An Investigation on the Spray Characteristics of DME with Variation of Nozzle Holes Diameter using the Common Rail Fuel Injection System

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Abstract

DME spray characteristics were investigated about varied ambient pressure and fuel injection pressure using the DME common rail fuel injection system when the nozzle holes diameter was varied. The common rail fuel injection system with DME cooling system was used since DME has properties of compressibility and vaporization in atmospheric temperature. The fuel injection quantity and spray characteristics were measured. The spray analysis parameters were spray shape, penetration length, and spray angle at each nozzle holes. Three types of injector were used, the nozzle holes diameter were 0.166 mm (Injector 1), 0.250 mm (Injector 2), and 0.250 mm with enlargement of orifice hole from 0.6 mm to 1.0 mm (Injector 3). The fuel injection pressure was varied by 5 MPa from 35 to 70 MPa when the ambient pressure was 2.5 and 5 MPa. When using Injector 3 compared with diesel injection quantity, the DME injection quantity was increased 1.69 ~ 2.02 times. Through this, it had the similar low heating value with diesel by Injector 1. In case of Injector 2 and 3, there were asymmetrical spray shapes at initial time. However as time goes by, the spray shape was symmetrical. Among three types of injectors, Injector 3 had the fastest development velocity of penetration length. In case of spray angle, Injector 2 and 3 got larger spray angle than Injector 1 and both injector had approximately same angle. Through these results, Injector 3 was optimized to solve the low heating value problem of DME.

Introduction

The investigation of DME which is alternative fuel of diesel is in progress to respond the environmental problems and the need for alternative fuel. Among these investigations, many advantage of DME was founded. Oh et al. [1] had a study of emission characteristics and fuel efficiency for the heavy-duty DME bus, the result was dynamic characteristics between DME and diesel is equal to the diesel engine. In addition, the exhaust characteristics are improved without after-treatment system. Seto et al. [2] found that when using the DME, CO_2 was decreased. However, DME also has some disadvantage. In the paper written by Ishikawa et al. [3], DME supply system is needed since its elastomer attack damage to the fuel supply system. Beside, in the paper by Ion et al. [4] low lubricity of DME makes wear and leakage problems. Investigation of the performance of a diesel engine with in-line DME injection system by Yoshino et al. [5], increasing the injection quantity of DME is needed to get the same LHV(Low Heating Value) of diesel. This means LHV of DME is lower than diesel. Because of this problem, the injection quantity of DME is more needed than diesel to get the same power of diesel. There are various research are in progress to solve the LHV of DME. There are three ways to solve this problem. One is increasing of the nozzle holes diameter, another is increasing of the injection pressure, and the other is converting of the needle tip. Among these ways, converting of the needle tip is difficult method with need to high technology. In contrast, applying the increasing of the nozzle holes diameter and injection pressure is easier way than converting of the needle tip. Therefore, this paper shows the solutions of the DME LHV problem by increasing the nozzle holes diameter and injection pressure with DME common rail injection system.

Experimental Apparatus

Figure 1 is a schematic of whole test apparatus with DME common rail injection system, spray visualization system, and DME injection quantity measurement device. In the DME injection system, the common rail system was applied for constant high pressure injection. DME was likely to leak and wear because of its bad lubricity as low viscosity [6, 7, 8, 9]. For this, DME was added the 1% of BDF (Bio-Diesel Fuel) to increase lubricity. Nitrogen was used to compress DME to liquefy when an amount of DME was lower than 0.8 MPa. DME was supplied to accumulator with cooling system by 1MPa since DME could be evaporated well at room temperature. By using the cooling system, DME was kept the liquid phase well. DME was supplied to air driven pump (Haskel INC, ASF-100) operated by compressed air and was compressed at high pressure. Pressurized DME was

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supplied to the common rail and was injected by common rail PCV (Pressure Control Valve) driver (Zenobalti, ZB-1000). Returned fuel at the test injector and common rail was moved to the initial DME supply line. A region of DME injection pressure was as follow in Figure 2 [10], thus injected DME was always liquid phase.

