An Experimental Study on DME Spray Characteristics by Using Schlieren Optical Systems

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1. INTRODUCTION

Dimethyl Ether (DME) is a promising alternative fuel suitable for compression ignition engines. The DME engine has the potential to solve the problems caused by the diesel engine's emissions of soot and NOx. Furthermore, engine performance is expected to be nearly equal to that of the diesel engine both in thermal efficiency and power output. It has been proved in some demonstration projects that the DME engine can meet the strictest current emission regulations for diesel engines.

The properties of DME are quite different from those of diesel fuel as shown in Table 1. Because of the low boiling point (249K) and the high vapor pressure, DME evaporates much more quickly than diesel fuel does. Therefore, the DME engine does not require very high injection pressures. On the other hand, since both the energy and mass densities of DME are lower than those of diesel fuel, approximately 1.8 times the volumetric quantity is required for the same fuel energy. This means that the flow area of a DME injector needs to be increased to meet the requirement of engine power. For the reasons mentioned above, the DME injection spray and evaporating process behaviors are predicted to be different from diesel fuel. Understanding the characteristics of DME spray and evaporating processes are very important for developing efficient and low emission DME engines optimized in fuel injection control and combustion processes. In this study, the DME spray characteristics and evaporating processes were investigated using the SCHLIEREN optical system and single-hole injectors in a constant volume chamber at room temperature. The photographs taken by using a high-speed video camera under different conditions were compared and analyzed.

Table 1. Comparison of fuel properties.

Fuel Property	DME	Diesel
Chemical Formula	CH_3OCH_3	$(C_{16}H_{34})$
C (wt.%)	52.2	85
H (wt.%)	13	15
O (wt.%)	34.8	0
Density of Liquid (kg/m^3)	668	840
Stoichiometric A/F Ratio	9.0	14.6
Boiling Point (K)	249	453-644
Lower Calorific Value (MJ/kg)	28.8	42.7
Cetane Number	>55	38-53
Vapor Pressure [293K] (kPa)	530	-
Auto Ignition Temperature (K)	508	523
Kin. Viscosity (cSt)	0.25	2.5/3.0

2. EXPERIMENTAL APPARATUS

Figure 1 illustrates the schematic diagram of the experimental apparatus (except the optical system). A common-rail fuel supply system was used in this experiment. Liquid DME from a special tank was pressurized by a high pressure pump driven by using compressed air. Diesel fuel was supplied by a high pressure diesel pump. The pressure in the common-rail was adjusted with a regulator. An electromagnetic DME injector was employed. The fuel pressure and temperature were measured at the inlet of the injector. The high-pressure constant volume chamber has two quartz glass windows for optical access. Nitrogen gas was used to pressurize the chamber pressure which could be adjusted from ambient value to 10MPa.

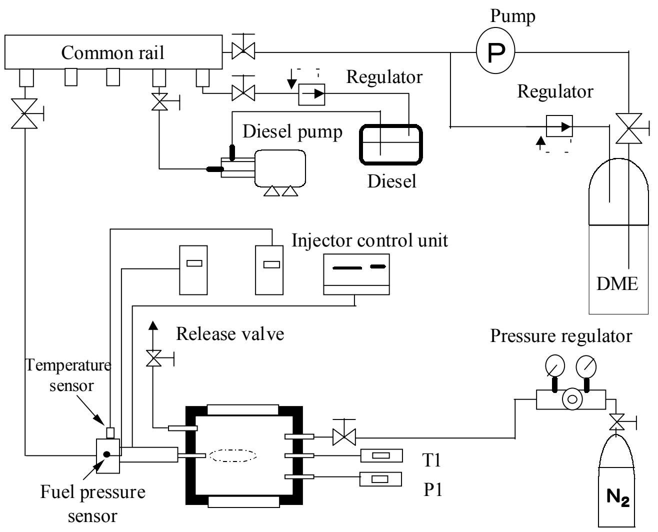


Figure 1. Experimental apparatus.

A double-pass optical system was used as shown schematically in Figure 2. The light from a 500W halide light source passed through a pair of objectives to produce an expanding cone of light. A pinhole spatial filter was placed at the focal point to improve the beam quality. The expanding beam passed through a lens, positioned such that its focal point is at the pinhole, to produce a collimated beam. The solid lines represent the light beam traveling toward the high-pressure chamber. After passing through the chamber, the light beam was reflected by a mirror and is focused by the same lens which collimated the beam (indicated by broken lines). A beam splitter was used to separate the returning beam, which contained the image information. A high-speed video camera was placed behind the knife-edge to take SCHLIEREN images of the spray.

