Spray and Ignition Characteristics of Dimethyl Ether Injected by a D.I. Diesel Injector

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ABSTRACT

Experiments were performed to establish the spray and ignition characteristics of dimethyl ether (DME) injected by a D.I. Diesel injector into a high-pressure, high-temperature vessel. The results clarified the differences between the DME and a conventional Diesel fuel in the spray characteristics such as spray tip penetration, spray angle and volume of the spray. A very wide spray angle was observed for the DME as compared with the conventional Diesel fuel, especially under a low ambient pressure. A non-luminous flame was observed in the ignition process of the DME spray. The ignition delay for the DME spray was almost the same as the Diesel fuel spray under a high ambient pressure, whereas under a low ambient pressure, the ignition delay for the DME spray was shorter than for the Diesel fuel spray.

INTRODUCTION

Simultaneous reduction of both particulate and NOx emissions from a Diesel engine only by modifying the fuel injection characteristics, the intake air motion and the combustion chamber shape is difficult. It was reported, however, that use of an oxygenated fuel easily reduced the NOx and particulate emissions from the Diesel engine (1). Among the oxygenated fuels, DME attracts attention as an alternate fuel for the Diesel engine since know-how development has been made of the mass production of DME from a natural gas, and the properties of DME are fitted to the Diesel engine combustion (2). Recent studies (3-6) also have shown that the use of DME has a great advantage in the simultaneous reduction of NOx, particulate and noise emissions from the D.I. Diesel engine. The changes of such exhaust emissions are supposed to be due to the spray properties, ignition and combustion characteristics of the DME spray, which are different from those of conventional Diesel fuel sprays.

Table 1 shows the properties of the DME and the Diesel fuel which affect the spray, ignition and combustion characteristics in the Diesel engine. The DME has features especially as shown here following:

1. The DME contains 34.8 wt% of oxygen.
2. The cetane number of the DME is higher than the Diesel fuel.
3. The DME becomes a vapor when the pressure is lower than 0.51 MPa at room temperatures.
4. The heat of combustion of the DME is lower than the Diesel fuel (about 68 % of the Diesel fuel).

It is considered that the high vapor pressure of the DME influences the spray characteristics due to the flush boiling in the fuel injection process. As shown in Fig. 1, when the DME with the pressure of Pvo, valve opening pressure of the injector, is injected into a low ambient pressure such as Pao=0.1 MPa, the pressure of the DME falls below the saturated vapor pressure, and the flush boiling occurs. Besides this, in the low pressure regions in the nozzle sac chamber and the hole inside the injector, cavitation in the DME flow occurs more easily than in the Diesel fuel flow. Such a cavitation flow including vapor bubbles enhances the atomization and influences the properties of the DME spray. It is also considered that, besides the physical property of the DME affecting the spray characteristics, the chemical property, such as the high oxygen content, results in the low formation and the high oxidation of the particulate during the combustion.

However, the above mentioned characteristics of the spray, the ignition and the combustion of the DME in the Diesel

<table>
<thead>
<tr>
<th>Fuel Property</th>
<th>DME</th>
<th>Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Formula</td>
<td>CH₃OCH₃</td>
<td>-</td>
</tr>
<tr>
<td>Molecular Weight</td>
<td>46.07%</td>
<td>-</td>
</tr>
<tr>
<td>Density of Liquid (kg/m³) at 293K</td>
<td>668</td>
<td>840</td>
</tr>
<tr>
<td>Carbon Content (wt%)</td>
<td>52.2</td>
<td>87</td>
</tr>
<tr>
<td>Hydrogen Content (wt%)</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Oxygen Content (wt%)</td>
<td>34.8</td>
<td>0</td>
</tr>
<tr>
<td>Solubility in H₂O (g/m³) at 293K</td>
<td>70000</td>
<td>-</td>
</tr>
<tr>
<td>Melting Point (K)</td>
<td>134.5</td>
<td>-</td>
</tr>
<tr>
<td>Boiling Point (K)</td>
<td>248.1</td>
<td>453-633</td>
</tr>
<tr>
<td>Vapor Pressure (MPa) at 293K</td>
<td>0.51</td>
<td>-</td>
</tr>
<tr>
<td>Heat of Vaporization (kJ/kg) at 293K</td>
<td>410</td>
<td>-</td>
</tr>
<tr>
<td>Heat of Combustion (MJ/kg)</td>
<td>29.8</td>
<td>43.5</td>
</tr>
<tr>
<td>Critical Pressure (MPa)</td>
<td>5.37</td>
<td>-</td>
</tr>
<tr>
<td>Critical Temperature (K)</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>Stoichiometric A/F Ratio</td>
<td>9</td>
<td>14.6</td>
</tr>
<tr>
<td>Autoignition Temperature (K)</td>
<td>508</td>
<td>523</td>
</tr>
<tr>
<td>Explosion Limits, Gas in Air (vol%)</td>
<td>3~17</td>
<td>0.6~7.5</td>
</tr>
<tr>
<td>Cetane No.</td>
<td>&gt;&gt;55</td>
<td>38~53</td>
</tr>
</tbody>
</table>
mm in length. Two quartz glass windows were attached to both sides of the vessel for optical access. Air was supplied by a compressor and was heated by an electric heater installed in the vessel. The DME or the Diesel fuel was supplied to a conventional, in-line type Bosch injection pump for the D.I. Diesel engine from a DME bomb or a Diesel fuel tank, respectively. The plunger diameter of the injection pump was 8 mm. The injection nozzle was single hole nozzle with hole diameter of 0.2 mm and a hole length of 0.8 mm. Single fuel injection was made by controlling the rack position of the injection pump with an electromagnetic solenoid. The valve opening pressure of the injection nozzle was set to 9.8 MPa for the both DME and Diesel fuel injections. The injection line pressure and the needle lift of the nozzle were measured and recorded by an oscilloscope. The signal of the injection line pressure was sent to a delay pulse generator and the delayed pulse signal was used as a trigger for firing a pulsed YAG laser and opening the shutter of a digital still camera. A schlieren optical system was adopted for visualizing the DME spray, which has a very high volatility as compared with the Diesel fuel. A YAG laser light with a wave length of 532 nm was used as the light source. The light from the YAG laser was collimated by a concave mirror, passed through the spray in the vessel, and focused by a concave mirror. A ring edge with a diameter of 4 mm was used as a schlieren stop and was set at the focal point of the concave mirror.