There were 3-type test injectors used to get the spray images and Figure 3 shows specifications of each injector. Injector 1 was conventional injector which has 0.166 mm nozzle holes diameter and 0.6 mm nozzle path

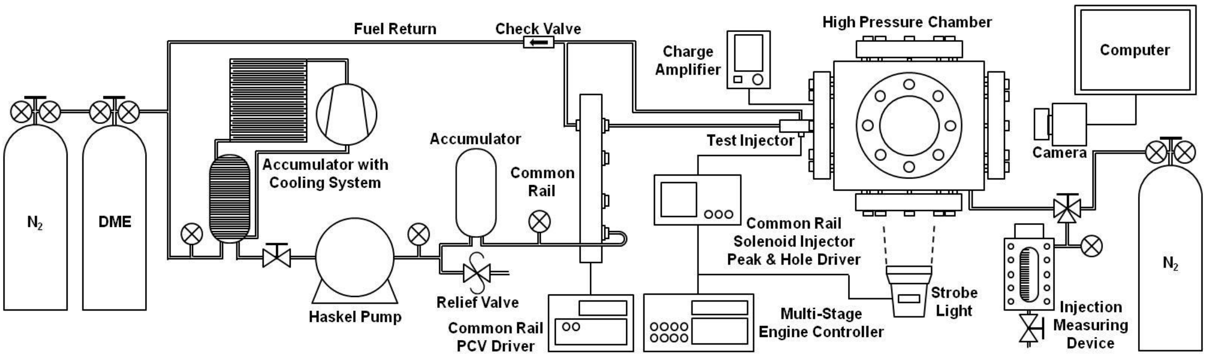

Figure 1 Schematic of experimental apparatus

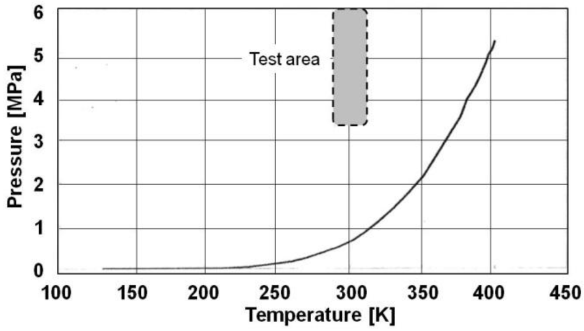

Figure 2 Vapor pressure curve of DME

Specification	Injector 1	Injector 2	Injector 3
Nozzle type	VCO		
Spray cone angle [degree]	139.6		
Number of nozzle holes	6		
Nozzle hole diameter [mm]	0.166	0.250	0.250
Nozzle path orifice [mm]	0.6	0.6	1.0

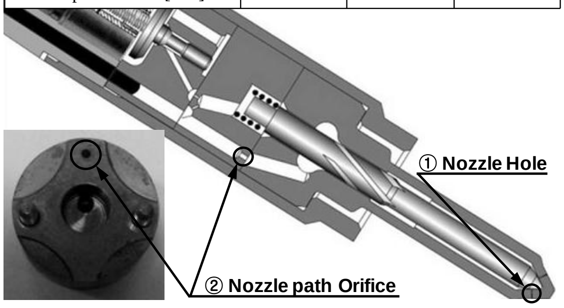

Figure 3 Specifications of test injectors

Table 1 Properties of DME and diesel

Property [unit]	DME	Diesel
Chemical structure	CH_3-O-CH_3	-
Boiling point at 1 atm [K]	248.1	450~643
Enthalpy of vaporization [kJ/kg]	467.13	300
Lower heating value [MJ/kg]	27.6	42.5
Gaseous specific heat capacity [kJ/kg K]	2.99	1.7
Ignition limits [vol% in air]	3.4/18.6	0.6/6.5
Modulus of elasticity [N/m^2]	6.37E+08	14.86E+08
Kinematic viscosity of liquid [cSt]	<0.1	3
Surface tension at 298K [N/m]	0.012	0.027
Vapor pressure at 298K [kPa]	530	<<10
Molar mass [g/mol]	46	170
Carbon content [mass%]	52.2	86
Oxygen content [mass%]	34.8	0
Critical temperature [K]	673.15	981.15
Critical pressure [MPa]	5.37	3.00[a]
Liquid density [kg/m^3]	667	831
Cetane number	55<	40~50
Auto-ignition temperature [K]	781.15	796.15
Stoichiometric air/fuel mass ratio	9.0	14.6

