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A Study on Effect of Intake Mixture Temperature upon Fuel Economy and Exhaust Emissions in Diesel Engines with a Scrubber EGR System

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Abstract : The effects of intake mixture temperature on performance and exhaust emissions under four kinds of engine loads were experimentally investigated by using a four-cycle, four-cylinder, swirl chamber type, water-cooled diesel engine with scrubber EGR system operating at three kinds of engine speeds. The purpose of this study is to develop the scrubber exhaust gas Recirculation (EGR) control system for reducing NO_x and soot emissions simultaneously in diesel engines. The EGR system is used to reduce NO_x emissions. And a novel diesel soot-removal device of cylinder-type scrubber with five water injection nozzles is specially designed and manufactured to reduce soot contents in the recirculated exhaust gas to the intake system of the engine. The influences of cooled EGR and water injection, however, would be included within those of scrubber EGR system. In order to survey the effects of cooled EGR and moisture on NO_x and soot emissions, the intake mixtures of fresh air and recirculated exhaust gas are heated up using a heater with five heating coils equipped in a steel drum. It is found that intake and exhaust oxygen concentrations are decreased, especially at higher loads, as EGR rate and intake mixture temperature are increased at the same conditions of engine speed and load, and that NO_x emissions are decreased, while soot emissions are increased owing to the decrease in intake and exhaust oxygen concentrations and the increase in equivalence ratio. Thus one can conclude that NO_x and soot emissions are considerably influenced by the cooled EGR.

Key words : Diesel Engine, NO_x and Soot Emissions, Scrubber Exhaust Gas Recirculation(EGR) Combined System, Intake Mixture Temperature, Cooled EGR, Intake and Exhaust Oxygen Concentrations, Equivalence Ratio

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1. Introduction

The diesel engine has the greatest heat-efficiency among the existing heat engines, with more than 50% of thermal efficiency in two-cycle, low speed, large-sized marine diesel engines and with more than 45% of maximum thermal efficiency in buses and trucks powered by diesel engines[1].

Despite its advantages, however, the major environ-mental problem with the diesel engine is that it generates vast amounts of NO_x and soot emissions. Naturally, the top priority of diesel combustion engineering has been to find ways to reduce hazardous exhaust gases without downgrading the engine's excellent thermal efficiency. Though NO_x and soot emissions, among harmful exhaust emissions, do not lend themselves to simultaneous reduction due to trade-off effect, there have been numerous experimental studies based on combinations of high pressure spray, intercooler system turbocharging, cooled EGR, oxidation catalyst, etc. These technologies, however, presuppose improvements in combustion engineering, such as lower sulfates and oxygen-containing fuel and at the same time after treatment must also be developed, such as lean burn, catalyst and DPF (diesel particulate filter trap)[2~5].

Though EGR is a widely known method that can reduce NO_x emissions drastically without additionally mounted devices or renovations, it tends to increase other exhaust gases, especially soot emissions. Controlled EGR systems, however, are widely adopted in small-sized diesel engines, and reliability and endurance tests are performed to make this system feasible in medium- and large-sized engines. The application of EGR to these larger engines is delayed for the same reason: increase in soot emissions and other exhaust gases[6~13].

Bae et al. employed a simple EGR system to investigate the effect of recirculated exhaust gas on fuel consumption rate, NO_x and soot emissions, with intake and exhaust oxygen concentrations, and equivalence ratio as parameters for increases in EGR rate[14, 15].

Recently, Bae et al. devised a scrubber EGR system that eliminates soot emissions from exhaust gases by spraying water onto these gases; this EGR system incorporated an EGR system for reducing NO_x and a scrubber-type water-spray system for eliminating soot contents in order to investigate the effect of recirculated exhaust gas on the engine's internal wear, fuel consumption rate, heat release rate and exhaust emissions [16~18].

Pure EGR effect, however, could not be determined, because exhaust gases contained moisture and recirculated exhaust gas mixed with fresh air at the surge tank underwent cooled EGR due to water sprayed for eliminating soot contents regardless of intention.

The purpose of this study is to investigate the effects of moisture and cooled EGR in a diesel engine with the scrubber EGR system. For this purpose, mixed gases (recirculated exhaust gases + fresh air) were heated in a cylinder-shaped electrical heater to eliminate moisture and to ensure hot EGR, in order to examine the effect of temperature variations in intake mixtures on fuel economy, combustion, and exhaust characteristics.

2. Experimental apparatus and procedures

2.1 Apparatus

The schematic diagram of apparatus used in the experiment is shown in Fig. 1. The test engine employed for the experiment is a four-stroke, four-cylinder, water-cooled, swirl chamber type, automobile diesel engine manufactured in Korea. The major specifications of the test engine are presented in Table 1.

