Dimethyl Ether (DME) Spray Characteristics in a Common-rail Fuel Injection System

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ABSTRACT

Fundamental spray characteristics of DME (Dimethyl Ether) and conventional diesel were investigated in a constant volume vessel pressurized by nitrogen gas. A common-rail fuel injection system was adopted with a sac type injector. DME and diesel were injected into the chamber at two different chamber pressures (atmospheric and 3MPa chamber pressures) and three different injection pressures (25MPa, 40MPa and 55MPa) under room temperature condition. A CCD (Charge Coupled Device) camera was employed to capture time series of 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 of the DME spray using an Ar-ion laser and an ICCD (Intensified Charge Coupled Device) camera was adopted, in conjunction with Mie-scattering imaging technique for single-hole spray. Intermittent hesitating DME spray was observed depending upon injection conditions and might be due to unstable force balance inside the common-rail nozzle during injection period. Macroscopic spray characteristics of the DME in the atmospheric chamber conditions proved intrinsic physical properties of the DME, while became diesel-like under 3MPa ambient pressure. Higher injection pressure produced wider vapour phase area while it decreased with higher chamber pressure conditions.

Keywords : DME (Dimethyl Ether), diesel, common-rail, spray characteristics

LIST OF NOTATION

C_v : coefficient of contraction

d_o : nozzle hole diameter

ΔP : pressure drop across nozzle

S : spray tip penetration

SOE : start of energizing injector solenoid

T_g : ambient gas temperature

t : time elapsed

t_b : break-up time

ρ_ℓ : liquid density

ρ_a : ambient gas density.

θ : half angle of spray cone.

1 INTRODUCTION

Emission substances generated from compression ignition engine, mainly PM (Particulate Matter) and NOx (Nitric oxide and nitrogen dioxide) make serious environmental problems and additionally CO_2 (carbon dioxide) has been noticed as a growing target to be reduced according to tightening emission requirements. The difficulties in simultaneously reducing the emission levels of both soot and NOx have introduced DME, which has been nominated as a potential alternative fuel due to its having no carbon-carbon bond and its oxygen-content [1-3]. The DME has been adopted as an additive for ignition improvement in alcoholic fuel due to its excellent auto-ignition characteristics, so as a result many attempts have now been made to utilize it in diesel engines. Main advantages of the DME compared to diesel are similar order of cetane number, extremely low PM emissions due to high oxygen content (34.8 %) and the low noise level resulting from short ignition delay during engine operation [3-6]. However, since it is in a gaseous phase at room temperature and pressure conditions due to its high vapor pressure, it requires a pressurizing system for the fuel supply. 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 the fuel injection system may be damaged due to the extremely low viscosity of the DME. These drawbacks of the DME have been resolved by employing a 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 (carbon monoxide) and UHC (Unburned Hydrocarbon) emission characteristics in compression ignition engines operated with DME have been recorded as lower than those from diesel fuel, while effect of DME on NOx emissions has not been identified yet [2, 7, 11]. The effect of EGR (Exhaust Gas Recirculation) method has, therefore, been realized as an effective way to minimize NOx in DME-operated compression ignition engines [2].

Majority of research on the DME has focused on either the engine performance or the emissions point of view in DME fuelled engines but not the spray itself, even if fundamental spray characteristics is strongly linked to them. One of the main characteristics of the DME injection is a highly 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 understand spray characteristics of the DME and to compare it with diesel in pressurized conditions.

2 EXPERIMENTAL SETUP

2.1 Fuel injection system

Fuel injection system employed in this study is a common-rail type and comprises an air driven fuel pump (MS 188, 69MPa, Haskel Ltd), an accumulator and a back pressure regulator (69MPa, Tescom Ltd), as shown in Fig. 1. DME fuel was pressurized to 1.5MPa by nitrogen gas in a storage vessel to keep it in the liquid phase before compressing it inside the pump. The back pressure regulator maintained pressure of the accumulator (literally same to the injection pressure) at a preset pressure. An identical fuel supply line was used for diesel fuel injection. 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 2.5Hz throughout the study. Lubricity enhancer (Infineum R655) of 500ppm was added to the neat DME, expecting to minimize any damage of the fuel injection system. The injection rate was measured with so-called Bosch tube method, which is in principle based on hydraulic pulse theorem[12].

