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EXPERIMENTAL STUDY ON EMISSION CHARACTERISTICS AND ANALYSIS BY VARIOUS OXYGENATED FUELS IN A D.I. DIESEL ENGINE

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ABSTRACT–This paper investigates the effect of oxygen composition in mixed fuel on the exhaust emissions for the direct injection diesel engine. These effects were tested to estimate the change in engine performance and exhaust emission characteristics when commercial diesel fuel and oxygenates blended fuels at a certain fuel and mixed ratio are used. Individual hydrocarbons (C_1–C_6) in exhaust gases, as well as the total amount of hydrocarbons, were analyzed by using gas chromatography to find the mechanism by which smoke emission was remarkably reduced for various oxygenated fuels. The chromatograms between a diesel fuel and a diesel fuel blended DGM (diethylene glycol dimethyl ether), MTBE (methyl tert-butyl ether) and EGBE (ethylene glycol mono-n-butyl ether) were compared. The results showed that the number of individual hydrocarbons as well as the total number of hydrocarbons of oxygenated fuel reduced more remarkably than those of diesel fuel.

KEY WORDS : Oxygenated fuel, Diesel engine, Smoke emission, Gas chromatography, Hydrocarbon

1. INTRODUCTION

Diesel-powered vehicles are popular for heavy-load transportation because their fuel efficiency is higher than those of gasoline-powered vehicles. Although diesel engines provide convenience for our daily lives, they produce a foul smell from their emission, which also contains many types of toxic air pollutants, including hydrocarbons, carbon monoxide, nitrogen oxides, sulfur oxides, volatile organic compounds, semivolatile organic compounds and soot (Monaghan, 2000). And so, to improve air quality, diesel engines are subject to severe emission regulations. These regulations throughout the world have placed the limitations of design modifications on diesel engines.

Recent studies indicated that the cetane number, aromatic content and type, sulfur content, distillation temperature, and density are important factors for emission control (Wall and Hoekman, 1984; Ulman, 1989). Reduction in the aromatic content and/or removal of heavy fractions, or the use of lighter fuels are considered to be effective measures against the mentioned problems (Manuch, 1993; Richard *et al.*, 1996).

The demand for petroleum-derived fuel is increasing. Improvements of fuel properties have become essential for emission reduction as well as for optimization of directly-related design factors and exhaust gas after-treatment. Several reports (Yukio and Takanobui, 1990; Frank and Daniel, 1993) have elucidated the remarkable effects of the addition of oxygenated organic compounds in fuel to obtain cleaner burning. The addition of lower alcohol such as methanol and ethanol to diesel fuel is effective in reducing particulate emissions without sacrificing other emission components (Likos, 1982). Non-alcohol oxygenated organic compounds have also been investigated for improvements of diesel combustion and emission reduction (Murayama, 1982). Some reports mentioned the effect of adding liquid oxygenated agents in fuel on the diesel combustion and emissions (Yukio *et al.*, 1990; Oh and Choi, 2000). Many of these oxygenates are conventionally used as organic solvents, and their production cost is a key factor in their practical use.

The authors have investigated various oxygenated fuels for direct injection diesel engines, including the conventional diesel fuel blended with carbonates and ethers up to 2.5–40 vol-%. The results indicated that smoke and particulate could be reduced without sacrificing thermal efficiency, and that the reduction rate depended almost entirely on the oxygen content of the

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In this study, we tried to achieve the remarkable reduction of smoke and efficient diesel combustion with highly liquid oxygenated fuel. And, hydrocarbon analysis as well as the remarkable reduction of smoke was attempted, too. In general, the simple measurement for exhaust emission has been performed THC (total hydrocarbon) or PM (particulate matter) using a general measuring instrument. Simple measurement methods on smoke emission with a smoke meter could not obtain accurately quantitative information between smoke creation and unburned hydrocarbons in fuel.

