Dimethyl Ether (DME) Spray Characteristics in Common-Rail High Pressure Injection System

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ABSTRACT

Dimethyl Ether (DME) has been considered one of the most attractive fuels for compression ignition engine. Its main advantage in compression-ignition engine application is high efficiency of diesel cycle with soot free combustion though conventional fuel injection system has to be modified due to the intrinsic properties of the DME. Experimental study of the DME and conventional diesel spray employing a common-rail type fuel injection system with a sac type injector was performed in a constant volume vessel pressurized by nitrogen gas. A CCD camera was employed to capture time series of Mie-scattered spray images, so that spray cone angles and penetrations of the DME spray were characterized and compared with those of diesel. For evaluation of the evaporation characteristics, shadowgraphy employing an Ar-ion laser and an ICCD camera was adopted, in conjunction with Mie-scattered single hole spray imaging technique. Tip of the DME spray was formed in mushroom like shape at atmospheric condition, which disappeared in higher chamber pressure. On the contrary, spray characteristics of the DME became similar to diesel under higher ambient pressure, 3MPa in this study. Evaporating spray characteristics of the DME was investigated with different injection pressures in the atmospheric and 3 MPa chamber pressure conditions. Higher injection pressure produced wider vapor phase area while it decreased with higher chamber pressure condition.

INTRODUCTION

Emission substances generated from compression ignition engine, mainly PM and NOx make serious environmental problem and especially CO_2 has been noticed as a growing target to be reduced due to tightening emission requirements. The difficulties to simultaneously reduce the emission levels of both soot and NOx have introduced Dimethyl Ether (DME) that has been nominated as a potential alternative fuel due to no carbon-carbon bond and oxygen-contents [1-3]. The DME has been adopted as an additive for ignition improvement in alcoholic fuel due to its excellent auto-ignition characteristics and many attempts have been made to utilize it in diesel engine. Main advantages of the DME are similar order of cetane number as diesel, high oxygen content (34.8 %) with generating low particulate matter and low noise level during engine operation compared to diesel [3-6]. However, it is in gaseous phase at room temperature and pressure conditions due to high vapor pressure, therefore requires a pressurizing system. More compression pump work for the DME is needed, compared to the diesel, because of its higher compressibility [3, 7]. Adoption of an additive for viscosity enhancement is also necessary as fuel injection system may be damaged without the additive due to the extremely low viscosity of the DME. These drawbacks of the DME have been resolved with employing common-rail injection system and introducing additives for the viscosity enhancement [2, 8, 9]. It has also been suggested that further modification (longer injection duration or bigger nozzle hole size) of the injection system may be required to compensate lower heating value of the DME [10]. CO and HC emission characteristics in compression ignition engine operated with DME have been noticed lower than that with diesel fuel while effect of DME on NOx emission has not been identified yet [2, 7, 11]. EGR (Exhaust Gas Recirculation) method has, therefore, been noticed as an effective way to minimize NOx in DME-operated compression ignition engines [2]. Majority of research on the DME has been focused on either engine performance or emission point of view in DME fuelled engines but spray itself, even if fundamental spray characteristics is strongly linked to them. One of the main characteristics of the DME is evaporating spray, resulting in atomization enhancement and rapid fuel and air mixing. It is therefore of importance to understand fundamental non-evaporating and evaporating spray characteristics of the DME. Aims of this study are to investigate and to understand spray characteristics of the DME and to compare it with diesel in pressurized conditions.

