The Experimental Investigations of Recirculated Exhaust Gas on Exhaust Emissions in a Diesel Engine

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The effects of recirculated exhaust gas on the characteristics of NOx and soot emissions under a wide range of engine loads were experimentally investigated by using a four-cycle, four-cylinder, swirl chamber type, water-cooled diesel engine operating at three engine speeds. The purpose of this study was to develop the EGR-control system for reducing NOx and soot emissions simultaneously in diesel engines. The EGR system is used to reduce NOx emissions, and a novel diesel soot removal device with a cylinder-type scrubber for the experiment system was specially designed and manufactured to reduce soot contents in the recirculated exhaust gas to the intake system of the engine. The experiments were performed at the fixed fuel injection timing of 4° ATDC regardless of experimental conditions. It was found that soot emissions in exhaust gases were reduced by 20 to 70% when the scrubber was applied in the range of the experimental conditions, and that NOx emissions decreased markedly, especially at higher loads, while soot emissions increased owing to the decrease in intake and exhaust oxygen concentrations, and the increase in equivalence ratio as the EGR rate is elevated.

Key Words : NOx and Soot Emissions, Exhaust Gas Recirculation (EGR), Scrubber EGR Control System, Diesel Engine, Intake and Exhaust Oxygen Concentrations, Equivalence Ratio

1. Introduction

Diesel engines are not only energy-efficient but also desirable for minimally reducing the greenhouse effect from exhaust gases because they are higher in thermal efficiency than other heat engines. However, because diesel engines emit relatively greater amounts of nitrogen oxides (NOx) and soot emissions, various measures should be made to reduce exhaust emissions without degrading engine performance in order for these engines to be commercially competitive (Kobayashi, 1996; Ikegami, 1996; Kamimoto, 1999).

Measures for reducing NOx emissions in diesel engines have so far focused on aspects of the combustion process such as delay of injection timing and the cooling of incoming air. With increasingly rigorous environmental regulations on NOx emissions, however, it is essential to incorporate the before- and after-treatment systems, fuel modifications, combustion improvement techniques, *etc.* (Girard et al., 1999).

Though EGR is known as one of the most representative methods for reducing NOx emissions without significant modifications in diesel engines, EGR cannot be applied alone

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because it causes increased soot emissions (Girard et al., 1999; Bae, 1999). Experimental studies of fuel economy for EGR application in diesel engines show three major different results in their findings. According to Bae et al. (1999), there were no significant variations in a specific fuel consumption rate when EGR was applied alone up to 40% EGR rate and when the scrubber was incorporated with EGR up to 20% EGR rate; other studies (Larsen and Levendis, 1997; Kreso et al., 1998) reported degradation in fuel economy due to an EGR application. According to Psaras et al. (1997), however, optimized EGR application in diesel engines produced no significant variation in fuel economy.

The purpose of the present study is to investigate the soot-elimination efficiency of the scrubber applied in diesel engines and the combustion characteristics of the scrubber EGR system, and to examine the effect of recirculated exhaust gas on the characteristics of exhaust emissions, based on the intake and exhaust oxygen concentrations, and equivalence ratios.

2. Experimental Apparatus and Method

2.1 Experimental apparatus

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

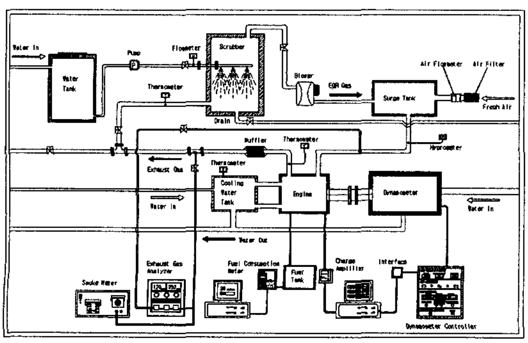


Fig. 1 Schematic of experimental apparatus

The engine power was measured by a eddy current dynamometer. The piezoelectric pressure transducer (Kistler 6061B) was installed in the head part of the first cylinder of the engine to monitor the cylinder pressure in the combustion chamber.

Fuel consumption rate was measured by a mass flow meter (HF-2000GD) as the amount of fuel consumed per unit time. The intake air amount was measured with an orifice flow meter. Exhaust emissions were measured by an exhaust analyzer (QUIN TOX KM-9006) and a Reflection Photometry-Filter-Type Smoke Tester (DST-210).