And so, the number of individual unburned hydrocarbons (C_1–C_6) exhausted from commercial diesel fuel and blended fuels, DGM (diethylene glycol dimethyl ether) 5 vol-% (+ diesel fuel 95 vol-%), MTBE (methyl tert-butyl ether) 10 vol-% (+ diesel fuel 90 vol-%) and EGBE (ethylene glycol mono-n-butyl ether) 20 vol-% (+ diesel fuel 80 vol-%), were investigated using GC (gas chromatography). And, this paper defines a lower boiling point hydrocarbon (below C_4) and a higher boiling point hydrocarbon (above C_5) (Y. T. Oh and S. H. Choi, 2000).

2. EXPERIMENT

2.1. Test Engine and Fuels

A horizontal, water-cooled, single cylinder, naturally aspirated, direct injection diesel engine was used and the principal specifications of the engine are shown in Table 1. Particular properties for the three kinds of oxygenates and the commercial diesel fuel are shown in Table 2, and the blended types of these fuels were used in the test. Various oxygenates were blended in a conventional diesel fuel at a volume percentage ranging from 0 vol-% to 40 vol-% at 2.5–10 vol-% intervals. To find the optimum oxygenate blending ratio, we carried out engine performance tests at various blending ratios. DGM 5 vol-%, MTBE 10 vol-% and EGBE 20 vol-% were the optimum blending ratios in engine performance test. To investigate the influences of oxygen content in the fuel and type of oxygenate on smoke emission, diesel fuel was used as the base fuel, and other oxygenate additives were blended in it. The oxygenates can be classified into a diether group (-O-), a mono ether group (-O- + -OH), a carbonate group (-O(C:O)O-), or a lower alcohol group. Several other liquid oxygenates with different oxygen contents as shown in Table 2 were used, and all oxygenates, which were used in this experiment, are alkanes group organic components; that is, they belong to the saturated hydrocarbons group.

Table 1. Specifications of test engine.

Items	Specifications
Engine model	ND130
Bore × Stroke (mm)	95 × 95
Displacement (cc)	673
Compression ratio	18
Combustion chamber type	Toroidal
Injection timing (CA)	BTDC 23
Coolant temp. (°C)	80 ± 2

Table 2. Properties of test fuels.

Proterties	diesel fuel	DGM	MTBE	EGBE
Molecular formula	$C_{16}H_{34}$	$C_6H_{14}O_3$	$C_5H_{12}O$	$C_6H_{14}O_2$
Stoichiometric Air fuel ratio	1:14.9	1:8.2	1:12.55	1:11.11
Molecular weight	226	134.2	88.15	118.18
Heating value [MJ/kg]	43.12	24.5	32.1	32.4
Oxygen content (%)	0	35.79	18.16	27.10

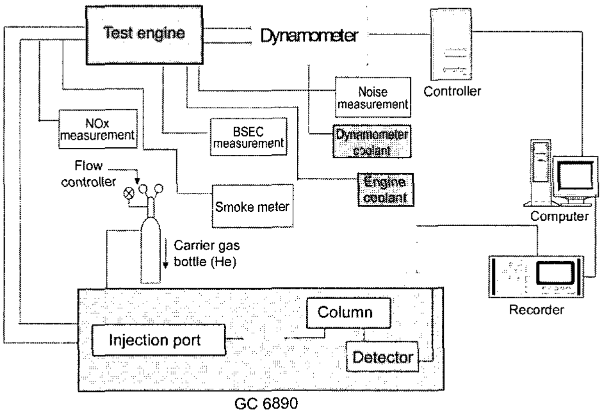

Figure 1. Schematic diagram of experimental apparatus.

2.2. Experimental Apparatus

The schematic diagram of the experimental apparatus is shown in Figure 1. The engine speeds and loads are controlled by an eddy current dynamometer. Smoke

Table 3. Specification of gas chromatography.