2.2 Spray visualization system

DME and diesel were injected in a constant volume vessel having three windows to allow optical access at room temperature condition while nitrogen gas was supplied to pressurize the chamber up to 7MPa. Macroscopic spray images were at first taken with Mie-scattering technique, adopting a CCD camera (PCO Sensicam) coupled with a strobe light system. Microscopic imaging technique using an ICCD camera (Stanford, 4Quick 05A) with nano light illumination, allowing imaging area of 2.1mm X 1.7mm, was also made at limited conditions to implement discussion for the macroscopic spray characteristics. For acquiring the Mie-scattered spray images, the injector was placed horizontally in the chamber and the CCD camera oriented toward the nozzle tip along with positioning the strobe light at right angles to the camera. For microscopic spray imaging, a nozzle holder was purpose-built and placed on the nozzle tip to allow fuel injected into the chamber from only one of the five nozzle holes while the fuel discharged from other four holes was drained through the drain ports. The CCD camera was placed at the position of the strobe light location as used in the macroscopic imaging and then the nano light was sighted through the test section. To investigate evaporation characteristics of the DME, shadowgraphic technique adopting an Ar-ion laser as a light source was employed with the nozzle holder. The laser beam from the Ar-ion laser system was expanded by a microscope objective lens and passed through a 50μm 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 the ICCD camera. To separate the liquid phase of the

DME spray from vapour phase in the image, single hole Mie-scattered image was also acquired; 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 lighting systems using common-rail injector signals.

3 SPRAY TIP PENETRATION MODEL

Many spray tip penetration models have been proposed and evaluated. Hiroyasu and Arai [13] applied two-zone theory that spray comprises liquid jet and gas jet. For a period of injection start to liquid break-up, disintegrating process from liquid column to fine spray was developed along the liquid column so that spray tip penetration (S) can be written in a function of pressure drop across nozzle (ΔP), liquid density (ρ_ℓ) and time elapsed (t).

$$0 < t < t_b, \quad S = 0.39 \left(\frac{2\Delta P}{\rho_\ell}\right)^{0.5} t \tag{1}$$

where break-up time, $t_b = 28.65 \frac{\rho_\ell d_o}{(\rho_a \Delta P)^{0.5}}$; d_o is a nozzle hole diameter and ρ_a is ambient gas density.

After the liquid break-up, spray tip penetration was modeled by ;

$$t_b < t, \quad S = 2.95 \left(\frac{\Delta P}{\rho_a}\right)^{0.25} (d_o t)^{0.5} \tag{2}$$

For limited geometry and injection condition, Dent [14] suggested a model with jet mixing theory considering the ambient temperature effect ;

$$S = 3.07 \left(\frac{294}{T_g}\right)^{0.5} \left(\frac{\Delta P}{\rho_a}\right)^{0.25} (d_o t)^{0.5} \tag{3}$$

where T_g is ambient gas temperature.

Wakuri *et al.* [15] proposed a spray model based on momentum theory that air entrained into fuel produced mixed gas together with fuel droplets for density ratio range, 40~60 ;

$$S = (2C_v)^{0.25} \ (\frac{\Delta P}{\rho_a})^{0.25} \ (\frac{d_o t}{\tan\theta})^{0.5} \qquad (4)$$

where C_v is a coefficient of contraction and θ is a half angle of spray cone.

Atreya *et al.* [16] and Siebers and Naber [17] also suggested their spray tip penetration models but basic form of the models was within boundary of the conventional models ;

$$S = f\,[\,(\frac{\Delta P}{\rho_a})^{0.25}, t^{0.5}, \theta, \text{etc}] \qquad (5)$$

In the current study, Dent's model was chosen to compare with DME spray data.