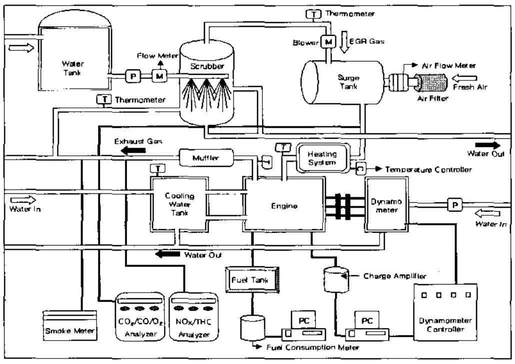

Fig. 1 Schematic of experimental apparatus

The engine power was measured by DC eddy current dynamometer. The piezoelectric pressure transducer (Kistler 6061B) was installed onto the head part of the first cylinder to monitor the cylinder pressure in the combustion chamber. Fuel consumption rate was calculated by measuring the amount of fuel consumption per time unit on a mass flow meter (HF-2000GD). The intake air amount was measured by a laminar flow element. Exhaust emissions were measured by exhaust analyzers; CO and CO_2 emissions by a NDIR exhaust analyzer (CGT-7000); O_2 emissions by an O_2 analyzer employing Zirconia method; NO_x emissions by a NO_x analyzer employing chemiluminescent method (Signal 4000VM); THC emissions by a THC analyzer employing HFID (Signal 3000HM); and soot emissions by Reflection Photometry-Filter type diesel smoke meter (DST-210).

Tabel 1 Specifications of test engine

Item	Specification
Type	4 Cylinder, 4 Cycle Water-cooled, Swirl chamber, Natural aspiration
Piston displacement(cc)	2476
Bore(mm) × Stroke(mm)	91.1×95
Maximum power	58.82kW/4200rpm
Fuel injection timing	ATDC 4°
Compression ratio	21 : 1

A surge tank was installed on the side of the engine intake manifold, not only to ensure the effective mixing of fresh air and recirculated gas but also to minimize the surging. A digital thermometer/hygrometer was installed to measure the temperature and humidity of intake mixtures (fresh air + recirculated exhaust gas). In order to allow an adequate supply of recirculated exhaust gas and minimize the backpressure in the engine due to the soot-removal device, a Roots blower was connected between the scrubber outlet and the surge tank inlet.

2.2 Soot-removal system and intake mixture heater

Figure 2 shows the soot-removal system with a cylinder-type scrubber that is installed between the exhaust pipe and the surge tank. The exhaust gases emitted from the engine are directed into the inlet port in the lower side of the scrubber, and collide with agitating materials, finally its soot contents being eliminated by water sprayed from five conical nozzles. To ensure a constant and continuous water flow, the sprayed water is adjusted by a flow control valve installed next to a pump. An orifice flow meter was installed to measure the water supply amount. The resultant soot-free exhaust gas is passed through a demister to remove water, which is fanned through the outlet port into a surge tank, where it is mixed with incoming fresh air before being fed back into the cylinders.

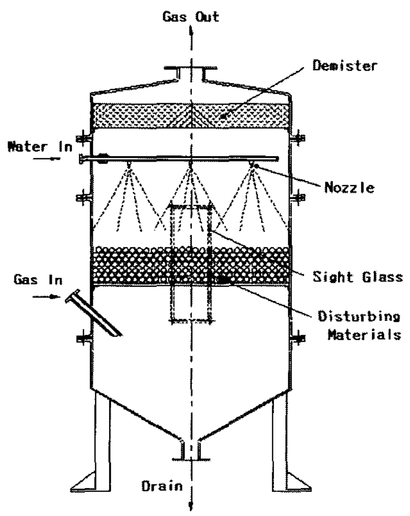

Fig. 2 Cross-section of a novel diesel soot-removal system with a cylinder-type scrubber

Water-spray for removing the soot contents is predicted to cause cooled EGR on recirculated exhaust gas. The influence of water injection for reducing NO_x emissions in general may be further included within scrubber EGR System. To examine the effects of these two factors, an electrical heater was installed to eliminate moisture from intake mixtures. A 850 mm × ø 560 mm steel plate was shaped into a cylinder, inside of which was installed by five circular heating coils with an electrical current of 6.7 A. Recirculated exhaust gas and fresh air mixed in the surge tank are fed into the heating cylinder through a ø 100 mm pipe and then is heated before flowing into the intake manifold. The mixed gases were heated up to 80℃ in normal operation: it was found that it would be difficult to heat at temperatures higher than this particular temperature.