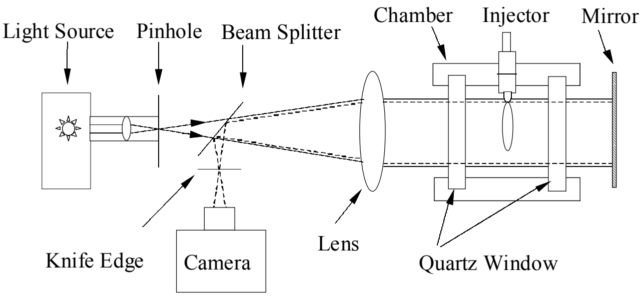
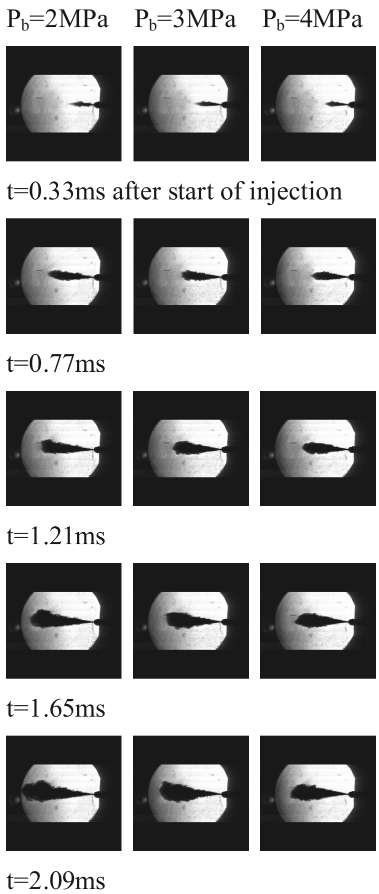
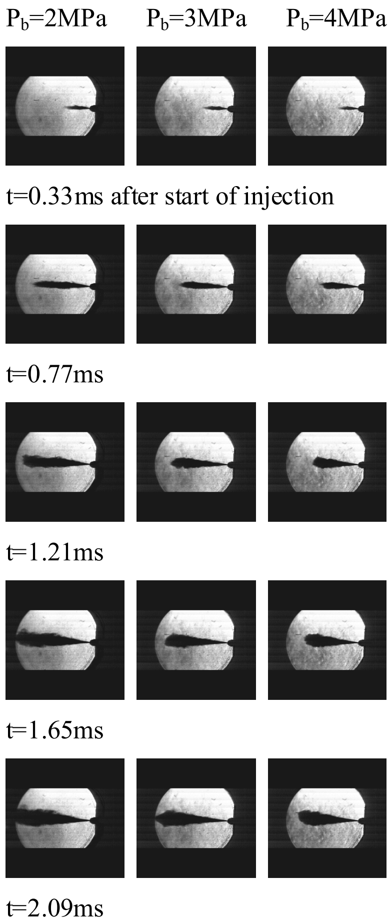


Figure 2. Schematic diagram of the optical system.



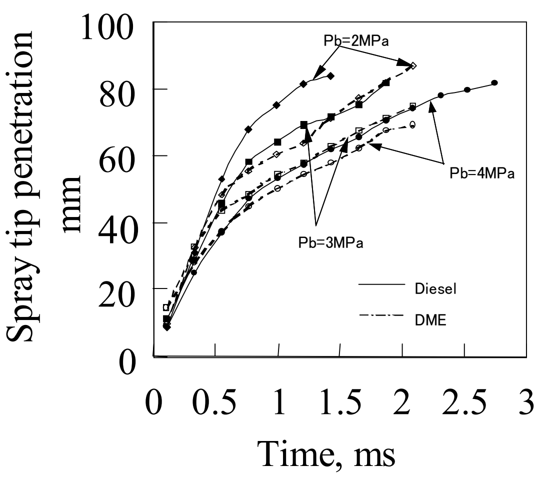
DME



Diesel

Pf=16MPa, Q=72mm^3/str, dn=0.5mm

Figure 3. Photographs of spray at different chamber pressures.