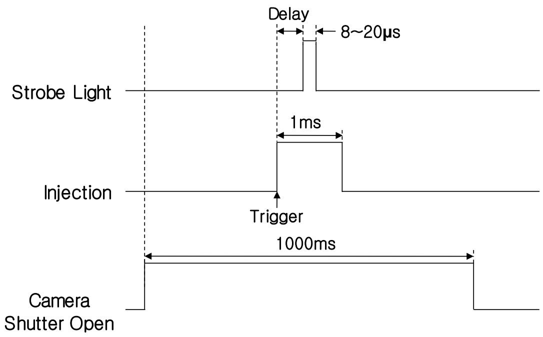

Figure 4 Signal synchronization

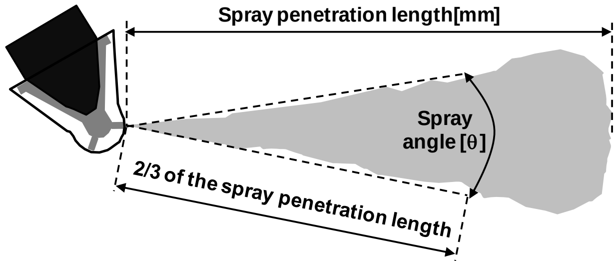

Figure 5 Spray shape measurement elements

Table 2 Condition of injection quantity measurement tests

Injector	Injector 1	Injector 1 / 2 / 3
Fuel	Diesel	DME
Ambient pressure [MPa]	5.0	
Injection pressure [MPa]	35 / 40 / 45 / 50 / 55 / 60 / 65 / 70	
Injection duration [ms]	1.0	
The number of injection [times]	1000	

Table 3 Condition of spray visualization tests

Injector	Injector 1	Injector 1 / 2 / 3
Fuel	Diesel	DME
Ambient pressure [MPa]	2.5 / 5.0	
Injection pressure [MPa]	35 / 70	
Injection duration [ms]	1.0	

orifice. Another test injector, Injector 2, was converted only the nozzle holes diameter from 0.166 to 0.250 mm to get the same LHV (Low Heating Value) with single injection quantity of diesel. However, there was hard to get the same LHV by only converted the nozzle holes diameter [11]. In addition, the enlarged nozzle holes diameter, the larger SMD (Sauter Mean Diameter). Thus, the other test injector, Injector 3, was enlargement both the nozzle holes diameter (0.166 → 0.250 mm) and the nozzle path orifice (0.6 → 1.0 mm) to increase the injection quantity and to keep the fuel particle diameter.

In spray visualization system, test injectors were controlled the injection duration and the number of injection by a multi-stage engine controller (Zenobalti, ZB-8035) which also controlled a strobe light. As Table 1, the three test injectors were used. Nitrogen was supplied to a high pressure chamber to form the ambient pressure. The inside pressure of high pressure chamber was measured by a pressure sensor (Kistler, 6056A) mounted in the high pressure chamber. The pressure sensor signal was amplified by a charge amplifier (Kistler, 5015). A camera (Nikon, D90) was connected and controlled by a computer for spray image capture and save.

DME injection quantity measuring device was compressed by nitrogen to maintain DME liquid phase. At front side of device, the liquid DME was shown through quartz which was marked the volume grid. After checking the quantity, the exhaust valve was opened to drain out DME.

Signal synchronization of spray visualization system was shown as Figure 4. First, camera shutter opened during 1000 ms, and trigger signal was inputted through the multi-stage engine controller, then DME was injected into the high pressure chamber during 1ms. The strobe light input signal was passed to the strobe light after the delay time from the trigger time. The time of strobe light was approximately 8 ~ 20 μs, at this moment the spray image was captured.

Table 2 shows the condition of injection quantity measurement test. In this research, injection quantity of DME was measured using the test injectors when the injection pressure was varied by 5 MPa from 35 to 70 MPa. In all conditions, the injection duration was 1 ms and 1000 times injected in each condition. Nitrogen was used to pressurize inside the high pressure chamber by 5 MPa to modify the ambient pressure of driving engine and to remain liquefied DME at atmospheric temperature.

The spray visualization tests were carried out as condition of Table 3. DME was injected at atmospheric temperature ambient pressure at 2.5 and 5 MPa when injection pressure was 35 and 70 MPa. In this test, three test injectors were used with setting the 1 ms of injection duration in all conditions. The subjects were measuring of the penetration length and spray angle which were based on Figure 5.