2.3 Procedure

At engine speeds of 1800, 2800 and 3800 rpm, the experiments were conducted over engine load ranges of 25 and 100% with a 25% interval. The EGR rates of 0, 10 and 20% were tried on intake mixtures heated to 40, 60 and 80℃ (with 25℃ as baseline). 25℃ means the intake mixture temperature mixed in the surge tank passed through a cylinder-type scrubber without heating. At the engine speed of 3800 rpm, however, the gases could not be heated to higher than 40℃, because a higher temperature would lead to unstable engine operation due to unsatisfactory intake charging efficiency. Of engine speed, load, EGR rate and intake mixture temperature, three parameters were kept constant and only one parameter was varied. Of all the engine speeds, however, the data involving with 2800 rpm were adopted in the discussion of this study because the whole data were too vast for presenting and because there was a similar tendency for the other engine speeds. Though the engine was operated in the same conditions, the variation of EGR rate is less than ± 3%; the variation rate of engine load, less than ± 5%; and the temperature variation rate of heated intake mixture, less than ± 1℃.

A water-cooled heat exchanger was employed to control the temperature of cooling water and lubricating oil, and K-type thermocouples(CA) were inserted into the engine and its components (exhaust manifold, the inlets and outlets of the scrubber and the surge tank, and the inlets and outlets of cooling water and lubricating oil) to check regularly the engine operation and combustion. The amount of water sprayed in the soot-removal device was fixed at 30 ℓ/min.

CO_2 concentration was measured at the intake and exhaust manifolds to calculate the EGR rate by using the following equation[16~18].

$$\text{EGR Rate}(\%) = \frac{[CO_2]_{EGR} - [CO_2]_{w/o\,EGR}}{[CO_2]_{EXH}} \times 100 \qquad (1)$$

where $[CO_2]_{EGR}$ is the CO_2 concentration in intake air with EGR; $[CO_2]_{W/O\ EGR}$ is CO_2 concentration in intake air without EGR; and $[CO_2]_{EXH}$ is CO_2 concentration in the exhaust manifold with EGR. Though the fuel injection timing is usually one of experimental parameters in applying EGR, this study fixes it at ATDC 4°, as shown in Table 1.

3. Results and discussion

3.1 Removal efficiency of soot emissions

To investigate the performance of the soot-removal device, the cylinder-type scrubber manufactured for this study, engine speed was varied from 1200 to 3900 rpm at an interval of 300 rpm, with engine load increased at an interval of 25%. Fig. 3 shows the measured soot concentrations as a function of engine load when the whole exhaust gases go through with and without the scrubber at the typical engine speeds of 2100, 2400 and 2700 rpm. Though showing variations depending on engine speeds and loads, when passed through the scrubber, soot emissions were found to be reduced by 30 ~ 44% at 100% engine load; by 40 ~ 70% at 75% engine load; by 40 ~ 100% at 50% engine load; and by 100% at 25% engine load. The reduction rate of 100% here means that there is no soot concentrations detected by the smoke meter. To sum up the results, the reduction rate induced by the scrubber was 30% greater than without the scrubber; at the engine speed of 25%, 100% soot removal was achieved regardless of engine speeds. At higher engine speeds, in particular, lower engine loads produced more remarkable soot removal rates, and lower engine speeds generated much the same removal effect regardless of engine loads.

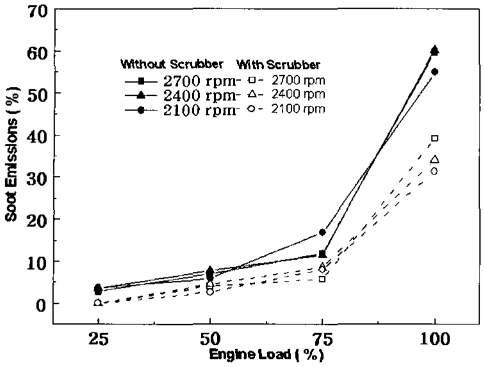

Fig. 3 Comparison of the soot reduction rate between without and with scrubber in a given engine speed 2100, 2400 and 2700rpm

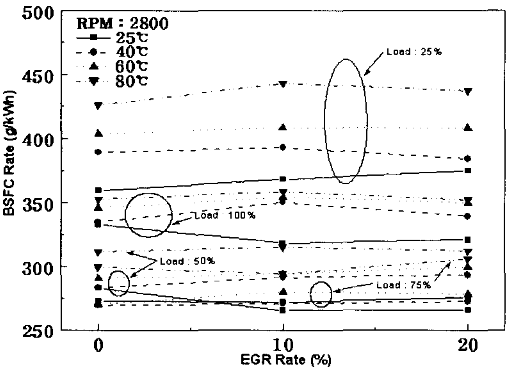

Fig. 4 Effect of EGR rate on brake specific fuel consumption rate as a parameter of intake temperature at an engine speed of 2800rpm

3.2 Specific fuel consumption rate

To investigate the effect of intake mixture temperature with EGR application on the specific fuel consumption rate, the engine speeds of 1800, 2800 and 3800 rpm were applied to the engine, with engine load, intake mixture temperature and EGR rate as parameters. Figure 4 shows typically the measured results at the engine speed of 2800 rpm. As indicated in the figure, in case of the same engine speed and load, the increase or decrease in the specific fuel consumption rate with increasing EGR rates was not significantly great up to the EGR rate of 20%. Moreover, the variation was not significant as compared with a serious effect on air pollutions, and the variation rate was below 2 to 3%.