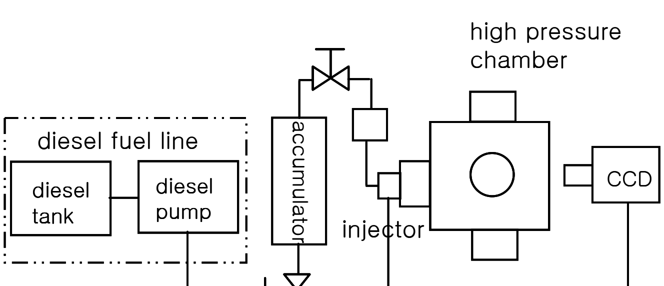
EXPERIMENTAL SETUP

FUEL INJECTION SYSTEM

Fuel injection system employed in this study is a common-rail type and comprises an air driven fuel pump (MS 100, 69 MPa, Haskell Ltd), an accumulator and a back pressure regulator (69 MPa, Tescom Ltd), as shown in Fig. 1. DME fuel was pressurized to 1.5 MPa by nitrogen gas in a storage vessel to keep in liquid phase during compressing it inside the pump. The back pressure regulator maintained pressure of the accumulator (literally same as the injection pressure) at a preset pressure. For diesel spray, identical fuel supply line was adopted but careful handling was engaged to avoid any confusion of mixing of diesel with DME. A five hole sac type commercial common-rail injector (hole diameter 0.168 mm) was adopted and activated with a purpose-built injector driver (TDA 3000H, TEMS Ltd), and the fuels were injected in a rate of 2.5 Hz throughout the study. Lubricity enhancer (Infineum R655) of 500 ppm was added to the neat DME, expecting to minimize any damage of the fuel injection system.

SPRAY IMAGE VISUALISATION SYSTEM

DME and diesel were injected in a constant volume vessel (Max. 7 MPa) having three windows to allow optical access at room temperature condition while nitrogen gas was supplied to pressurize the chamber. Macroscopic spray images were taken with Mie-scattering technique adopting a CCD camera (PCO Sensicam) coupled with a strobe light system. For acquiring the Mie-scattered spray images, the injector was placed horizontally in the chamber and



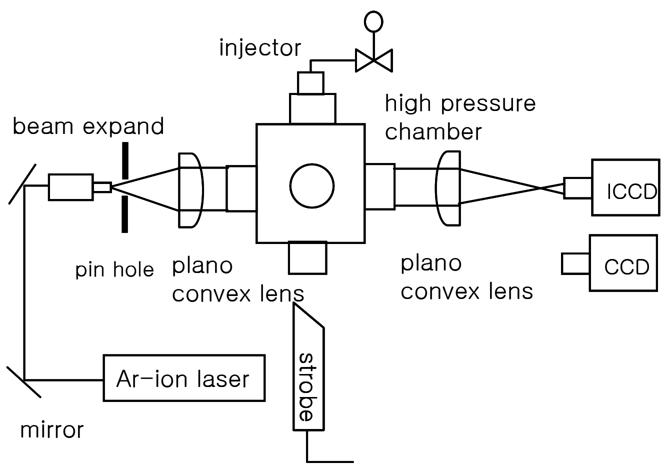
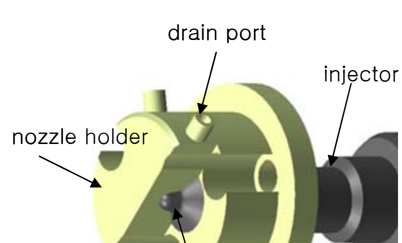


Fig 2. Schematic diagram of single hole spray imaging

the CCD camera viewed the nozzle tip along with positioning the strobe light at right angle of the camera. To investigate evaporation characteristics of the DME, shadowgraphic technique adopting an Ar-ion laser as a light source was employed with a nozzle holder (Fig. 2) ; the nozzle holder was carefully designed and placed on the nozzle tip to allow fuel injected from only one of the five nozzle holes and the fuel discharged from other four holes were drained through four drain ports, as shown in Fig. 3.



The laser beam from the Ar-ion laser system was expanded by a microscope objective lens and passed through a 50 μm diameter pinhole and converged using a plano-convex lens (1000mm of focal length). After passing through the two optical windows of the chamber, the beam catching the shadowgraphic spray image was re-focused by a 300mm focal length of another plano-convex lens. The divergent beam then passed into an ICCD camera (Stanford, 4Quick 05A). To separate the liquid phase of the DME spray from vapor phase, Mie-scattered image was also acquired using the Mie-scattered imaging technique employing the strobe light system and the nozzle holder; the ICCD camera was replaced with the CCD camera and the strobe was placed at the right angle of the camera. The cameras were synchronized with the lightening systems using common-rail injector signals.

RESULTS AND DISCUSSION

In the present study, DME and diesel at three different injection pressures were injected into the chamber at atmospheric and 3 MPa chamber pressures under room temperature condition. Ten spray images were acquired for each injection event and repeatability of the injection-to-injection was evaluated in terms of spray tip penetration prior to spray image processing. It was concluded that the repeatability of injection-to-injection was within 10 %. Start of injection (SOI) was determined as the first appearance of liquid phase fuel at each case.