4 RESULTS AND DISCUSSION

DME and diesel at three different injection pressures (25MPa, 40MPa and 55MPa) were injected into the chamber at atmospheric and 3MPa chamber pressures under room temperature conditions. Ten spray images were acquired for each injection event so that repeatability of the injection-to-injection was evaluated in terms of spray tip penetration prior to spray image processing. It was confirmed that the repeatability of injection-to-injection was within 10% in terms of spray tip penetration. Start of injection (SOI) was determined as the first appearance of liquid phase fuel in the images at each case.

4.1 LINE PRESSURE HISTORY

Shown in Fig. 2 are pressure time history of the DME and diesel in a fuel injection line during injection period at a preset injection pressure value of 55MPa. 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 ~ 200MPa, Kistler Ltd). After the end of an injection event, duration of the pressure oscillation for the DME was longer than that of diesel and its amplitude was lower due to high compressibility of DME, as similar trends were reported with in-line pump systems [8, 18]. 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 found that the fluctuations for the DME and diesel were within ± 0.18MPa and ± 0.05MPa, respectively.

4.2 SPRAY DEVELOPMENT

To activate the common-rail injector employed in the study, 20 Ampere(A) of high current had to be supplied to a solenoid valve in the injector with certain dwelling time (high current holding time) and then down to 10 A throughout the injection duration. As shown in Fig. 3, high current holding time affected whether DME became intermittent hesitating spray or atomized in continuous spray development (at least on the macroscopic point of view). The intermittent hesitating DME spray could also be observed in terms of spray tip penetration as shown in Fig. 4. Under 25MPa and 40MPa injection pressure conditions, DME spray discharged with 200μs high current holding time was paused and re-injected, while this phenomenon did not appear with 400μs high current dwelling time. Two possible reasons could be supposed. First possible reason might be deteriorated throttling of the nozzle due to high compressibility of the DME ; Egnell [19] investigated pressure drop between common-rail and nozzle sac and found that for DME injection the pressure drop was higher than that of diesel, resulting in throttling inside the nozzle. The throttling generated during the early stages of DME injection at 25MPa and 40MPa of injection pressures might lead to the hesitation and intermittent injection behavior. Another possibility is unstable force balance around a ball valve inside the common-rail injector (Fig. 5) ; movement of the ball valve and diameters of the bleed and feed orifices dominantly affect flow rate of the injector whilst solenoid valve energizing period, and are originally attenuated toward the diesel fuel. During the injection period, forces acting on the ball valve were balanced with magnetic force (proportional to the solenoid energizing time), spring force (generating from the springs), damping force (representing physical properties -compressibility and modulus of elasticity- of the fuel) and pressure force (from the injection pressure). In this study, attenuation of the injection pressure and high current holding time might have caused alternation of the damping and magnetic forces and therefore might affect the force balance, possibly coupled with cavitation inside the fuel passage. Hence, the intermittent hesitating DME spray might be generated under the certain conditions. Similar intermittent hesitating spray from a VCO (Valve Covered Orifice) single hole injector was previously reported, which was concluded due to temporary unbalanced pressure followed by nozzle hole blockage by the needle inside the injector [21]. Further detailed investigation will be carried out in the future on this matter. Throughout the hereafter study, 400μs of high current holding time was applied to eliminate ambiguity of the intermittent hesitating spray.

Figure 6 shows microscopic spray development near the nozzle tip taken with the single hole microscopic spray acquiring system at 55MPa injection pressure and atmospheric chamber pressure condition, while corresponding diesel spray is shown in Fig. 7. DME vapour appeared prior to a gushing liquid phase, as shown in Fig. 6 (a). On being exposed in atmospheric pressure condition, the DME was rapidly spread both longitudinal and axial directions with being broken into small droplets and evaporated while in the diesel spray rather narrow edge of the spray boundary appeared and the break-up time seemed to be longer (Figs. 6 (b) and (c) compared with Figs. 7 (b) and (c)). In the later stages of spray development, the behavior of draining off the diesel was quite different from that of DME ; diesel had structure of a long liquid column with several branches (Fig. 7 (d)), while atomized small droplets which then evaporated appeared in the DME, as shown in Fig. 6 (d). At elevated chamber pressures, there were many difficulties in obtaining the microscopic images of diesel and DME. Although they are not shown in the paper, the general microscopic diesel spray near the nozzle tip was similar to that of atmospheric pressure conditions. However, microscopic DME spray near the nozzle tip seemed to contain finer droplets.