Previous research results of the effect of EGR rate on the fuel consumption rate are classified into the following categories: increased EGR rate producing 1) greater fuel consumption rate at a certain threshold of EGR rate[19, 20]; 2) decreased fuel consumption rate[21, 22] ; and 3) no significant variation in fuel consumption rate[23, 24]. To generalize the results of Bae et al. and other researchers, however, there was no significant variation in fuel consumption rate within 40% EGR rate, beyond which the rate was found to increase due to decrease in intake oxygen concentration [15, 17]. Under the same conditions, higher temperatures of intake mixture generally produced greater fuel consumption rate in hot EGR than in cooled EGR: when these gases were heated from 25 to 80℃, in this study, maximum increases in fuel consumption rate were found to be 20.3% at 25% engine load; 18.4% at 50% engine load; 10.7% at 75% engine load; and 13.8% at 100% engine load. The effect of increased EGR rate proved to be insignificant.

The reason why increases in intake mixture temperature led to greater fuel consumption rates may be attributed to the possibility that instead of enhancing combustion by increasing flame temperature, higher intake mixture temperature caused local incomplete combustion due to relative decrease in intake oxygen concentration[14].

Though fuel consumption rate was significantly variable depending upon experimental conditions, increased EGR rate generated a slight increase or decrease in fuel consumption, whereas increase in intake mixture temperature produced significant increases in fuel consumption.

3.3 Combustion characteristics

To investigate the effects of EGR rate and temperature variation in intake mixture on combustion characteristics of the engine, the combustion pressure in the cylinder was measured at each of the engine loads and at the engine speeds of 1800, 2800 and 3800 rpm, and the measured pressures were used to calculate the rate of heat release. Figure 5 shows typically the result obtained at the engine speed of 2800 rpm, with 100% engine load, with EGR rate at 0, 10 and 20%, and with intake mixture temperatures at 25, 40, 60 and 80℃. When all the other conditions were equal, increased EGR rate led to a slight increase in ignition delay. In addition, the rate of heat release with higher temperatures of intake mixture tended to increase at 20% EGR rate, and ignition delay increased slightly.

In their study of EGR and supercharging based on a single-cylinder, four-cycle, direct injection diesel engine, Uchida et al[25]. found that ignition delay increased with higher EGR rate, with great variation in the peak value of premixed combustion and with little or no effect on the one of diffusion combustion. The reasons they suggested are local combustion temperature decrease due to increase of inert contents in charging and reduction in oxygen concentration.

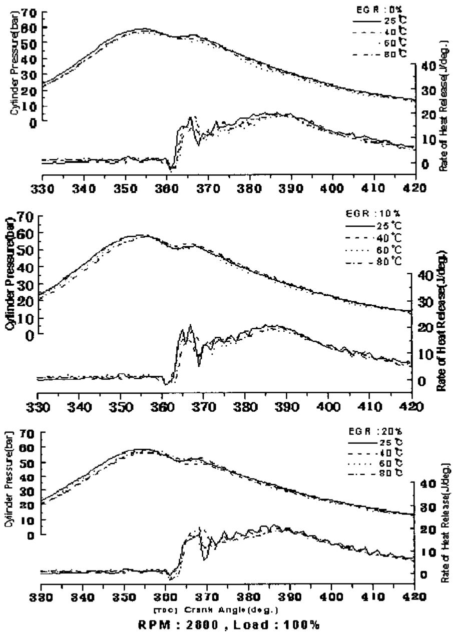

Fig. 5 Comparisons of cylinder pressure and rate of heat release as a parameter of intake mixture temperature at an engine speed of 2800rpm and an engine load of 100%

Satoh et al[26]. in their research of EGR based on a single-cylinder, four-cycle, direct injection, non-turbocharger diesel engine reported that the ignition delay was hardly changed with increasing EGR, and that the duration of diffusion combustion grew longer because the peak value of premixed combustion decreased. The reason they explained was that decrease of oxygen concentration in intake mixture led to reduced mixing probability between fuel and oxygen, which resulted in decreased combustion rate at a certain time point or at a certain spot in the combustion chamber, thereby reducing the rate of heat release and deterring combustion temperature from rising.

