Engine Performance and Emission Characteristics of CRDI Diesel Engine Equipped with WCC and DOC using Ethanol Blended Diesel Fuel

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Abstract

Emission characteristics of CRDI diesel engine equipped with a warm-up catalyst (WCC) and a diesel oxidation catalyst (DOC) were investigated. The experimental investigation was conducted a neat diesel fuel, a blend of diesel fuel with 15% ethanol, a blend of diesel fuel with 15% ethanol and cetane improver EHN (2-ethylhexyl nitrate) of 7500ppm. The experiments measured the emission and engine performance according to ECE 13 mode cycles. The maximum torque provided by the ethanol-diesel-EHN blended fuel was higher than that by the neat diesel fuel at high-load conditions. The specific fuel consumption in g/kWh slightly increased with the 15 % ethanol blended diesel fuel in the low load. Smoke was decreased by more than 28-58% in the entire ECE 13 mode cycles. HC and CO emissions of the ethanol blended fuel were slightly increased; however, the mean conversion efficiencies of HC and CO on the catalysts appeared about 60-80% in the ECE 13 mode cycles. Based on measurement by the Scanning Mobility Particle Sizer(SMPS), the particulate matter(PM) nano-particle number and mass of the diesel fuel with 15% ethanol and EHN decreased by 30-40 % compared with neat diesel PM emission. The results showed that the CRDI diesel system with the diesel fuel with 15% ethanol and EHN with WCC and DOC can meet emission regulations before enforcement of a strengthened regulation such as EURO V.

Keywords: Diesel engine, CRDI (common rail direction injection), Ethanol, WCC (warm-up catalytic converter), DOC (diesel oxidation catalyst)

INTRODUCTION

Diesel engine has a high thermal efficiency and gives low greenhouse effect due to its low rate of fuel consumption and low amount of CO_2 emission compared to the gasoline engine. However, diesel engine has the problem of generating large amount of smoke because its diffusion combustion characteristics causes air to be used at a low rate, and its localized high temperature generates NOx which is a source of air pollution in the city. To solve these problems, electric control high pressure fuel injection system[1)] has been adopted recently in diesel engine. This system can atomize the spray droplet for the fuel so that the high rate of air utilization can reduce the amount of smoke. However, it is difficult to reduce emission of NOx and PM at the same time because of the properties of diffusion combustion. Ethanol blended diesel fuel has been recently studied[2-7)] as a possible alternative fuel for the petroleum[4-7)].

Because ethanol contains oxygen (35% of oxygen content) in the fuel, it can effectively reduce particular matter emission in the diesel engine. Ethanol is appropriate for the mixed fuel in the gasoline engine because of its high octane number, and its low cetane number and high heat of vaporization impede self-ignition in the diesel engine. So, an ignition improver, glow-plug, surface ignition, and pilot injection are applied to promote self-ignition by using diesel-ethanol blended fuel. Diesel emission problem in cold start is the same as that of the case of gasoline. Especially, diesel engine has low exhaust gas temperature, so it will require a warm-up catalyst (WCC) to get easily the light-off temperature for the catalyst.

Diesel with WCC and DOC can reduce THC, CO, PM, aldehydes, smell and so on. Catalyst durability can reduced because of the agglomeration and sintering of the metal by exposure in the high temperature and the poisoning process by the solid carbon such as sulfur components or PM. Ethanol blended fuel has lower emission of PM because oxygenated fuel and ethanol do not have sulfur, a property that improves the durability of WCC and DOC. PM is generally composed of soluble organic fraction (SOF), carbon soot, sulfate which is a sulfur compound, etc. Nanoparticles emitted from diesel engine are classified as a carcinogenic substance. The study shows that the smaller they are, the more they penetrate deeply into the respiratory system and greatly affect the human body. Therefore, the regulation of emitted gas for the diesel engine is expected to add not only the usual PM weight but also the number of particle concentration.

In this study, from this point of view, the ethanol blended diesel fuel is used to reduce PM in CRDI (common rail direct injection) diesel engine before enforcement of a strengthen regulation such as EURO V. The worse ignitability of ethanol blended diesel fuel can be improved by using cetane improver, EHN (2-ethylhexyl nitrate). Unburned fuel and intermediate components from combustion will be oxidized by the WCC and DOC. THC, CO, smoke, and NOx are measured in the ECE 13 mode. Especially, the particle size distributions were measured by SMPS.

