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SPRAY CHARACTERISTICS OF DME IN CONDITIONS OF COMMON RAIL INJECTION SYSTEM(II)

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ABSTRACT–Dimethyl Ether (DME) is an excellent alternative fuel that provides lower particulate matter (PM) than diesel fuel under the same engine operating conditions. Spray characteristics of DME in common rail injeciton system were investigated within a constant volume chamber by using the particle motion analysis system. The injector used in this study has a single hole with the different orifice diameter of 0.2, 0.3 and 0.4 mm. The injection pressure was fixed at 35MPa and the ambient pressure was varied from 0.6 to 1.5 MPa. Spray characteristics such as spray angle, spray tip penetration and SMD (Sauter mean diameter) were measured. Spray angle was measured at 30d_o downstream of the nozzle tip. The measured spray angle increased with increase in the ambient pressure. Increase of the ambient pressure results in a decrease of spray penetration. The experimental results of spray penetration were compared with the predicted one by theoretical and empirical models. Increase in the ambient pressure and nozzle diameter results in an increase of SMD at a distance 30, 45 and 60d_o downstream of the nozzle, respectively.

KEY WORDS : DME, Common rail injection system, Spray angle, Spray tip penetration, SMD

1. INTRODUCTION

The various effective methods in reducing particulate matter (PM) and NOx emitted from compression ignition (CI) engines have been investigated and tried by many researchers (Chikashisa *et al.*, 2002; Oh *et al.*, 2002; Huai *et al.*, 2003). Introduction of oxygenated fuels is known as one of solutions considered for solving NOx and PM emission in CI engines.

Dimethyl Ether (DME) has been famous for an excellent alternative fuel that provides lower PM than diesel fuel under the same engine operating conditions.

Yoshizaki *et al.* (1998) and Wakai *et al.* (1999) revealed spray characteristics of DME with a constant volume vessel experiments. The experimental results of spray tip penetration were compared with the computed one from the empirical equation suggested by Xu *et al.* (1992). The calculated results revealed considerably good agreements with the experimental one under only a high ambient pressure conditions.

Sorenson *et al.* (1998) had reported the spray tip penetration and spray angle for the hole and pintle type nozzles spray under the high pressure injection into nitrogen using conventional jerk pump injection system. Spray tip penetration of DME spray can be predicted with methods developed for diesel fuel by Hiroyasu and co-workers for the injection at 0.4 MPa ambient pressure. However, the comparison of spray tip penetration between experimental and calculated results was not favorable and they only suggested the possibility of prediction.

Oguma *et al.* (2001) had studied the effect of ambient pressure on atomization characteristics of DME. DME was injected with the injection pressure of 5.0 MPa into the ambient pressures of 1.0 and 1.5 MPa, equivalent to the compression ratio of 12 and 17.7 at the engine used for the measurement of performance and exhaust emissions. They concluded that the effect of ambient pressure on DME spray characteristics such as spray angle and SMD show the similar tendency with diesel fuel. However, previous works include the limited information of spray characteristics of neat DME in the application of the diesel engines. The spray characteristics of fuel injection process are important in terms of understanding and improving the combustion process and pollutant emissions.

The objective of this study is to investigate the spray characteristics of DME such as spray angle, spray tip penetration and SMD by using the conditions of common rail injection system.

2. EXPERIMENTAL SETUP

The schematic diagram of experimental apparatus used in

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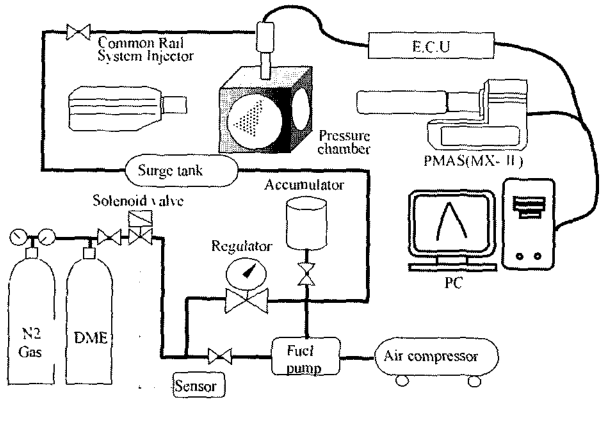

Figure 1. Schematic diagram of experimental apparatus.

