

A STUDY ON THE NITROGEN OXIDES REDUCTION USING THE LOW TEMPERATURE COMBUSTION FOR COMPRESSION IGNITION ENGINES FUELED WITH DME

Su Han Park, Junepyo Cha, Sung Wook Park, and Chang Sik Lee*
Department of Mechanical Engineering,
Hanyang University,
17 Haengdang-dong, Sungdong-gu,
Seoul, Republic of Korea,
E-mail: cslee@hanyang.ac.kr

ABSTRACT

This study describes the spray, combustion and exhaust emission characteristics of dimethyl-ether (DME) fuel at various exhaust gas recirculation rate (EGR). Especially, the high EGR rate was applied to reduce the nitrogen oxides (NO_x) in the low temperature combustion conditions. Spray characteristics such as spray tip penetration, spray cone angle, and tip velocity were investigated using the DME spray images analysis which obtained from the spray visualization system including high speed camera and constant volume chamber. Combustion and exhaust emissions characteristics acquired from the DME fueled single cylinder diesel engine and emission gas analyzer, respectively.

It was revealed that DME spray had higher tip velocity than ULSD at the same injection condition; however, the reduction rate of tip velocity of DME was fast due to the evaporation. DME fuel had short ignition delay when comparing ULSD, however, the application of EGR make the ignition delay of DME extended. In addition, EGR reduced the oxygen concentration in the engine cylinder. With higher EGR, the peak combustion pressure and the rate of heat release rate slightly increased, and combustion phasing was retarded and slower heat release was observed. DME combustion exhausted lower soot and NO_x emissions than ULSD, and it showed similar or slightly lower HC and CO emissions. The application of EGR significantly reduced NO_x emission, however, the soot emission showed negligible increment. In addition, HC and CO emissions were increased slightly by EGR due to the reduction of oxygen concentration and low cylinder temperature.

INTRODUCTION

Recently, the environmental conservation and energy saving are an important issue in the industrial society. Especially, the air pollution by the exhaust gases from an internal combustion engine is essential environmental problem to solve. The major nations tighten up the regulation for the exhaust emissions from the ground vehicles. At the same time, they invest human

resources and capital to develop the new combustion technology [1-3], and to research the alternative fuels [4, 5] for the simultaneous solving of environmental conservation and energy saving.

The compression ignition diesel engine has superior thermal efficiency and lower emission of carbon dioxides which is a major reason of the global warming, compared to the spark ignition gasoline engine. However, diesel engines exhaust a large amount of particulate matter (PM) and nitrogen oxides (NO_x) due to the nature of its combustion characteristics. These characteristics of diesel engine is difficult to satisfy the strengthen regulation of exhaust emissions. Hence, many researchers are attempting to reduce the diesel emissions using new combustion technology (homogeneous charge compression ignition, low temperature combustion etc.) and alternative fuels (biodiesel, dimethyl-ether, liquefied petroleum gas, hydrogen etc.). Among them, the representative alternative fuel to replace the conventional diesel fuel is dimethyl-ether (DME). DME is produced from the de-hydrogenation reaction of methanol. Before this reaction, a methanol is derived from the synthetic gas which consists of carbon monoxide and hydrogen as a main

NOMENCLATURE

P_{amb}	[MPa]	Ambient pressure
P_{inj}	[MPa]	Injection pressure
m_{DME}	[mg]	Injection quantity of DME fuel
m_{ULSD}	[mg]	Injection quantity of ULSD
t_{asoe}	[ms]	Time after the start of energizing
SOE	[degree]	Start of energizing
EGR	[%]	Exhaust gas recirculation
\dot{m}_{air}	[g/s]	mass flow rate of total inlet air
\dot{m}_{EGR}	[g/s]	mass flow rate of total inlet air
\dot{m}_i	[g/s]	mass flow rate of total inlet air

exhaust emission characteristics. Experimental results of DME were compared to conventional diesel fuel under the same equivalence ratio condition.

