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Analysis of Diesel Combustion Flames with Highly Oxygenated Fuels

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Abstract : With highly oxygenated fuels the smoke emissions decreased sharply and linearly with increases in the fuel oxygen content and entirely disappeared at an oxygen content of 38wt-% even at stoichiometric mixture conditions. The NOx also decreased monotonically with increases in oxygen content, and thermal efficiency slightly improved because of a reduction in cooling loss and improvement in the degree of constant volume combustion. The mechanisms of the significant reductions in emissions and improvement in engine performance were analyzed with a bottom view type DI diesel engine. Together with direct flame images, flame images were taken through an optical filter passing only two wavelengths for use in 2-D two-color analysis. The results showed that luminous flame decreased significantly with increases in oxygen content and was not detected for neat dimethoxy methane(DMM). The decrease in flame luminosity with highly oxygenated fuels corresponds with decreases in soot and cooling losses, including those due to heat radiation. The 2-D two-color flame analysis indicated that the high temperature flame and high KL factor areas apparently decreased with increasing fuel oxygen content. These results correspond strongly with decreases in NOx, smoke, and cooling loss with increases in oxygen content.

Key words : Diesel engine(디젤기관), Oxygenated fuel(함산소 연료), Combustion(연소), Optical measurements(광학계측), Two-color method(2색법), Soot(매연)

1. Introduction

Several reports have elucidated the improvements in diesel combustion and emissions by the utilization of oxygenated organic compounds for fuels or as fuel additives[1]-[6]. Dimethyl ether(DME) is a promising oxygenated fuel for diesel engines as it has sufficient ignitability and is easily made from methanol, natural gas, or coal[1],[2]. Some reports have mentioned the effect of the utilization of liquid oxygenated agents on diesel combustion and emissions[3]~[6],

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and in this case production cost would be a key factor in their practical use. Our previous reports investigated several kinds of oxygenates, including carbonates, ethers, and acetates in a DI diesel engine. Neat oxygenates or their high content blends were investigated as ideal fuels to realize desirable levels of diesel performance and emissions. The results showed significant simultaneous improvements in smoke, particulate matter, NOx, THC, engine noise, and thermal efficiency[4]. Further combustion improvements may be expected with oxygenated fuels—their smokeless nature overcomes limitations on the NOx-smoke trade off relation, making it easier to reduce NOx in other ways. Our next report revealed that ultra low emission and efficient diesel combustion including stoichiometric diesel combustion was realized with a combination of exhaust gas recirculation(EGR), a three-way catalyst, and a highly oxygenated fuel(80% diethylene glycol diethyl ether(DGM)—20% dimethyl carbonate (DMC) blend). This combustion strategy was called partial load high EGR and high load stoichiometric diesel operation[5]. However, DGM is expensive to adopt for practical use and more economical and producible liquid fuels with high oxygen content and sufficient ignitability are desired. Our most recent report attempted to apply dimethoxy methane (DMM), which would have a lower production cost than DGM, to partial load high EGR and high load stoichiometric diesel operation[5],[6]. Results comparable to those with a DGM-DMC blend were obtained with neat DMM.

In this report the combustion processes with oxygenates including DGM based highly oxygenated fuels and neat DMM were investigated with a high-speed color video camera in a bottom view type engine to reveal the mechanism of improvement in thermal efficiency as well as reductions in smoke and NOx emissions with the oxygenated fuels.

