size distribution can be measured through particle image velocimetry (PIV), phase Doppler particle analyzer (PDPA) or laser diffraction particle analyzer (LDPA) systems.

### Macroscopic spray properties

An investigation on the effect of injection pressure on the macroscopic spray characteristics showed that the spray tip penetration increased with increase in injection pressure [3]. The spray angle was slightly influenced by injection pressure and remained nearly constant during the whole injection process. Suh et al. [4] studied the effect of injector driver energizing duration (injection duration) and ambient pressure on diesel spray characteristics.

Spray characteristics of diesel and biodiesels under ultra-high injection pressure (up to 300 MPa) were studied by Wang et al. [5]. This study showed that biodiesel had longer spray tip penetrations than diesel fuel. The spray cone angles of biodiesel fuels were smaller than that of diesel fuel. Gao et al. found that although biodiesels were produced from different inedible oils, their viscosities and densities and therefore their macroscopic spray characteristics were similar [6]. Fang et al. investigated the spray and combustion of diesel and biodiesel blends in an optical diesel engine using a common rail fuel injection system [7]. Longer spray penetration was observed for blends with more biodiesel content and less flame luminosity and higher NOx emissions were found for biodiesel fuels. However, applying advanced multiple fuel injection strategies can reduce the emissions of biodiesel fuels under clean diesel combustion mode [8].

In addition, due to the “one fuel forward” policy from the Army requirements, application of jet fuels in diesel engines is important for military vehicles [9]. Spray tip penetration of JP-8 were measured in an optical combustion vessel and compared with diesel fuel by Pickett and Hoogterp [10]. Results showed that the liquid-phase penetration of JP-8 was shorter than that of diesel, due to the lower boiling point of JP-8. However, the vapor penetration rate of JP-8 was not much different from that of diesel. Lee et al. [11] found that JP-8 had a shorter spray tip penetration and wider spray angle than diesel fuel mainly due to the faster vaporization characteristic of JP-8.

### Microscopic spray properties

An experimental investigation of diesel and coalwater slurry SMDs near the spray tip region was conducted by Kihm et al. [12]. Their results showed that average SMDs of both fuels increased with ambient pressure and distance from the nozzle but decreased significantly with increasing injection pressure. Labs and Parker [13] characterized the interior properties of diesel spray liquid portion near the injector nozzle. Their results indicated that the trend of SMD was increased with radial and axial distance from the nozzle tip. Thus, the smallest droplets were on axis and close to the injector tip.

An analytical study of atomization characteristics of 7 different kinds of biodiesels were developed by Ejim [14]. Results from statistical analysis showed that B100 coconut biodiesel had similar atomization characteristics to No. 2 diesel, because of its similar properties, i.e. density, surface tension, and viscosity. Other biodiesels such as palm, soybean, cottonseed, peanut and canola had slightly larger droplet sizes compared with diesel. Gao et al. conducted experiments of the spray characteristics of inedible oils such as jatropha oil, palm oil and used fried oil blended fuel and compared their effects on diesel engines.

### Table 1. Physical properties of fuels.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Abbreviation</th>
<th>Density (g/ml)(40˚C)</th>
<th>Viscosity (mm2/s)(40˚C)</th>
<th>Surface tension (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>D</td>
<td>0.83</td>
<td>2.65</td>
<td>30.3</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>B100</td>
<td>0.87</td>
<td>4.60</td>
<td>34.7</td>
</tr>
<tr>
<td>20% biodiesel blend</td>
<td>B20</td>
<td>0.84</td>
<td>3.04</td>
<td>27.7</td>
</tr>
<tr>
<td>Renewable diesel</td>
<td>R</td>
<td>0.76</td>
<td>2.48</td>
<td>30.3</td>
</tr>
<tr>
<td>Jet A</td>
<td>J</td>
<td>0.79</td>
<td>1.15</td>
<td>28.7</td>
</tr>
</tbody>
</table>

According to a U.S. Environmental Protection Agency (EPA) report, more than 90% of greenhouse gas emissions come from the combustion of fossil fuels [1]. In order to retard the depletion of fossil fuels and reduce the global warming effect, discovering alternative, renewable and reliable fuel sources to replace the usage of fossil fuels had become an essential issue for scientists. On the other hand, optimizing combustion process in IC engines also contributes to the reduction of both fossil fuel consumption and pollutant emissions. As a highly efficient IC engines, diesel engines offer superior thermal efficiency and low fuel consumption. They are widely used in both light duty vehicles and heavy duty trucks. Spray characteristics of diesel and its alternative fuels play important roles for optimizing the engine performance.