Item	Specifications
Column	HP-PLOT/Al_2O_3 30 m × 0.53 mm × 15.0 μm film thickness
Carrier Gas	He, 3 ml/min constant flow
Oven	80°C for 7.5 min, 20°C/min to 180°C
Injector	Split (15:1), Inlet 250°C
Detector	FID, 250°C

density was measured with a smoke meter (HBN-1500) and the NOx concentration was measured with an exhaust gas analyzer (Mod. 588). And exhaust gas sampling was carried out for individual hydrocarbon analysis with 50cc glass syringes, too. After the fuel consumption time was measured with a stop watch, the brake specific energy consumption rate (BSEC) of each fuel was calculated with the amount measured by a volumetric flow meter. In the experiments, the engine was operated with 80 ± 2°C cooling water under all operating conditions. The engine was tested at speeds of 1000, 1500, 2000 and 2500 rpm, at an engine load ranging from 0% to 100% at 25% intervals. A case with 90% load was also investigated.

Gas chromatography (GC; Hewlett Packard 6890, U.S.A) was used to measure the total number and individual hydrocarbons from C_1 to C_6. GC also has three gas sampling valves for gas flow control. The major specifications of the gas chromatography are presented in Table 3.

3. RESULTS AND DISCUSSION

3.1. Engine Performance on Oxygenate Fuels

Figure 2 shows the engine power performance curve versus the optimum blending ratio when each oxygenate additive was used. The engine power performances were almost similar regardless of the amount of oxygenate that was added at full load for all fuels. Although the heating value of an oxygenate fuel is much lower than that of a commercial diesel fuel, engine performance was similar for both types of fuel because the oxygen component in an oxygenate fuel improved combustion efficiency.

The various oxygenate fuels, which were used in this experiment, were formed at the maximum blending ratio of EGBE 40 vol-% + diesel fuel 60 vol-%. In this case, the difference in the heating value between the oxygenated fuel and commercial diesel fuel was approximately 9.95%, but the difference in the engine power was only 6.04%; these differences show the effect of the oxygen component in the fuel.

Figure 3 shows the exhaust smoke density of each oxygenate fuel blending ratio at varying engine speeds and loads. This figure shows the remarkable differences in exhaust smoke emission density between the diesel fuel and blended fuel; the differences in smoke density were more remarkable, at high loads and speeds. This difference may be mainly due to the difference in the excess air ratio between the diesel fuel and the oxygenate blended fuels by the oxygen content of oxygenates, that is, the oxygen in the oxygenate fuels themselves increasingly promoted the oxidization of fuel particles at high loads and speeds during the diffusion combustion period. In general, the oxygen concentration in the diffusion combustion period is leaner than that of the premixed combustion period. The exhausted smoke density of the diesel fuel under all operating conditions was remarkably different as the load changed from low to high. But, compared to the diesel fuel, oxygenate fuels didn't show much difference. When oxygenate fuels were used in a diesel engine, the difference between generated quantity and oxidized quantity of carbonaceous particulate matter reduced. The oxygen component in the oxygenated fuels is believed to have promoted the rate of fuel particle oxidization.

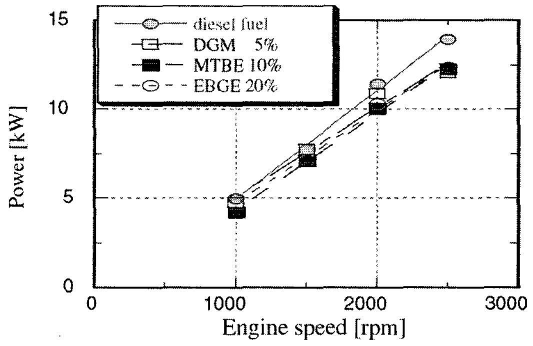

Figure 2. Performance of power at full load.