Pf=16MPa, Q=72mm^3/str, dn=0.5mm

Figure 4. Spray tip penetrations

3. DME SPRAY CHARACTERISTICS

3.1. GENERAL CHARACTERISTICS

The experiments were conducted at room temperature 293K under different chamber pressures. DME and diesel fuel were injected into the constant volume chamber filled with quiescent nitrogen gas. The fuel injection pressure was 16MPa. The injection quantity was 72mm^3/str. Ten (10) mm^3/str was used for the comparison of the evaporating processes. The single-hole nozzle with an orifice diameter of 0.5mm and a length of 2.45mm was used for the experiments. The images were taken at a camera speed of 9000FPS.

Figure 3 to Figure 5 show the photographs and curves of the spray development with time at different chamber pressures for both the fuels.

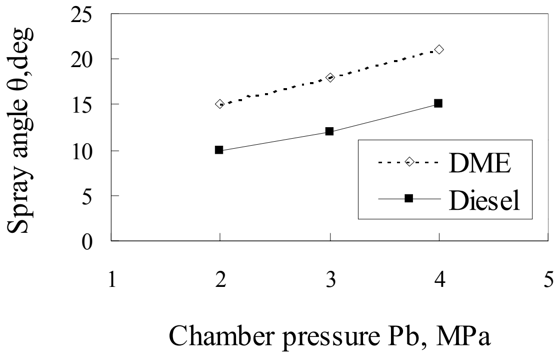


Figure 5. Spray angle.

DME spray tip penetrations decreased and spray angles increased with the increase in chamber pressure, which were similar to the changing trends of the diesel spray. However, under the same condition, the spray tip penetration of DME was shorter and spray angle was wider than that of diesel fuel, Moreover, the differences between the two fuels decreased with the chamber pressure increase.

With the development of the DME spray, the volume at the front of the spray increased rapidly. The spray angle of the tail remained nearly constant. The shape of diesel spray was thin and long compared to the DME spray.

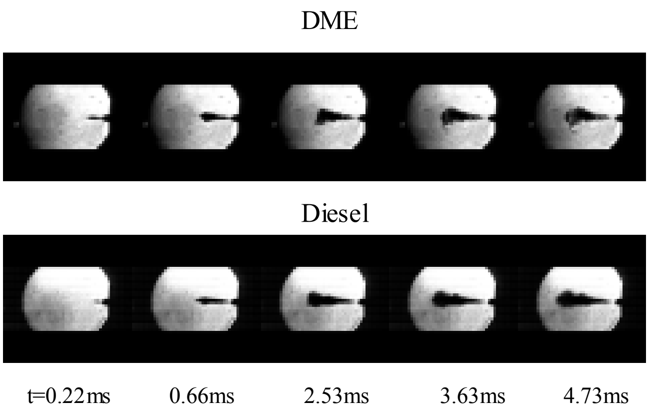


Figure 6. Comparison of evaporating processes

Due to its low boiling point and low viscosity, DME spray had a shorter breakup time (0.3ms to 0.5ms) than the diesel spray (0.5 ms to 0.7ms). The evaporating processes of the DME were more rapid than that of diesel fuel. In the conditions shown in Figure 6 at 4.73ms after the start of injection, the DME spray evaporated and mixed with ambient gas almost completely. The diesel spray, however, still had a clear liquid core.

3.2 INFLUENCE OF INJECTION QUANTITY

To investigate the influence of the injection quantity, the experiments were conducted with four injection quantities of 10 mm^3/str., 20mm^3/str., 58 mm^3/str. and 72mm^3/str. The injection and chamber pressure were 16MPa and 4MPa respectively. The orifice diameter of the nozzle was 0.5mm and the length/diameter ratio was 4.9. The results are shown in Figure 7.

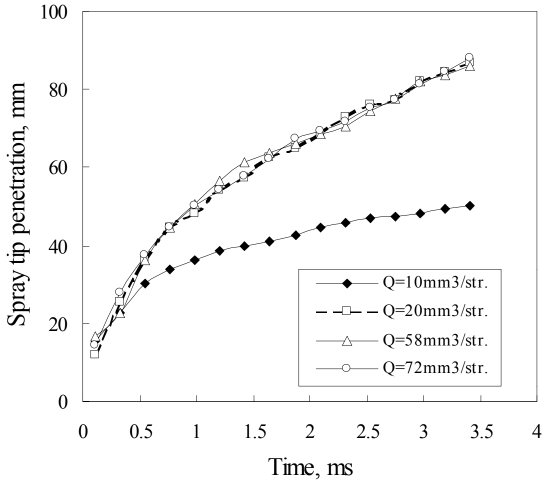


Figure 7. Spray tip penetrations of DME at different injection quantities.