A blower was installed between the outlet of the scrubber and the inlet of a surge tank so as to allow an adequate supply of recirculated exhaust gas and to minimize the backpressure in the engine resulting from the soot removal device. A surge tank was installed at the side of the intake manifold in order to reduce surging and to ensure that fresh air would be effectively mixed with recirculated exhaust gas. A digital thermo-meter and hygrometer were installed to measure the temperature and humidity of intake mixtures (fresh air + recirculated exhaust gas).

2.2 Water-spray soot removal system

Figure 2 shows the water-spray soot removal

Table 1 Specification of test engine

Item	Specification
Type	4 Cylinder, 4 Cycle, Indirect-injection, Water-cooled, Swirl chamber, Natural aspiration
Piston Displacement (cc)	2476
Bore (mm) × Stroke (mm)	91.1×95
Max. Power	58.82 kW/4200rpm
Fuel Injection Timing	4° ATDC
Compression Ratio	21 : 1

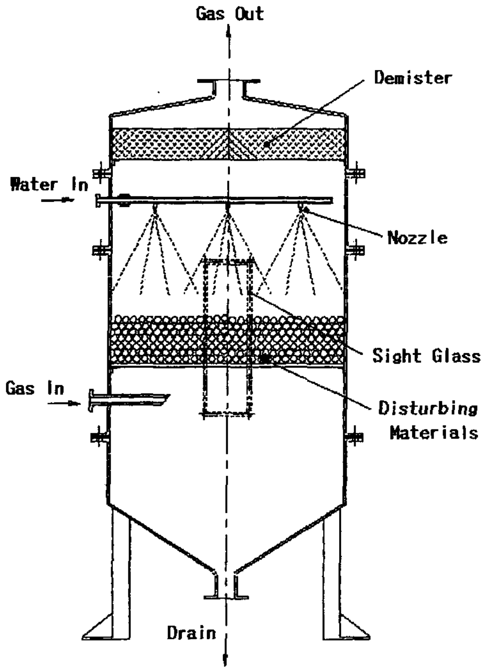


Fig. 2 Cross-section of a novel diesel soot-removal system with a cylinder-type scrubber

system that was designed to eliminate soot contents in the recirculated exhaust gas. The exhaust emitted from the engine is directed into the inlet port in the lower side of the scrubber, and then is passed through the disturbing materials. The soot contents are then eliminated by water sprayed from five conical nozzles. A water tank (5 m^3), an electrical-motor pump, and a flow-control valve were installed to ensure continuous and constant water supply. And the supply amount was checked by an orifice flow meter. The amount of water-spray in the soot removal system was fixed at 0.03 m^3/min. The resultant soot-free exhaust gas is passed through a demister to remove water, which is fan-blown through the outlet port into the surge tank, where it is mixed with the incoming fresh air.

2.3 Experimental procedures

At engine speeds of 1800, 2800, and 3800 rpm, the experiments were conducted in engine load ranges of 25 and 100% with a 25% interval, and at the same time EGR rate was increased from zero to 20% with an interval of 5%. Of the three parameters (engine speed, load and EGR rate), two parameters were kept constant and only one parameter was varied. Although the experiments were carried out under the same conditions in this study, the variation rate of EGR was less than $\pm$ 3%, and the variation rate of the engine loads was less than $\pm$5%.

A water-cooled heat exchanger was employed to control the temperatures of cooling water and lubricating oil, and K-type thermocouples (IC) were inserted into the engine and its components (the exhaust manifold, the inlet and outlet of scrubber, the inlets and outlets of cooling water, lubricating oil, and the surge tank) so as to check regularly the engine operation and combustion conditions.

In the present experiment for recirculating exhaust gases, CO_2 concentration was measured at the intake and exhaust manifolds to calculate EGR rate by using the following equation:

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

where $[CO_2]_{EGR}$ and $[CO_2]_{w/o\ EGR}$, and $[CO_2]_{EXH}$ are the concentrations of CO_2 in intake air with EGR and without EGR, and in the exhaust manifold with EGR, respectively. Though fuel injection timing is usually considered as one of experimental parameters, this study fixed it at 4° ATDC regardless of operating conditions.