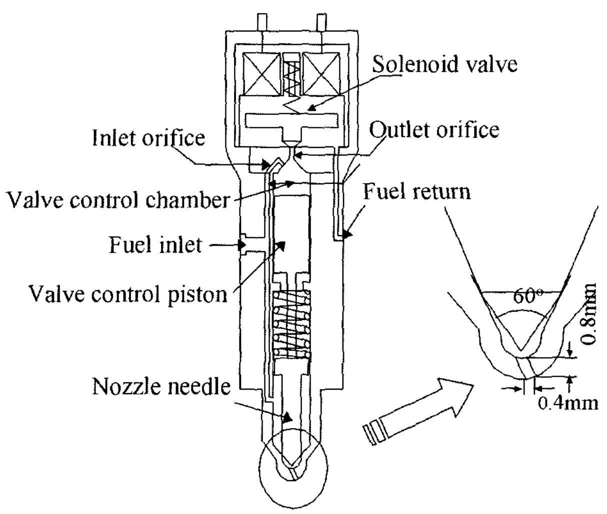

Figure 2. Schematic diagram of injector used.

this study was shown in Figure 1. It consists of a constant volume chamber, common rail system injector, control unit, fuel pump (Haskel, MS-71), air compressor, pressure regulator and PMAS(Particle Motion Analysis System, V-tek, Co., Korea).

The fuel supply system in this study was organized by considering the high vapor pressure of DME. In order to avoid vaporization in the fuel line, it was pressurized from the fuel tank to the fuel pump (MS-71, Haskel INC, USA) by using nitrogen at 1.6 MPa.

To protect leakage of DME in the fuel line, a solenoid valve and pressure sensor were used as safety devices. The regulator was utilized to keep constant injection pressure and the high fuel pressure to be required. A fuel pump that was operated with an air compressor was installed. The pressurized DME at 35 MPa was injected into a constant volume chamber that was filled up by nitrogen at ambient pressure of 0.6, 1.0 and 1.5 MPa. The ambient pressure within the constant volume chamber was measured by Bourdon tube pressure gauge.

The injector used in this study is shown in Figure 2. The injector is electronically controlled common rail system one that has single hole with nozzle diameter of 0.2, 0.3 and 0.4 mm. In the case of diesel fuel, this injector operates the maximum injection pressure up to 140 MPa. In the application of diesel engine, DME did not require the high injection pressure due to the lower density and higher vapor pressure than that of diesel fuel. The injection period and injection timing were controlled by changing the TTL pulse signal of PMAS. The spray angle, spray tip penetration and SMD (Sauter mean diameter) were measured by using PMAS. It consists of a spark light source with very short time duration of about 50 ns, a field lens, a CCD camera and a personal computer with an image board.

The spray angle and spray tip penetration measured by using the shadowgraph method based on the macroscopic spray measurement function of PMAS. The shadowgraph image passes through the diaphragm of camera lens and is recorded on CCD. Spray angle was measured at a distance 30, 45 and 60d_o (d_o: orifice diameter) downstream of the nozzle tip when the ambient pressure was varied from 0.6 to 1.5 MPa.

SMD was measured by using the microscopic spray measurement function of PMAS at a distance 30, 45 and 60d_o downstream of the nozzle and edge of the spray. Spray angle, spray tip penetration and SMD were obtained by averaging the values from 30 images for each condition.

3. RESULTS AND DISCUSSIONS

3.1. Spray Angle

The threshold level that is related to the transmittance of the backlight is used to separate the spray area from the background in the raw images. The edge of diesel spray was usually defined 80% (Dan *et al.*, 1997) or 95% (Chang *et al.*, 1997) transmittance in the measurement of spray angle. In order to measure the spray angle in this study, the edge of spray was applied as a line of 80% transmittance.

In the case of spray angle of DME spray, it is difficult to measure since the angle is not easily defined as in diesel spray. It is because the DME itself has higher vapor pressure than that of diesel fuel and DME spray increases irregularity to the edge of spray.