2. Experimental Apparatus and Procedure

The experiments, except for visualization analysis were conducted on a single cylinder four stroke cycle, DI diesel engine(YANMAR NF-19) with an ordinary toroidal cavity, a bore x stroke of ϕ 110 x 106mm, a stroke volume of 1007cm^3, and a compression ratio of 16.3[8]. The fuel injection system of the engine uses a four hole(Φ 0.33mm) injection nozzle that was optimized for operation with ordinary diesel fuel. Typical operating conditions were an engine speed of 1320rpm, start of dynamic fuel injection at 5℃A BTDC (optimum for fuel consumption), and an inlet coolant temperature of 80℃. Heat loss to the coolant was obtained from the difference between inlet and outlet coolant temperatures. The tested oxygenated fuels with different oxygen contents were obtained by using diethylene glycol dimethyl ether(DGM) as the base, and blending it with other oxygenates and ordinary diesel fuel as additives. Neat dimethoxy methane(DMM) and diesel fuel are also examined. The properties of the tested oxygenates are shown in Table 1. No modification to the ordinary diesel engine was made except when using neat DMM. Due to the lower boiling point of DMM, it was necessary to cool the fuel supply pipeline to the injection pump to prevent vaporization of the fuel[8].

A bottom view type engine(Nissan SC77) with the piston crown shown in Fig. 1 was used to observe the combustion processes with oxygenated fuels. The specifications of the engine include a bore x stroke of 85 x 88mm, a piston displacement of 499cm^3, a nozzle opening pressure of 18MPa, and a compression ratio of 20. The combustion processes with the oxygenated fuels in the bottom view type engine were observed with a high-speed color video camera(PHOTRON FASTCAM-ULTIMA-RGB) at a frame speed of 4500frame/s. The operating conditions during combustion observation were an engine speed of 1000rpm, an equivalence ratio of 0.56, and a coolant temperature of 85℃.

Flame images in the bottom view type engine were also taken through a filter that only passes the central wavelengths of 488nm and 610nm to measure the temperature distributions with the 2-D two-color method[7]. Light from a tungsten lamp was simultaneously recorded with the flame image to calibrate the correlation between luminous temperature and RGB signals. A rotating disk installed with seven different neutral density filters and one blank hole was placed between the tungsten lamp and the video camera to obtain eight luminous temperatures. The luminous temperatures for both wavelengths of the lamp were measured with an optical pyrometer.

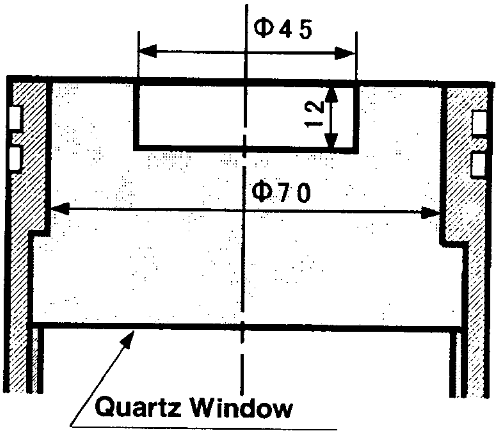

Fig. 1 Piston of the bottom view type DI diesel engine

Table 1 Properties of tested oxygenates

Oxygenates	Abbre-viation	Molecular formula	Oxygen content [wt-%]	Density [g/cm^3]	Boiling point [℃]	Calorific value [MJ/kg]
Diethylene glycol dimethyl ether	DGM	$CH_3O(CH_2)_2O(CH_2)_2OCH_3$	35.8	0.950	163	24.5
Dimethoxy methane	DMM	$CH_3O(CH_2)CH_3$	42.1	0.860	43.0	22.4
Di-n-butyl ether	DBE	$CH_3(CH_2)_3OCH_3(CH_2)_3$	12.3	0.771	142	38.7
Ethylene glycol di-t-butyl ether	EDTB	$(CH_3)_3CO(CH_2)_2OC(CH_3)_3$	18.4	0.800	169	35.8
2-ethylhexyl acetate	EHA	$CH_3(CH_2)_7O(CO)CH_3$	18.6	0.878	199	35.2
Ethylene glycol mono-n-butyl ether	ENB	$CH_3(CH_2)_3O(CH_2)OH$	27.1	0.905	171	32.4
Diethyl succinate	DES	$CH_3(CO)O(CH_2)_4O(CO)CH_3$	36.8	1.047	218	22.9
Methanol	MEOH	CH_3OH	50.0	0.793	65.1	20.5
Dimetyl carbonate	DMC	$CH_3O(CO)OCH_3$	53.3	1.079	90.9	13.5