PRESSURE HISTORY

Shown in Fig. 4 are pressure time history of the DME and diesel in a fuel injection line during injection period at a preset value of 55 MPa injection pressure. The pressure history was detected in the fuel line between the accumulator and the injector using a piezo-resistance type pressure transducer (4067A 2000, range 0 ~ 200 MPa, Kistler Ltd). After the end of an injection event, duration of the pressure oscillation for the DME was longer than that of diesel and amplitude was lower due to high compressibility of the DME, as similar trends were reported with in-line pump system [8, 12]. In the preliminary experiments, pressure fluctuation was evaluated during the period of ready-state injection at injection pressures preset by the back pressure regulator and it was concluded that the fluctuations for the DME and diesel were within ±0.18 MPa and ±0.05 MPa, respectively.

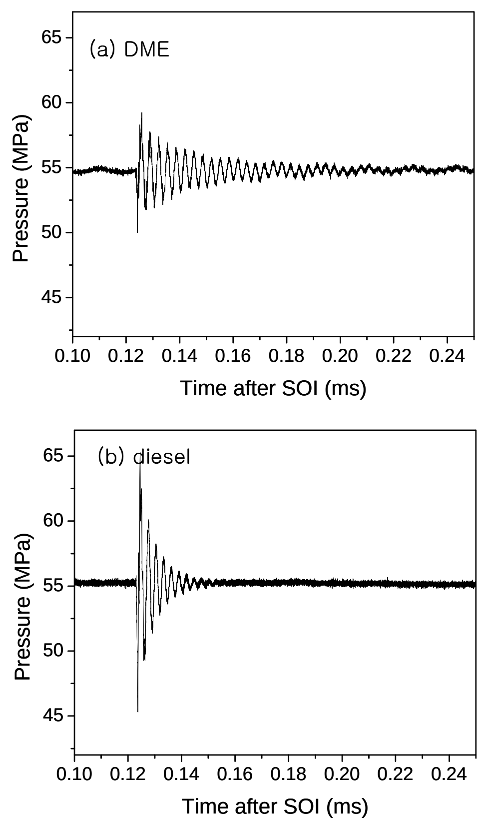


Fig 4. Pressure time history in fuel line at injection pressure 55 MPa

SPRAY TIP PENETRATION

Shown in Fig. 5 is the definition of nozzle hole numbers. Fig. 6 demonstrates spray penetration of the DME and diesel at 55 MPa injection pressure and 3 MPa chamber pressure. As can be seen in Fig. 6, spray tip penetration was similar to that of diesel as the macroscopic behavior of the DME above saturation vapor pressure became liquid-like. Effect of injection pressure on DME spray tip penetration is shown in Fig. 7 ; the results present spray tip penetration averaged by taking mean value of penetrations from the five nozzle holes.

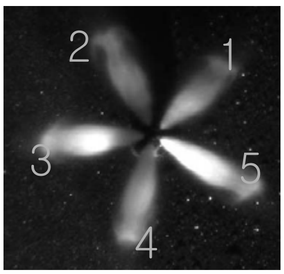


Fig 5. Definition of nozzle hole number

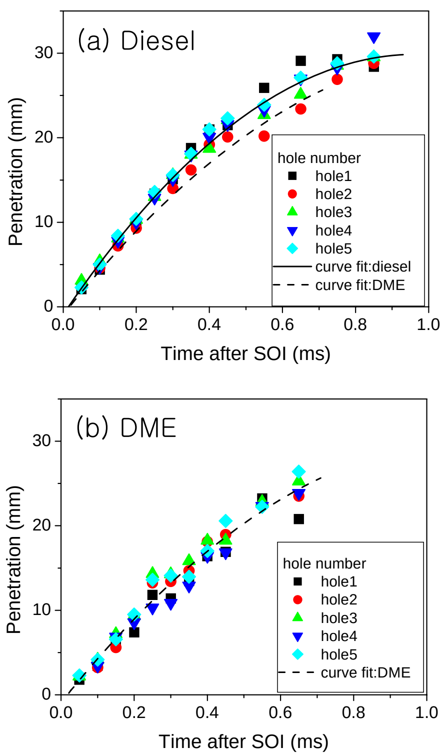
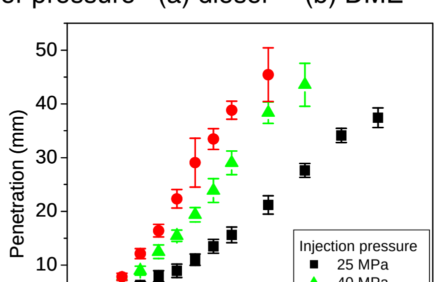


Fig 6. Spray tip penetration of DME and diesel at 55 MPa of injection pressure and 3 MPa chamber pressure (a) diesel (b) DME



As injection pressure increases, regardless of chamber pressure, spray tip penetrations were longer. Spray tip penetration was shortened with higher chamber pressure. In the present work, effect of chamber and injection pressures on DME spray tip penetration was faithfully coincided with trend of well-known diesel macroscopic spray characteristics [13, 14].