Dünholz et al.[12] have showed that an inconsistent intake air temperature has no serious effect on ignition delay with increasing EGR rate (up to an EGR rate of 40%), while ignition delay increases with the EGR rate at a constant intake air temperature.

It is difficult to draw an exact conclusion on combustion characteristics including the rate of heat release, since results are significantly dependent upon experimental conditions. According to the previous research results of Bae et al.[29], however, the reason why ignition delay increases with the EGR rate may be attributed to reduce oxygen concentration in the intake air. The higher temperature in compressed mixture during ignition due to increased temperature in intake mixture may leads to the increase in ignition delay.

3.4 Exhaust emissions

3.4.1 NO_x emissions

To measure NO_x emissions, the engine speeds of 1800, 2800 and 3800 rpm were applied to the diesel engine, with intake mixture temperature, engine load and EGR rate as parameters. Figure 6 shows the measurements at the engine speed of 2800 rpm. As shown in the figure, at the same engine load and intake mixture temperature, NO_x emissions decreased with higher EGR rate, with greater engine loads producing even higher reduction in NO_x emissions. At the same engine load, hotter EGR led to higher temperature in intake mixture, which causes higher flame temperature, resulting in greater NO_x emissions.

When intake mixture temperature was increased from 25 to 80℃ at 100% engine load, NO_x emissions at the engine speed of 1800 rpm increased by 6, 13.5 and 18.7% with regard to the EGR rates of 0, 10 and 20%; at 2800 rpm, by 17.6, 30.3 and 67.5%. When intake mixture temperature was increased from 25 to 40℃ at the engine speed of 3800 rpm, NO_x emissions increased by 1.5, 2 and 4.6% with regard to the EGR rates of 0, 10 and 20%. All these results demonstrated that temperature had a significant effect on increase in NO_x emissions, and that intake mixture temperature had a greater effect with increases in EGR rate and engine speed.

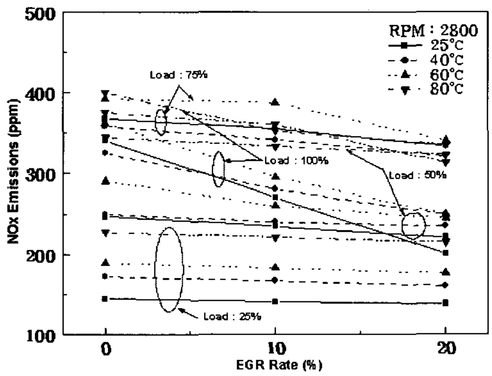

Fig. 6 Effect of EGR rate on NO_x emissions as parameters of intake mixture temperature and engine load at an engine speed of 2800rpm

The reason why higher EGR rates caused a remarkable reduction in NO_x

emission may be attributed to the possibility that inert gases admixed into mixture may have caused increase in the heat capacity of these gases, which lowered maximum combustion temperature, at the same time leading to longer ignition delay due to decrease in intake oxygen concentration[13].

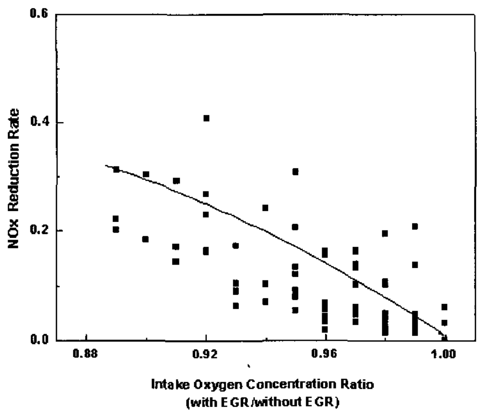

Fig. 7 Effect of intake oxygen concentration (with EGR/without EGR) NO_x emissions

Figure 7 shows the effect of decreased intake oxygen concentration on NO_x emissions. The whole data were analyzed without regard to engine speeds, engine loads, ERG rates and intake mixture temperatures, in order to examine the effect of intake oxygen concentration ratios with EGR and without EGR on reduction rates of NO_x emissions. As indicated in the figure, decrease in intake oxygen concentration led to greater reduction in NO_x emissions; here, lower intake oxygen concentration means higher EGR and higher temperature of intake mixture. These results indicate that hot EGR tended to produce a greater amount of NO_x emissions than the scrubber EGR system in the previous studies[16~18].