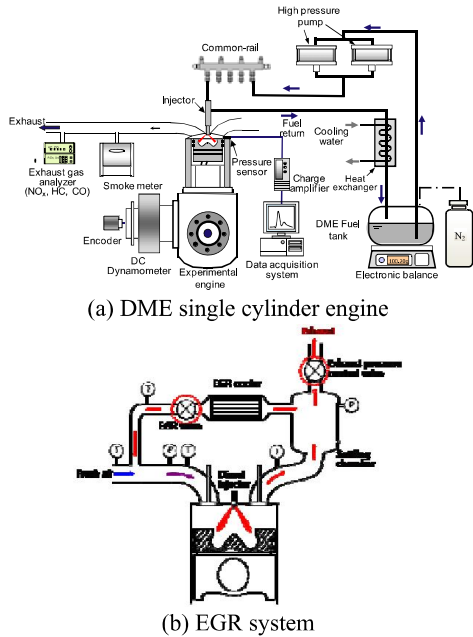


Figure 2 Schematic of DME fuelled single cylinder diesel engine with exhaust emissions analyzer and EGR system

Exhaust gas recirculation (EGR) control system

The high EGR rate was applied to this work for the reduction of NO_x emissions. As shown in Figure 2(b), the EGR system, which consists of two valves and EGR cooler, was placed between the intake and exhaust surge tanks. The EGR flow was driven by the pressure difference between the exhaust and intake surge tanks, and was varied by controlling the flow rate of intake air. The EGR rate was defined as the percentage of the total intake mixture reduced by the inducted exhaust gas, and was calculated as

$$EGR (\%) = \frac{\dot{m}_i - \dot{m}_{air}}{\dot{m}_i} \times 100 = \frac{\dot{m}_{EGR}}{\dot{m}_i} \times 100$$

where, \dot{m}_i is mass flow rate of total inlet air, \dot{m}_{air} is the mass flow rate of air, and \dot{m}_{EGR} is the mass flow rate of EGR when an exhaust gas recirculation is induced. In order to reduce the fluctuation of exhaust pressure and maintain a constant exhaust pressure, a settling chamber with a volume of 0.0093m³ was used as the exhaust surge chamber. EGR was attained by a direct link between the exhaust surge chamber and the intake pipe. The re-inducted exhaust gas was cooled with a water-cooled EGR cooler, and the subsequent intake air temperature rise occasioned by the operation of the EGR was kept lower than 5°C.

RESULTS AND DISCUSSIONS

DME spray behaviour characteristics

Figure 3 shows the spray development process of ULSD and DME fuels. In order to compare to combustion results, the

injection quantities of ULSD and DME are fixed to 6.1mg and 9.9mg, respectively. As shown in Figure 3, the ULSD spray shows slightly faster and narrower development compared to the DME spray at the same injection conditions. It is believed that the high density and kinematic viscosity of ULSD. In DME sprays, it is observed that the low ambient pressure condition caused a fast evaporation of DME droplets. Because a vapour pressure of DME is about 0.6MPa, it is believed that DME droplets easily evaporated at ambient conditions.

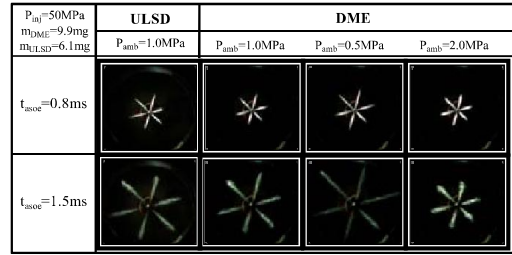
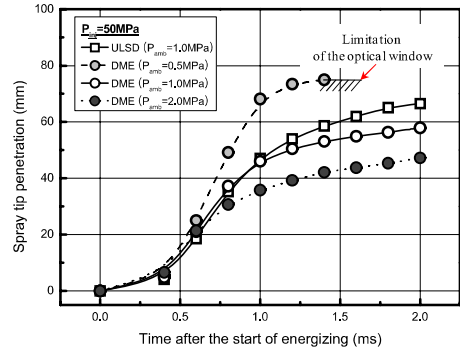
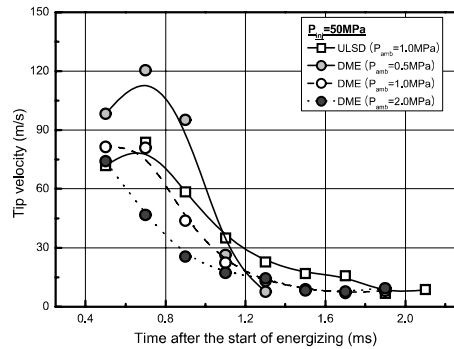