Figure 3 shows the effect of ambient pressure on spray angle with the variation of time after start of injection for the different measurement locations. It is clear from the figure that an increase in the ambient pressure results in an increase of spray angle for measurement location of 30, 45 and 60d_o in the later stage of spray after 1.1 ms.

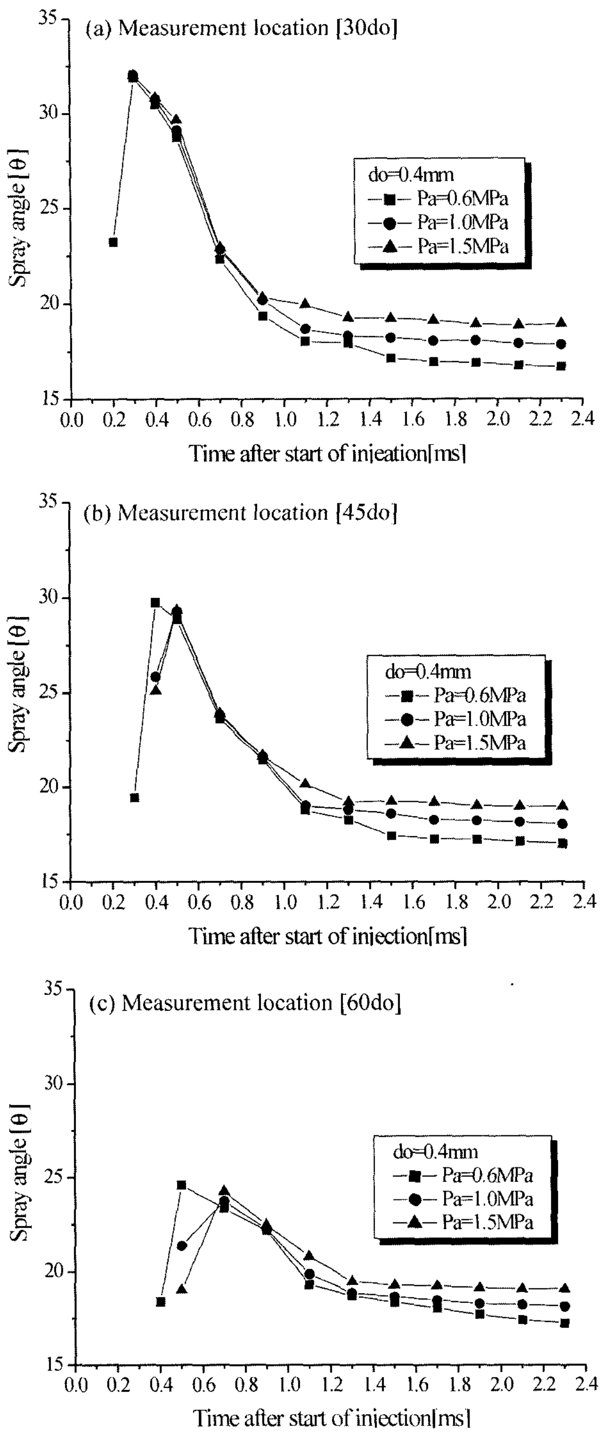

Figure 3. Effect of ambient pressure and measurement location on spray angle for orifice diameter of 0.4 mm.

