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The Experimental Study on the Low-temperature Combustion Characteristics of DME Fuel in a Compression Ignition Engine

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Key Words: Low-temperature combustion (LTC), Exhaust gas recirculation (EGR), Dimethyl ether (DME), Diesel engine, Nitrogen oxides (NO_x), Start of energizing (SOE)

Abstract

The aim of this work is to investigate the combustion and exhaust emission characteristics of low-temperature combustion (LTC) at various EGR test conditions using a single cylinder common-rail diesel engine. In high EGR rate combustion mode with DME fuel, 30% (Φ = 0.61) and 50% (Φ = 0.86) of EGR were respectively examined, and then the combustion, exhaust emissions, nano-particle characteristics of each cases were measured. From these results, it revealed that The ignition delay and combustion duration are prolonged as the increase of EGR rate. In addition, at an advanced injection timing (BTDC 30°), ignition delays were fairly increased because the dilution effect of EGR and also low charge in-cylinder temperature created a lean mixture, thus decreased the peak release rate.

1. Introduction

Compression ignition (CI) engine, as a typical representation of diesel engine, is widely used as power source for automobile due to their high thermal efficiency, excellent fuel economy and low regulated emissions of unburned hydrocarbon (HC), carbon monoxide (CO) and carbon dioxide (CO_2) compared to those of spark ignition (SI) engine(1-2).

However, the in-cylinder temperature in a conventional diesel engine is about 2700 K, which leads to a larger amount of NOx emissions. In addition, in the high fuel concentration regions, a large amount of soot is formed because of the absence of O_2. For diesel engines, a trade-off relationship between these two emissions is observed, and their problem is how to break through the compromise between NOx and PM (particulate matter) emissions. The regulations for PM and NOx emissions from diesel engines have strengthened and reductions in CO_2, which is greenhouse gas, emissions are also raised the important issues from environmental problems. For these reasons, alternative fuels have been subject to intensive research work all over the world because they are extraordinarily attractive alternative fuels that can be substituted for petroleum fuels for the internal combustion engines(3-4).

Dimethyl ether (DME, CH_3OCH_3) is a representative alternative fuel for diesel engine which can be synthesized from natural gas, coal, crude oil, as well as from non-fossil fuel feed-stocks, such as biomass and waste products. DME fuel is advantageous in compression ignition (CI) engines, with an oxygenated molecular structure composed of an oxygen atom (about 35% by volume) between two methyl radicals (CH_3). Due to the absence of direct carbon-carbon (C-C) bonding, DME can drastically reduce or suppress the formation and development of soot during combustion while still providing conventional diesel-like thermal efficiency. In addition, DME has

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good ignition capability in engines because it has a relatively high cetane number, as compared with conventional diesel fuel and the high latent heat of DME fuel leads to lower cylinder temperature of air-fuel mixtures early in the combustion phase. DME also has good atomization properties due to its low boiling point. Due to these benefits in diesel engines, DME is the most promising alternative fuel for diesel engines[5-6].

In recent years, low-temperature combustion (LTC) has attracted more attention for its potential to simultaneously reduce the NOx and PM emissions, even at high loads[7-8].

The objectives of this study are to analyze and evaluate the optimal operating conditions of LTC fueled with a alternative fuel (DME) in the compression ignition diesel engines.

2. Experimental Apparatus and Procedure

2.1 Experimental Apparatus

The overall setup of the experimental engine and measurement systems are illustrated schematically in Fig. 1. The arrangements of apparatus are mainly consist of the test engine, engine control system, fuel delivery and injection system, intake air-flow control system, cooled-EGR control system, combustion data-acquisition system, exhaust gas emissions analysis