SPRAY CONE ANGLE

In general, spray angle has been defined at $60d_o$ (hole diameter). However, for the DME spray injected under atmospheric chamber pressure, the $60d_o$ spray angle was not appropriate as the longitudinal spray dispersion was quite serious and spray boundary had smaller curvature so that two lines to define the spray angle does not follow the spray boundary fairly [15]. Hence, in the present study, spray cone angle was defined near the nozzle tip following the spray boundary from the nozzle, as shown in Fig. 8. In the case of fuel injected into 3 MPa chamber pressure condition with 55 MPa injection pressure, spray cone angles of the DME were similar to those of diesel because of reduced flash boiling effect, as shown in Fig. 9.

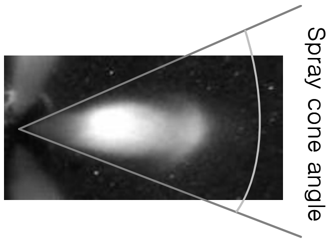


Fig 8. Definition of spray cone angle

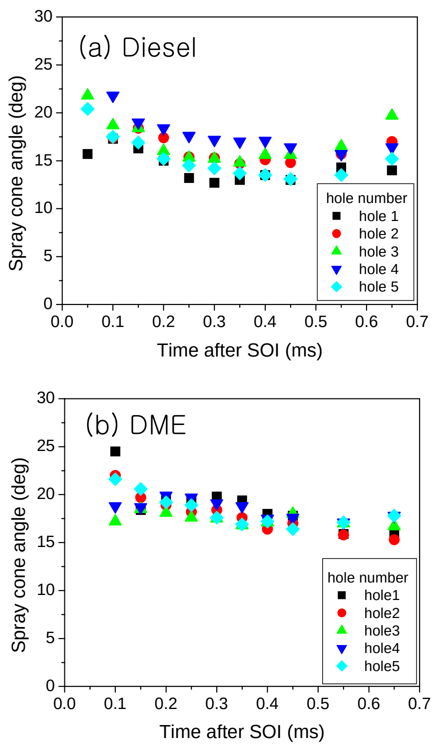
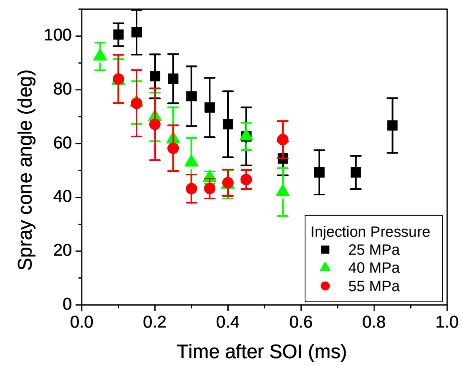
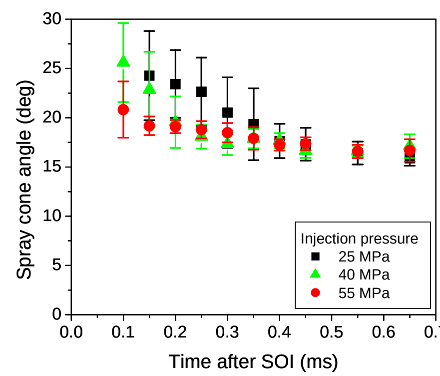


Fig 9. Comparison of spray con angle of DME
with diesel at 55 MPa injection pressure and 3 MPa chamber pressure

Variation of the spray cone angles of each nozzle hole was relatively lower than that of diesel because of the high compressibility of the DME. It might be due to active bubble of the DME formation inside the nozzle [16]. Figure 10 shows the effect of injection pressure on DME spray cone angle. The spray angles were obtained by taking mean value of spray cone angles created from the five nozzle holes. In the case of atmospheric chamber condition, spray cone angle decreased with injection pressure while its contribution was minimal in 3 MPa of chamber pressure. In the case of DME spray atomized into atmospheric chamber pressure condition, initial spray cone angle was large but drastically decreased with time, as shown in Fig. 10 (a).