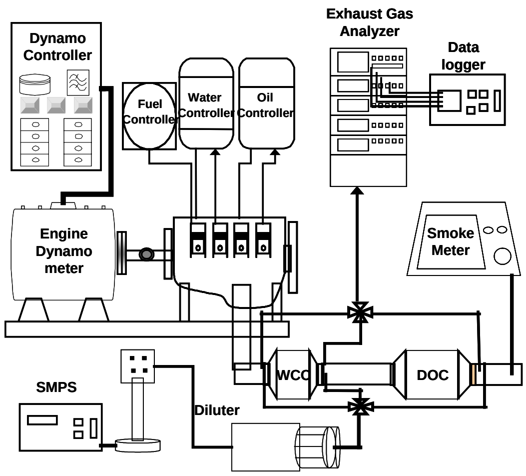

Fig. 1 Diagram of experimental apparatus

EXPERIMETNAL APPARATUS

Fig. 1 is the diagram of the main experimental device for studying the engine performance and emission characteristics. Test engine was a four-cylinder, four-stroke, after-cooled and turbocharger CRDI diesel engine with a bore of 91mm and a stroke of 96mm, and displacement of 2.497 liter. Table 1 shows specifications of the test engine.

Table 1 Specification of test engine.

Item	Specification
Engine Type	Common rail 4 cylinder
Bore × Stroke (mm)	91 × 96
Displacement (cc)	2497
Compression ratio	17.1 : 1
Power output (ps/rpm)	145 / 3800
Max. Torque (kg.m/rpm)	33 / 2000
Aspiration	Turbocharger & after cooler
Engine model	Hyundai D4CB
Valves per cylinder	4

WCC is installed in the rear part of exhaust manifold, and DOC is set up 1.2m apart from the outlet of exhaust manifold. Emission characteristics are measured at the inlet and outlet catalyst. An eddy current dynamometer (Fuchino, ESF-600) capable of adsorbing 440 kW was used. An exhaust gas analyzer (Horiba, MEXA-9100DEGR) was also used to measure HC, CO, NOx, CO_2 and O_2 concentrations. The Bosch-type smoke meter (World Env. Co. EMX-200) measured the amount of smoke emission. THC, CO, and NOx were analyzed by the flame ionization detector (FID) method, non-dispersive infrared analyzer (NDIR) method, and chemiluminescence detector (CLD) method, respectively. PM size distribution was measured by SMPS. Table 2 shows the specification of SMPS and the rotating cavity type diluter. Temperatures in the front and rear of the catalysts were measured by K-type thermocouples.

Table 2 Specification of SMPS and rotating cavity type diluter.

	SMPS		Diluter
Measuring range (nm)	5.5~340	Dilution ratio	1:15~1:300(10 cavity) 1:150~1:3000(2 cavity)
No. of channels	255	Input gas flow (ℓ/min)	Appr.1
Sample flow (lpm)	0.3	Output gas flow (ℓ/min)	0.5~5(Admissible)
measuring concentration (1/cm³)	10^{10}	Particle size range (nm)	10~1000
Scanning time	405	Heating range(℃)	OFF/80/120/150

TEST PROCEDURE

The engine performance and the emission characteristic of the exhaust gas from a WCC and DOC equipped CRDI diesel engine, which used 3 kinds of fuels, the neat diesel fuel (D100), a blend of diesel fuel with 15% ethanol (E15+D), and a blend of diesel fuel with 15% ethanol and cetane improver (E15-D-CI). In blended fuel, 1% of co-solvent (tetrahydrofuran, C_4H_8O)[9] was added into the ethanol blended fuel to improve the solubility of ethanol, and EHN 7500 ppm[10] was used as the cetane number improver. Li[11] indicated that 15% content of ethanol in diesel fuel was the optimum content for optimum smoke emission and engine performance of the direct injection diesel engine. The steady-state of ECE (economic commission for europe) 13 mode was used in the experiment[8]. The concentration of THC, CO, CO_2, O_2, NOx and smoke were continuously measured at the front and rear of catalysts in each mode. The conversion efficiency is calculated as $((1- A_{out})/A_{in}) \times 100$ (%).