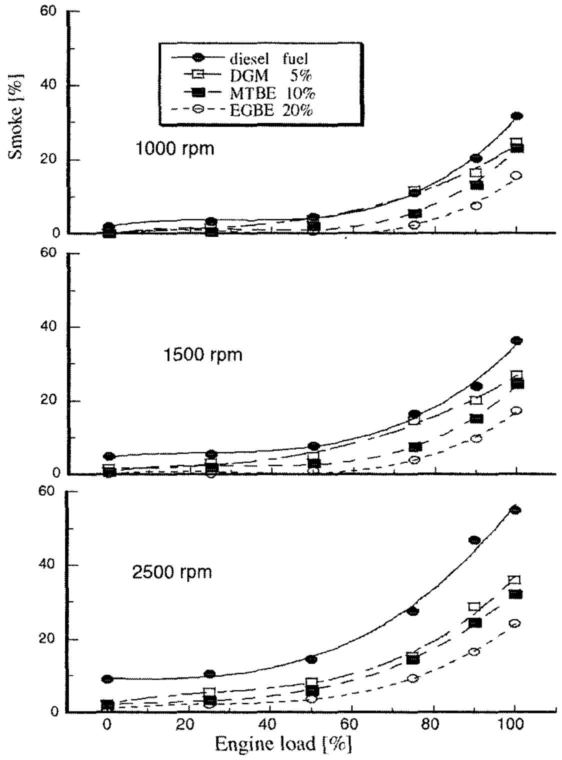

Figure 3. Comparison of smoke density at varying engine loads and speeds on oxygenate blending levels.

Figure 4 shows the effect of oxygen content in fuel on

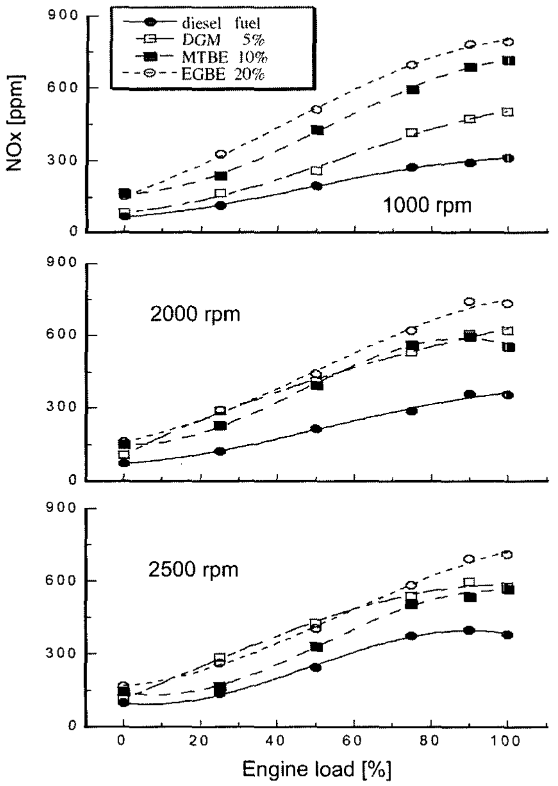

Figure 4. Comparison of NOx concentration at varying engine speeds and loads on oxygenate additive blending levels.

NOx emission at the same operating conditions as in Figure 3. The NOx concentration of the diesel fuel decreased slightly as compared with that of the oxygenated fuels, but NOx concentration increased as the oxygenate additive blending ratio increased. When the oxygen contents were increased, the temperature of the combustion chamber due to improved thermal efficiency increased, too. And, a fair amount of NOx increased in a higher temperature combustion chamber.

It was thought that NOx emission formation was affected by the rise of the cylinder temperature due to the oxygen component in the oxygenated fuels. As oxygenate additive increased, smoke density decreased and NOx concentration increased. It was thought that the oxidization process of fuel particles was activated because of the abrupt rise in flame temperature in the combustion chamber. To investigate another effect of the oxygen component, brake specific energy consumption (BSEC) was measured and calculated at various engine speeds and loads.

Figure 5 shows the performance curve of BSEC of each oxygenate fuel at various engine speeds and loads. Even though the blending ratio increased, the BSEC curves did not change significantly. Besides, the BSEC of EGBE 20 vol-% (+ diesel fuel 80 vol-%) slightly improved at higher engine speed and load operating regions.