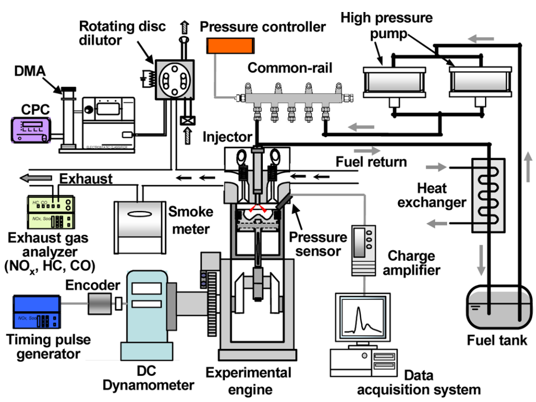


Fig. 1 Schematic diagrams of experimental apparatus for single-cylinder engine

Table 1 Specification of test engine system

Item	Description
Type	DI diesel engine
Bore×Stroke (mm)	75.0 × 84.5
Swept volume (cc)	373.3
Compression ratio	17.8
Combustion chamber type	Re-entrant
Fuel injection system	Common-rail
Number of nozzle	6 holes
Nozzle diameter (mm)	0.128
Spray angle	156°

system and nano-particle measurement system, and so on. The experimental major test engine used for this study consists of a single cylinder modified DI diesel engine (Engine-tech, RSI-090A). It has a bore of 84.5 mm, a stroke of 75.0 mm, and a displacement volume of 373.3 cm^3. The compression ratio of engine is a 17.8 and it is natural aspirated (NA), four-stroke and direct injection (DI) diesel engine.

All engine tests were performed at a constant speed of 1200 rpm using a DC dynamometer at a constant engine speed mode, the coolant and oil temperatures were maintained at 70±1°C, and fuel injection pressure maintained at a 60 MPa to reduce the variation in the test results. The experimental investigation was conducted under a steady state condition with injection mass of 16.4 mg (equivalence ratio, Φ = 0.43), which is coincident to 10 mg of diesel fuel to consider the LHV of fuel.

In high EGR rate combustion mode with DME fuel, 30% (Φ = 0.61) and 50% (Φ = 0.86) of EGR were respectively examined, and then the combustion, exhaust emissions, nano-particle characteristics of each cases were measured and compared to without EGR combustion. The injection timing of DME fuel was varied from 40° BTDC to TDC in step of 5° crank angle. In order to reduce the effect of the induction of exhaust gas on the increase of intake air temperature, cooled-EGR was adopted. The detailed experimental test conditions for this study are listed in Table 2.

Table 2 Experimental test conditions

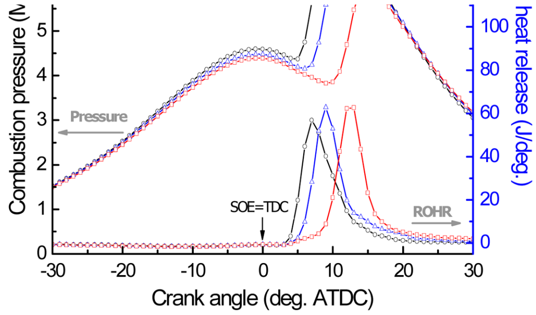
Item	Description
Test fuel	DME
Engine speed	1200 (rev./min)
Coolant temperature	70±1 (°C)
Oil temperature	70±1 (°C)
Injection pressure	60 (MPa)
Direct injection timing	BTDC 40°~TDC
Injection mass	16.4 (mg)
EGR rate	0, 30%, 50%
Total equevalence ratio	0.43, 0.61, 0.86

3. Results and Discussions

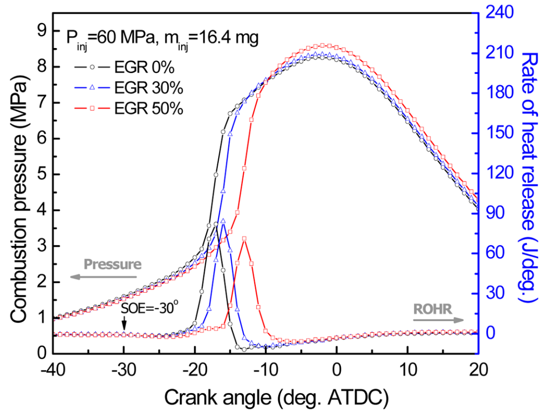
3.1 Effects of high EGR rate on combustion characteristics