When injection quantities are over a certain value, spray tip penetrations were unaffected by the injection quantity, but the spray shapes had some differences in the later stage of the spray development. The front of the spray at the large injection quantity was wider than at the small one. This difference is due to greater liquid fuel accumulation and evaporation at the top of the spray. When the injection quantity was very small such as 10 mm^3/str**,** the spray tip penetration was quite different from the normal one. Because the evaporation of DME is very quick, most of the liquid evaporated and mixed with ambient gas within a short time. Consequently, the spray penetration speed decreased markedly.

3.3 INFLUENCE OF INJECTION PRESSURE

Since DME evaporates very quickly, it is thought that the injection pressure of DME need not be as high as that of diesel fuel. In this experiment, the DME sprays at injection pressures of 16MPa, 13MPa and 10MPa were compared. As shown in Figure 8, the spray tip penetrations decreased with the decrease of the injection pressure. The initial spray angles at the three injection pressures were almost the same. With the decrease of injection pressure, the spray became unsteady. In the later stage of the spray development, the higher the injection pressure, the wider the head of the spray. The reason was that with the increase of injection pressure, the jet velocity increased, which caused the penetration of spray to increase and the drop size to decrease. Thereby, the surface area of the spray and of the total fuel drops increased, which promoted the more rapid spray evaporation. As there is more DME fuel accumulating and evaporating at the front of the spray, a spray cap was formed at the top of DME spray.

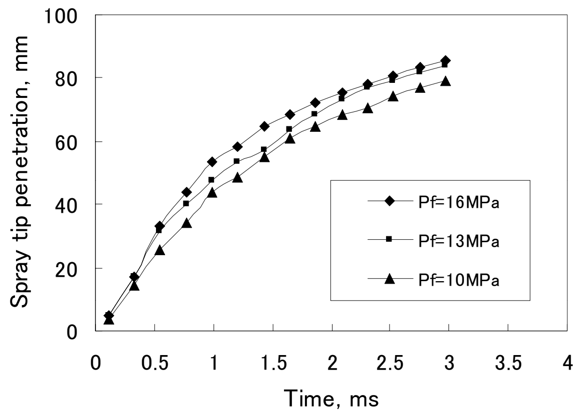


Figure 8. Spray tip penetrations of DME at different injection pressures.

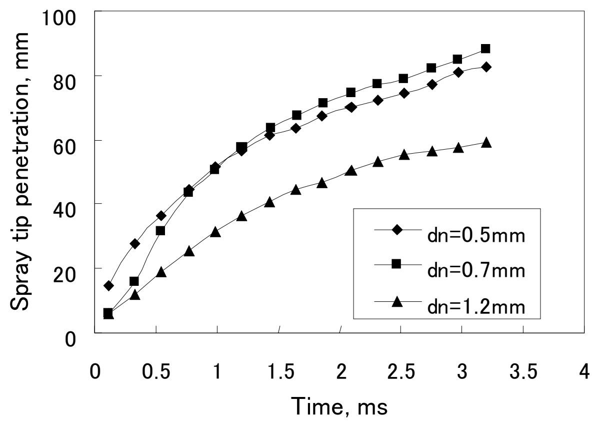


Figure 9. Spray tip penetrations of DME fuel at different orifice diameters.

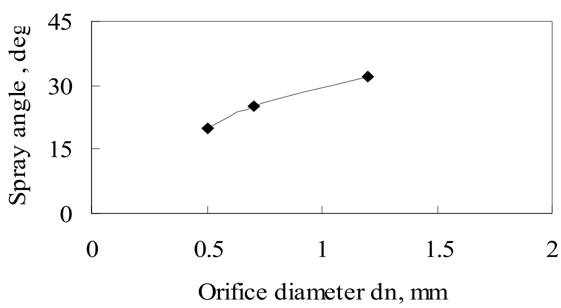


Figure 10. Spray angles of DME at different orifice diameters.

3.4 INFLUENCE OF ORIFICE DIAMETER

Both the mass and energy densities of DME are lower than that of diesel fuel. To get the same engine power output, the injection quantity must be increased. In order to keep short injection duration, the injector orifice diameter was usually increased. In this experiment, three nozzles with orifice diameters of 0.5mm, 0.7mm and 1.2mm were used. The results are shown in Figure 9.

