ANALYSIS AND EXPERIMENTAL INVESTIGATION OF SPRAY CHARACTERISTICS OF DIMETHYL ETHER

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ABSTRACT This study was conducted to investigate the profiles of injection rate, spray development, atomization characteristics, and the comparison of macroscopic characteristics between experimental results and empirical model for dimethyl ether (DME) and diesel fuel under the various experimental conditions.

In order to investigate the injection rate and the macroscopic characteristics of fuel spray experimentally, the injection rate measuring system and the spray visualization system which were composed of a long tube filled with fuel, pressure measuring system of injection line, Nd:YAG laser, an ICCD camera, and the image processing systems for the spray development processes of DME fuel were used in this study, respectively. A high pressure chamber with optical windows was used to allow the observation of the spray development of both diesel and DME fuels. The analysis of spray tip penetration and evolution process were investigated for the three different correlations of spray tip penetration both diesel and DME fuel. Detail comparisons between spray tip penetrations from empirical models and those from visualization experiments were conducted in various fuel injection parameters.

It was revealed that the injection delay of diesel fuel is longer than that of the DME because of higher kinetic viscosity and the maximum injection rate of DME fuel is almost constant except the 0.3ms of energizing duration. Three different empirical models applied in this study to predict the spray tip penetration of diesel and DME fuels provides the good agreement with the experimental data of spray tip penetration except in the early stages of the spray development.

Keywords: Dimethyl ether (DME), Injection rate, Spray tip penetration, Spray cone angle, Sauter Mean Diameter (SMD)

1. INTRODUCTION

The rapid increase of carbon dioxide (CO\textsubscript{2}) and harmful exhaust emissions from the burning of fossil fuels are suspected to cause global climate change and environmental problems. Recently, some promising clean alternative and renewable fuels, such as hydrogen, alcohol, dimethyl ether (DME), biodiesel have been investigated. Among these various alternative fuels, it is known that DME is an excellent alternative fuel for diesel which provides very low particulate matter (P.M.) emissions, while NO\textsubscript{x} emissions are similar to those from diesel fuel under the same engine operating conditions [1].

In a compression ignition engine, the characteristics of fuel spray and mixture formation have greatly effects on the combustion process in direct injection diesel engine, because fuel is directly injected into the combustion chamber, where flow is highly turbulent. Fuel injection takes place in a very short period of time and both liquid droplets and fuel vapor exist in the combustion chamber. The distributions of fuel droplets combustion chamber of diesel engine are a dominant factor in governing the fuel/air mixture formation, combustion process and engine performance. So, the characterization of liquid fuel atomization and vaporization is important because the atomization and evaporation of the fuel spray directly affect on the engine performance and emission characteristics.

The spray characteristics and evaporating processes of DME are very important for improving efficiency and low emission of engine optimized in fuel injection and combustion processes. Therefore many researches have been conducted on the spray characteristics and combustion processes of DME.

Yoshio et al. [2] investigated the spray characteristics and evaporating processes of DME using the optical system. They reported that the spray tip penetrating speed of DME was slower and spray angle was wider than that of diesel because the breakup time of DME is shorter and the evaporation process of DME is quicker than that of diesel. They also conducted the experimental investigation to clarify the affect of DME injection characteristics on heat release and exhaust emissions. [3, 4]

In compression ignition engines, the combustion and emission characteristics have close relations with the process of fuel-air mixture formation. In this point of view, the investigations on the spray characteristics of DME are required for optimizing combustion process of the engines fueled with DME.

Teng et al. [5] made a study about the effect of injection pressure on the liquid-DME viscosity. Ikeda et al. [6] measured the injection rate of multiple injection of common-rail injection system with diesel and DME. They reported that the maximum injection quantity of DME depends on the cavitation number. The macroscopic spray characteristics of DME fuel in combustion chamber was investigated by Suh et al [7]. They suggested that the applications of DME for diesel engine can be reduced the wall wetting problem of combustion chamber. Park et al. [8] revealed the spray development of DME compared with commercial diesel fuel. They reported that DME has a shorter spray tip penetration and a larger spray angle due to the effect of evaporation of DME.