The combustion pressure and heat release rates of DME fuel for 0%, 30%, and 50% of exhaust gas recirculation (EGR) rates at different injection timing are shown in Fig. 2(a) and (b), respectively. Generally, the combustion pressures and heat release profiles for three cases are similar at injection timing of TDC. However, ignition delay and combustion duration are prolonged as the increase of EGR rate. In addition, at an advanced injection timing (BTDC 30°), ignition delays were fairly increased because the dilution effect of EGR and also low charge in-cylinder temperature created a lean mixture, thus decreased the peak release rate. The use of high EGR rate lowers cylinder temperatures during the expansion stroke due to its greater heat capacity, thermal and chemical effects, with the dilution effect being more significant and that would result in the increased ignition delay period and thus more mixing of the charge. Consequently, the heat-release rates would be dominated by the low temperature premixed phase of combustion thereby simultaneously reducing the NOx and soot emissions.

In Fig. 3, the indicated specific effective pressure (IMEP) for 30% and 50% of EGR are slightly higher when compared to the without EGR because the heat release of fuel generated between the end of compression stoke and the beginning of expansion stroke due to the prolonged ignition delay and combustion duration. In addition, as the advance of injection timing, the difference of IMEP for EGR cases is lower



(a) Injection timing (tinj) = TDC



(b) Injection timing (tinj) = BTDC 30°

Fig. 2 Effect of EGR rate on the combustion characteristics of DME

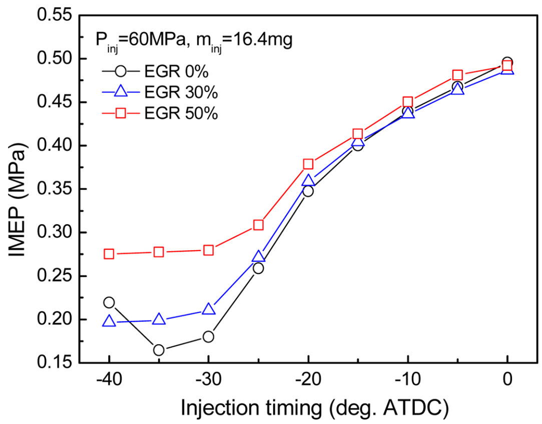
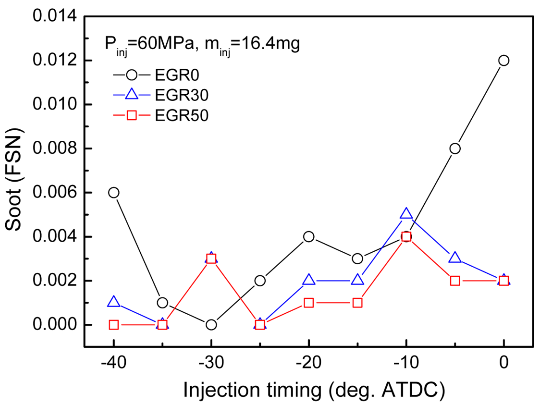


Fig. 3 Effect of EGR rate on the combustion performance of IMEP

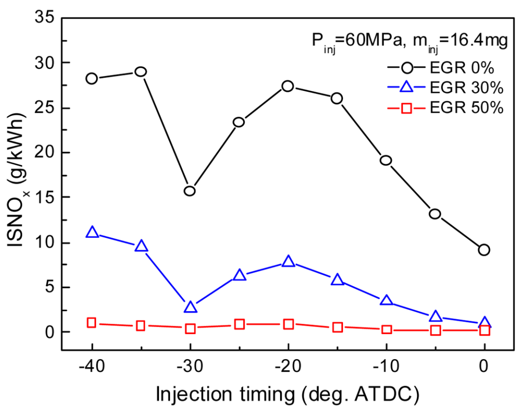
than that of without EGR. It can be concluded that longer ignition delay improved the conversion combustion heat to work.