When the orifice diameter of the nozzle was changed from 0.5mm to 0.7mm, the spray tip penetration increased at the middle and later stages of injection, and the spray angle increased too. However, in the early stage of injection, the penetration of the 0.7mm nozzle was shorter than that of the 0.5mm one. The reason is that when the needle lift was small, the flow area between the needle and nozzle was not enough to meet the requirement of the 0.7mm orifice. Therefore, the pressure drop across the nozzle had some decrease, which caused the spray penetration to decrease. With the diameter 1.2mm orifice, the spray penetration decreased markedly and the spray was not steady. This is because the orifice diameter was so large that the flow area between needle and nozzle was not suitable for the nozzle orifice.

3.5 COMPARISON OF SPRAY PENETRATIONS AT THE TIME OF IGNITION START

The penetration of spray at the time of ignition start is very important to the processes of mixture formation and combustion. According to the authors' experimental results in a single cylinder DI engine, when the injection quantity of diesel fuel was 40 mm^3/str. and engine speed was 1280 r/min, the time of ignition delay was 1.04ms, but at the same speed and power output of engine, the ignition delay of DME was 0.455ms. The penetrations of spray at the time of ignition start in different conditions are shown in Figure 11.

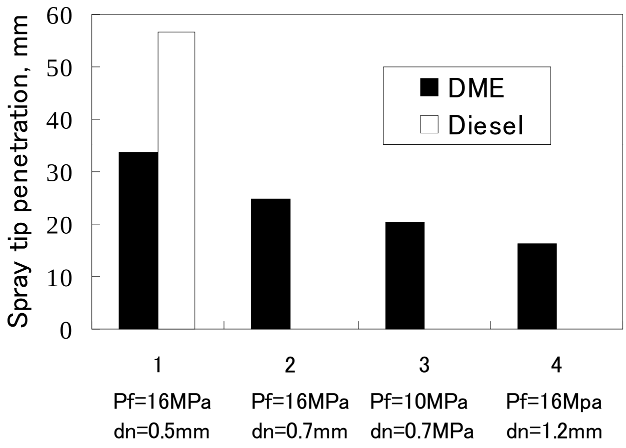


Figure 11. Spray penetrations at the time of ignition start.

The spray penetrations of DME were about half that of diesel fuel. The short spray penetrations of DME will result in poor air utilization since the air on the periphery of the chamber does not contact the fuel. Although DME evaporates very quickly, small penetration and short ignition delay will neutralize the advantages and result in an increasing trend of CO emission. For this reason, it is very important to optimize the shape of the combustion chamber, the pattern of intake air and the parameters of fuel injection to suit the DME spray characteristics.

4. CONCLUSIONS

- DME spray has the similar changing trends to the diesel spray with the variation of chamber pressure. However, the spray tip penetration of DME is shorter and spray angle is wider than that of diesel spray, moreover, the differences between the two fuels decrease with the increase in chamber pressure

- DME spray has a shorter breakup time of 0.3ms to 0.5ms and much more rapid evaporating processes than diesel spray.

- The spray tip penetrations of DME are almost unaffected by the injection quantities when the injection quantities were over a certain value, but some differences exist in the spray shapes in the later stage of spray development. When the injection quantity is very small**,** the spray tip penetration is much shorter than that at large injection quantity.

- The spray tip penetrations decrease and become unsteady with the decrease of injection pressure. In the later stage of spray development, the higher the injection pressure, the wider the front of the spray.

- The spray tip penetration and the spray angle increased with the increase of orifice diameter.

- The spray penetration of DME at ignition start is about half that of diesel fuel. The short spray penetrations will result in poor air utilization. Although DME evaporates very quickly, small penetration and short ignition delay will neutralize the advantages and result in an increasing trend of CO emission. For this reason, it is very important to optimize the shape of combustion chamber, the pattern of intake air and the parameters of fuel injection to suit the DME spray characteristics.

5. REFERENCES

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6. SYMBOLS

P_b : Pressure in the chamber

P_f : Fuel injection pressure

t : Time after start of injection

L_n : Orifice length of nozzle

d_n : Orifice diameter of nozzle

Q : Injection quantity

str : Stroke

θ : Spray angle