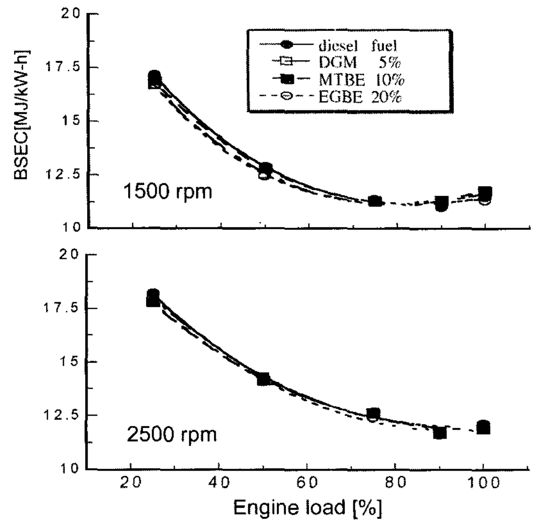

Figure 5. Comparison of BSEC at various engine loads and speeds on oxygenate additive blending level.

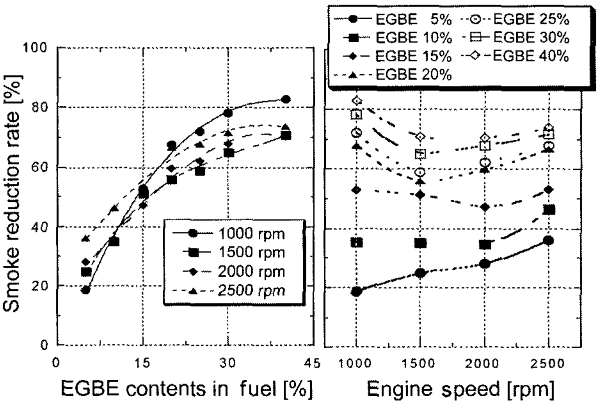

Figure 6. Rate of smoke reduction vs. engine speed at full load for EGBE 0 vol-%–40 vol-%.

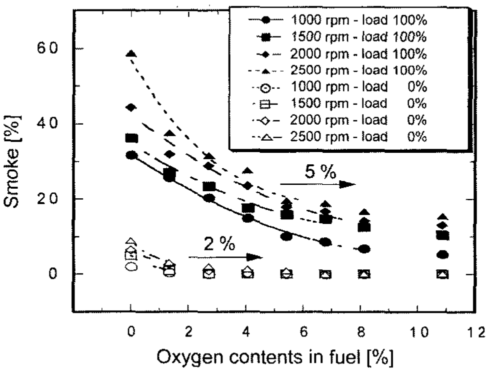

Figure 7. Comparison of smoke density of a load at 0% vs. full load with various oxygen contents.

This result means that the oxygen component was more efficient in the combustion chamber at higher loads and speeds. And combustion efficiency was improved, too.

The effect of oxygenate additives in fuel on smoke emission compared with the effect of commercial diesel fuel is shown in Figure 6. The rate of smoke emission reduced sharply with the increase in the blending ratio of oxygenate additives; therefore the reduction rate is a function of the oxygen content in fuel.

Because of the oxygen component of the oxygenate blended fuel supplied into the combustion chamber, fuel particles were able to have wider contact area with oxygen, and the fuel particles oxidized faster than when only diesel fuel was used.

Figure 7 shows the effect of oxygen contents in fuel between load 0% and full load at various engine speeds. In the non-load region, the amount of smoke emission does not change significantly with increased oxygen contents in fuels. Note that smoke emissions weren't almost exhausted at oxygen content above 2 wt-%, but the smoke increased with the decrease in the oxygen contents below 1 wt-%. At full loads, the smoke emission reduced significantly with increased oxygen contents in fuels. In particular, when the oxygen content in fuels was above 5 wt-%, the smoke emission was less than 30% at all operating ranges. This result means that much greater oxygen content in fuel is necessary to increase the smoke reduction rate. As described above, various oxygenates were blended in a conventional diesel fuel in the range of 0 vol-% and 40 vol-% with 2.5–10 vol-% intervals, and DGM 5 vol-%, MTBE 10 vol-% and EGBE 20 vol-% were found to be the optimum blending ratios during the engine performance test.