Studies of the fuel spray behavior can be classified into two categories: macroscopic parameters, such as spray tip penetration and cone angle can be measured by direct visualization methods; microscopic parameters, such as velocity, droplet size and size distribution can be measured through particle image velocimetry (PIV), phase Doppler particle analyzer (PDPA) or laser diffraction particle analyzer (LDPA) systems [2].
pared with 0# diesel [6]. SMD of blended fuels was greater than diesel, and spray was more concentrated, due to the higher viscosity and surface tension of biodiesel, compared with conventional diesel fuel. Choi et al. [15] investigated the droplet properties under different blending ratios of biodiesel (palm oil). They found that the peak of the particle size volume frequency distribution increased as increasing the injection pressure but the peak decreased while increasing the blending ratio. As the biodiesel blending ratio increased, SMD, mass median diameter (MMD), and span factor increased.

Mao et al. [16] compared the SMD of diesel, Jet-A and JP-8 under different injection pressures with a swirl atomizer. The results indicated the SMDs of Jet-A and JP-8 were both smaller than that of diesel fuel. The droplet size change among different fuels was demonstrated by Prommersberger et al. [17]. Their result showed that the droplet sizes of Jet A and JP-4 both decreased faster than that of diesel fuel due to their lower boiling points.

In this study, we compared the differences of commercial No. 2 diesel fuel and several alternative fuels by investigating their spray and atomization characteristics. Table 1 lists the physical properties of all the five fuels used. Biodiesel has the largest values of density, viscosity and surface tension. Renewable diesel fuel [18-19] has the lowest density but it is close to Jet-A, which has a very low viscosity.

Experimental Setup

The injection system is illustrated in Fig. 1. A first generation common rail fuel system is built to control and maintain the fuel at a given constant injection pressure (up to 1350 bar). A specially machined single holed injector nozzle with a diameter of 140 μm is used in this work. The chosen injection pressures in this study are 300, 500, 800 and 1000 bar.

The particle size of fuel spray was measured by a LDPA (laser diffraction particle analyzer) system (SprayTec, MAL, 1009475, Malvern Instruments Inc.). The data acquisition rate was set to be 10 kHz and 300 mm lens was used for the size range of 0.1-900 microns. The fuel injector and the LDPA system were synchronously triggered. The droplet sizes shown in this study are the average values of 10 experimental results. The error bars of the droplet size data are standard deviations calculated based on the 10 results of each case.

A high speed camera (Phantom 4.3, Vision Research Inc.) was used to capture the images of the fuel spray. It provided a frame rate of 7312 frames per second at a resolution of 608x128 with the exposure time of 7 s in this study. A 1000 Watt spot light was used as the light source for the image acquisition. The measurement trigger is also synchronized with the injector. The spray tip penetration and cone angle data in this study are the average values derived from 5 spray images for each case.

![Figure 1. Schematic of the common rail fuel injection system setup.](image)

Results and discussion

Sauter Mean Diameter (SMD)

Figures 2(a) to 2(c) depict the SMD results for different conditions. Fig. 2(a) shows the SMDs of different fuels under 300, 500, 800 and 1000 bar injection pressures with injection duration of 1.5 ms. For the figures shown in this study, the symbol J stands for Jet-A and R stands for renewable diesel fuel. Conventional biodiesel and 20% biodiesel blend are represented by B100 and B20. D is for diesel. It is clear to see from Fig. 2(a) that SMDs decrease with the increase in the injection pressure for all the fuels. The SMD difference among the fuels is mainly due to the differences in their viscosity and surface tension (Table 1). A higher viscosity leads to a lower fuel jet velocity, leading to larger droplet size. A lower surface tension makes the spray easier to break up into small droplets. According to Fig.2(a), biodiesel has much bigger droplet size than diesel fuel due to its highest viscosity and surface tension. The viscosity of B20 is higher than diesel but its surface tension is lower. These combined fuel properties affect the SMD of B20 by showing a close value to diesel at lower pressures (<500 bar). Jet-A has the smallest drop-let size due to its lowest viscosity and surface tension as well. Renewable diesel fuel has a similar surface tension to diesel; however, it has smaller droplet size than diesel and is closer to Jet-A due to its lower viscosity. The current results also show that the effect of viscosity is more significant on the SMD than that of surface tension due to the fact that viscosity variations among fuels are higher than that of surface tension.