3.2 Effects of high EGR rate on exhaust emission characteristics

Figure 4(a) and (b) show the effect of EGR rate and injection timing on the exhaust emissions of soot and ISNOx characteristics, respectively. As shown in Fig. 4(a), DME combustion exhibited extremely low level of soot emissions at all injection timing ranges in spite of EGR because the high oxygen content, the absence of soot precursors and the short diffusion combustion phase suppressed soot formation. In general, both soot formation and soot oxidation mechanisms are direct functions of combustion temperature



(a) Soot emission

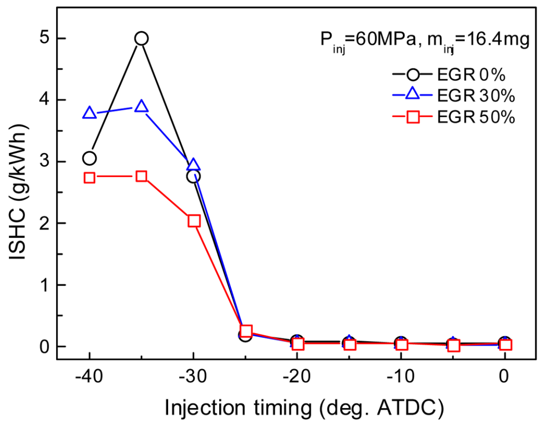


(b) NO_x emission

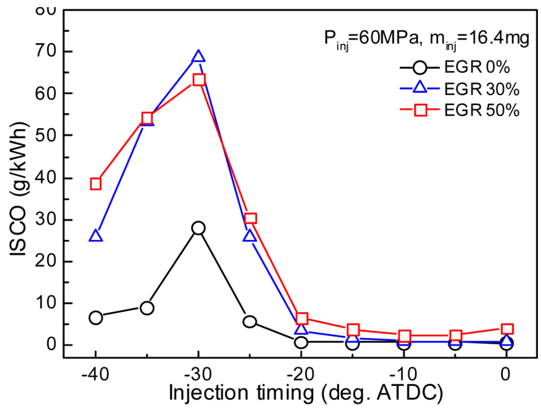
Fig. 4 Effect of EGR rate on the exhaust emissions of soot and ISNOx

and net soot release is maximized when the two mechanisms equally compete with each other. A decrease in temperature along an equivalence ratio isopleth from the location of maximum net soot release results in a more dramatic reduction of soot formation than soot oxidation, causing net soot release to decrease. However, if combustion temperature is higher than the location of maximum net soot release, then a decrease in combustion temperature will result in soot formation decreasing more slowly than soot oxidation, causing net soot release to increase. To consider the mechanism of soot creation, it can be suspected that high EGR combustion created reasonable combustion temperature for low soot emissions. In comparison with conventional diesel fuels, DME is the fuel-borne oxygen content in fuel, which could be about 35% by mass, may promote a more complete combustion and thus effectively reduce engine-out emissions of particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (UHC) in modern CI engines. However, it produced a fairly increase in emissions of nitrogen oxides (NOx), which could be partially caused by the fuel property, has been observed in the use of oxygenated fuels in general. Another possible explanation for the increased NOx formation in DME-fuelled combustion has been attributed to the lowered in-cylinder soot levels, thus lower radiation heat transfer resulting in higher in-cylinder temperatures.