3. Experimental Results and Discussion

3.1 Effects of highly oxygenated fuels on improvements in exhaust gas emissions and engine performance

Fig. 2 shows smoke emissions from fuels with various oxygen contents at an equivalence ratio $\Phi = 0.7$ and no EGR, a condition in which the smoke limit is slightly exceeded with ordinary diesel fuel, and at $\Phi = 1.0$ with 30% EGR, a condition in which smoke is generally formed easily. Diethylene glycol dimethyl ether(DGM) was the main base fuel and ordinary diesel fuel or one of several kinds of oxygenates, with abbreviations shown in Table 1, were blended with DGM or were used alone. The smoke emissions at both conditions decrease linearly and sharply with increases in oxygen contents. The reduction depends almost entirely on the fuel oxygen content regardless of the kind of blending agent, be it an oxygenate or ordinary diesel fuel. In particular, smoke in the stoichiometric and high EGR operation is very sensitive to the oxygen content. The oxygen content is clearly the dominant factor for the smoke emission as the compositionally different DGM 90% + diesel fuel 10% blend and DGM 60% + ENB 40% blend having the same oxygen content result in similar smoke levels, about 60% in Bosch units. The fuels with more than 38wt-% oxygen content, including neat DMM, have perfectly smokeless emissions even at the stoichiometric condition.

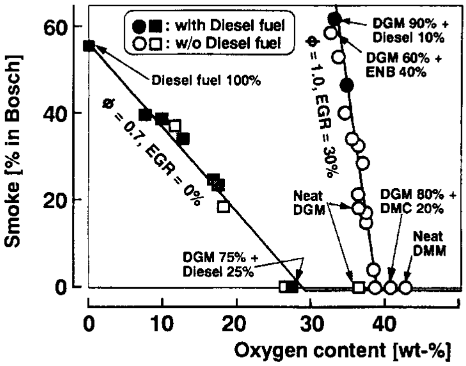

Fig. 2 Relationship between smoke emissions and fuel oxygen contents

This smokeless nature of highly oxygenated fuels even at stoichiometric conditions allows the application of a three-way catalyst, as there is no problem with soot deposition on the surface of the catalyst. Ultra low emission and efficient diesel combustion can be realized over a wide operation range with partial load high EGR and high load stoichiometric diesel operation with the highly oxygenated fuels. At 0.7 equivalence ratio, the smoke also linearly decreases with increases in oxygen content, through the sensitivity of smoke reduction to oxygen content is lower than at the stoichiometric ratio. Thirty wt-% oxygen content is necessary to realize smokeless operation at this lower equivalence ratio. Below this equivalence ratio($\Phi < 0.7$) the linearity between smoke and oxygen content shown by the straight lines in Fig. 2 gives way and the relationship is better represented by a convex line. Thus, at low equivalence ratio, the smoke reduction effect of fuel oxygen content decreases and significant smoke reduction cannot be expected from small additions of oxygenate.

Fig. 3 shows the relationship between NOx and oxygen content at 0.7 equivalence ratio. The NOx linearly decreases with an increase in oxygen content through the reduction is not as significant as in the smoke emission. This NOx reduction is mainly caused by a lowering of the adiabatic flame temperatures derived from original fuel properties as describe next.

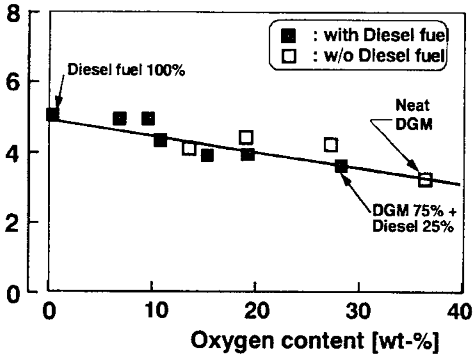

Fig. 3 Relationship between NOx emissions and fuel oxygen contents(ϕ= 0.7, EGR = 0%)

Fig. 4 shows adiabatic flame temperatures of fuels tested in this experiments. The adiabatic flame temperature linearly decreases with increasing oxygen content, in correspondence with the NOx reduction. However, adiabatic flame temperatures of several ethers are 60K higher than the other oxygenates with the same oxygen content. The reason for this higher adiabatic temperature of the ethers may be due to their lower dissociation energies. The slight fluctuation between NOx and oxygen content in Fig. 3 may be caused by differences in adiabatic flame temperatures and self-ignitability.