Many other researchers [9-12] have also reported on the combustion, emissions and injection characteristics of DME.
based on the experimental and numerical results. However, most of these studies are a little fundamental understanding about the macroscopic fuel spray characteristics.

The aim of this study is to analyze the DME fuel spray profiles such as injection rate, spray tip penetration, spray cone angle of DME spray by using injection rate measuring and spray visualization systems at various experimental conditions. For the analyzing the spray tip penetration and evolution process, three different correlations for spray tip penetration of diesel and DME fuel were also investigated. The experimental results about DME fuel spray characteristics compared with that of the diesel at the same experimental conditions.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Experimental apparatus

The injector that was used in this work is mini-sac type injector designed for common-rail injection system. It has single-hole nozzle with 0.3mm internal hole diameter (D) and 0.8mm hole length (L), as shown in Figure 1. The fuel injector was controlled by a peak current of 16.0A and a hold current of 5.0A. The injector driver and a time delay generator control injection timing and durations of spray.

Injection rate profile is important in analyzing the characteristics of injection system because the maximum flow rate and injection delay can be determined by analyzing the injection profile. In order to study the injection rate characteristics, the injection rate measuring system based on the Bosch’s suggestion [13] was used to analyze the injection characteristics of diesel and DME fuel at various experimental conditions.

This apparatus is based on the pressure variation within a tube filled with diesel fuel. When the fuel is injected into the tube, it created a pressure variation detected by a pressure sensor installed in the tube. The pressure in the tube was kept constant at 3MPa during the fuel injection. A piezo-type pressure sensor was utilized to measure the pressure of the tube and relief valve was installed to keep the constant line pressure higher than the vapor pressure of DME fuel. It prevents the generating of DME vapor in the tube that can be caused an error in measuring the injection rate. One-thousand continuous injections were averaged for a test case.

The macroscopic spray structure such as spray tip penetration and overall spray behaviors can be obtained from the frozen spray images by using the spray visualization system which is composed of a Nd:YAG laser (Continuum, SL2-10), cylindrical lenses and mirrors, a digital delay/pulse generator (Berkeley Nucleonics Corp, Model 555), an ICCD camera (The Cooke Corporation, Dicam-PRO), and PC installed an image grabber, as shown in Figure 2. As a light source, the Nd:YAG laser which has the 532nm of wave length was used and cylindrical lenses which form a laser sheet beam less than 1mm was used in order to illuminate the spray.

A high resolution ICCD camera is used to get the frozen spray images. A high-pressure injection system generated high pressure in common-rail for fuel injection and was made for an easier control of injection pressure. In order to pressurize the common-rail for the injection of a spray, two high pressure pumps (Haskel, HSF-300) that are operated by compressed air, generate a high pressure of fuel injection and store it in a common-rail. The pressure regulator and the quantity of the inlet air control the pressure of common-rail up to 200MPa. The high pressure chamber that can be pressurized up to 4MPa was used to generate the ambient pressure using the nitrogen gas. The temperature regulator was installed to keep the ambient temperature in the high pressure chamber. The DME was pressurized to 1MPa by nitrogen gas in fuel tank to avoid vaporization in the fuel supply line. The specifications of spray visualization system are shown in Table 1.

2.2 Experimental procedure

In this study, the spray tip penetration and spray cone angle were investigated at various injection conditions. The spray tip penetration is defined as the maximum distance that can be spray reached from nozzle tip and spray cone angle was defined that the angle formed by two straight lines drawn from the nozzle tip. The detail definition of spray characteristics is illustrated in Figure 3. To obtain spray tip penetration and spray cone angle, the bright distributions of the spray original images were analyzed and the optimal threshold level had to be determined. In this image, the
optimal threshold level is 30. By using threshold process of original spray images, the spray tip penetration and spray cone angle can be achieved and analyzed.

![Threshold processing images](image)

Figure 3. Definition of spray characteristics and image threshold process

Many researches have studied the spray tip penetration in diesel engines and suggested expressions for penetration of diesel spray. In this study, the experimental results have been compared with those of previous studies by estimating the results from the empirical equations. The empirical equation suggested by Hiroyasu and Arai [14] to predict the diesel spray tip penetration was used for two cases: where the injection time was longer than and shorter than the breakup time.