RESULT AND DISCUSSION

Fig. 2 shows the brake specific fuel consumption (BSFC) for each of the 3 kinds of fuels. The BSFC ranged 220-400 g/kWh except at the low load conditions (modes 2, 12). The BSFCs of the fuels were significantly different in low load conditions, but were similar in the middle and high load conditions. In case of E15-D and E15-D-CI fuels, BSFC was high at the low load condition of 10%. Especially, in case of 2 mode, E15-D fuel consumption increased because of incomplete combustion due to ignition delay. The BSFC of E15-D is the similar or lower value compared to the result of other research[7]. The BSFC of E15-D-CI is thought to be lower than those of the other fuels because of the effect of pilot injection in the CRDI diesel engine and combustion enhancement by the addition of the cetane improver.

Fig. 3 shows the break thermal efficiency. It can be calculated form the BSFC and lower heating value of the 3 kinds of fuel. The lower heating value of ethanol is about two thirds that of the diesel and is expected to increase the fuel consumption by about 6 % when 15 % of ethanol is blended in diesel. However, E15-D-CI has

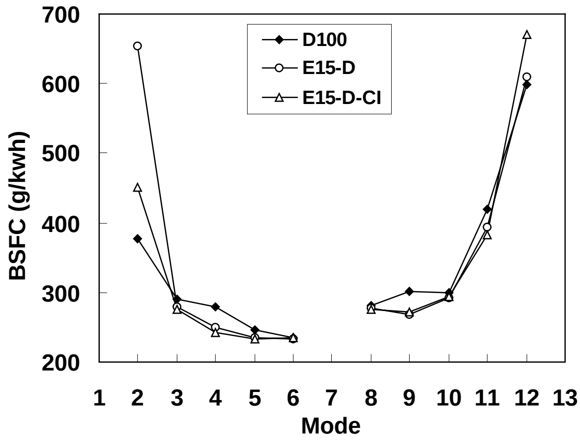

Fig. 2 Break specific fuel consumptions of the engine of 3 kinds of fuel according to ECE 13 mode cycles

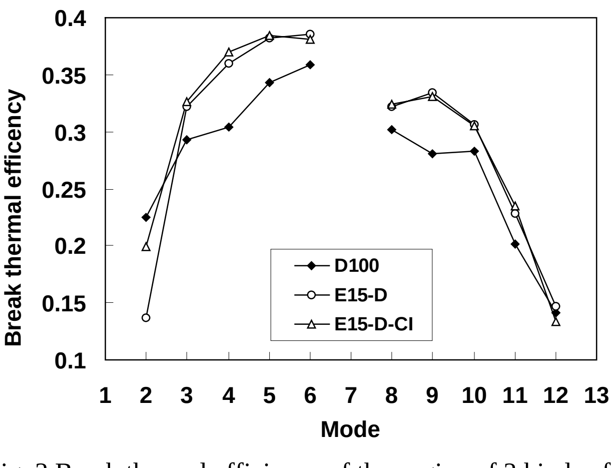

Fig. 3 Break thermal efficiency of the engine of 3 kinds of fuel according to ECE 13 mode cycles.

the highest thermal efficiency at the same horsepower. This result is due to the improved spray characteristics and atomization of fuel droplets from the lower surface tension of ethanol than the diesel and the rapid combustion from the addition of the cetane improver. And, in high speed and high load conditions, more perfect combustion is likely to occur because of the oxygenated of ethanol. Because the adiabatic flame temperature of ethanol is lower than that of diesel, the heat losses decrease in the cylinder. The exhaust gas temperature is about 10-30 °C lower than that of D100 in fig. 4.

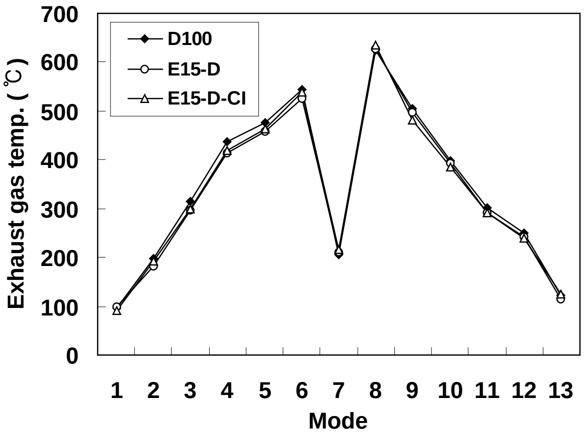

Fig. 4 Exhaust gas temperature of 3 kinds of fuel according to ECE 13 mode cycles.