3. Results and Discussion

3.1 Efficiency of the soot removal system

To investigate the soot removal performance of water-spray, a novel diesel soot removal system with a cylinder-type scrubber was installed in the engine, which was operated with the engine speeds ranging from 1200 to 3900 rpm at an interval of 300 rpm, and with engine loads at an interval of 25%. Figure 3 presents the soot concentrations measured in scrubber and non-scrubber treatments at the typical engine speeds of 3000, 3300, 3600, and 3900 rpm. The comparison of these two treatments shows that scrubber treatment was found to reduce soot emissions by 20 to 70%,

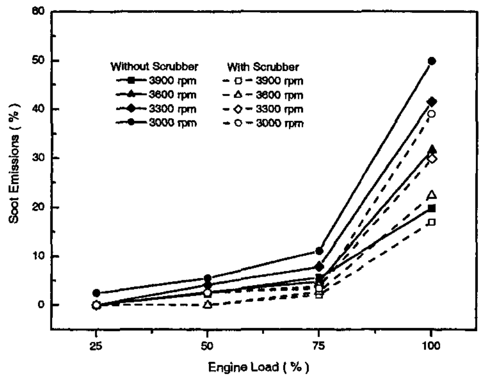


Fig. 3 Comparison of the removed soot emissions between EGR with scrubber and no EGR in a given engine speed of 3000, 3300, 3600 and 3900 rpm

though it might vary depending on the engine speeds and engine loads; in particular, lower engine loads at higher engine speeds produced more remarkable soot removal effect, and so did higher loads at lower engine speeds.

3.2 Specific fuel consumption rate

To investigate the effect of EGR application on the specific fuel consumption rate, each of the engine loads was applied to the engine at the engine speeds of 1800, 2800, and 3800 rpm at the same time that EGR rate was increased up to 20% at an interval of 5%. The result showed that increasing EGR rate up to 20% at the same engine speed and load regions led to no significant increase or decrease in fuel consumption rate. Figure 4 shows typically the fuel consumption at the engine speed of 3800 rpm, where higher EGR tended to increase slightly fuel consumption, but the variation was below 2 to 3 %, with no significant negative effect on environmental pollution.

According to the presently available studies on the application of EGR in diesel engines, there have been three types of results regarding fuel consumption as affected by increasing EGR rate within limited EGR percentage: increase (Nagai and Kawakami, 1989; Stumpp and Banzhof, 1978), decrease (Odaka, 1989; Narusawa and Odaka, 1990), and no significant variation (Walder, 1973; Mayer and Pauli, 1988) in fuel

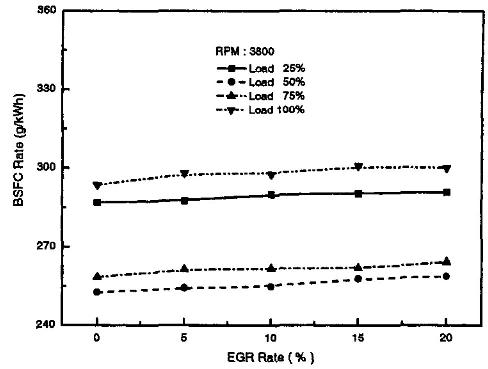


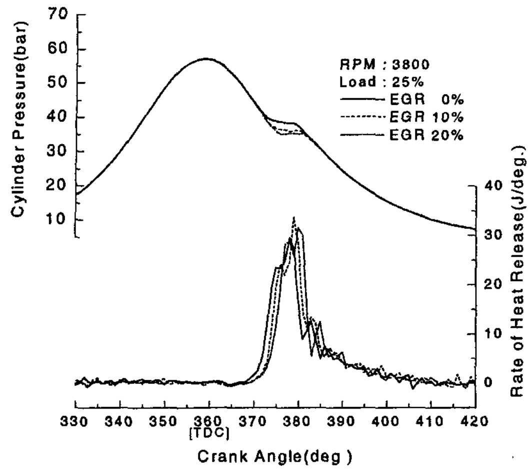
Fig. 4 Effect of EGR rate on brake specific fuel consumption rate as a parameter of engine load at 3800 rpm

consumption. To generalize the findings of the authors' previous studies and others, there was no remarkable variation in fuel consumption within 40% EGR rate, and beyond that fuel consumption did increase due to insufficient intake oxygen.

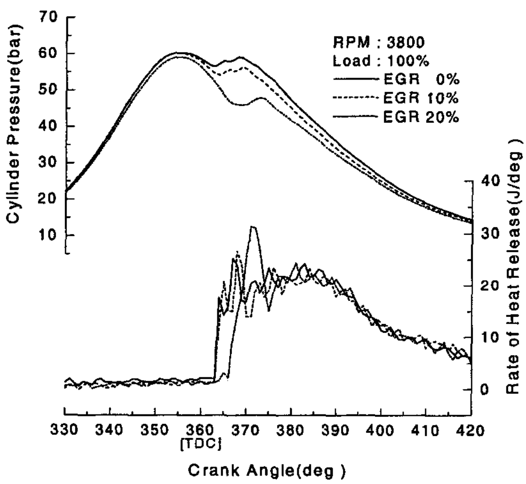
3.3 Combustion characteristics

To investigate the effect of EGR rate variation on combustion characteristics, the combustion pressure in the cylinder was measured at the engine speeds of 1800, 2800 and 3800 rpm, and the rate of heat release was calculated by using the combustion pressure measured in each condition. The results showed that the ignition delay increased with higher EGR rates. According to Durnholtz et al. (1992), there was little variation in the ignition delay due to the increase of EGR rate up to 40% in case of the inconstant intake air temperature, however, the ignition delay increased with EGR rate increase up to 40% in case of constant intake air temperatures.