Locating the laser beams of LDPA system at different positions can help us to understand the droplet sizes distribution within the spray plume. Fig 2(b) and 2(c) demonstrate the SMD changes at different spray axial and radial distances. The SMDs increase with increasing the distance between the measuring point
and the injector nozzle tip due to momentum loss along the penetration development. SMDs get larger while moving away from the nozzle tip. Fig. 2(c) shows the SMDs at different radial distances from the axis of the spray. The smallest SMDs are found along the axis of sprays and increase about 1 micron at the spray peripheries. This phenomenon is considered due to the spray pressure dropped to ambient pressure on the peripheries therefore decrease the effect of high injection pressure. At radial distance of 1 cm, it is already outside of the spray periphery, the sprays become loose and dilute. Therefore, their droplet sizes decrease again. These results are consistent with findings in [17].

Droplet size distribution

Particle size distribution of alternative fuels compared with conventional diesel under different injection pressures are illustrated in Figs. 3(a) to 3(d). At 300 bar, biodiesel, B20 and renewable diesel fuel shows similar distribution, slightly narrower than diesel, but the peak of volume frequency of these fuels and diesel are all about 16 µm. Jet-A shows distinct distribution in smaller diameter regions and its peak is about 13 µm for 300 bar injection pressure. At 500 bar, the droplet size distribution of biodiesel and B20 are still narrower than diesel but that of renewable diesel fuel becomes close to diesel fuel, Jet-A remains in the smallest region. All distributions of different fuels show a trend of moving toward smaller particle diameters. For 800 bar, all the fuels have similar droplet size distributions within a smaller range (from 1 µm to 30 µm) with peaks around 10 µm. This is the reason we chose 800 bar injection pressure as our standard condition for other experiments. The variation of droplet sizes of different fuels is the smallest under 800 bar injection pressure; therefore, we can clearly distinguish the effect of changing other experimental conditions on droplet size with this injection strategy. For the highest injection pressure used in this study, 1000 bar, the peaks of renewable diesel fuel, diesel and Jet-A go down into smaller diameter regions while the changes of biodiesel and B20 are not obvious compared with 800 bar.

Spray tip penetration

Spray tip penetrations of all the fuels at different injection pressures are shown in Figs. 4(a) to 4(d). Tip penetrations of 5 fuels grow up with time after being injected from the injector and a higher injection pressure promotes this growing. This trend can be easily observed by looking at diesel penetration under 300 bar in Fig. 4(a). At 1.5 ms after injection, the spray tip penetration is 10 cm compared with 14 cm under 1000 bar in Fig. 4(d). Biodiesel shows significantly longer penetration than other fuels at low injection pressure (300 bar) but the difference becomes small at higher injection pressures. This may be attributed to the fact that the relatively higher density and bulk modulus of biodiesel make it ejected from the nozzle faster than other fuels, thus increasing injection pressure has less effect on biodiesel to enhance the growing of spray tip penetration. Another interesting phenomenon is for B20 with shorter penetrations than diesel under all injection pressures. This might due to the higher viscosity of B20 raises the friction between fuel and the injector nozzle surface, and thus drags the injection started from the nozzle. But for pure biodiesel, B100, this dragging effect is overcome by its large density and bulk modulus, which make biodiesel have the longest penetration.