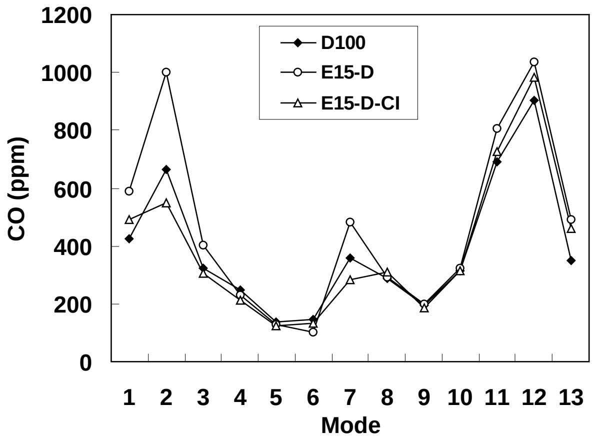

Fig. 5 CO concentrations of 3 kinds of fuel according to ECE 13 mode cycles.

Fig. 4 shows the exhaust gas temperature measured in the front of the WCC catalyst for each fuel. Ethanol blended fuels, E15-D and E15-D-CI, show about 10-30°C lower exhaust gas temperature than D100. Although the exhaust gas temperatures of the ethanol blended fuels were lower than D100 in all modes, NOx concentrations were high in some modes because of the localized high temperature spot in the combustion chamber.

Fig. 5 represents the CO emission in each mode. In case of E15-D, the CO concentration increased in idling and low load conditions, but was similar to those of other fuels in the high load conditions. The CO emission from E15-D can be explained by the increase of the quench layer due to the high latent heat vaporization of ethanol. The lower combustion 9temperature throughout the cycle resulted in the low oxidation rate of the CO. E15-D-CI gave similar or lower CO emission than D100, except the low load. Combustion efficiency was improved by the addition of the cetane improver.

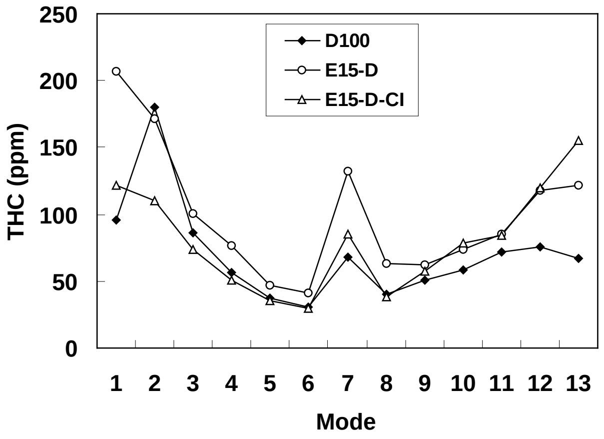

Fig. 6 THC concentrations of 3 kinds of fuel according to ECE 13 mode cycles.

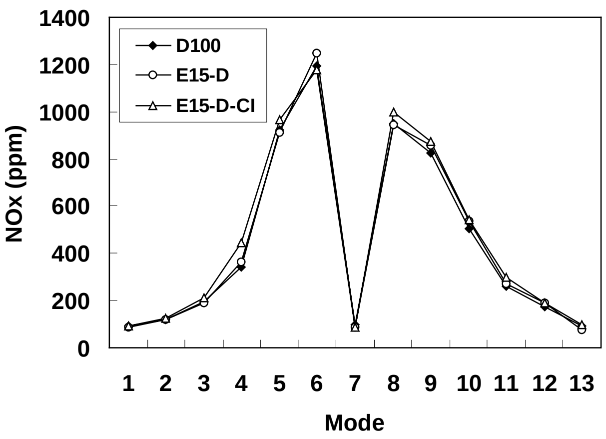

Fig. 7 NOx concentrations of 3 kinds of fuel according to ECE 13 mode cycles.

Fig. 6 shows the THC emission in each mode. The THC emission characteristic is similar to CO emission. In case of the E15-D fuel, THC emission is remarkable in the idling and low load because of the high heat of vaporization[7] of ethanol. High heat of vaporization produce slow vaporization and mixing of fuel and air. The cetane improver in E15-D-CI lowers the THC emission to a level lower than that of D100 up to mode 6, but the emission increases slightly after mode 8.

The NOx emissions of the 3 kinds of fuel were similar, as shown in Fig. 7. The NOx emissions of D100 and E15-D were the most similar, but NOx emission of E15-D-CI increased by 4-20% more than that of D100. This increase resulted in the localized high combustion temperature by the premixed combustion.