Figure 5 shows the combustion pressure and the rate of heat release for the EGR rates of 0, 10, and 20% at the engine loads of 25 and 100%. At the engine load of 25%, the ignition delay increased with increase in EGR rate, and the peak value of premixed combustion showed a significant variation. At the engine load of 100%, the ignition delay significantly increased at EGR rate of 20% and so did the peak value of premixed combustion. The EGR rate of 10%, on the other hand, led to slight increase in the ignition delay,



(a) Engine Load 25%



(b) Engine Load 100%

Fig. 5 Comparison of combustion pressure in the cylinder and the rate of heat release with EGR rate at an engine speed of 3800 rpm

and there was no significant difference in peak value between pre-mixed combustion and diffusion combustion.

According to Uchida et al. (1993) on the effect of combined EGR and supercharging in a single cylinder, four-cycle, direct injection diesel engine, greater EGR rate caused increase in ignition delay, with significant variations in the peak value of premixed combustion, but with no change in diffusion combustion. They attributed these results to the increase of inert compositions in the intake air and local decrease in combustion temperature due to oxygen concentration reduction.

Satoh et al. (1996) have demonstrated that there was little variation in ignition delay when EGR was applied in the experiment by using a single cylinder, four-cycle, direct injection, non-turbocharger diesel engine, and that the duration of diffusion combustion grew longer because the peak value of premixed combustion decreased. They attributed these results to the possibility that decreased oxygen concentration in intake gas led to decrease in combustion rate at a certain time point or at a certain spot in the combustion chamber, resulting in lower rate of heat release at that time point and inhibiting increase in combustion temperature.

In the present study, injection timing was set after the top dead center of the four-cylinder, indirect-injection diesel engine combined with EGR and the scrubber. The results obtained were similar to those of Uchida et al. (1993). On the other hand, Bae's previous study (1999) with fuel injection timing set before the top dead center showed similar findings as those of Satoh et al. (1996). Since the combustion characteristics show significant differences depending on experimental conditions as shown in these examples, it is not simple to make clear-cut conclusions. It is, however, very important to notice that the ignition delay in EGR application may be attributed to reduced oxygen concentration in the intake air; the main factor affecting the ignition delay at lower load regions is the increase of intake air temperature due to recirculated exhaust gas, and increased intake air temperature may lead to the rise of compressed air temperature at ignition.

3.4 NOx emissions

In the experiment for recirculated exhaust gas that was soot-removed by the scrubber, the engine was operated at the engine speeds of 1800, 2800, and 3800 rpm in order to measure NOx emissions as affected by EGR rate variation. It was found that increased EGR rate led to significant reduction in NOx emissions, in particular, the reduction being greater in proportion to higher engine loads. This tendency was almost the same regardless of the engine speeds; in particular, higher engine speeds produced greater reduction rates. That is, at the engine speed of 1800 rpm, every 25% increase of engine load at 20% EGR rate led to 35, 49, 59 and 52% higher reduction than without EGR. At 2800 rpm, the reduction rate was 46, 50, 67 and 71%, and at 3800 rpm, the reduction rate was 46, 53, 62 and 75% at the engine load of 25, 50, 75 and 100% respectively.

Figure 6 presents the measured values of NOx emissions that were obtained by increasing 5% EGR rate between 0 and 20% with the engine load as a parameter. At a fixed engine load, higher EGR rate resulted in decrease in NOx emissions. In particular, at higher engine loads, higher EGR rates led to greater reductions in NOx emissions

As has been widely known, the reason why increased EGR rate produces significantly greater reduction in NOx emissions in diesel engines is that the mixing of inert gas leads to increase in heat capacity of mixture and thus decrease in maximum combustion temperature, at the same time that decreased intake oxygen concentration leads to increased ignition delay.