Spray cone angle

Figs 5(a) to 5(d) illustrate the spray cone angle results under different injection pressures with time after the start of injection. As the spray penetrates, the droplets on the boundaries become smaller and diffuse easily, generating a decreasing trend of spray cone angle. The spray cone angles decrease rapidly after injection to about 10 degrees for each injection pressure, however, with different reducing speed. As seen from the figures, the spray cone angles of the five fuels converge to a constant value (steady state of the spray) at around 0.8 ms after start of injection at 300 bar injection pressure and it becomes to 0.7 ms for 500 and 800 bar. Under 1000 bar injection pressure, the spray cone angles converge at 0.6 ms after injection. These results show that the distinction of different fuels after the convergence decreases while increasing the injection pressure. More obvious disparity of different fuels can be seen before their convergence. The spray of biodiesel starts with the smallest cone angle according to its highest viscosity. From the above observations, it is found that increasing the biodiesel blend ratio reduces the cone angle of fuel spray due to the increase of viscosity. As for renewable diesel fuel and Jet-A, the effect of density is more significant than the effect of viscosity and makes the cone angle of Jet-A smaller than the renewable diesel fuel under different injection pressures.

Spray image

The spray images taken by the high speed camera capture the transient shape of sprays at different timings. These images are sorted in Figs 6 to 7 by 3 time periods (0.7, 1.0, and 1.5 ms) after the injection trigger signal. It can be seen from the figures that biodiesel has the largest penetration length, spray projected area, and thus the largest spray volume. This phenomenon is most obvious in the images at 1.0 ms after injection trigger. At this time period, the spray already achieves steady state and develops in a constant velocity. This trend can be observed by comparing the volume difference of 0.7 ms and 1.5 ms with 1.0 ms. The penetration slows down and the perturbation area increases at 1.5 ms. An interesting characteristic of fuel sprays can be
found in these figures are the perturbation regions of sprays occur earlier at higher injection pressures by comparing the images under different pressures at 0.7 ms after injection. This effect is due to the higher spray speeds under high injection pressures making the sprays penetrate and contact with air faster.

Conclusions
In this work, the spray and atomization characteristics were investigated for diesel fuel and its four alternatives, including biodiesel derived from waste cooking oil, blend of biodiesel and diesel, pure hydrocarbon biofuels, and jet A fuel. Both microscopic and macroscopic parameters were measured. The observations and findings can be summarized as follows:
1. Biodiesel and its blend lead to larger droplets compared with diesel. However, Jet-A and renewable diesel fuel have smaller droplet sizes. Increasing injection pressure is effective for reduction in droplet size;
2. Droplets at the spray periphery have larger diameters than those in the center of the spray. Droplet diameters become larger with the increase of the distance from the nozzle tip;
3. B100 has the longest penetration beyond other fuels. Longer penetration of fuel spray is observed under higher injection pressure. The spray penetrations at 1000 bar injection pressure are about 40% longer than those at 300 bar, which is more pronounced for Jet-A and renewable diesel fuel;
4. Effect of injection pressure on spray cone angle is not evident compared with that on droplet size and spray tip penetration. Spray cone angle converges to its steady state very rapidly with increasing injection pressure;

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References
Figure 2. SMD variation under different parameters: (a) injection pressure (Axial distance: 8 cm, Radius distance: 0 cm, Injection Duration: 1.5 ms); (b) spray axial distance from injector nozzle tip (Injection pressure: 800 bar, Injection duration: 1.5 ms, radial distance: 0 cm); and (c) radial distance from the spray axis (Axial distance: 8 cm, Injection pressure: 500 bar, Injection duration: 1.5 ms).

Figure 3. Comparison of particle size distribution for different fuels under different injection pressures: (a) 300 bar; (b) 500 bar; (c) 800 bar; and (d) 1000 bar.
Figure 4. Spray tip penetration for different fuels under different injection pressures: (a) 300 bar; (b) 500 bar; (c) 800 bar; and (d) 1000 bar.

Figure 5. Spray cone angles for different fuels under different injection pressures: (a) 300 bar; (b) 500 bar; (c) 800 bar; and (d) 1000 bar.
Figure 6. Comparison of spray development images with time after injection trigger signal at 300 bar (left) and 500 bar (right) injection pressure at different times of 0.7 ms, 1.0 ms, and 1.5 ms (from top to bottom) after the injection trigger.
Figure 7. Comparison of spray development images with time after injection trigger signal at 800 bar (left) and 1000 bar (right) injection pressure at different times of 0.7 ms, 1.0 ms, and 1.5 ms (from top to bottom) after the injection trigger.