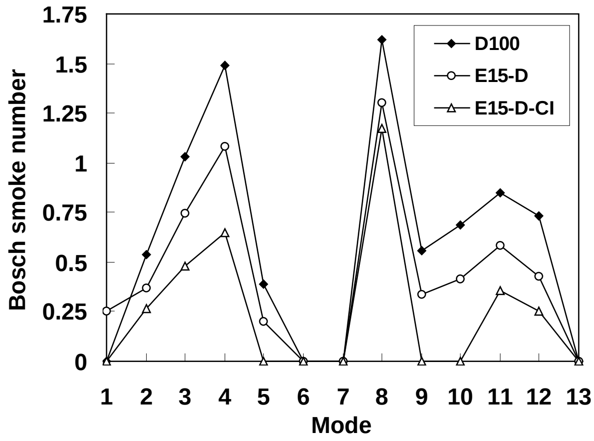

Fig. 8 Bosch smoke index of 3 kinds of fuel according to ECE 13 mode cycles.

Fig. 8 shows the smoke emission as BSN (Bosch smoke number). The smoke emission value of D100 is over 15% of the peak value in middle and high load conditions (modes 4, 8); that of E15-D is lower than the value of D100; and that of E15-D-CI is half the value of D100. The diesel engine has a trade-off relationship between NOx generation and soot generation. The oxygenated fuel and cetane improver contribute to the suppression of soot generation. In all modes, the average smoke reduction rates E15-D and E15-D-CI is 28% and about 58% of that of D100, respectively. The addition of cetane improver to the 15% of ethanol is recommended to reduce the PM (particulate matter) for CRDI diesel engine before enforcement of a strengthen regulation such as EURO V

Fig. 9 shows the CO conversion efficiency of the 3 types of fuel of the diesel engine in steady state in each mode. The CO conversion efficiency in a WCC+DOC system maintains at about 80% in each mode, except in modes 1, 2 and 13 (lower temperature conditions). Conversion efficiencies of modes 1, 2, 13 in WCC were low (it is below 190 ^{o}C), because WCC did not reach the light-off temperature. High CO conversion efficiency was maintained in the other modes because the temperature of WCC maintained over the light-off temperature. Therefore, WCC is required to reduce the emission at cold start in the diesel engine, as in the gasoline engine. The CO conversion efficiency in DOC is lower than in WCC, and it is higher in modes 8 to13 than in modes 1 to 6. However, mode 2 shows minus conversion efficiency because the exhausted CO is absorbed on the surface of catalyst in low temperature conditions. And absorbed CO is desorbed in mode 2 as the catalyst temperature increases. WCC+DOC system shows high CO conversion efficiency except in idling and mode 2. The conversion efficiency is low in mode 8 despite the highest exhaust gas temperature because the space velocity (SV) is the highest in the modes.