The ignition processes of the DME and Diesel fuel sprays were observed by the schlieren optical system as shown in Fig. 2, where a xenon lamp was used as the light source instead of the YAG laser, and a high-speed video camera was used instead of the digital still camera. The frame speed of the video camera was 9,000 frames per second. The ignition delay of the spray was measured by using the photo-sensor which had a sensitivity in the wavelength range from visible to ultraviolet.

When the observation of the spray was made, the ambient air temperature was room temperature and the pressure was set to 1.5 MPa, whose density was almost the same as the air density in the combustion chamber at the fuel injection timing of the D.I. Diesel engine. Also the observation of the spray was made under an ambient air pressure of 0.1 MPa for the comparison. When the ignition delay of the spray was measured, the ambient air temperature and pressure varied from 723 K to 873 K and from 1.1 MPa to 4.1 MPa, respectively.

**SCHLIEREN PHOTOGRAPHS OF THE DME AND DIESEL FUEL SPRAYS**

Figure 3 shows schlieren photographs of the DME and Diesel fuel sprays injected into room temperature air with pressures of $P_a=1.5$ MPa and 0.1 MPa. The time from the start of injection was around $t=1.0$ ms for the ambient pressure of $P_a=0.1$ MPa and $t=2.5$ ms for $P_a=1.5$ MPa. In the schlieren optical system using the ring edge, the background light around the spray, which was not scattered or refracted by the spray, was intercepted by the ring edge. Thus, the background around the spray is seen as dark in the photograph. The central portion along the spray axis is also seen to be dark since the attenuation of the incident light was large due to the high number density of the spray drops. Peripheral portions of the spray are seen bright
since the incident light scattered by the drops and refracted by the vapor reached the camera beyond the ring edge. Thus, the bright regions in the peripheral portions of the spray are supposedly the region with a low number density of the drops in the case of the Diesel fuel spray and, in the case of the DME spray, the region with the vapor as well as the drops.

In the DME spray under $P_a=0.1$ MPa shown in Fig. 3 (b), several rugged clusters on a relatively large scale are seen at the bright peripheral region of the spray. These clusters are considered to be the vapor cloud. On the other hand, in the Diesel fuel spray under $P_a=0.1$ MPa, the drops are scratched by the ambient air and the tree branch structure is seen in the bright peripheral region of the spray. The spread of the DME spray is large and independent of the ambient pressure. However, the spread of the Diesel fuel spray depends on the ambient pressure; the spread of the Diesel fuel spray is larger under $P_a=1.5$ MPa than that under $P_a=0.1$ MPa. It is considered that the large spread of the DME spray under $P_a=0.1$ MPa is due to the enhancement of the atomization by the flush boiling and the expansion of the spray volume by the vaporization of DME.

TIP PENETRATION, SPRAY ANGLE AND SPRAY VOLUME

Figures 4, 5 and 6 show comparisons of the tip penetration, spray angle and spray volume between the DME and Diesel fuel sprays. In each figure, (a) and (b) show the results under $P_a=1.5$ MPa and 0.1 MPa, respectively. Figure 4 shows the temporal variation of the spray tip penetration. The tip penetration of the DME spray is a little smaller than or almost the same as that of the Diesel fuel spray. Both tip penetrations of the DME and Diesel fuel sprays are shorter under $P_a=1.5$ MPa than those under $P_a=0.1$ MPa.