Figure 3 Comparison of the spray development process between ULSD and DME, and the DME spray development according to ambient pressure (P_{inj}=50MPa)



(a) Spray tip penetration



(b) Tip velocity

Figure 4 Spray tip penetration and tip velocity characteristics of DME fuel

The quantitative analysis on the spray images of Figure 3 shows in Figure 4 and 5. Figure 4 shows the spray tip penetration and tip velocity characteristics of DME fuel. It is well known that DME fuel has a shorter penetration and wider cone angle because the DME droplets evaporated more quickly

and has low kinematic viscosity [10, 11, 13]. In the present work, DME spray characteristic also shows similar to experimental results of previous investigations that the low ambient pressure caused a long spray tip penetration and fast spray development. Based on these results, the tip velocity at low ambient pressure shows the highest value and sudden reduction as shown in **Figure 4(b)**. In comparison of tip velocity between ULSD and DME, DME tip velocity is lower than ULSD due to the fast evaporation and fast momentum loss characteristics.

Figure 5 illustrates the spray cone angle characteristics. The spray cone angle of DME is wider than that of ULSD because lower surface tension and kinematic viscosity of DME promotes droplet breakup and atomization. Thus, small droplets easily spread to outer direction by entrained air. In addition, the high ambient pressure induced the wide spray cone angle by the restrained of the axial direction progress. In **Figure 4 and 5**, the spray behaviour at 1.0MPa and 2.0MPa of ambient pressure is regarded as that at about BTDC 25° and TDC [14]. In addition, these results can be used to analyze the combustion and exhaust emissions characteristics.

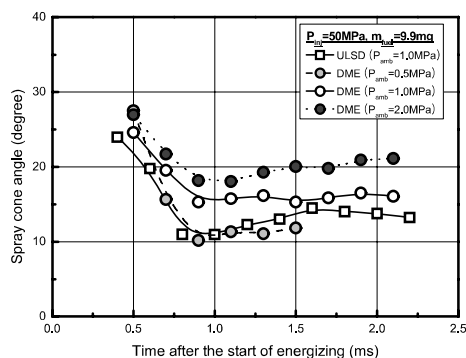
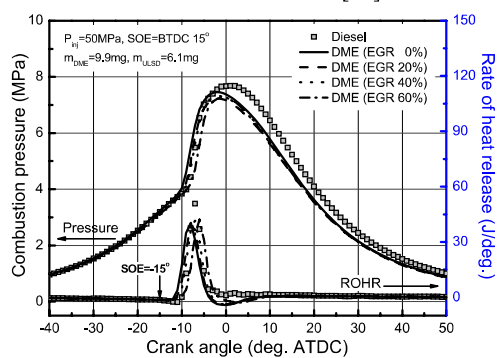


Figure 5 Spray cone angle characteristics of DME fuel at various ambient pressure conditions ($P_{inj}=50\text{MPa}$, $m_{fuel}=9.9\text{mg}$)

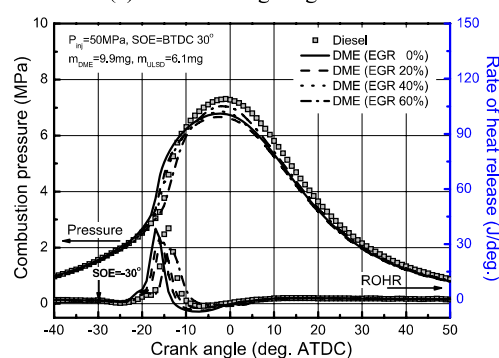
Combustion and exhaust emission characteristics of DME fuel