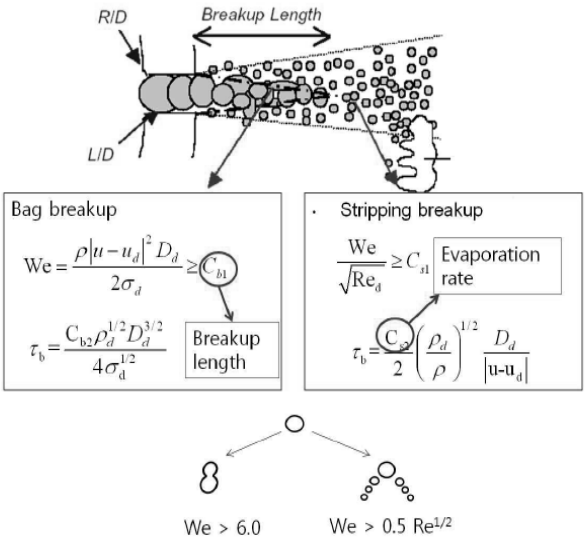

Figure 6 Reitz-Diwakar break-up model

Table 4 Simulation model and numerical condition

Simulation model	k-w SST turbulence model
	Implicit unsteady - Time step : 5.0E-3 ms - Maximum physics time : 3.1 ms
	Lagrangian multiphase - Reits-Diwakar break up - Drag force - Quasi-steady evaporation
Numerical condition	Ambient pressure : 5 MPa
	Ambient temperature : 500 K
	Fuel temperature : 310 K
	Adiabatic

There were many investigations to analyze correctly about the turbulent flow by using DNS (Direct Numerical Simulations) or LES (Large Eddy Simulations). However these are not able to get satisfied results because of its low computational performance and convergence time limitation. On the other hand, 2nd turbulent model one of the of eddy viscosity models in RANS (Reynolds Average Navier-Stokes) was shown the satisfied results from the various flow field at the short time. In this analysis, a k-w SST (Shear Stress Transport) model by Menter was accepted to the turbulent model. This model was indicated to expect the back-pressure gradient or flow field of separation flow respectively.

STAR-CCM+ ver.6.02 was used to analyze the DME spray shape at the enlarged injector nozzle hole and spray visualization tests. The simulations were accomplished at the same condition of experiment. Table 4 shows the simulations model and numerical condition. Reitz-Diwakar break-up model was assumed two types of separation processes that were Bag break-up and Stripping break-up. The Bag break-up occurs when the internal pressure of fuel particle overcomes the surface tension due to the effect of low pressure around the fuel particle ($We>We_{crit}$). Stripping break-up takes place when fuel is trimmed on the particle surface by surface tension. Here, surface tension is dependent on ambient condition of fuel particle surface ($We>cRe^{0.5}$). Fuel particle split is affected dominantly by Weber number described to function of velocity, density, and surface tension. Figure 6 shows the 2-separation processes at the Reitz-Diwakar break-up model. Quasi-Steady Evaporation model is assumed the evaporation rate of fuel particle based on the mass conservation law. At this model, the fuel particle evaporation and gaseous fuel liquefaction are related to variation of the fuel particle mass as the conservation law. To improve reliability of the analysis, variation of properties by temperature and pressure of applicable fuel was inputted.

Results and Discussion

Figure 7 shows the DME and diesel injection quantity using the test injectors. All results were calculated as single injection quantity. Case of Injector 3, DME injection quantity was the largest than using Injector 1 and 2. Compared diesel injection quantity by Injector 1 and DME injection quantity by Injector 3, DME injection quantity was 1.69 ~ 2.02 times more than case of diesel. Converted these result to base on the LHV, DME injection quantity by Injector 3 was gotten the almost same LHV with diesel injection quantity by Injector 1, this results was shown Figure 8. Though this, the LHV problem of DME could be solved.

Figure 9 shows the DME and diesel spray development process. Each case shows from initial injection time to spray fully development. When Injector 2 and 3 were used, the spray shapes before 1.1ms were not symmetric. It seems that since a single needle guide was used, when needle was opened the needle could be vibrated. Thus, entire spray shapes were asymmetric. After 1.1ms, every spray was gotten the symmetric shapes. Though this,

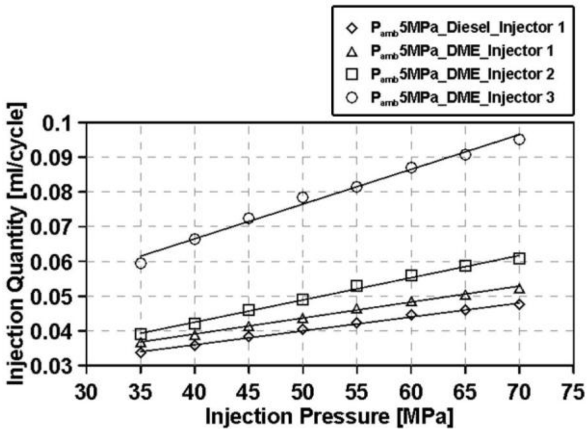

Figure 7 Single injection quantity [ml/cycle]