4.3 SPRAY TIP PENETRATION

Figure 8 illustrates spray penetration of the DME and diesel at 55MPa injection pressure and 3MPa chamber pressure. As can be seen in Fig. 8, spray tip penetration was similar to that of diesel as the macroscopic behavior of the DME above saturation vapour pressure might become liquid-like. This might be observed in following microscopic spray images of diesel and DME, as shown in Fig. 9. The microscopic images of DME and diesel were obtained at a location of 20 mm along the axial centre line of the spray at different injection and chamber pressure conditions. As can be seen in Fig. 9 (a) and (b), for the case of atmospheric chamber condition and 25MPa of injection pressure, break-up of the diesel spray was not still completed, therefore, large aggregated diesel lumps appeared (Fig. 9 (b)) , while DME spray already broke up in small droplets (Fig. 9 (a)). On the other hand, in the condition of 3MPa chamber pressure and 55MPa of injection pressure (Fig. 9 (c) and (d)), both spray droplets size seemed to be similar but diesel spray was more dense in the spray cone volume. Effect of injection pressure on DME spray tip penetration is shown in Fig. 10 ; the results present spray tip penetrations averaged by taking mean value of penetrations from the five nozzle holes. As injection pressure increases, regardless of chamber pressure, spray tip penetrations were longer. The spray tip penetration was shortened with the higher chamber pressure. In the present work, the effect of chamber and injection pressures on DME spray tip penetration was faithfully coincided with trend of well-known diesel macroscopic spray characteristics [22, 23].

Fig. 11 shows the DME injection rate measured by a purpose-built injection rate meter following Bosch method[12]. It shows the effect of fuel supply pressure on the injection rate under 3MPa pressure condition. DME injection rate was described as the fuel flow rate from a nozzle hole. The fuel injection rate shows triangular shape in time domain, which represents the elapsed time after the injector solenoid is energized(SOE). The transient characteristics of fuel injection rate imply that the steady or quasi-steady spray models may not be able to estimate the spray development especially penetration. The pressure drop across nozzle(ΔP) should be rapidly changing while injection rate is increasing at the initial development phase of spray from a common-rail system. The spray penetration models, reviewed in section 3, have been verified when density inside the spray was identical to the ambient density and injection rate increased rapidly, resulting in a top-hat like shape of injection rate curve. As previously studied with a similar injector [24], however, the fuel injection system employed in this study was unlikely to provide such a rapid injection rate and density of the spray might be far from that of the ambient condition. Hence, these models should over-predicted the spray tip penetration when ΔP is using a fixed common-rail pressure. The spray tip penetration models were applied by utilizing the instantaneous ΔP at each moment calculated from the transient injection rate.

Shown in Fig. 12 are comparison of experiments with a penetration model. It was found that Dent's model, eq.(3), resulted best fit for the DME spray in this work, while ΔP in the equation adopts the calculated value from the measured injection rate profile in Fig. 11.

4.4 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 since 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 [25]. Hence, in the present study, spray cone angle was defined near the nozzle tip following the spray boundary from the nozzle. In the case of fuel injected into 3MPa chamber pressure condition with 55MPa injection pressure, spray cone angles of the DME were similar to those of diesel because of reduced flash boiling effect, as shown in Fig. 13. Variation of the spray cone angles of each nozzle hole was relatively (approximately 0.65°) smaller than that of diesel because of the high compressibility of the DME. Figure 14 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 3MPa of chamber pressure. In the case of DME spray atomized into the atmospheric chamber pressure condition, spray cone angle was large due to the flash boiling atomization. As the chamber pressure increased to 3MPa, however, the spray cone angle became hardly affected by the flash boiling and eventually lead to the diesel-like value (Fig. 14(b)).