(a) atmospheric chamber pressure



(b) 3 MPa chamber pressure

Fig 10. Effect of injection pressure on DME spray
cone angle at different chamber pressures
(a) atmospheric chamber pressure

It might be due to the flash boiling atomization occurred in the injection period. As the chamber pressure increased to 3 MPa, however, the spray development became hardly affected by the flash boiling and eventually lead diesel-like (Fig. 10(b)).

EVAPORATION CHARACTERISTICS

Shown in Fig. 11 are Mie-scattered single spray images taken with the nozzle holder at 25 MPa of injection pressure and atmospheric chamber pressure condition and corresponding shadowgraphic images are shown in Fig. 12. Spray tip of the DME in atmospheric chamber pressure formed in mushroom like shape.

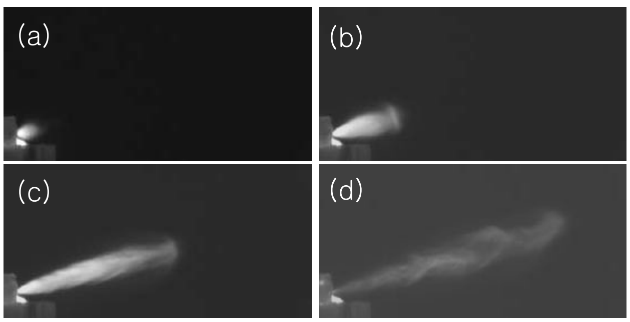


Fig 11. Mie-scattered DME spray images at 25 MP injection pressure under atmospheric chamber pressure
(a) ASOI 0.15 ms (b) ASOI 0.4 ms
(c) ASOI 0.7 ms (d) ASOI 0.9 ms

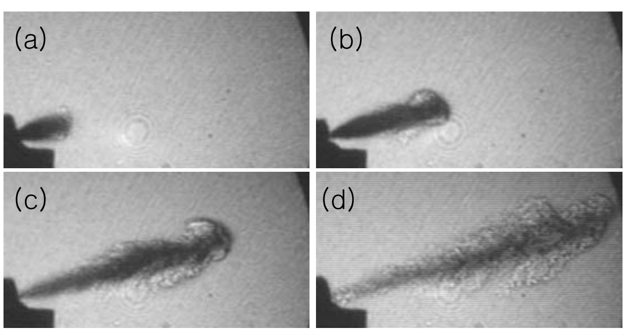


Fig. 12. Shadowgraphic DME spray images at 25 MP injection pressure under atmospheric chamber pressure
(a) ASOI 0.15 ms (b) ASOI 0.4 ms
(c) ASOI 0.7 ms (d) ASOI 0.9 ms

For the DME spray, forming the mushroom shape might be due to the fact that DME spray droplets abruptly evaporated as the highly pressurized DME was discharged into the atmospheric condition from the nozzle inside. Rapid momentum loss of each droplet and shear stress created by interaction with ambient gas resulted in slowing down migration of the droplet and generating vortex ; the DME was rapidly spread both longitudinal and axial directions with being broken into small droplets and evaporated upon being exposed in atmospheric pressure condition [15]. As the chamber pressure increased to 3 MPa (Fig. 14), the mushroom-like

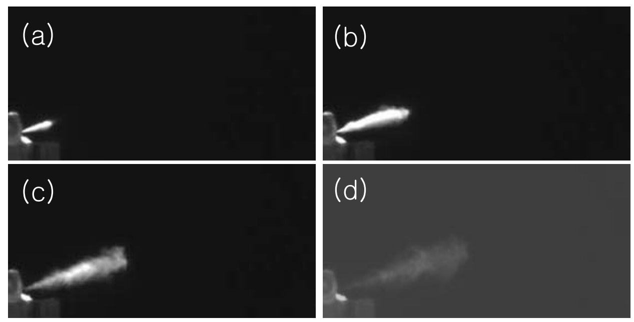


Fig. 13. Mie-scattered DME spray images at 55 MP injection pressure under 3 MPa chamber pressure
(a) ASOI 0.15 ms (b) ASOI 0.35 ms