For injection times shorter than the breakup time $t_b$,$$
S = 0.39 \times t_{\text{aw}} \times \sqrt{(2 \times \Delta P)/\rho_f} \quad (t_{\text{aw}} \leq t_b) \quad (1)
$$

For injection times longer than the breakup time $t_b$,$$
S = 2.59 \times \sqrt{D \times t_{\text{aw}} \times (2 \times \Delta P/\rho_f)^{0.25}} \quad (t_{\text{aw}} \geq t_b) \quad (2)
$$

The breakup time is given by the dimensionally correct equation,

$$
t_b = \frac{28.65 \times \rho_f \times D}{\sqrt{\rho_g \times \Delta P}} \quad (3)
$$

The jet mixing model suggested by Dent [15] is different with other empirical equations for considering the ambient temperature conditions. The empirical equation based on the gas jet mixing theory can be expressed as follows,

$$
S = 3.36 C_d^{0.5} (\Delta P/\rho_g)^{0.25} (Dt)^{0.5} (294/T_g)^{0.25} \quad (4)
$$

Two phase flow model for prediction of spray tip penetration was suggested by Sazhin et al. [16]. This empirical equation was derived under the assumption that the droplets and entrained air form a two-phase flow and it can be expressed as follows,

$$
S = 1.189 \left[ \frac{1}{(1-\alpha)^{0.5}} \right]^{0.5} \left( C_d/\tan \theta \right)^{0.5} (\Delta P/\rho_g)^{0.25} (Dt)^{0.5} \quad (5)
$$

where, $C_d$ is discharge coefficient, $\alpha$ is breakup length coefficient and $\theta$ is half angle of spray cone.

In order to investigate the spray characteristics of DME fuel, the experiments and theoretical analysis was conducted according to the various injection and ambient condition. The specifications of experimental condition are illustrated in Table 2.

<table>
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<tr>
<th>Table 2. Experimental conditions</th>
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<tr>
<td><strong>Injection rate</strong></td>
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<td>Injection pressure ($P_{inj}$)</td>
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<tr>
<td>Ambient pressure ($P_{amb}$)</td>
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<tr>
<td>Number of injection</td>
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<tr>
<td>Energizing duration ($t_{eng}$)</td>
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<th>Spray visualization</th>
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<tr>
<td>Injection pressure ($P_{inj}$)</td>
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<td>Ambient pressure ($P_{amb}$)</td>
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<td>Energizing duration ($t_{eng}$)</td>
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<th>Nozzle</th>
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<tr>
<td>Nozzle type</td>
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<td>Number of holes</td>
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<tr>
<td>Hole diameter (mm)</td>
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<td>Sac volume (mm$^3$)</td>
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In the case of injection rate measuring experiment, different type of injector was used for improve the pressure variation detection at low energizing duration. The detail specifications of injector nozzle are also shown in Table 2.

3. RESULTS AND DISCUSSIONS

3.1 Injection rate characteristics

In general, DME fuel has a low boiling temperature and it induces the rapid evaporation and shorter ignition delay as compared to diesel fuel. So, in order to achieve the suitable application of DME fuel on diesel engine, accurate measurement of the fuel injection rate is needed. From the reason of like this, in this work, the injection characteristics of diesel and DME are investigated.

![Fuel injection quantities](image)

Figure 4. Fuel injection quantities of diesel and DME fuel ($P_{inj}$=50MPa, $P_{amb}$=0.1MPa)
Figure 4 shows the variation of fuel injection quantities between diesel and DME measured by Bosch’s method when the energizing duration was changed. The injection pressure is 50MPa and number of injection is 1000 samples. The injection quantities of both fuels are in proportion to the increase of energizing duration. In the case of comparison of injection quantities, diesel fuel injection quantities are small before 0.49ms and inject large amount of fuel than that of the DME fuel after 0.49ms. It must be pointed out that higher kinetic viscosity of diesel fuel impede the fuel injection at the short energizing duration. However, as the energizing duration is increased, the higher fuel droplet momentum injected from the nozzle overcomes the effect of fuel viscosity. It also can be said that the low kinetic viscosity and boiling temperature of DME fuel allow faster evaporation. So, in order to apply the DME fuel to diesel engine, longer energizing duration is necessary.