Variations of the spray angle with the spray tip penetration are shown in Fig. 5. The spray angle was defined as the angle between the two lines connecting the nozzle tip and two peripheral points of the spray at 10 mm from the nozzle tip. The spray angles of the DME and the Diesel fuel are almost the same under $P_a=1.5$ MPa, whereas under $P_a=0.1$ MPa the spray angle of the DME is much larger than that of the Diesel fuel. The comparison of the spray angle between $P_a=1.5$ MPa and $P_a=0.1$ MPa indicates that the spray angle of the DME increases as the ambient pressure decreases; however the spray angle of the Diesel fuel shows a change contrary to the DME spray with the ambient pressure.

Figure 6 shows variations of the spray volume with the spray tip penetration. As is similar to the spray angle, the spray volumes of the DME and the Diesel fuel are almost the same under $P_a=1.5$ MPa, whereas under $P_a=0.1$ MPa, the spray volume of the DME is much larger than that of the Diesel fuel. The spray volume of the DME increases a little as the ambient pressure decreases from $P_a=1.5$ MPa to 0.1 MPa. However the spray volume of the Diesel fuel decreases a lot as the ambient pressure decreases.

It is considered that the differences of the DME spray from the Diesel fuel spray in the changes of the spray angle and the spray volume with the ambient pressure are mainly due to the enhancement of atomization by the flush boiling as well as the expansion of the spray volume by the vaporization of the fuel, especially under low ambient pressures.

IGNITION CHARACTERISTICS

Figures 7 (a) and (b) show schlieren photographs of the ignition processes of the DME spray and the Diesel fuel spray, respectively. The ambient air temperature and pressure are $P_a=3.1$ MPa and $T_a=823$ K. The DME spray ignites at $t=2.6$ ms after the start of injection. The first ignition occurs around
Fig. 4 Temporal variations of spray tip penetration of DME and diesel fuel

Fig. 5 Variations of spray angle of DME and diesel fuel with spray tip penetration

Fig. 6 Variations of spray volume of DME and diesel fuel with spray tip penetration
the middle portion of the spray, and then the flame spreads mainly in the downstream direction of the spray. The flame is non-luminous and light emission from the flame is very weak. The ignition of the Diesel fuel spray occurs almost at the same time after the start of injection and at the same location as those of the DME spray. However, the flame is luminous and the light emission from the flame is much stronger than the DME spray.

Figures 8 (a) and (b) show the Arrhenius expression of the ignition delay of the DME and Diesel fuel sprays. The ordinate is the logarithmic ignition delay and the abscissa is the ambient temperature.
reciprocal ambient air temperature. The ambient pressure was varied from \( P_a = 1.1 \) MPa to 4.1 MPa. The DME sprays under ambient pressures of \( P_a = 4.1 \) MPa and 3.1 MPa have almost the same variation of the ignition delay with the ambient temperature. The Diesel fuel sprays under \( P_a = 4.1 \) MPa and 3.1 MPa have almost the same variation of the ignition delay as those of the DME spray. However the DME spray can not be ignited around the reciprocal temperature of \( 1/T_a = 1.4 \) (\( T_a = 714 \) K), whereas the Diesel fuel spray can be ignited. This is supposedly due to the difference in the amount of fuel injected, that is, the amount of fuel injected for the DME spray is much smaller than that of the Diesel fuel spray. Under the lower ambient pressures of \( P_a = 2.1 \) MPa and 1.1 MPa, the ignition delay of the DME spray becomes shorter than that of the Diesel fuel spray. Under \( P_a = 1.1 \) MPa, the DME spray can be ignited around \( 1/T_a = 1.3 \) (\( T_a = 770 \) K), whereas the Diesel fuel can not be ignited. It can be considered that shorter ignition delay of the DME spray than that of the Diesel fuel spray especially under a low ambient air pressure is closely related to the improvement of the spray properties such as the spray angle and the spray volume as compared with those of the Diesel fuel spray under a low ambient air pressure.

CONCLUSIONS

Experiments were performed to determine the spray and ignition characteristics of dimethyl ether (DME) injected through a D.I. Diesel injection system into a high-pressure, high-temperature vessel. The main results are summarized as follows:

(1) The spray angles of the DME and the Diesel fuel are almost the same under high ambient pressures, whereas under low ambient pressures, the spray angle of the DME is much larger than that of the Diesel fuel. The spray angle of the DME increases as the ambient pressure decreases; however the spray angle of the Diesel fuel shows a change contrary to the DME spray with the ambient pressure.

(2) The spray volume shows almost the same variation as the spray angle when the fuel and the ambient pressure are changed.

(3) A non-luminous flame is observed in the ignition process of the DME spray.

(4) The ignition delay of the DME spray is almost the same as that of the Diesel fuel spray under a high ambient pressure, whereas under a low ambient pressure, the ignition delay of the DME spray is shorter than that of the Diesel fuel spray.

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REFERENCES