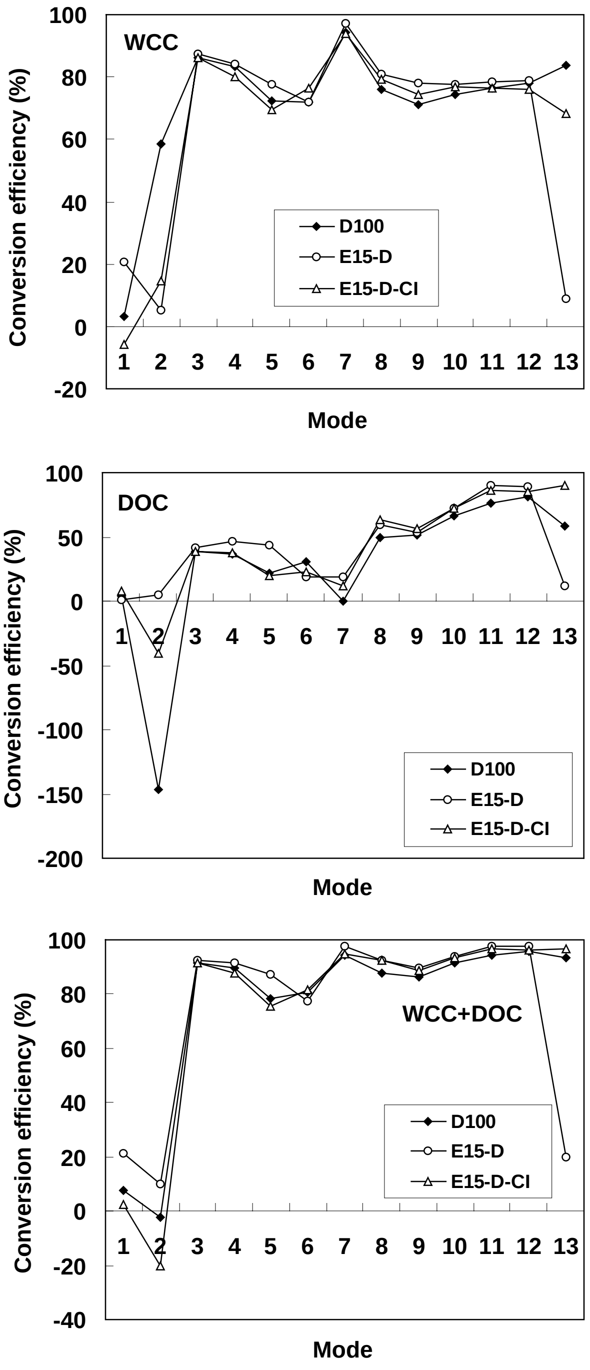

Fig. 9 CO conversion efficiencies of catalysts.

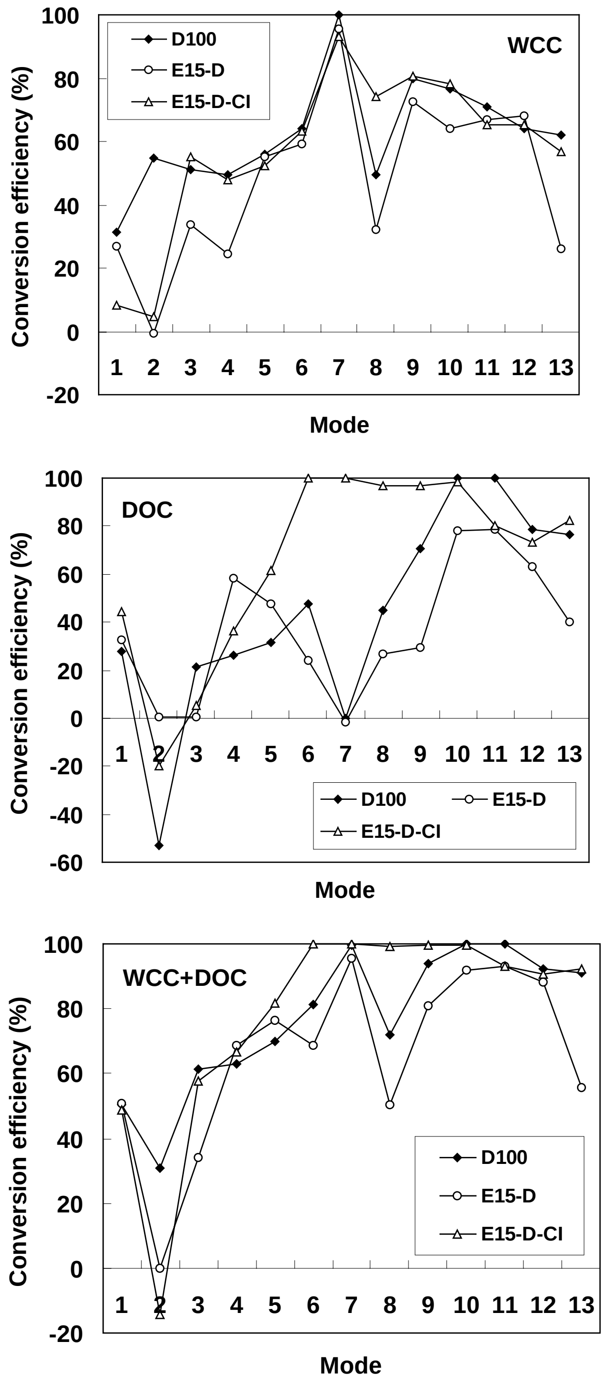

Fig. 10 THC conversion efficiencies of catalysts.

Fig. 10 shows the THC conversion efficiency in each catalyst. At WCC, THC conversion efficiency of E15-D is lower than that of D100 in all modes. However, that of E15-D-CI is almost the same or partially higher than that of D100. Especially, THC conversion efficiencies at all catalysts are close to 100% in mode 7. This is due to the influence of THC absorption rather than the influence of the perfect oxidation in the lower exhaust gas flux condition. The low conversion efficiency in mode 8 explains it as shown fig.9. In case of DOC, THC conversion efficiencies of D100 and E15-D are quite low compared to that of E15-D-CI because of the effect of the cetane improver.