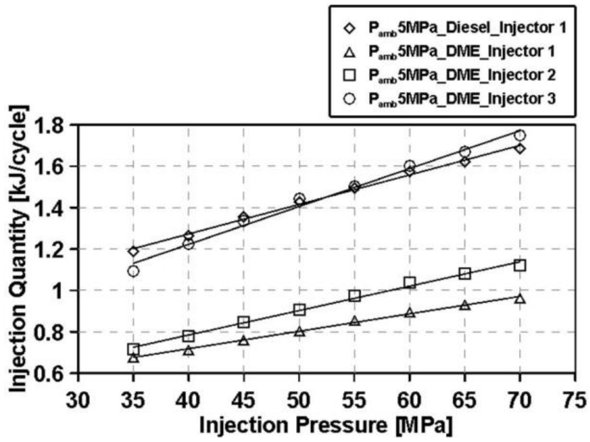

Figure 8 Single injection quantity [kJ/cycle]

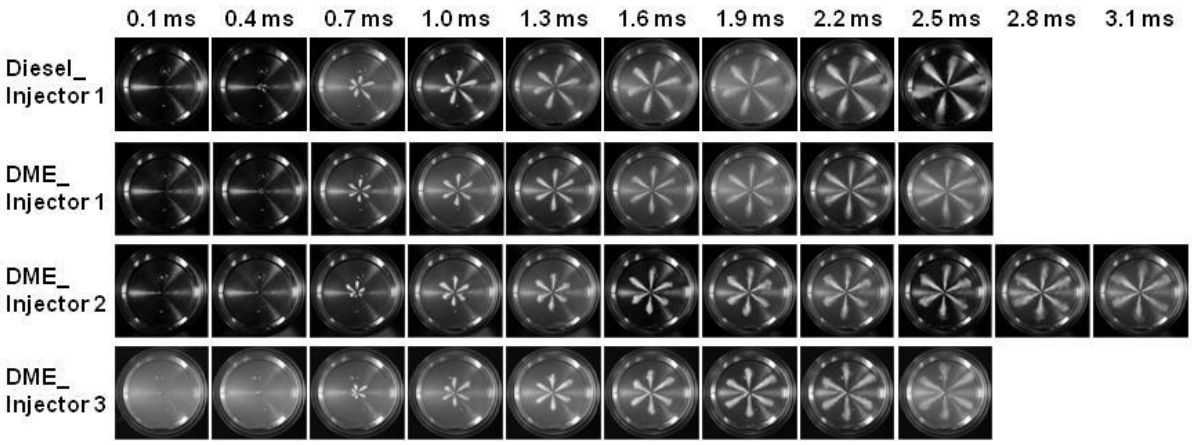

Figure 9 Spray development process at P_{amb} : 5 MPa, P_{inj} : 70 MPa

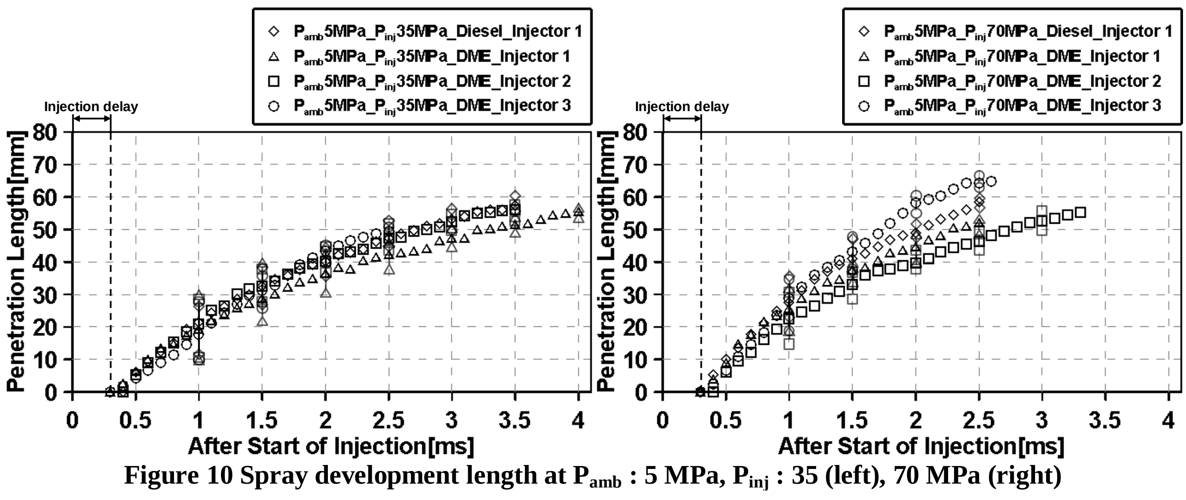

Figure 10 Spray development length at P_{amb} : 5 MPa, P_{inj} : 35 (left), 70 MPa (right)