The comparison of injection rate between diesel and DME is illustrated in Figure 5. Figure 5(a) shows injection rate of both fuels when the energizing duration is 0.3ms. As can be seen in the figure, the injection delay (\(t_d\)) of diesel fuel is longer than that of the DME about 0.05ms and the injection rate of diesel fuel is lower. As mentioned above, from these results, it can be said that the higher kinetic energy of diesel fuel prevents the fuel injection at short energizing duration. The fuel injection quantities and injection rate of diesel fuel is smaller than that of DME at 0.3ms of energizing duration. However, in the case of \(t_{\text{eng}}=0.7\)ms, the maximum injection rate of both fuels increased with energizing duration and has almost the similar value.

### 3.2 Spray development process

In this study, experiments were carried out to analyze the effects of injection pressure, ambient pressure, ambient temperature, and injection duration on the spray characteristics.

Figure 6 shows the spray development process at various experimental conditions. The effect of injection duration on DME fuel spray development was illustrated in Figure 6 (a). Injection duration of DME fuel was varied from 0.8ms to 1.4ms in steps with 0.2ms and injection pressure, ambient pressure and ambient temperature were 40MPa, 0.1MPa and 293K, respectively. In the case of \(t_{\text{eng}}=0.8\)ms, the spray development of DME was shorter because the injector nozzle was not fully opened. It can be postulated that the injector nozzle was never fully opened at \(t_{\text{eng}}=0.8\) ms; therefore, it can be said that the spray never developed completely due to the lower fuel mass injected. However, the spray developments of other cases are all much the same.

Figure 6 (b) shows the comparison of spray development between diesel and DME fuels at 60MPa injection pressure, 1MPa ambient pressure, and room temperature. The spray development process of both fuels was marked in proportion to the elapsed time after the start of injection. The comparison of the spray development process between diesel and DME shows that the spray development was thinner and longer than DME under identical experimental conditions.

The effect of ambient pressure on the DME spray development process is illustrated in Figure 6 (c). DME spray development at high ambient pressure was slower and the spray angle was wider than at atmospheric conditions. The evaporating process that can be seen in the outer spray region at \(P_{\text{amb}}=0.1\) MPa disappears in high ambient pressure. It can be said that the amount of liquid phase of a DME spray increases at the higher ambient pressures due to decreased evaporation.

Figure 6 (d) shows the effect of ambient temperature on the spray development process. As the ambient temperature increased, the liquid phase of both fuels became shorter and the spray wider due to the improvement of evaporation and enhanced momentum of ambient gas at increased ambient temperature. The diesel spray shapes were longer and wider as the ambient temperature increased. In the case of DME fuel, it can be seen that the evaporating processes of the DME were more rapid at high ambient temperature because DME fuel remains in the vapor phase at room temperature.

From the spray images captured by the spray visualization system, the spray tip penetration and spray cone angle were compared for both diesel and DME fuel as shown in Figure 7. The predicted spray tip penetration from the empirical equations [14-16] is also shown with the experimental results for reference. As can be seen in the Figure 7 (a), the spray tip penetration of DME fuel was shorter and spray cone angle was wider than that of diesel fuel in the experimental results because the DME droplets evaporated more quickly. Based on these results, it can be said that the momentum of DME droplets injected from nozzle tip was lost more quickly than for diesel at the same ambient conditions.
However, the empirical equation result shows somewhat different trend. The spray tip penetration suggested by Hiroyasu et al. [14] underestimated the spray tip penetration at atmospheric condition. As for breakup time, the DME fuel breakup time is quicker than diesel fuel about 0.198ms, as can be seen in the empirical spray tip penetration results. It can be guessed that the empirical equation results before breakup time depends on the fuel density. However, the predicted spray tip penetration from Dent et al. [15] and Sazhin et al. [16] overestimated the spray tip penetration at initial spray injection time before 0.6ms of time after start of injection.

