Correlation of Mixture Formation and Combustion Processes in D.I. Diesel Sprays

Wu Zhang \(^1\)  Kalya Nishida \(^2\)

A micro-hole nozzle and an ultra-high injection pressure were employed to investigate the effects of the nozzle hole diameter and injection pressure on the spray, mixture formation, and combustion processes. The laser absorption-scattering (LAS) technique was adopted to obtain the qualitative and quantitative information on spray characteristics. A high-speed video camera system was employed to record auto-ignition and combustion processes. OH chemiluminescence was used as a marker of auto-ignition and as a measure of the flame lift-off length. The effects of injection parameters on auto-ignition and flame lift-off length were presented. The data on gas entrainment and fuel vaporization acquired in the evaporating sprays under the same ambient conditions were correlated to the auto-ignition process and flame lift-off length.

Key Words: Diesel, Spray, Combustion, OH chemiluminescence, Auto-ignition, Lift-off length

1. Introduction

In direct injection (D.I.) Diesel engines, when Diesel fuel is injected into the hot air in the combustion chamber, the liquid atomization, ambient gas entrainment, and fuel vaporization take place. Then auto-ignition occurs at multiple points downstream of the spray almost simultaneously\(^1\). After the auto-ignition process, in a D.I. Diesel spray under quiescent conditions, the flame stabilizes at a quasi-steady, axisymmetric location downstream of the nozzle tip. The most upstream location of the flame during the injection is referred to as the flame lift-off length\(^2\). Many studies have been carried out to clarify the detailed mechanism of the physical and chemical processes during auto-ignition and lift-off\(^3-6\). The chemiluminescence imaging has been proved to be an effective approach\(^7\). Experimental studies also show that OH chemiluminescence provides an excellent marker for determining lift-off lengths because it is known to occur under high temperature, stoichiometric combustion conditions\(^8\).

To obtain insight into the relationship between the mixture formation and combustion processes of Diesel sprays from a micro-hole nozzle under ultra-high injection pressures, direct photography of OH chemiluminescence was employed to investigate the auto-ignition process and lifted Diesel jet flames. Comparisons were made with the spray characteristics acquired by the laser absorption-scattering (LAS) technique.

2. Experimental Apparatus and Conditions

2.1. Experimental Apparatus

(1) High Pressure Injection System

The schematic diagram of the injection system is shown in Fig. 1. A manually operated piston screw pump, High Pressure Generator (High Pressure Equipment Co., Model 37-5.75-60), was used to generate the ultra-high injection pressure up to 300 MPa, measured with a pressure transducer, in the common rail. A Diesel injector, electronically controlled by an injector driver, was specially designed to meet the requirement of ultra-high injection pressures. Two pulse generators (Stanford Inc., DG 502) were used to provide the external triggers for the injector driver and to synchronize the Nd:YAG laser, CCD cameras, and injection system. To simulate the free Diesel sprays under elevated ambient conditions, high pressure fuel was injected into a high-temperature and high-pressure constant volume vessel.

(2) LAS System

The LAS technique was employed to investigate the spray and mixture characteristics of single-hole nozzles in the constant volume vessel filled with nitrogen gas. The detailed principle and image processing procedure were described in the previous paper\(^9\). The brief summary was as follows. The second harmonic (visible light, 532 nm) and fourth harmonic (ultraviolet (UV) light, 266 nm) of an Nd:YAG laser (Continuum, NY 61-10) were selected as the incident light. The two initially coaxial beams were separated into an UV beam and a visible beam by a dichroic mirror. The separated
beams were expanded by the respective beam expanders and were made coaxial again using a harmonic separator. Then the beams were directed to a fuel spray. After being attenuated by the spray, the beams were separated into two beams by another harmonic separator; the two beams were then focused to the respective CCD cameras (Hamamatsu Photonics, C 4880). The light extinction at the two wavelengths was recorded at 14 bit images by CCD camera chips. The image acquisition and arithmetic processing were carried out by using IPLab (Spectrum Signal Analytics). To minimize the shot-to-shot variation, the LAS images were determined by averaging four images that were taken at four times under the same conditions. The overall accuracy of the LAS technique was estimated by the experiment of completely evaporated free sprays. Results show that, under completely evaporated conditions, the average measurement error of vapor mass is approximately 11%\(^\text{20}\). This error increases with increasing the ratio of liquid phase fuel in the mixture.

(3) High-Speed Video Camera System

As shown in Fig. 1, a high-speed video camera (Photron Co., ultima APX RS) was employed to take the direct photography of Diesel jet flames. An image intensifier (LaVision Inc., HS-IRO) was coupled and a UV-Nikkor lens (Nikon, 105 mm, f4.5) was used to visualize the broadband natural flame luminosity. The gain and gate of the image intensifier were adjusted carefully to acquire clear flame images. A band-pass filter, centered at 313 nm with 10 nm full width at half maximum (FWHM), was used to visualize the line-of-sight OH chemiluminescence. DaVis (LaVision Inc., DaVis 7.0) was used for data acquisition and processing.