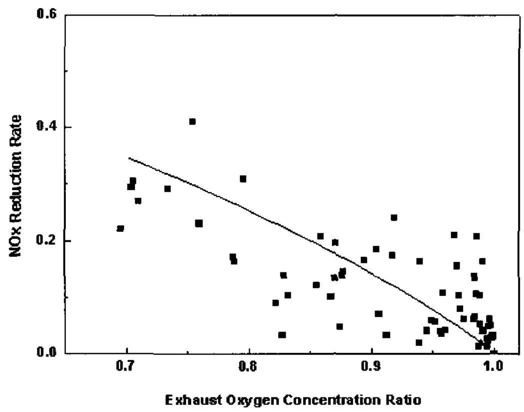

Fig. 8 Effect of exhaust oxygen concentration (with EGR/without EGR) on NO_x emissions

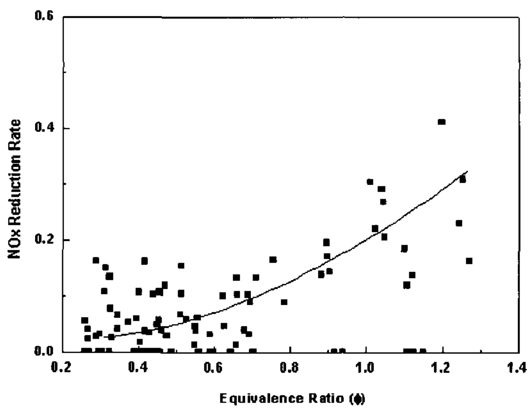

Fig. 9 Effect of equivalence ration on NO_x emissions

In general, combustion in diesel engines is performed in superfluous air, but in case intake oxygen concentration decreases, local rich fuel regions will increase, which will lower combustion temperature in NO_x generating areas, thereby resulting in lower NO_x generation and thus emissions. In addition, decrease in intake oxygen concentration will lead to longer ignition delay, which will shorten high-temperature combustion, a major factor in NO_x generation, ultimately achieving reduction in NO_x emission[13, 17].

Figure 8 indicates reduction in NO_x emissions as affected by exhaust oxygen concentration with and without EGR; though higher EGR rates and increased temperature of intake mixture caused decrease in exhaust oxygen concentration, which led to greater reduction in NO_x, but the reduction was considerably smaller as compared to the result obtained in previous studies on the scrubber EGR system[27]. Bae[17], in his study of the effect of recirculated exhaust gasses on exhaust emissions in a diesel engine mounted with the scrubber EGR system, suggested that even though intake oxygen concentration decreased with increase in EGR rates almost regardless of engine speeds and loads, EGR rates could not be taken as the only factor in the case of exhaust oxygen concentration, because the latter is related not only with EGR rates but also with engine loads and engine speeds. In addition he suggested a possible correlation between exhaust oxygen concentration and NO_x emissions.

Odaka[21] reported that decrease in exhaust oxygen concentration at intake oxygen concentrations higher than 18% led to a significant increase in NO_x emission, but when intake oxygen concentration went down below less than 18%, the dependency of exhaust oxygen concentration on NO_x emissions became considerably lower. His observation corresponds qualitatively to Bae et al.'s previous[15, 17] and present study results. Bae et al.'s previous studies[15, 17] reported that higher EGR rates increased equivalence ratio, with greater engine load leading to greater increase rate in equivalence ratio; the ratio was not significantly affected by engine speeds at lower engine load, while higher engine speeds at higher engine loads tended to result in a slight decrease in equivalence ratio. This study observed a considerably greater equivalence ratio because increased temperature of intake mixture aggravated charging efficiency. In this study the equivalence ratio is defined as the average value calculated on oxygen and fuel amounts fed into the cylinders. Figure 9 shows the correlation between equivalence ratio and NO_x emissions; increase in equivalence ratio with hot EGR resulted in a gentle increase in NO_x emission reduction. The reduction in NO_x emissions was smaller than in previous studies on the scrubber EGR system[27], because the temperature effect of intake mixture was added. Bae et al.'s previous studies[15, 17] demonstrated that the maximum equivalence ratio at which the reduction rate of NO_x emissions became zero was approximately between 0.74 and 0.8; another study on a automobile diesel engine mounted with the scrubber EGR system[27] reported a considerably greater equivalence ratio of 1.1; the present study obtained the same equivalence ratio.

These tendencies were qualitatively similar to the theoretical calculations of previous studies[28] : higher EGR rates or greater intake mixture temperature led to a greater equivalence ratio and relative superfluous fuel, which resulted in decreased flame temperature due to local insufficient oxygen concentration, thereby reducing NO_x emissions.

3.4.2 Soot emissions

At the engine speeds of 1800, 2800 and 3800 rpm, measurements were taken of soot concentrations as affected by the variations of intake mixture temperature and EGR rate at each of the engine loads. Figure 10 shows the measurements at the engine speed of 2800 rpm. At the same engine load, higher EGR rates caused greater increases in soot emissions; at less than 75% engine load, EGR rate did not have a significant effect on soot emissions, whereas EGR rates had a considerable influence at 100% engine load. In addition, at the same EGR rate, greater engine loads led to higher soot emissions, showing a drastic increase at 100% engine load.