PM (particulate matter) size ranged between 5.5 nm to 350 nm. Fig. 11 shows the particle size distribution in each mode for the used fuels. The number of particles in ethanol blended fuel reduced by at least 20-40% more than that in D100, and appears to have reduced more by the addition of cetane improver. This is due to the low

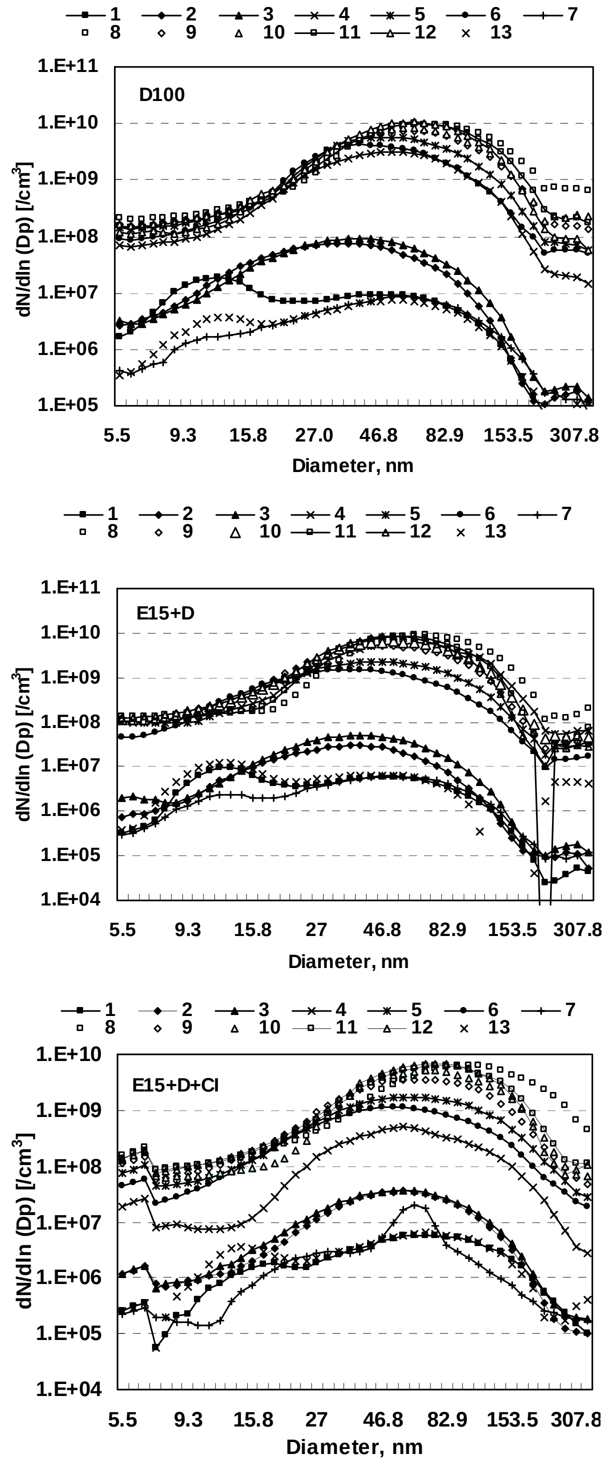

Fig. 11 The particle size distribution of engine out of 3 kinds of fuel according to ECE 13 mode cycles.