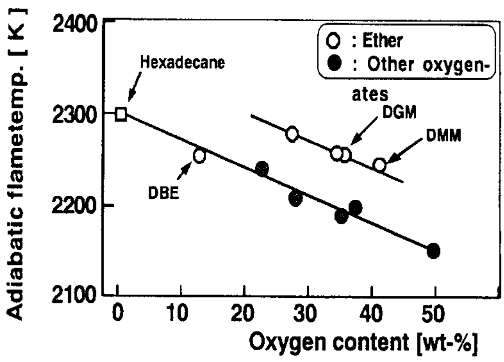

Fig. 4 Relationship between adiabatic flame temperature and fuel oxygen contents in fuels

Fig. 5 shows comparisons of brake specific energy consumption(BSEC), heat loss to coolant, the degree of constant volume combustion, combustion efficiency, and equivalence ratio between ordinary operation with diesel fuel and partial load high EGR and high load stoichiometric diesel operation with neat DMM and DGM 80% + DMC 20% blend. Compared with ordinary diesel engine, the partial load high EGR and high load stoichiometric diesel operation with the highly oxygenated fuels show comparable performance and emissions under 0.7MPa BMEP. Over 0.7MPa BSEC is superior even at higher equivalence ratios because of the high EGR, and the maximum BMEP is significantly higher at stoichiometric operation. The improvements in BSEC with highly oxygenated fuels are caused by increases in the degree of constant volume combustion and decreases in cooling loss as shown in Fig. 5. The main reasons for the decrease in cooling loss with highly oxygenated fuels may be lowered flame temperatures with EGR as well as lower adiabatic flame temperature originating from the properties of the oxygenated fuels shown in Fig. 4. A reduction in radiation heat loss with lowered flame luminosity that will be mentioned later is also not negligible.

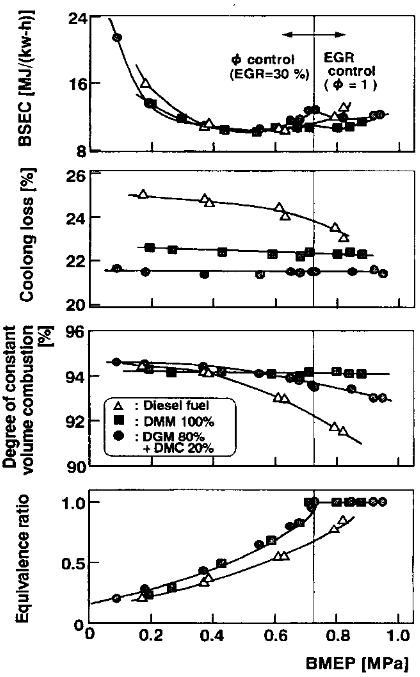

Fig. 5 BSEC and its related factors in partial load high EGR and high load stoichiometric diesel operation for Diesel fuel, neat DMM, and DGM-DMC blend

3.2 Observation of combustion flame in a bottom-view type DI diesel engine

Fig. 6 shows the direct flame images in a bottom-view type DI diesel engine with highly oxygenated fuels and ordinary diesel fuel. The flame luminosities from highly oxygenated fuels are much lower than from diesel fuel, and the luminosities significantly reduce with the increase in oxygen content, corresponding to the results in Fig. 2. In particular, luminous flame is not detected from neat DMM, showing very little soot formation. Here, with the same iris and frame speed for all fuels, there is significant difference as the R component of the RGB signal from the video camera with diesel fuel flames saturates while no luminosity is detected from DMM flames. This non-luminous flame with DMM corresponds to the decrease in cooling loss shown in Fig.5 as well as to the absence of soot formation.