### 2.2 Experimental Conditions

Test conditions for both spray and combustion measurements are listed in Table 1. The ambient density was maintained at 15 kg/m\(^3\) to simulate the engine condition at the crank angle of -10 deg. ATDC.

<table>
<thead>
<tr>
<th>Table 1 Test Conditions for Spray and Combustion Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ambient Gas Density (kg/m(^3))</strong></td>
</tr>
<tr>
<td><strong>Ambient Gas Pressure (MPa)</strong></td>
</tr>
<tr>
<td><strong>Ambient Gas Temperature (K)</strong></td>
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<tr>
<td><strong>Nozzle Type</strong></td>
</tr>
<tr>
<td><strong>Spray Measurement</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Fuel</th>
<th>Nozzle Hole Diameter (mm)</th>
<th>Injection Pressure (MPa)</th>
<th>Injection Quantity (mg)</th>
<th>Injection Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,3-Dimethylxanthene</td>
<td>0.16</td>
<td>100</td>
<td>15.47*</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.87*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Combustion Measurement</strong></th>
<th>JIS #2 Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Fuel</td>
<td>Nozzle Hole Diameter (mm)</td>
</tr>
<tr>
<td>-----------</td>
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</tr>
<tr>
<td>JIS #2 Diesel Fuel</td>
<td>0.16</td>
</tr>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame Rate (fps)</td>
<td>10,000</td>
</tr>
<tr>
<td>Resolution (pixel)</td>
<td>512 x 512</td>
</tr>
</tbody>
</table>

*Injection quantities for simulated multi-hole nozzles (0.16 mm x 4.5 holes and 0.08 mm x 18 holes) are 70 mg/stroke.
The nozzle with a diameter of 0.16 mm was selected as the baseline, and the performance of a micro-hole nozzle (d = 0.08 mm) was investigated. To simulate the operating condition of the prototype engine at full load, the injection quantities of the single-hole nozzles were determined by holding the total injection quantity at 70 mg/stroke and the total cross-sectional hole area at the same value for the multi-hole nozzles[11]. Injection durations were determined by the injection rate curves measured with the Bosch method at different injection pressures (Fig. 2). Since the objective of the present study is to achieve the premixed compression ignition (PCI) combustion close to top dead center (TDC), end of injection (EOI) was used as the temporal reference point. For the spray measurement, two combinations of the nozzle hole diameter and injection pressure, including the baseline condition (0.16 mm and 100 MPa) and objective condition (0.08 mm and 300 MPa), were investigated. 1,3-Dimethylhexahydropthalene (DMN), a test fuel of the LAS technique, was used as the surrogate of Diesel fuel. DMN had similar physical properties as those of Diesel fuel. At the same time, it was a strong UV light absorber and was transparent in visible light. Its absorption coefficient was not strongly dependent on the temperature. For the combustion measurement, both of the two test nozzles were measured at three injection pressures (100, 200, and 300 MPa) respectively to clarify the effects of the nozzle hole diameter and injection pressure on the auto-ignition and combustion process. The commercial Diesel fuel (JIS #2, Cetane Number = 56) was selected as the test fuel.

3. Results and Discussion

3.1. Auto-Ignition Process

When the Diesel fuel is injected into the hot air in the constant volume vessel, the fuel vaporization and the auto-ignition processes take place. In Diesel engines, the auto-ignition timing is commonly defined as the crank angle when the apparent heat release rate reverses direction or first goes positive. However, relatively weak flame emission that is due to chemiluminescence occurs prior to the conventional auto-ignition timing[7]. In this study, the initial auto-ignition was detected using the OH chemiluminescence imaging. Figure 3 shows the images of the auto-ignition process.
for free sprays under different conditions. The top of each image is
the position of the nozzle tip. Note that, in this paper, the visual
comparisons of brightness level between images cannot be used to
make quantitative comparisons of actual measured intensities. The
reason is that the sensitivity of the detection system was optimized
for each image separately to use the full dynamic range of the
camera. Therefore, the same apparent brightness in two images
with different sensitivity values will correspond to different numbers
of incident photons. The images given here only show the overall
structures of the spray flames.

The OH chemiluminescence images at auto-ignition timings
clearly show the effects of the injection pressure and nozzle hole
diameter. As the injection pressure increases, the auto-ignition
region moves downwards and the area decreases obviously. At the
same time, as the nozzle hole diameter decreases from 0.16 to 0.08
mm, the auto-ignition region moves upwards and the area decreases
significantly.

Figure 4 shows the ignition delay for the two test nozzles under
different injection pressures. It obviously indicates that, the
increased injection pressure has a great influence on reducing the
ignition delay. For the 0.16 mm nozzle, as the injection pressure
increases from 100 to 300 MPa, the ignition delay reduces by half.
The elevated injection pressure greatly increases the turbulent
mixing rate and accelerates the preparation process of the
appropriate air-fuel mixture for auto-ignition. Note that, the
ignition delays for 0.08 mm are shorter than those for 0.16 mm
except for the condition of 300 MPa. One possible reason for the
slight increase in the ignition delay is that the very fast fuel
vaporization at 300 MPa causes a decrease in the temperature, thus
resulting in an increase in the ignition delay.