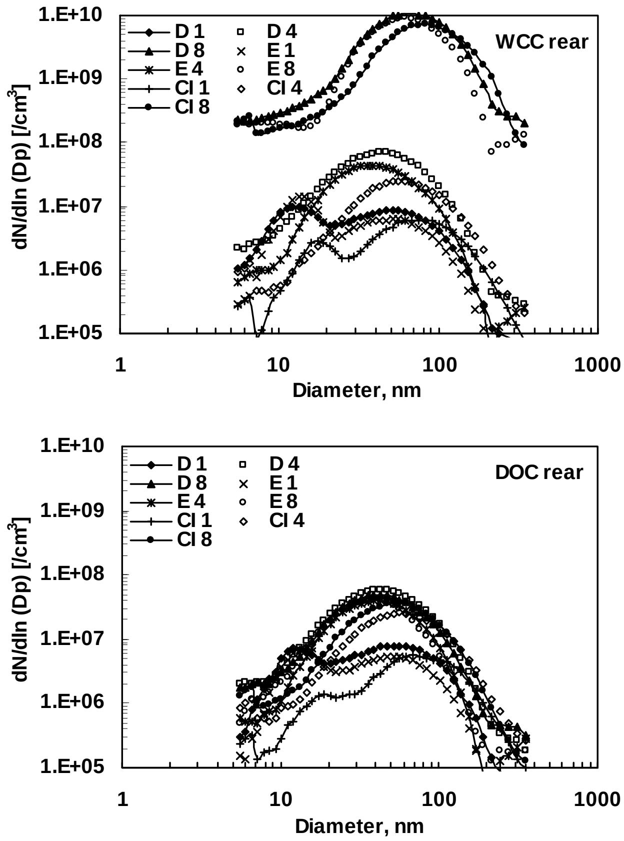

Fig. 12 The particle size distribution in the DOC rear of 3 kinds of fuel according to modes 1, 4, 8, 11.

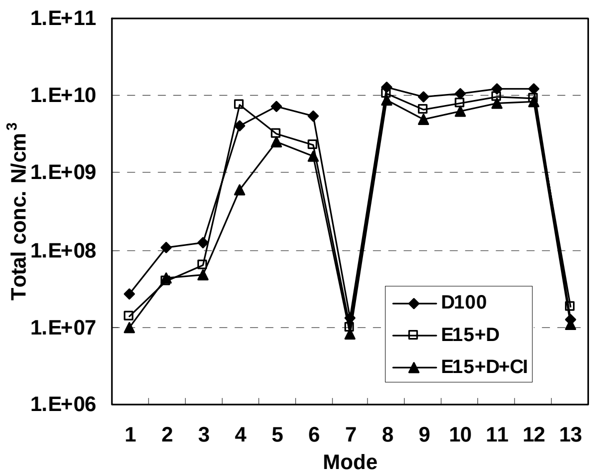

Fig. 13 Comparison of the total concentration number of 3 kinds of fuel according to ECE 13 mode.

soot characteristics of ethanol, which is the oxygenated fuel, and the reduction of sulfur oxides generation since ethanol does not contain sulfur.

The addition of cetane improver also promotes PM oxidation. The 35nm diameter particles were the greatest in number in the low load condition. In the middle and high load conditions, the 60 nm diameter PM was the greatest in number. As the condition of high load and EGR develop from PM surface growth and coagulation by increased incomplete combustion, the number of big particles of diameter over 150 nm increases.

Fig. 12 presents the particle size distribution of each fuel and mode measured on the rear of the WCC and DOC. These results show reduction of particle numbers 1/10-1/100 compared to D100 engine-out emission of the PM number. The oxidization of soluble organic fractions (SOF) and PM on the WCC and DOC, and especially, SOF oxidization are thought to contribute to the reduction of PM emission in the nuclei mode nano-sized range. Mode 4 has the highest PM number because of the effect of EGR. This result is similar to the smoke emission characteristics as shown fig. 8.

Fig. 13 shows the total PM concentration number of the 3 kinds of fuel in each mode. The ethanol blended fuels reduce the PM concentration number more than D100 emitted its PM number except mode 4. The PM number of E15+D+CI reduces the PM concentration number by up to 20-60% more than that of D100. WCC and DOC contribute to the reduction of SOF among PMs, and they are expected to the amount of harmful exhaust gas such as aldehydes are reduced almost perfectly.

CONCLUSIONS

The engine performance and emission characteristics of the CRDI diesel engine equipped with WCC and DOC using diesel-ethanol blended fuel and cetane improver were investigated under the ECE 13 mode. The results are summarized as follows:

1. The engine performance from E15-D and E15-D-CI was similar to that of the base diesel engine with respect to power output, and E15-D-CI had the highest thermal efficiency because of the addition of the cetane improver (EHN).
2. Smoke emission from the use of the ethanol blended fuel was remarkably reduced; the smoke reduction rates with E15-D and E15-D-CI were 28% and 58%, respectively. From this result, for the CRDI diesel engine, 15% of ethanol with cetane improver is recommended to reduce PM to less than half.
3. The CO conversion efficiency in WCC and DOC reached to 80-90% in the ECE 13 mode, and not in modes 1, 2 (below 200 ^{o}C conditions).
4. The THC conversion efficiency in E15-D-CI reached up to 60-80%, an improvement by the addition of the cetane improver.
5. The addition of ethanol 15% and cetane improver in diesel fuel reduced the total number of the 5.5 to 340 nm diameter particles by 20-40%.

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