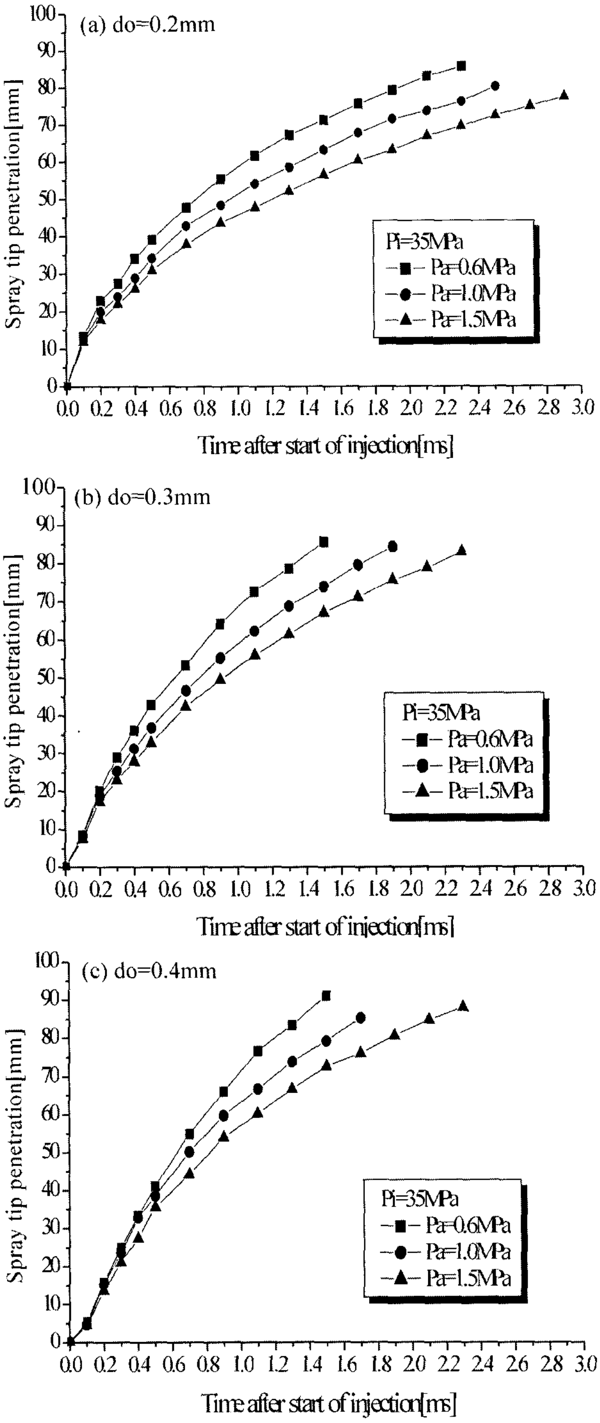

Figure 4. Effect of ambient pressure and orifice diameter on spray tip penetration.

The spray angle decreases as the measurement location processes further downstream. Many researchers have measured the spray angle for diesel fuel at $60d_0$ downstream from nozzle tip. In the case of DME spray, it was difficult to measure the spray angle because of the different evaporation characteristics resulting from the higher vapor pressure than that of diesel fuel. It can be recommended that the measurement location of spray angle for DME spray should be between 30 and 45d_o from the nozzle tip.

3.2. Spray Tip Penetration

Spray tip penetration is one of the important factors to decide the combustion chamber size in diesel engine. The effect of ambient pressure on spray tip penetration of DME spray is shown in Figure 4. As can be found from this Figure that an increase in ambient pressure and nozzle diameter results in an increase of spray tip penetration. The initial spray tip penetration from 0.1 ms after start of injection increases sharply with time up to 0.5 ms and then increases smoothly with time.

Most studies for the prediction of spray tip penetration of DME have introduced the empirical correlation of Hiroyasu and Arai (1990) based on the jet disintegration theory for the diesel spray as

$0 < t < t_b$

$$S = 0.39\left(\frac{2\Delta p}{\rho_l}\right)^{0.5} \quad (1)$$

$t < t_b$

$$S = 2.95\left(\frac{\Delta p}{\rho_a}\right)^{0.25}(d_o t)^{0.5} \quad (2)$$

where $$t_b = 28.65\frac{\rho_l d_o}{(\rho_a \Delta p)^{0.5}} \quad (3)$$

where Δp is injection pressure differential, ρ_l is the liquid density, d_o is the nozzle diameter, ρ_a is the ambient density, t_b is the breakup time.

Kajitani *et al.* (2000) had also suggested the empirical correlation for the prediction of the spray tip penetration of DME, which modify the theoretical correlation developed by Wakuri (1960) based on the momentum theory as

$$S = \left(\frac{\rho_l}{\rho_a}\right)^{0.25}\left(\frac{d_o u t}{\tan\theta}\right)^{0.5} \quad (4)$$

where ρ_l is the liquid density, d_o is the nozzle diameter, ρ_a is the ambient density, u is the velocity of initial fuel spray, θ is the half of spray angle. In the calculation of the initial velocity, they assumed the discharge coefficient as unit. However, Wakuri *et al.* (1960) considered the discharge coefficient as 0.6 to predict the spray tip penetration for diesel fuel.