4.5 EVAPORATING SPRAY CHARACTERISTICS

Shown in Fig. 15 are Mie-scattered and shadowgraphic DME spray images taken with the nozzle holder for the single hole spray. As can be noticed in the shadowgraphic DME spray images (Figs. 15 (b) and (d)), vapour 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 droplet size of the spray in those regions was smaller, therefore resulting in more chance to be ignited [26, 27]. The flash boiling effect can also provide better atomization and fuel/air mixing and reduced wall wetting by shortening spray tip penetration [28, 29]. It can also be noticed that, regardless of injection pressure, spray tip of the DME in atmospheric chamber pressure formed in mushroom-like shape but it disappeared and became diesel-like under 3MPa of chamber pressure. 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 a vortex.

In this work, evaporating characteristics of the spray was evaluated in terms of apparent vapour phase area obtained by subtraction of Mie scattered image from shadowgraphic spray image. Shown in Fig. 16 are the effect of injection pressure on DME evaporating characteristics at the different chamber pressures. As seen in Fig. 16 (a), at atmospheric chamber pressure condition, 40MPa of injection pressure provided wider vapour phase area than that of 25MPa but contribution of further higher injection pressure (55MPa) was minimal. For the case of 3MPa chamber pressure, the DME seemed to be still evaporated though it was lower than that of atmospheric chamber pressure because of increased ambient resistance. This implies that the DME spray could provide better chance to contact with surrounding oxidant in an engine cylinder, but further investigations would be necessary in more realistic conditions considering in-cylinder temperature effect. It may also imply that higher injection pressure would provide faster and better atomization.

5 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 evaporating characteristics of the DME allowing the following conclusions to be drawn.

(1) Intrinsic spray characteristics of the DME appeared in atmospheric pressure conditions, characterized by forming mushroom-like shape of the spray tip and flash boiling, while it became diesel-like with elevated ambient pressure conditions.

(2) Unstable force balance on the ball valve inside the nozzle might lead to hesitating intermittent DME spray; the hesitating intermittent spray appeared depending upon injection pressure and high current holding time, representing damping force and magnetic force, respectively.

(3) In atmospheric chamber pressure conditions, DME vapour was ejected before the discharging liquid, while only the liquid phase of DME observed in 3MPa chamber pressure.

(4) Vapour phase of the DME spray dominantly appeared in the region of spray edge and downstream, suggesting more chance to be ignited there in the application of compression-ignition engines.

(5) Vapourising region of the DME spray increased with injection pressure, regardless of chamber pressure conditions, and DME was still evaporated at 3MPa though the area of the vapour phase decreased. Further investigations considering temperature effect would be necessary.

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LIST OF CAPTION

Fig. 10 Effect of injection pressure on DME spray tip penetration

(a) atmospheric chamber pressure (b) 3MPa chamber pressure

Fig. 11 DME injection rate, representing the amount of fuel from a nozzle hole, at different supply pressure under 3MPa pressure condition

Fig. 12 Comparison of experiments with Dent's model at 3MPa chamber pressure

Fig. 13 Comparison of spray con angle of DME with diesel at 55MPa injection pressure and 3MPa chamber pressure (a) diesel (b) DME

Fig. 14 Effect of injection pressure on DME spray cone angle at different chamber pressures

(a) atmospheric chamber pressure

(b) 3MPa chamber pressure

Fig.15 Effect of chamber pressure on DME evaporation at different injection conditions

(a) 0.7ms ASOI Mie scattered spray at 25MP injection pressure and atmospheric chamber pressure

(b) 0.7ms ASOI shadowgraphic spray at 25MP injection pressure and atmospheric chamber pressure

(c) 0.6ms ASOI Mie scattered spray at 55MP injection pressure 3MPa chamber pressure

(d) 0.6ms ASOI shadowgraphic spray at 55MPinjection pressure and 3MPa chamber pressure

Fig. 16 Apparent DME vapour phase area with different injection conditions

(a) atmospheric chamber pressure

(b) 3MPa chamber pressure