The combustion pressure profile and the rate of heat release history of ULSD and DME fuels at BTDC 15° and BTDC 30° of the energizing timing are represented in **Figure 6**. **Figure 6** also shows the effect of the EGR rate on the combustion and emissions characteristics. The heat release rates are acquired from the simple thermodynamic analysis which assumes the conservation of energy with the measured in-cylinder pressures. The simple thermodynamic method does not consider the heat loss to cylinder wall and mass loss (blow-by) to crevice volume. As shown in **Figure 6**, DME combustion showed a fast ignition due to the high cetane number, and its peak combustion pressure is lower than ULSD due to the low lower heating value (LHV). Considering the end of the fuel spray (about 7~8degree after energizing), the combustion as the fuel injected at BTDC 15° start before the end of spray due to the short ignition delay. However, in case of BTDC 30°, the ignition began after the end of spray. It is believed that these characteristics have an influence on the emission characteristics, especially HC emission [15]. The rise rate and peak of

combustion pressure at BTDC 30° is more smooth than those of BTDC 15°. On the other hand, as EGR rate increased, combustion phasing is retarded and more gradual heat release is observed. Therefore, the ignition delay is extended due to the low oxygen concentration in the combustion cylinder by high EGR. Due to the extended ignition delay and high cooled EGR rate, more premixed in-cylinder condition and lower combustion temperature were achieved, which enable to reduce NO_x and soot emissions at the same time [16].



(a) Start of energizing = BTDC 15°



(b) Start of energizing = BTDC 30°

Figure 6 Effect of the increase of the EGR rate on the combustion pressure and rate of heat release characteristics of DME fuel at BTDC 15° and BTDC 30°

Figure 7 shows the soot and NO_x emissions characteristics of DME under the various EGR rate conditions. As shown in **Figure 7(a)**, the soot emission of DME is lower than that of ULSD in overall injection timings. It is well known that soot is formed in fuel-rich regions under high temperature conditions, and the soot precursors are unsaturated hydrocarbons such as acetylene (C_2H_2), ethylene (C_2H_4), and propargyl (C_3H_3) in combustion products [7]. As previous investigations, the increase of the oxygen content in fuel induced the decrease of the proportion of fuel carbon [7], the number of C-C bond [17], and soot precursors [18]. Therefore, DME with about 34.8 wt% oxygen content have naturally low soot emission. In addition, the slight increase of soot emission by the increase of EGR rate is due to the reduction of in-cylinder temperature and oxygen concentration. However, the increment of DME soot emission by the EGR is negligible. On the other hand, NO_x emission as illustrated in **Figure 7(b)**, showed low level for DME fuel

compared to ULSD. This can be explained by a short ignition delay, small amount of fuel injected during the ignition delay, and small amount of fuel burned during the premixed burning phase of DME [19]. These characteristics caused that the initial enthalpy change was lower, resulting in a reduction of the peak combustion temperature. In addition, the effect of oxygen content in DME fuel is insignificant on NO_x formation [20]. The higher gaseous specific heat capacity and lower adiabatic flame temperature of DME fuel compared to ULSD is also reasons of the low NO_x emission of DME fuel [21]. On the other hand, the application of high EGR rate showed considerable reduction of NO_x emission because the application of EGR reduces a burned gas temperature in a burned gas region. In addition, from Figure 8, it is observed that a low NO_x emission can be achieved by high EGR rate without the deterioration of soot emission, because the fuel droplets in DME spray quickly evaporate as well as high cetane number [22, 23].

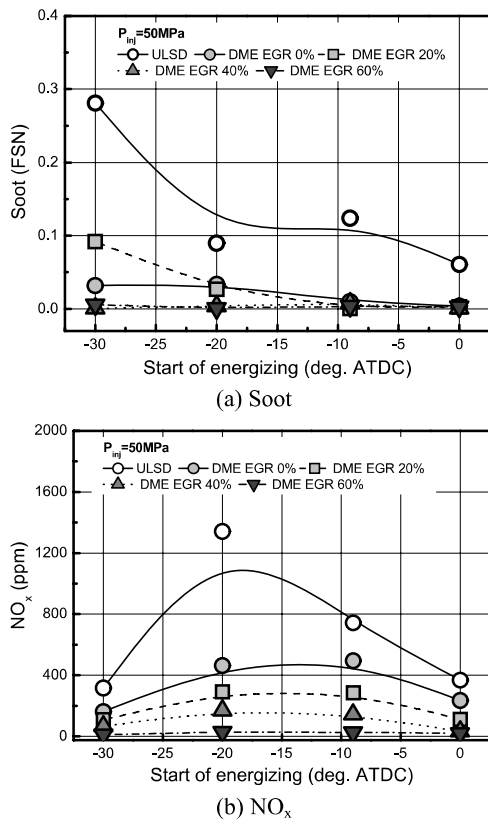


Figure 7 Effect of the EGR rate and injection timing on the soot and NO_x emissions ($m_{\text{ULSD}}=6.1\text{mg}$, $m_{\text{DME}}=9.9\text{mg}$)