Figure 5 shows the comparison between experimental and calculated spray tip penetration with the variation of ambient pressure and the measurement location of spray angle for the nozzle diameter of 0.4 mm.

It is clearly seen from the figure that the calculated spray tip penetration by Equation (4) is close to

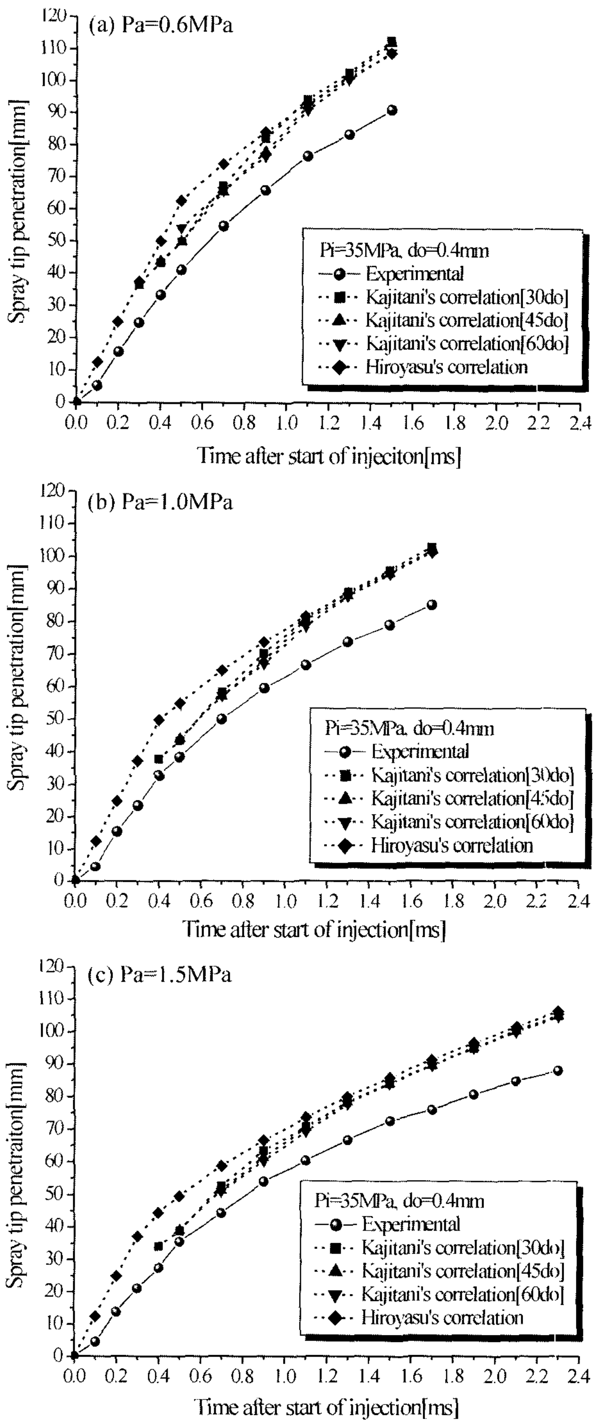

Figure 5. Comparison between calculated and measured spray tip penetration for different nozzle diameter.

experimental findings than Equations (1) and (2), but the calculated prediction are not in good agreement with the experimental data. This reveals that the more advanced theoretical or empirical correlations taking into account