The reason why increased EGR rates caused increase in soot emissions may be attributed to the possibility that increased EGR rates lowered intake oxygen concentration for combustion, thereby de-creasing oxygen amounts when sprayed fuel was premixed with recirculated exhaust gases. And since decrease in intake oxygen concentration reduced oxygen amounts necessary for oxidizing soot during expansion stroke, soot emissions increased and the range of EGR rate at higher loads in diesel engines tended to be considerably restricted[6].

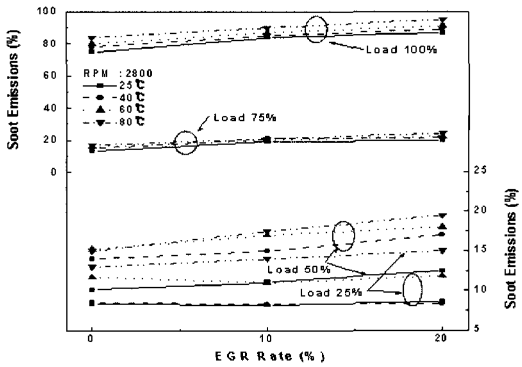

Fig. 10 Effect of EGR rate on soot emissions as parameter of intake mixture temperature and engine load at an engine speed of 2800rpm

Figure 10 also shows the effect of temperature variation in intake mixture; when intake mixture temperature was increased from 25 to 80℃ at 100% engine load, soot emissions at 1800 rpm increased by 35.8, 31.7 and 21.1% with regard to the EGR rates of 0, 10 and 20%; at 2800 rpm, by 12, 7.1 and 9.2%; an at 3800 rpm, when intake mixture temperature was increased from 25 to 4 0℃, soot emissions increased by 7.5, 3.3 and 4.5%. These results demonstrated that at the same engine load, hotter EGR resulted in greater soot emissions. This increase rate, however, was shown to be lower with higher EGR rates.

The reason why soot emissions increased with higher temperature of intake mixture may be that these hotter mixtures lowered intake charging efficiency, thereby decreasing intake oxygen concentration. In addition, the effect of increased intake mixture temperature was relatively weakened, because hotter temperatures in the combustion chamber have generated by combustion at high engine loads more than 50%.

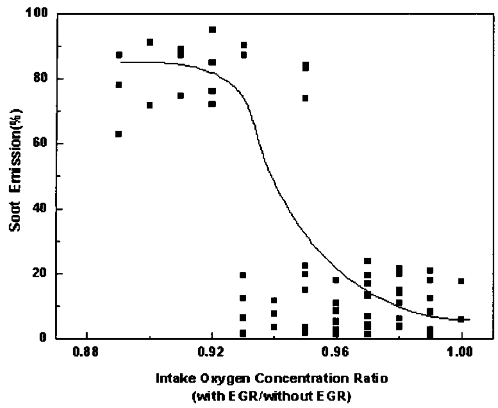

Fig. 11 Effect of intake oxygen concentration (with EGR/withou EGR) on soot emissions

Figure 11 shows the effect of intake oxygen concentration on soot emissions. The whole data were analyzed without regard to engine speeds, engine loads, EGR rates and intake mixture temperatures, in order to examine the effect of intake oxygen concentration ratios with EGR and without EGR on reduction rates of soot emissions. As indicated in the figure, decrease in intake oxygen concentration led to greater increase in soot emissions.

As is observed in the figure, soot removal by the scrubber cannot function satisfactorily if EGR rates increase or higher temperature of intake mixture aggravates charging efficiency. This qualitative tendency corresponds to the results of previous studies on the only EGR in marine diesel engines[14, 15], studies on the scrubber EGR system in marine and automobile diesel engines[16, 17, 27], but cooled EGR appeared to be much more effective because temperature increase in intake mixture led to all the greater increase in soot emissions.

Bae[17], in his experimental study on the scrubber EGR in a diesel engine, demonstrated that the characteristics of soot emissions were governed by ignition delay, combustion gas temperature, heat release rate (the maximum values of premixed and diffusion combustions) and combustion duration; higher EGR resulted in lower intake oxygen concentration, thereby having a bad influence upon combustion characteristics such as ignition and mixing. He added that though in theory longer ignition delay might seem to increase fuel amount consumed in premixed combustion period, decreased oxygen for combustion due to decrease in intake oxygen concentration led to lower combustion velocity in premixed phase. Combustion temperature also decreased, and thus shortened combustion period, thereby increasing soot emissions.