To identify the reason for smoke emission reduction, hydrocarbons were analyzed individually to find the optimum oxygenate additive blending ratio, too.

3.2. Hydrocarbon Analyses for Optimum Mixing Ratio of Oxygenate Additives using GC

Figure 8 shows the peak area on the chromatogram, when diesel fuel, DGM 5 vol-% (+ diesel fuel 95 vol-%), MTBE 10 vol-% (+ diesel fuel 90 vol-%) and EGBE 20 vol-% (+ diesel fuel 80 vol-%) were used in the diesel engine. To investigate the emitted unburned hydrocarbon characteristics, the engine speeds of 1000, 1500, 2000 and 2500 rpm were applied to the diesel engine, setting the engine load as the variable. As can be seen from the figure, at the same engine speed and load, the concentration of the unburned hydrocarbon in the exhaust diesel fuel increased more significantly than that of the oxygenate additive blending fuel, and the increase of the oxygenate additive was closely related to the decrease of the total unburned hydrocarbons.

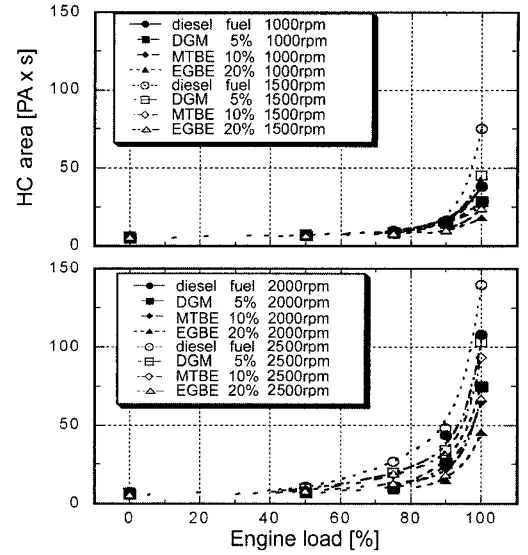

Figure 8. Total area of hydrocarbons of each fuel on chromatogram analysis under varying engine speeds and loads.

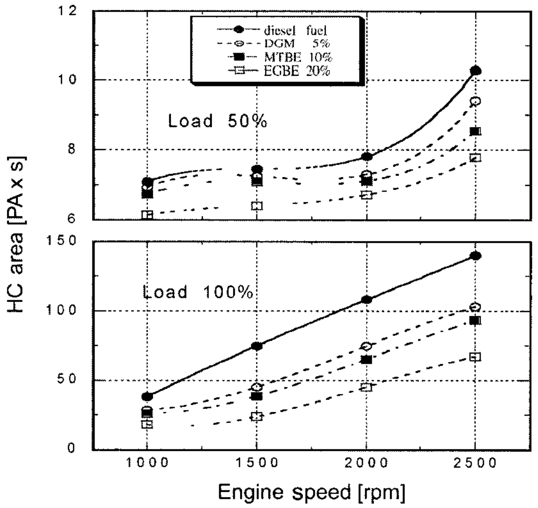

Figure 9. Total area of hydrocarbons on chromatogram analysis under varying engine loads.