Figure 8 shows the HC and CO emissions characteristics of DME fuel according to EGR rate. As shown in Figure 8(a), the HC emission of DME fuel is almost similar or lower than that of ULSD except an early injection case [21, 24]. HC emissions mainly generated from the combustion region where combustion take place under fuel-rich conditions due to incomplete air-fuel mixing, and it consist of partially or completely unburned fuel. DME fuel has a small over-rich or

over-lean regions which formed in ignition delay due to short ignition delay. In addition, about 34.8wt% of oxygen content of DME fuel and good mixing characteristics reduce the HC emissions [20].

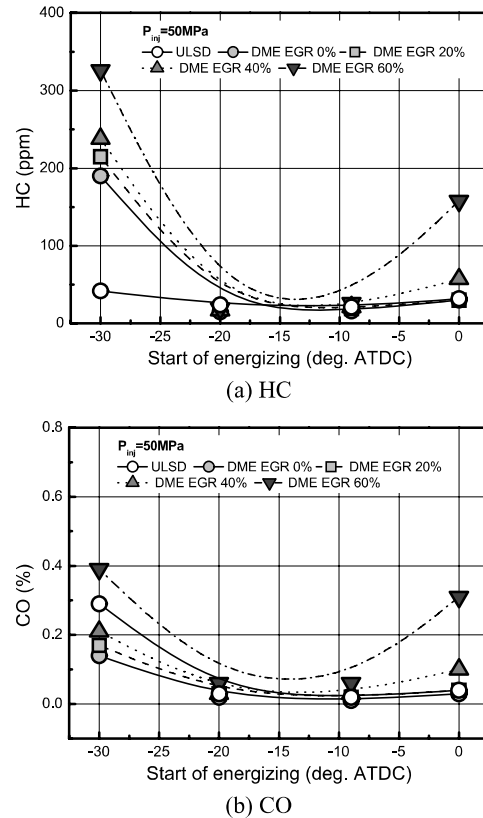


Figure 8 HC and CO emission characteristics for the EGR rate and injection timings ($m_{\text{ULSD}}=6.1\text{mg}$, $m_{\text{DME}}=9.9\text{mg}$)

In Figure 8(a), HC emission shows the minimal value at BTDC 15° of energizing timing. This is the reason why the combustion started before the end of the spray due to short ignition delay [15]. On the other hand, the good mixing characteristics of DME fuel induce the reduction of the fuel-rich regions in the combustion period and result in lower CO emission [20]. Figure 8(b) also shows a low CO emission compared to ULSD. In HC and CO emissions characteristics, the application of EGR make worse when comparing to no EGR condition because the oxygen concentration in engine cylinder decreased by the exhaust gas recirculation.

CONCLUSION

In the present work, the spray, combustion, and exhaust emission characteristics of DME were investigated and compared to results of ULSD at the same injection and combustion conditions. In addition, the high EGR rate was applied to achieve the low NO_x emission with low soot emission. From results, the conclusions are summarized as follows.

DME spray has higher tip velocity than ULSD at the same injection condition; however, the reduction rate of tip velocity of DME is fast due to the evaporation. Then, both tip velocity showed similar value at the latter stage of spray. In addition, the lowered ambient pressure caused high tip velocity, however it also showed fast decrease.

DME fuel has short ignition delay when comparing ULSD, however, the application of EGR make the ignition delay of DME extended. In addition EGR reduced the oxygen concentration in the engine cylinder. By EGR application, the peak combustion pressure and the rate of heat release maintained or slightly increased, and combustion phasing is retarded and more gradual heat release is observed.

DME combustion exhausted lower soot and NO_x emissions than ULSD, and it showed similar or slightly low HC and CO emissions. The application of EGR significantly reduced NO_x emission, however, the soot emission showed negligible increment. In addition, HC and CO emissions little increased by EGR due to the reduction of oxygen concentration and low cylinder temperature.

Synthesizing the above results, DME fuelled diesel engine can be realized nearly low emission engine by the application of EGR and the operating of the fuel injection from BTDC 20° to BTDC 10°.

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