Though higher temperature of intake mixture was supposed to increase flame temperature and thus contribute to combustion, it nevertheless aggravated intake charging efficiency and local poor mixing, thereby resulting in increased soot emissions.

To investigate the effect of exhaust oxygen concentration on soot emissions, Fig. 12 presents soot emissions as affected by exhaust oxygen concentration ratio with and without EGR. As shown in the figure, increased exhaust oxygen concentration resulted in a drastic reduction in soot emission. It may be hoped that this result may be employed in constructing commercialized EGR control systems. The combustion process in the diesel engine is basically lean burn by superfluous air, but lower EGR rates or cooler EGR is expected to induce higher intake oxygen concentration, which will enhance oxygen concentration for combustion, thereby yielding less soot emission and relatively higher exhaust oxygen concentration.

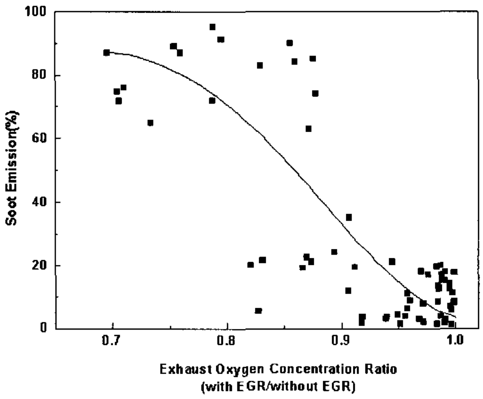

Fig. 12 Effect of intake oxygen concentration(with EGR/without EGR) on soot emissions

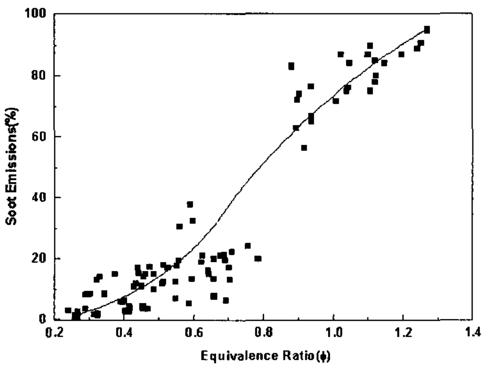

Fig. 13 Effect of equivalence ratio on soot emissions

Figure 13 shows the relation between equivalence ratio and soot emission: less than 40% soot emissions observed at lean burn regions less than 0.8 equivalence ratio, beyond which the emissions increased linearly, and at equivalence ratio higher than theoretical mixture ratio they increased remarkably to higher than 60%.

According to Bae et al.'s[29] study on premixed combustion, the effect of equivalence ratio on the soot formation was significantly great, because increased equivalence ratio led to increase in heavier hydrocarbon ions, the precursor of soot emissions, rather than increase in lighter hydrocarbon ions. Despite being macroscopically diffusion combustion, the combustion in the diesel engine can be regarded microscopically as a set of premixed combustions, thus probably producing a similar phenomenon. This qualitative tendency corresponds to other study results[30~32]. Most of the soot is generated because of prolonged duration of diffusion combustion, which results from decreased ignition delay due to high-temperature during compression stroke. Oxygen concentration in residual gases also has an important role in the recombustion of soot. In this regard, increase in equivalence ratio due to greater EGR rates and higher intake mixture temperature is predicted to result in relatively insufficient oxygen concentration, which will contribute to soot formation process, thereby adding to soot emissions[33~37].

4. Conclusions

A four-stroke, four-cylinder, water-cooled, swirl chamber type diesel engine was experimentally investigated with engine speeds, engine loads, EGR rates and intake mixture temperatures as a parameter, in order to clarify the effect of water-spray and cooled EGR on the characteristics of NO_x and soot emissions with intake and exhaust oxygen concentrations, and equivalence ratio. The major results obtained are as follows:

1) The soot removal rate of the scrubber, though variable depending upon engine speeds and loads, ranged roughly from 30 to 100%.
2) NO_x emissions decreased with greater EGR rates, but hotter EGR (greater intake mixture temperature) increased NO_x emissions.
3) Soot emissions increased with higher EGR rates and hotter EGR.
4) At the same engine speeds and loads, higher EGR rates and higher intake mixture temperatures resulted in decreased intake and exhaust oxygen concentration, with higher engine loads leading to even greater increase rates.
5) Decreased intake and exhaust oxygen concentrations caused decrease in NO_x emissions and increase in soot emissions: Cooled EGR resulting from intake mixture temperature had a significant effect.
6) Increased equivalence ratio led to decrease in NO_x emission, but soot emissions increased linearly increased: here again, cooled EGR resulting from intake mixture temperature had a significant effect.

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