In particular, the unburned hydrocarbon quantity at 2500 rpm and full load from EGBE 20 vol-% was less than that of diesel fuel at 1500 rpm and full load approximately 9.7%. When the engine was operated below the middle load, because excess air ratio was sufficient, the oxygen component in the oxygenate fuel did not significantly affect the oxidization of fuel particles. As the engine was operated above 75% load and at higher speeds, the different oxygen components between diesel and oxygenate fuels greatly changed the amount of unburned hydrocarbon emission; that is, the

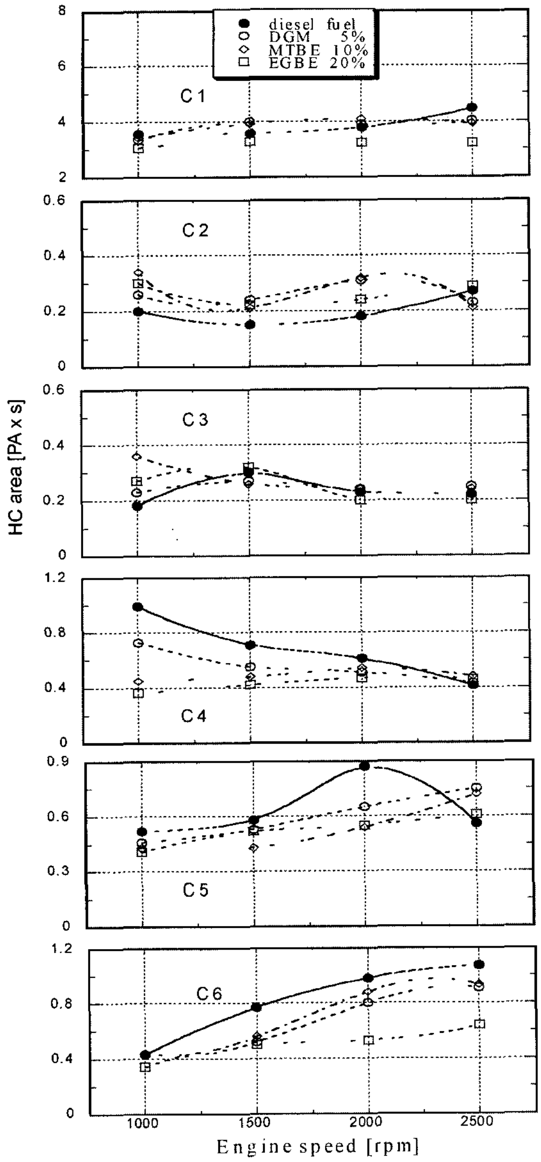

Figure 10. Area of each hydrocarbon at various engine speeds at 0% load from the chromatogram analysis.

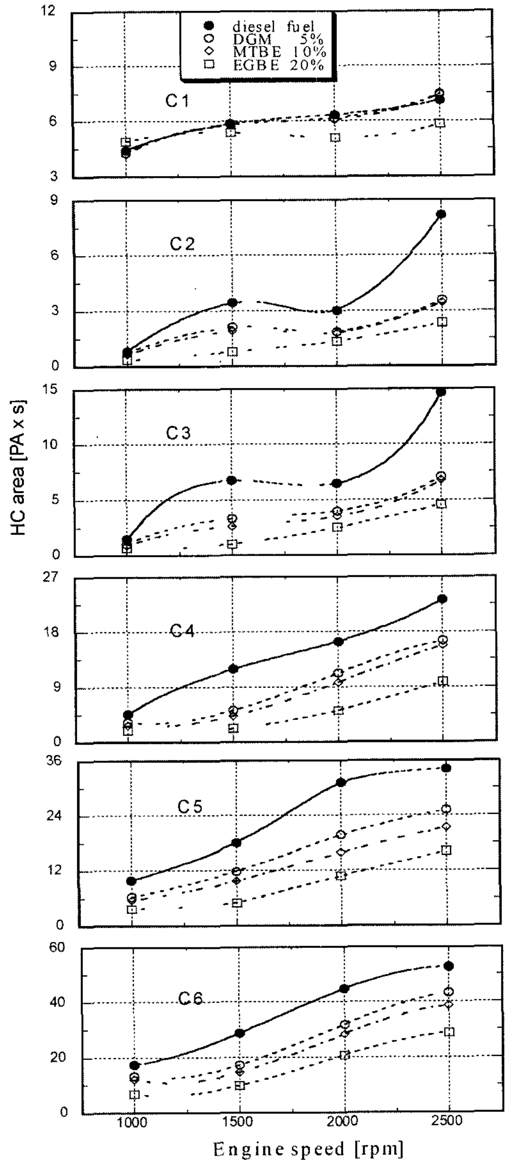

Figure 11. Area of each hydrocarbon at various engine speeds at full load from the chromatogram analysis.