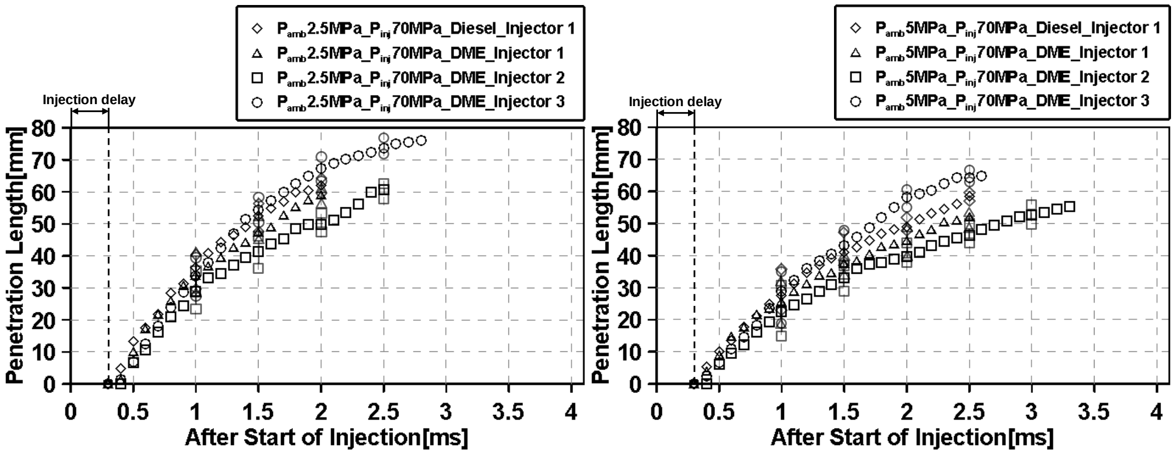

Figure 11 Spray development length at P_{amb} : 2.5(left) and 5 MPa (right), P_{inj} : 70 MPa

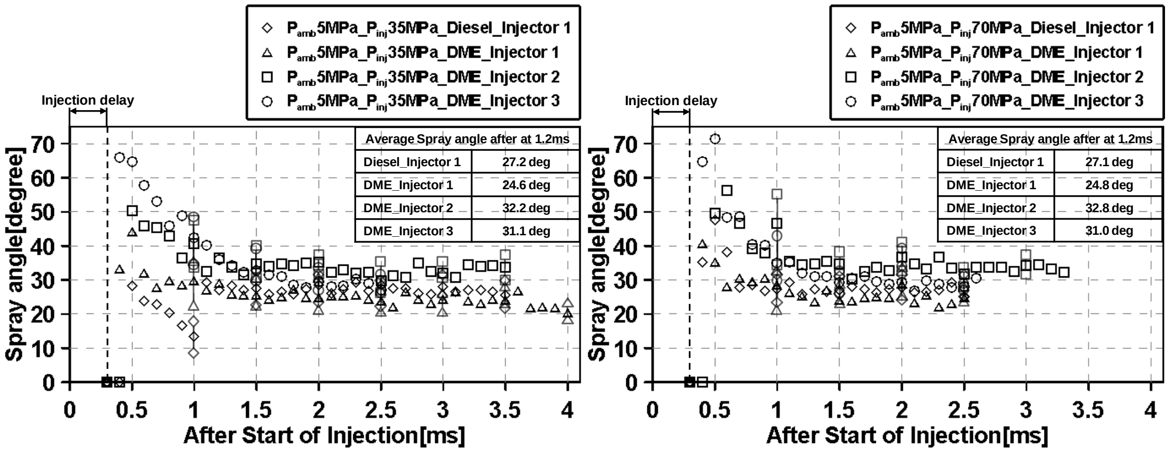

Figure 12 Spray angle at P_{amb} : 5 MPa, P_{inj} : 35 (left) and 70 MPa (right)