In Fig. 4(b), 50% EGR combustion indicated very low NOx concentrations. This low NOx is mainly due to the dilution, thermal and chemical effects of EGR, as mentioned above. The EGR dilutes the oxygen concentration of the working fluid. Concurrently, The EGR increases the specific heat capacity of the working fluid thereby reducing the flame temperatures. Furthermore, the endothermic dissociation of the EGR constituents such as H_2O may contribute to the reduction in the flame temperatures. Therefore, at steady-state conditions in diesel engines, as the EGR is increased the NOx emissions would relatively decreased as seen in this figure. In addition, 30% EGR also decreased according to the retard of injection timing. Because the continuous retard in injec-



(a) HC emission



(b) CO emission

Fig. 5 Effect of EGR rate on the exhaust emissions of ISHC and ISCO

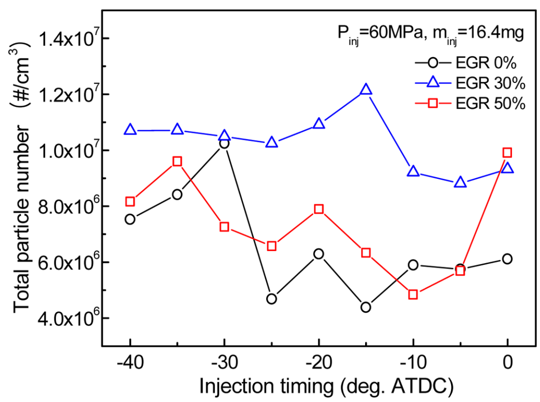
tion timing results in a continuous decrease in combustion temperature, NOx concentrations shown in this figure as continue to decrease.

Fig. 5 showed the effect of EGR rate on the exhaust emissions of ISHC and ISCO. It can be seen that the concentrations of ISHC and ISCO emissions with 30% and 50% of EGR are slightly higher than those of without EGR at injection timing range from TDC to BTDC 20°. These results can be attributed to the short diffusion combustion phase and high oxygen content of DME. The oxygen content and lower C-H ratio definitely resulted in a better complete combustion and thus the suppressed productions of unburned hydrocarbon and carbon oxidization emissions can be achieved despite of dilution effect of EGR.

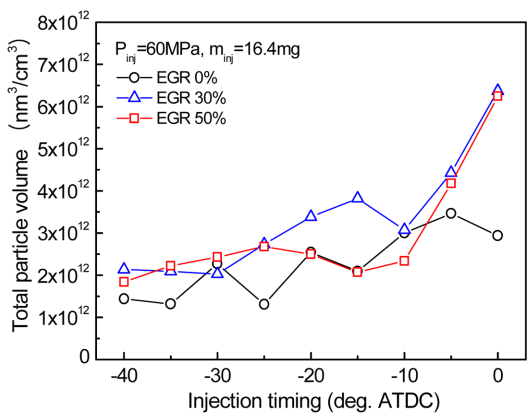
However, at advanced injection timing over BTDC 25°, the HC and CO emissions rapidly increased for all cases, and for EGR cases are considerably higher than that of EGR 0%. These results caused by that a larger amount of injected fuel trapped in the crevice volume during the prolonged ignition delay and that there is greater possibility of unburned emission formation by the crevice effect than that of EGR 0%. There can be also a fairly low combustion temperature due to high EGR rate. In addition, early injected fuel combustion produced lower combustion temperature, so it deteriorated the completion of CO to CO_2 reaction

3.3 Effects of high EGR rate on nano-particle emission characteristics

Figure 6(a) and (b) showed the effect of EGR rate



(a) Total particle number



(b) Total particle volume

Fig. 6 Effect of EGR rate on the nano-particle emissions characteristics and injection timing on the total particle number and particle volume characteristics. As shown in this figure, total particle number and volume of EGR 30% and 50% combustions indicated relatively higher than that of EGR 0 at all injection timing. In addition, 50% EGR combustion revealed lower total particle number and particle volume compared to 30% EGR. In the case of total particle volume, its levels for all cases are decreased with the advance of injection timing.