oxygen component of the oxygenate additive blending fuels promoted the oxidization of fuel particles, which greatly affected smoke production, and the amount of unburned hydrocarbon was reduced significantly.

Figure 9 shows the characteristics of the unburned hydrocarbon in the exhaust for four kinds of fuels at various loads and various engine speeds. When oxygenate fuels were used, the emission quantity of the exhausted unburned hydrocarbon emissions was much lower than that of the commercial diesel fuel. As can be seen from the figure, the unburned hydrocarbon emissions increased rapidly in the diesel fuel at full load, possibly because of the lack of oxygen components. However, the unburned hydrocarbon emissions did not increase rapidly, as indicated by a rapid rise of chromatogram, in the oxygenate-added blending fuels at a high load above 75%. Because the charging efficiency of a diesel engine reduces at higher speeds, the air for complete combustion cannot be sufficiently supplied to the combustion chamber. In addition, a supply of sufficient oxygen quantity can increase the promotion of the oxidization of fuel particles, but significantly reduce the production of smoke emissions.

Figure 10 and Figure 11 show the exhausted individual unburned hydrocarbons from C_1 to C_6 at loads of 0% and 100%. Figure 10 shows the case of 0% load. The boiling points of hydrocarbons made no large difference at all operating conditions. Figure 11 shows that the case of 100% load. Individual hydrocarbon of diesel fuel increased significantly except C_1 (methane). With respect to NMHC (non-methane hydrocarbons), the comparison data between the diesel fuel and the blended EGBE 20 vol-% (+ diesel fuel 80 vol-%) showed that C_2 was reduced by 71.1%, C_3 by 78.2%, C_4 by 61.2%, C_5 by 59.8% and C_6 by 51.3% at 2500 rpm.

When compared to the results in Figure 3, the two results had many points in common for exhaust emission characteristics. As can be found from the figure, smoke emission increased linearly with engine speed. And the rising curve of individual hydrocarbon for the diesel fuel represented higher slope than that of any other case. A hydrocarbon C_1 of a low boiling point was emitted similarly among the four kinds of fuels, while hydrocarbons C_5 and C_6 of higher boiling point was emitted very differently among the fuels. As the engine speed increased, the oxidization of the hydrocarbon component, which influenced the production of smoke emission was reduced.

If oxygenate-added blending fuels (oxygen content over 2–5 wt-%) in the diesel fuel are used in diesel engines, the oxygen component in the fuel significantly reduces the smoke emission.

4. CONCLUSIONS

A four stroke, one-cylinder, water-cooled, direct injection diesel engine operating at various engine speeds and loads was experimentally investigated. Various oxygenate-added blending fuels were used in the diesel engine and were set as variables. The effect of these oxygenated fuels on the smoke emission and unburned hydrocarbons of the diesel engine was clarified to find the relationship between smoke and unburned hydrocarbons.

The conclusions may be summarized as follows:

(1) When oxygenate-added blending fuels (2.5–40 vol-%) were used instead of the commercial diesel fuel, the engine torque and brake specific energy consumption did not change significantly.

(2) As the oxygen content in fuel was increased, smoke emission reduced significantly. In particular, when the oxygen content in the fuel was above 2 wt-% at a low load, and above 5 wt-% at high load, the smoke emission rate reduced significantly.

(3) A quantitative analysis method using gas chromatography was established for C_1 to C_6. And the relationship between smoke and unburned hydrocarbons with higher boiling points above C_5 was detected on the chromatogram.

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