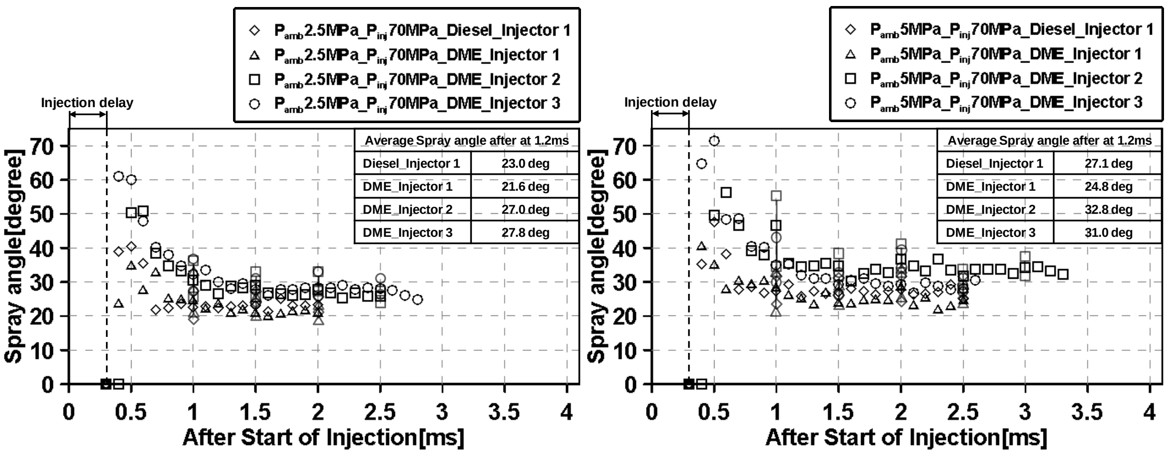

Figure 13 Spray angle at P_{amb} : 2.5 (left) and 5 MPa (right), P_{inj} : 70 MPa

when the injector is converted, it should be considered to needle vibration.

Figure 10 shows the penetration length development process of DME and diesel by using test injectors while the ambient pressure was 5 MPa in the high pressure chamber. Before 2.5 ms from initial fuel injection at 70 MPa of the injection pressure, the penetration length of Injector 3 was the longer than other injectors. It means that the DME penetration velocity was fastest when Injector 3 was used. Compared the different injection pressure, 35 and 70 MPa, when the injection pressure was higher the penetration velocity was faster. From this, high pressure fuel injection would be needed to get more combustion efficiency.

Figure 11 shows the DME penetration length by test injectors while the ambient pressure was 2.5 and 5 MPa and the injection pressure was 70 MPa. When Injector 3 was used, the DME penetration length was almost same

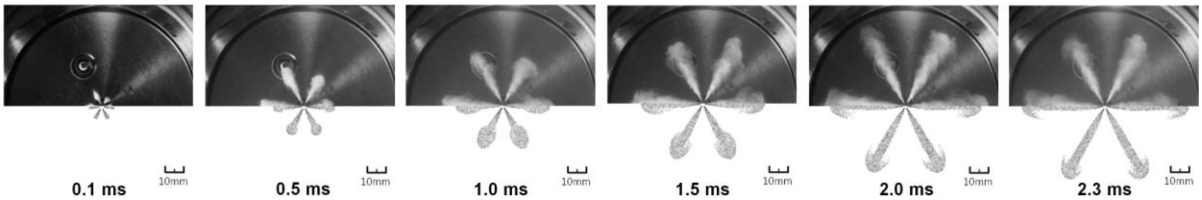

Figure 14 Comparison between experiment and simulation of the DME spray at P_{amb} : 5 MPa, P_{inj} : 35 MPa

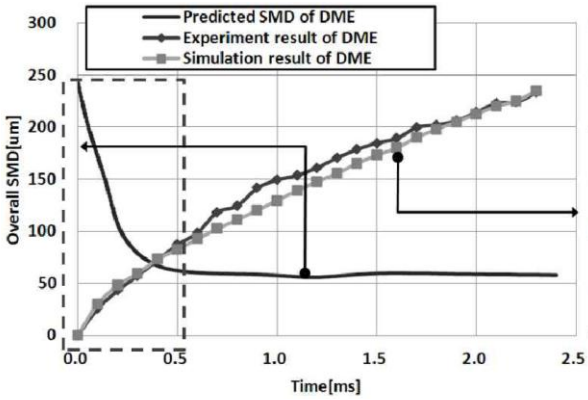

Figure 15 Penetration length of DME and predicted SMD

of even longer than case of Injector 2 even though the ambient pressure was varied. Injector 3 was designed to get more DME injection quantity than Injector 2. Some of injected DME at initial time formed gaseous DME ambient. The droplet of injected DME at later time was able to penetrate easily since DME droplet was not evaporated well inside of the preformed gaseous DME region. Thus, penetration length of Injector 3 was longer than Injector 2 at every second.