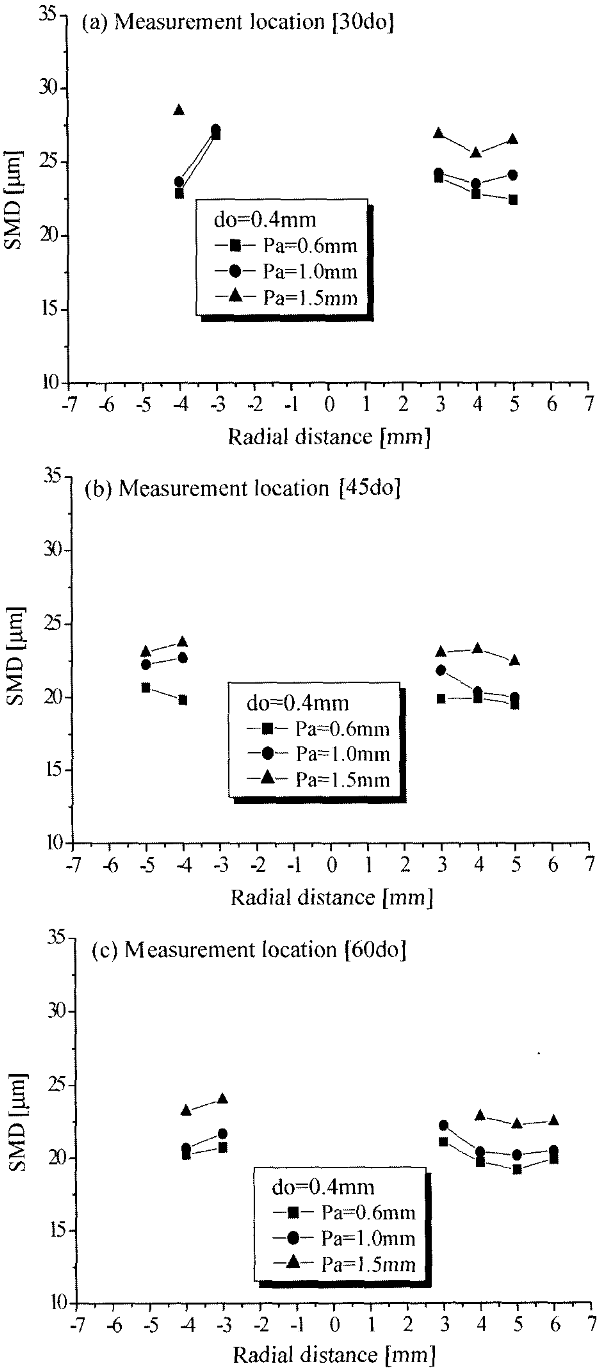

Figure 6. Effect of measurement location and ambient pressure on SMD.

the spray angle and discharge coefficient of nozzle for DME spray are required.

3.3. SMD

Figure 6 shows the effect of ambient pressure and measured location on SMD with the variation of radial distance at nozzle diameter of 0.4 mm. SMD was measured at 1.1 ms after start of injection. An increase in the ambient pressure results in an increase of SMD at a distance 30, 45 and 60d_0 downstream of the nozzle, respectively. The instrument (PMAS) could not measure SMD at the center of DME spray. This may be due to existence of the core and dense spray.

As can be seen from Figure 6, the spray structure of DME spray is not symmetrical. This means that DME spray increases irregularity to the edge of spray as emerged from the nozzle orifice. This may be attributed to the physical properties of DME that is a higher vapor pressure and lower boiling point than those of diesel fuel.

The effect of ambient pressure and nozzle diameter on SMD for the measurement location of 45d_0 from the nozzle tip is shown in Figure 7. It is clear from Figure 7 that SMD increase with an increase in nozzle diameter and ambient pressure. However, it is clear that the more precise measurement of SMD or reliable diagnostics in the case of nozzle diameter of 0.2 mm are required.

This might be due to the assumption of spherical droplet in the calculation of SMD in PMAS even though the DME droplet is not spherical. It seems to be that higher vapor pressure of DME results in the irregular shape of droplet.

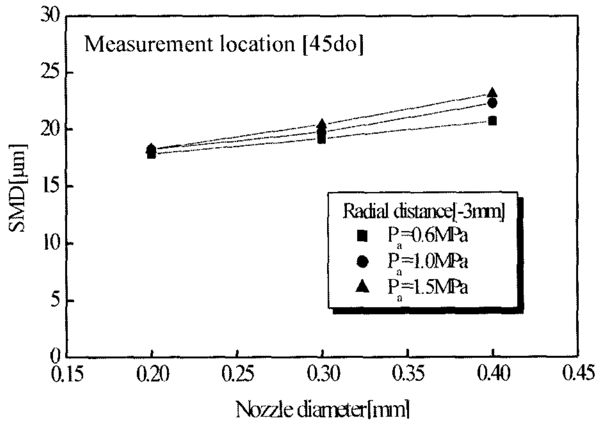

Figure 7. Effect of nozzle diameter and ambient pressure on SMD.