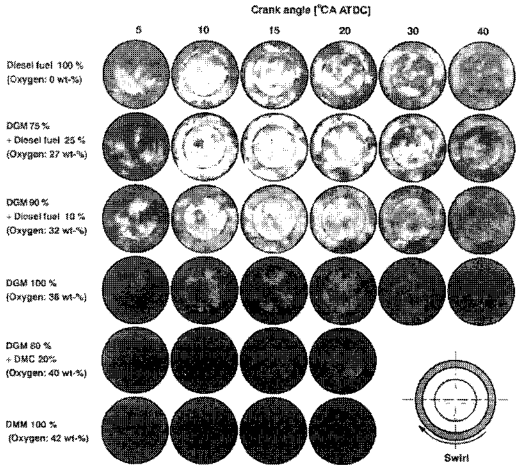

Fig. 6 Sequence of in-chamber direct flame image with highly oxygenated fuels and ordinary diesel fuel in a bottom view type diesel engine(ϕ =0.56, 1000rpm, 4500frame/s, f/16)

On the other hand, there is little difference in direct flame images between diesel fuel and DGM 75% + diesel fuel 25% blend(oxygen content : 27wt-%). And actually, the luminosity in the squish area from DGM 75% + diesel 25% blend is rather higher than from diesel fuel at several crank angles. However, reasonable results corresponding to Fig. 2 are obtained in the 2-D two color analysis that will be discussed in the following section.

The flame luminosity from DGM 90% + diesel fuel 10% blend(oxygen content :

32wt-%) is much higher than from neat DGM(oxygen content : 36wt-%) through the difference of in oxygen content between the two fuels is only a few percent. To clarify whether this increase in flame luminosity is caused by the diesel fuel addition or lowered oxygen content, direct flame images from DGM 60% + ENB 40% blend, which has the same oxygen content as the DGM 90% + diesel fuel 10% blend, are shown in Fig. 7 along with the images from the DGM 90% + diesel fuel 10% blend. While the flame luminosity from the DGM + ENB blend is slightly lower during the early stage of combustion due to lower self-ignitability, similarly luminous flames are observed at later points. Thus, the increase in flame luminosity with addition of diesel fuel like the increase in smoke shown in Fig. 2 is explainable solely from the decrease in fuel oxygen content.

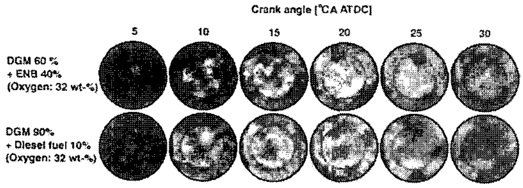

Fig. 7 In-chamber flame sequence comparing same oxygen content fuels, one with and one without ordinary diesel in blend, in a bottom view type diesel engine(ϕ = 0.56, 1000rpm, 4500frame/s, f/16)

3.3 Analyses of flame temperature and KL distributions using the 2-D two-color method

The combustions of the DGM 75% + diesel fuel 25% blend and neat diesel fuel were analyzed using the 2-D two color method. The luminosity of fuels with higher oxygen content than these was too low to analyze with the 2-D two-color method. Fig. 8 shows flame areas of high and low temperature in the combustion chamber for both fuels, and Fig. 9 shows the fractional size of flame area with temperature over 2100K where NOx are significantly formed. The high temperature flame area from the DGM 75% blend is much smaller than from neat diesel fuel during early combustion. Through the high temperature area from DGM 75% fuel is somewhat grater during later combustion, the high temperature volume from diesel fuel is likely substantially grater even during the later stage as the high temperature region from the DGM 75% blend is concentrated in the squish area where the depth is shallower. These results correspond well to the NOx reduction with the increase in oxygen content shown in Fig. 3.