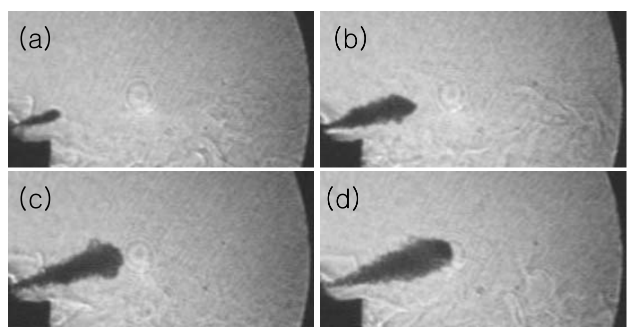
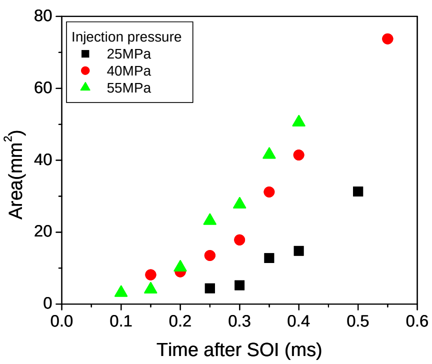


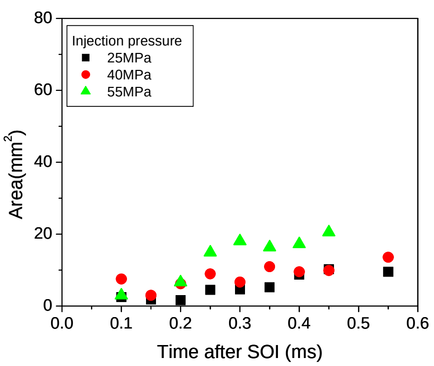
Fig. 14. Shadowgraphic DME spray images at 55 MP injection pressure under 3 MPa chamber pressure
(a) ASOI 0.15 ms (b) ASOI 0.35 ms
(c) ASOI 0.5 ms (d) ASOI 0.6 ms

shape of the DME spray tip disappeared and the DME spray became similar to that of diesel. As can be noticed in the shadowgraphic DME spray images

(Figs. 12 and 14), vapor phase of the DME was dominantly generated in the region of spray edge and downstream rather than upstream as the DME might be well-atomized in the region of spray downstream and edge, implying faster vaporization. It implies that droplets size of the spray at those regions was smaller, therefore resulting in more chance to be ignited [16,17]. The flash boiling effect can also provide better atomization and fuel/air mixing and reduced wall wetting by shortening spray tip penetration [18,19]. In this work, evaporation characteristics of the spray was evaluated in terms of apparent vapor phase area obtained by subtraction of liquid phase spray area from vapor phase spray area.



(a) Atmospheric chamber pressure



(b) 3 MPa chamber pressure

Fig 15. Apparent vapor phase area with injection pressure
(a) atmospheric chamber pressure
(b) 3 MPa chamber pressure

Shown in Figure 15 shows the effect of injection pressure on DME evaporating characteristics at different chamber pressure. As seen in Fig. 15 (a), at atmospheric chamber pressure condition, 40 MPa of injection pressure provided wider vapor phase area than that of 25 MPa but contribution of further higher injection pressure (55 MPa) was minimal. For the case of 3 MPa chamber pressure, the DME was still evaporated and effect of injection pressure on evaporating characteristics appeared similar to that of atmospheric chamber pressure condition though it was lower than that of atmospheric chamber pressure because of increased ambient resistance [20]. It implies that the DME spray could provide better chance to contact with surrounding oxidant than of diesel in an engine cylinder but further investigation would be necessary in more realistic conditions considering temperature effect. It may also imply that higher injection pressure would provide faster and better atomization but it may have limitation (in this study, it might be 40 MPa of injection pressure).

CONCLUSIONS

The study employing a common-rail type fuel injection system demonstrated macroscopic spray characteristics of the DME, compared with those of diesel in a constant volume chamber, and evaporation characteristics of the DME allowing the following conclusions to be drawn.

• Intrinsic spray characteristics of the DME appeared in atmospheric pressure condition, characterized by forming mushroom-like shape of the spray tip and flash boiling, while it became similar to diesel with elevated ambient pressure condition, suggesting that DME spray characteristics could be estimated with well-known diesel data in pressurized conditions.

• Evaporation characteristics was evaluated in terms of apparent vapor phase area ; subtraction of liquid phase spray area from vapor phase, obtained from the Mie-scattered and shadowgraphic single hole spray images, respectively.

• Vapor phase of the DME spray dominantly appeared in the region of spray edge and downstream, suggesting more chance to be ignited there.

• Higher injection pressure produced wider vaporized region, regardless of chamber pressure conditions. DME was still evaporated at 3 MPa though vapor phase area decreased, implying better chance to be mixed and burnt.

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