Figure 8 illustrates the effect of injection pressure on DME fuel spray development parameters such as spray tip penetration and spray cone angle. The experimental data
shows that spray tip penetration increased as the injection pressure increase. The empirical equation suggested by Hiroyasu et al. [14] that is indicated a thick line in the figure are well matched the experimental data and the jet breakup time (t_b) is faster as the injection pressure is increased. However, in the case of predicted spray tip penetration suggested by Sazhin et al. [16] that is indicated a thin line is also overestimated before 0.6ms after injection start. After 0.6ms of injection start, the predicted spray tip penetration shows good agreement with experimental data. In the case of spray cone angle, as the injection pressure is increased, the spray cone angle is decreased.

Figure 9 shows the effect of ambient pressure on the DME fuel spray development parameters such as spray tip penetration and spray cone angle. As can be seen in the figure, the spray tip penetration decreased with the ambient pressure increase due to the slow spray development at high ambient pressure. The comparison between experiments and empirical equations of spray tip penetration suggested by Hiroyasu et al. [14] and Sazhin et al. [16] shows as the ambient pressure increased, the predicted spray tip penetration by empirical equations showed good agreement with the experimental data. In the case of spray cone angle, an increase in ambient pressure induced a decrease of spray momentum in the axial direction. Therefore, droplet could not spread in the axial direction, and thus stagnated and spread in the radial direction. This is why the DME spray cone angle increased at high ambient pressure.

Figure 10. Analysis of SMD distribution between diesel and DME fuel (P_inj=60MPa, P_amb=2MPa, t_inj=1.5ms)

Comparison of Sauter Mean Diameter(SMD,D32) distribution between diesel and DME fuel at 60MPa of injection pressure, 2MPa of ambient pressure is illustrated in Figure 10. As can be seen in the figure, a strong down stream flow that causes to reduce the drag on the subsequently injected fuel spray can be observed. It can be also seen that the small SMD of DME fuel droplets are distributed in DME spray’s outer region because of droplet evaporation. From these results, it can be inferred that the DME fuel has better atomization characteristics than those of diesel fuel.

4. CONCLUSIONS

This work was conducted to investigate the fuel injection rate, spray development, atomization characteristics, and the comparison of macroscopic characteristics between experimental results and empirical model for dimethyl ether(DME) and diesel fuel under the various experimental conditions. The conclusions that are obtained by these investigations are as follows:

(1) The higher kinetic viscosity of diesel fuel prevents the fuel injection at short energizing duration. Therefore, the fuel injection quantities and injection rate of diesel fuel is smaller than that of DME at 0.3ms of energizing duration.

(2) The spray tip penetration of DME fuel is shorter and spray cone angle is wider than of diesel fuel because DME evaporated quickly at atmospheric conditions. In the ambient conditions, the spray tip penetration of DME decreased and the spray cone angle increased with increase in ambient pressure.

(3) Three different empirical models applied in this study to predict the spray tip penetration of diesel and DME fuels provides the good agreement with the experimental data of spray tip penetration except in the early stages of the spray development.

(4) Analysis of SMD distribution between diesel and DME fuel shows that the small SMD of DME fuel droplets are distributed in DME spray’s outer region because of droplet evaporation.
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5. NOMENCLATURES

\begin{itemize}
  \item \( C \) coefficient
  \item \( D \) diameter [mm]
  \item \( L \) length [mm]
  \item \( N \) number of injections
  \item \( P \) pressure [MPa]
  \item \( R \) radial distance from spray centerline [mm]
  \item \( S \) spray tip penetration [mm]
  \item \( T \) temperature [K]
  \item \( t \) time [ms]
  \item \( Z \) axial distance from the nozzle tip [mm]
  \item \( \alpha \) breakup length [mm]
  \item \( \theta \) angle [\(^\circ\)]
  \item \( \rho \) density [kg/mm\(^3\)]
\end{itemize}

Subscripts

\begin{itemize}
  \item amb ambient
  \item asoi after start of injection
  \item b breakup
  \item d delay
  \item eng energizing
  \item f fuel
  \item g gas
  \item inj injection
  \item w wall
\end{itemize}

6. REFERENCES

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