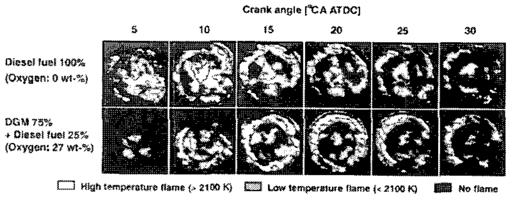

Fig. 8 Distributions of high and low temperature flame areas with ordinary diesel fuel and a DGM 75 vol% + diesel fuel 25 vol% blend

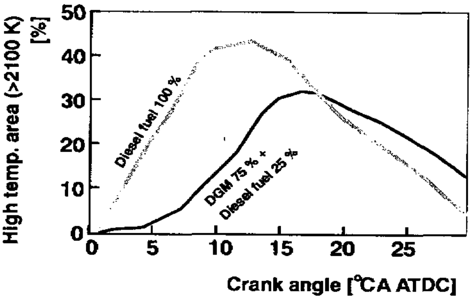

Fig. 9 Area of flame at high temperature with a DGM 75 vol% + diesel fuel 25 vol% blend and ordinary diesel fuel

Fig. 10 shows the KL factor distribution that corresponds to Fig. 8 and Fig. 11 shows the development of the fractional area with high KL factor(KL 〉 0.8)[7]. While there was very little difference between the DGM 75% + diesel fuel 25% blend and the neat diesel fuel in direct flame images, the high KL factor area from the DGM 75% blend is significantly smaller than that from the neat diesel fuel especially in the cavity area, showing that soot formation from the DGM blend is entirely less than from the diesel fuel.

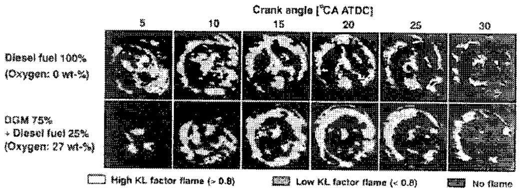

Fig. 10 Distributions of high and low KL factor flame areas with ordinary diesel fuel and a DGM 75 vol% + diesel fuel 25 vol% blend

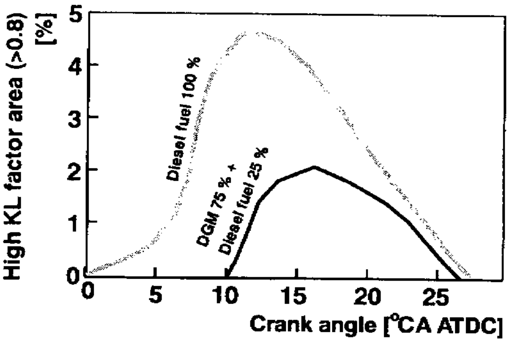

Fig. 11 Fractional area with high KL factor(>0.8) with a DGM 75 vol% + diesel fuel 25 vol% blend and ordinary diesel fuel

4. Conclusions

In this research the mechanism of the significant reductions in exhaust gas emissions and improvement in engine performance were analyzed with a bottom view type DI diesel engine. Together with direct flame images, flame images were taken through a filter passing only two wavelengths for 2-D two-color analysis. The results may be summarized as follows:

(1) Luminous flame decreases significantly with increases in fuel oxygen content and is not detected for neat dimethoxy methane(DMM). The decrease in flame luminosity with highly oxygenated fuels corresponds with the decreases in soot and cooling losses, including those due to heat radiation.

(2) The 2-D two-color flame analysis indicated that the high temperature flame areas apparently decrease with increasing fuel oxygen content. This result corresponds strongly with decreases in NOx with increased oxygen content.

(3) The flame areas with high KL factor also decrease with increased oxygen content. This result corresponds with decreases in smoke with increased oxygen content.

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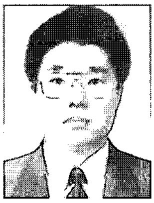

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