3.2 Correlation of Mixture Formation and Auto-Ignition
The ignition delay is defined as the time interval from the start of
fuel injection to the onset of combustion. During this period both
physical and chemical processes have pronounced effects. If the
chemical time-scale is relatively short compared with the physical
time-scale, the mixing and fuel vaporization processes might be the
most important factors which contribute to the elapsed time before
auto-ignition. In this work, data on the spray and mixture
formation process were collected using the LAS technique. With
assuming the Diesel sprays injected into the quiescent constant
volume vessel to be axisymmetric, the equivalence ratio
distributions of liquid and vapor phases were obtained through the
image processing.

The OH chemiluminescence images and comparison of the
evaporating spray and combusting jet injected from the 0.08 mm
nozzle at 300 MPa is shown in Fig. 5. The horizontal lines in the
auto-ignition image and equivalence ratio distribution contours show
the upper and lower positions of the auto-ignition region. It is
obvious that auto-ignition occurs at the tip region with an
appropriate vapor phase equivalence ratio. After auto-ignition, the
area of OH chemiluminescence emission increases significantly.
At EOI the flame propagates slightly upstream and travels
downstream very fast. It is worth noting that, since the images
acquired in this study are integrated along the line of sight through the
jet flame plume, they do not show whether the chemical
reactions are confined to the peripheral regions or are volumetric.
However, inspection of Fig. 5 shows some interesting features.
Due to the relatively low vapor phase equivalence ratio in the very
thin boundary mixing layer of the spray tip, it is difficult for the
auto-ignition to occur in this thin peripheral region. The
auto-ignition may start at multi-points inside the spray tip.

3.3 Flame Lift-Off Length
After the auto-ignition process is completed, in a high-temperature
D.I. Diesel spray under quiescent conditions, the flame stabilizes at a

Fig.5 OH Chemiluminescence Images at Auto-Ignition and EOI Timings, Optical Thickness Images and Equivalence Ratio Distribution
Contours of Evaporating Spray at Auto-Ignition Timing (-0.6 msAOEI), d = 0.08 mm, P_{eq} = 300 MPa
The most upstream location of the flame during the injection is referred to as the lift-off length. Due to the transient characteristics of the Diesel sprays, the quasi-steady state of the lifted flame is assumed to be achieved close to EOI. In this study, 0.1 msAEOL was selected. Figure 6 shows OH chemiluminescence images of the lifted Diesel jet flames under different conditions. For 0.16 mm nozzle, it is obvious that the lift-off length increases greatly with increasing the injection pressure from 100 to 200 MPa, while the difference between 200 and 300 MPa is not pronounced. For 0.08 mm nozzle, the lift-off length increases gradually with increasing the injection pressure from 100 to 300 MPa. Stebers and Higgins have investigated the effects of the injection pressure on the flame lift-off length and have found that the lift-off length is linearly dependent on the injection velocity. This linear dependence agrees with the results observed for atmospheric pressure gas jets. The authors' previous work has proved that the Diesel sprays from a micro-hole nozzle are more similar to the gas jets than those from the conventional nozzles. The slight difference between 0.08 and 0.16 mm nozzles in the effect of the injection pressure on the lift-off length might be the consequence of the discrepancy between two-phase Diesel sprays and single-phase gas jets. For the micro-hole nozzle, the faster fuel vaporization during the initial stage of the injection duration and smaller density difference between the spray plume and ambient gas result in the above phenomenon.

3.4. Correlation of Mixture Formation and Lift-Off Length

To correlate the lift-off length to the mixture formation process in greater detail, data on the lifted Diesel jet flames were compared with the results of the evaporating sprays at the same ambient conditions. Figure 7 shows the ratio of entrained gas to total injected fuel versus time after EOI before auto-ignition timings for the baseline and objective conditions. At the timing of 0.3 ms before auto-ignition, for 0.08 mm and 300 MPa, the ratio of entrained gas to total injected fuel is almost 1.5 times larger than that for 0.16 mm and 100 MPa. The increased ambient gas entrainment is caused by the combined effect of the increased injection pressure and decreased nozzle hole diameter. The enhanced gas entrainment intensifies the mixing process and will have a great influence on the lift-off length, which may result in a decrease in soot formation.

Figure 8 shows the equivalence ratio distributions for the baseline and objective conditions. The horizontal lines in Fig. 8 show the lift-off locations for two test conditions. By examining the liquid phase fuel distributions, the relationship between fuel vaporization and combustion that plays a major role in the soot formation will be clarified. For 0.16 mm and 100 MPa, the liquid phase penetration is much longer than the lift-off length, suggesting the interaction between fuel vaporization and combustion zone. Since the rich reaction zone has been believed to occur downstream of the lift-off length, the relatively cool core in the central region of the spray will penetrate beyond the lift-off length and will have a pronounced...
The increased injection pressure and decreased nozzle hole diameter promote the gas entrainment process, resulting in a longer flame lift-off length. At the same time, the interaction between fuel vaporization and combustion processes is reduced. The combination of the two above effects may have a great influence on reducing soot formation in Diesel jet flames.

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REFERENCES