Figure 12 shows the spray angle of DME and diesel injected by test injectors while the ambient pressure was 2.5 MPa. At initial time, since the spray was kept going to develop, spray shapes were unsteady and it is shown Figure 9. After 1.3 ms, trend of spray angle was easy to analyze. Although the injection pressure was varied from 35 to 70 MPa, the spray angle was similar. Formation of the spray angle was related to nozzle geometry, there was no effect of the spray angle by varying of the injection pressure during the same ambient pressure [12]. As Figure 13, the ambient pressure effect was better that the injection pressure effect since all spray angle were larger when the ambient pressure was varied from 2.5 to 5 MPa. This phenomenon was an advantage to get a large spray angle to form a good air and fuel mixture. As Figure 12 and 13, it shows a trend that the spray angle was formed widely by Injector 2 and 3. The spray angle by Injector 2 was a little larger than Injector 3, the deviation of spray angle by each injector was about 5 %. However this rate was too small for comparison and this rate was able to ignore [13]. In addition, Injector 3 had more advantages of injection quantity and spray penetration development than case of Injector 2. Through these, enlargement of nozzle holes diameter and orifice hole is needed to get the more DME injection quantity synthetically.

DME and diesel spray behaviour as variation of the ambient pressure and temperature into the high pressure chamber were confirmed to the spray visualization tests and simulations. Both were shown that the spray penetration was increased as low ambient pressure and high injection pressure. Figure 14 shows the DME spray development process for experimental results and simulations. In Figure 15, each penetration length of both spray visualization tests and simulations was compared when fuel injection pressure was 35 MPa and ambient pressure was 5 MPa. The Error rate was 3.75 %. Penetration length of the spray visualization tests was a little longer than simulations results. SMD was dramatically decreased since fuel particle were split by the increase of Weber number as fast injection velocity at initial spray injection.

Summary and Conclusions

In this study, DME spray characteristics were confirmed by spray visualization system with 3-type injectors and the DME common rail system. Also some cases were comparison with the simulations. Through these, DME and diesel spray characteristics into the high pressure chamber were analyzed by spray visualization test and spray shape simulations. In addition, a basis data of DME engine was acquired to get the optimization of fuel supply characteristics. Summary and conclusions were as follow.

1. When Injector 3 was used, the single fuel injection quantity of DME was larger than diesel single injection quantity by Injector 1. Also DME had almost the same LHV with diesel case. Through this, it seemed that the LHV problem of DME could be solved.

2. The injection pressure was increased while the ambient pressure was constant, the development velocity of spray penetration was faster. Since the momentum of DME particle was increased due to the high injection pressure. The development velocity trend of diesel by Injector 1 and DME by Injector 3 was similar generally. Particularly, Injector 3 was shown faster penetration development than the other test injectors. Injector 2 was only converted the nozzle holes diameter, however Injector 3 was changed the nozzle holes diameter and orifice size. From this, lots of single injection quantity of Injector 3 had acquired, the evaporation of DME was less than case of Injector 2. Through this, DME particle could be moved farther.

3. The effect of spray angle by injection pressure variation was less. However the ambient pressure was higher, the spray angle was larger. The increase of ambient pressure was equal to the increase of ambient density. High ambient density of nitrogen was interrupted movement of the DME fuel particle and was made air entrainment effect well. This phenomenon was plus factor of spray angle formation. In general, the spray angle by Injector 2 was larger than case of Injector 3. The condition of Injector 3 was good to make the penetration length however it had minus factor to form the spray angle. On the other hand, Injector 1 injected DME was made a small spray angle since small amount of DME could be evaporation easily, it was vaporization before the formation of spray angle.

4. Compared the visualization test and simulations, the trend of DME spray was seemed that then the ambient pressure and injection pressure were higher the penetration length and velocity were increased. When DME injection pressure was 35 MPa and the ambient pressure was 5 MPa, the error between the visualization tests and simulations was 3.57 % and the penetration length by tests was a little longer than the simulations. The penetration length of DME was longer 12 % approximately than case of diesel. Since the momentum of injected DME by enlargement of the nozzle holes diameter was larger than conventional injector, the 1st injector.

Acknowledgements

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