4. CONCLUSIONS

The experiment was conducted to investigate the spray characteristics of DME in conditions of common rail injection system. The conclusion revealed from this study can be summarized as

(1) An increase in the ambient pressure results in an increase of spray angle for measurement location of 30, 45 and 60d_0 but the early injection of DME spray

is not so great. It can be recommended that measurement location for DME should be between 30 and $45d_0$ downstream of the nozzle tip.

(2) Spray tip penetration increases with an increase in ambient pressure. This tendency is similar to the diesel spray. It is clear that the increase in ambient pressure causes a shorten spray tip penetration.

(3) The calculated spray tip penetration by Kajitani et als correlation is close to experimental findings than Hiroyasu and Arais correlation. However, the calculated predictions are not good agreement with the experimental data.

(4) An increase in the ambient pressure and nozzle diameter results in an increase in SMD at a distance 30, 45 and $60d_0$ downstream of the nozzle.

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REFERENCES

Chang, C. T. and Farrell, P. V. (1997). Effects of fuel viscosity and nozzle on high injection pressure diesel spray characteristics. *SAE Paper No.* 970353.

Chikachisa, T., Hishinuma, Y. and Ushida, H. (2002). Mixing condifions with spray-jet interaction for effective soot reduction in diesel combustion. *Int. J. Automotive Technology* **3, 1,** 17–25.

Dan, T., Yamamoto, T., Senda, J. and Fujimoto, H. (1997). Effect of nozzle configurations for characteristics of non-reacting diesel fuel spray. *SAE Paper No.* 970355.

Hiroyasu, H. and Arai, M. (1990). Structures of fuel spray in diesel engines. *SAE Paper No.* 900475.

Huai, T., Durbin, T. D., Rhee, S. H. and Norbeck, J. M. (2003). Investigation of emission rates of ammonia, nitrous oxide and other exhaust compounds from alternative-fuel vehicles using a chassis dynamcmeter. *Int. J. Automotive Technology* **4, 1,** 9–18.

Kajitani, S., Oguma, M. and Mori, T. (2000). DME fuel blends for low-emission, direct-injection diesel engines. *SAE Paper No.* 2000-01-2004.

Oguma, M., Hyun, G., Alam, M., Goto, S. and Kajitani, S. (2001). Effect of ambient pressure on atomization characteristics of dimehtyl ether. *Proc. of the 6th Annual Conference on Liquid Atomization and Spray Systems-Asia*, 11–13 Oct., Busan, Korea, 196–201.

Oh, S. K., Baik, D. S. and Han, Y. C. (2002). Performance and exhaust gas characteristics on diesel particulate filter trap. *Int. J. Automotive Technology* **3, 3,** 111–115.

Sorenson, S. C., Bek, B. H., Glensvig, M. and Abata, D. L. (1998). Dimethyl ether injection studies. *Proc. of the Second Int. Workshop on Advanced Spray Combustion*. 24–26 Nov., Hiroshima, Japan, 151–164.

Wakai, K., Nishida, K., Yoshizaki, T. and Hiroyasu, H. (1999). Spray characteristics of dimethyl ether from a DI diesel injection nozzle. *Trans. of JSAE* **30**, **1**, 41–47.

Wakuri, Y., Fuji, M., Amitani, T. and Tsuneya, R. (1960). Studies on the penetration of fuel spray in a diesel engine. *Bulletin of JSME* **3**, **9**, 123–130.

Xu, M., Nishida, K. and Hiroyasu, H. (1992). A practical calculation method for injection pressure and spray penetration in diesel engines. *SAE Paper No.* 920624.

Yoshijaki, T., Wakai, K., Nishida, K. and Hiroyasu, H. (1998). Experimental and numerical analysis on spray tip penetration of DME spray. *7th Symposium (ILASS-Japan) on Atomization*, 21–23 Dec., Gunma University. Japan, 184–188.