5. Summary

In order to achieve the simultaneous reduction of soot and NOx emissions fueled with DME fuel, the effects of high EGR rate on combustion characteristics, performance, exhaust emissions, and nano-particle characteristics were investigated. The following conclusions are drawn from the results.

(1) The ignition delay and combustion duration are prolonged as the increase of EGR rate. In addition, at an advanced injection timing (BTDC 30°), ignition delays were fairly increased because the dilution effect of EGR and also low charge in-cylinder temperature created a lean mixture, thus decreased the peak release rate.

(2) IMEP for 30% and 50% of EGR are slightly higher when compared to the without EGR because the heat release of fuel generated between the end of compression stoke and the beginning of expansion stroke due to the prolonged ignition delay and combustion duration. In addition, as the advance of injection timing, the difference of IMEP for EGR cases is lower than that of without EGR.

(3) DME combustion exhibited extremely low level of soot emissions at all injection timing ranges in spite of EGR because the high oxygen content, the absence of soot precursors and the short diffusion combustion phase suppressed soot formation. In the case of NOx emission, 50% EGR combustion indicated very low NOx concentrations. This result is mainly due to the dilution, thermal and chemical effects of EGR. In addition, 30% EGR also decreased according to the retard of injection timing. Because the continuous retard in injection timing results in a continuous decrease in combustion temperature.

(4) The concentrations of ISHC and ISCO emissions with 30% and 50% of EGR are slightly higher than those of without EGR at injection timing range from TDC to BTDC 20°. At advanced injection timing over BTDC 25°, the HC and CO emissions rapidly increased for all cases, and for EGR cases are considerably higher than that of EGR 0 %.

(5) Total particle number and volume of EGR 30% and 50% combustions indicated relatively higher than that of EGR 0% at all injection timing. In addition, 50% EGR combustion revealed lower total particle number and particle volume compared to 30% EGR. In the case of total particle volume, its levels for all cases are decreased with the advance of injection timing.

References

(1) J. B. Heywood, "Internal combustion engine fundamentals", McGraw-Hill, 1988.

(2) C. D. Marriott, M. A. Wiles, J. M. Gwidt, S. E. Parrish, "Development of a naturally aspirated spark ignition direct-injection flex-fuel engine", SAE paper 20008-01-0319, 2008.

(3) C. S. Lee, K. H. Lee and D. S. Kim, "Experimental and numerical study on the combustion characteristics of partially premixed charge compression ignition engine with dual fuel," Fuel, Vol. 82, No. 5, pp. 553-560, 2003.

(4) D. J. Lee, M. Y. Kim, H. G. Roh, D. S. Kim, J. H. Lee and C. S. Lee, "Combustion and exhaust characteristics of a common-rail diesel engine with homogeneous charge compression ignition combustion," Spring Conference Proceedings, KSAE, pp. 357~362, 2004.

(5) M. Y. Kim, S. H. Bang, and C. S. Lee, "Experimental investigation of spray and combustion characteristics of dimethyl ether in a common-rail diesel engine", Energy & Fuels, Vol. 21, pp. 793~800, 2007.

(6) E. Rolf, "Comparison of heat release and NOx formation in a DI diesel engine running on DME and diesel fuel", SAE paper 2001-01-0651, 2001.

(7) N. A. Henein, B. Bhattacharyya, J. Schipper, A. Kastury, W. Bryzik, “Effect of injection pressure and swirl motion on diesel engine-out emissions in conventional and advanced combustion regimes”, SAE paper 2006-01-0076, 2006.

(8) D. Choi, P. C. Miles, H. H. Yun, R. D. Reitz, “A parametric study of low-temperature, late-injection combustion in a HSDI diesel engine”, Spec Issue Adv Combust Technol Intern Combust Engines, Vol. 48, No. 4, pp. 656~664, 2005.

(9) D. S. Kim, Combustion and Emission Characteristics of Premixed Charge Compression Ignition Diesel Engine, Ph.D. Thesis, Department of Mechanical Engineering, Hanyang University, 2004.