Figure 7 shows the correlation between the reduction rate of NOx emissions and the ratio of intake oxygen concentration (with EGR/without EGR). It can be seen that increased EGR rate

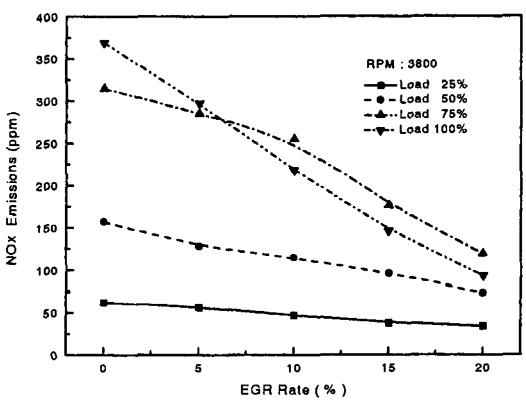


Fig. 6 Effects of EGR rate on NOx emissions as a parameter of engine load at an engine speed of 3800 rpm

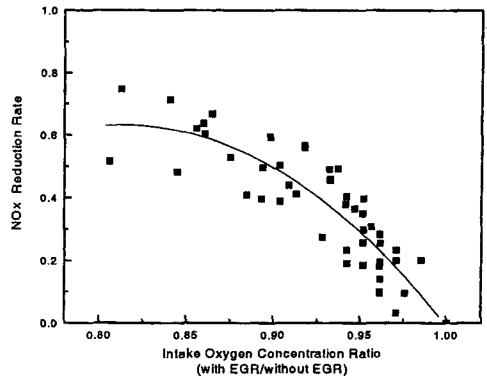


Fig. 7 Effect of intake oxygen concentration (with EGR/without EGR) on NOx emissions

resulted in decreased intake oxygen concentration. Higher EGR rates tend to reduce intake oxygen concentration and thus increase fuel-rich region, which causes lower combustion temperature of NOx formation region, resulting in reduction in NOx formation, and emissions are also reduced. In addition, reduction in intake oxygen concentration due to increased EGR rate brings about increased ignition delay, resulting in a shortened duration of high temperature combustion, a major factor of NOx formation, and thus leading to decreased NOx emissions (Bae, 1999; Daisho, et al., 1994; Khan, et al., 1973; Ladommatos, et al., 1998).

The relationship between the reduction rate of NOx emissions and the ratio of exhaust oxygen concentration (with EGR/without EGR) is shown in Fig. 8. The reduction rate of NOx emissions increases remarkably with EGR rate between 0.6 and 1 of exhaust oxygen concentration rate, while the rate increases gently at less than 0. 6. According to Bae's study on the effect of recirculated exhaust gas upon exhaust emissions with a scrubber EGR system in diesel engines (Bae, 1999), though increase in EGR rate led to decrease in intake oxygen concentration regardless of the engine speeds and loads, exhaust oxygen concentration could not be determined by EGR rate alone because exhaust oxygen concentration is associated not only with EGR rate but

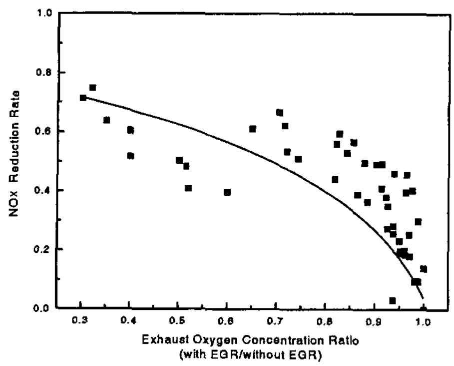


Fig. 8 Effect of exhaust oxygen concentration (with EGR/without EGR) on NOx emissions

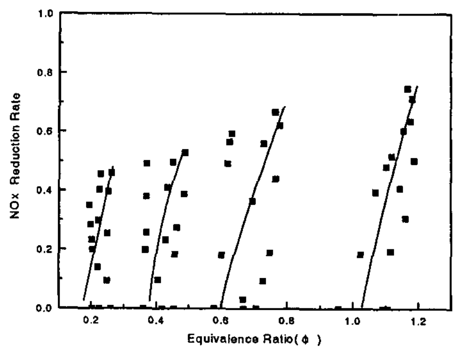


Fig. 9 Effect of equivalence ratio with EGR on NOx emissions

same study was the potential correlation between exhaust oxygen concentration and NOx emissions.

Figure 9 shows the relation between equivalence ratio and the reduction rate of NOx emissions, in which equivalence ratio is an average value calculated based on the oxygen and fuel amounts flowing into the cylinder. According to previous studies (Bae, 1999; Bae, et al., 1999), increased EGR rate led to higher equivalence ratio, especially greater at higher load regions. Equivalence ratio variation as affected by the engine speed showed no significant differences at lower load regions, but increased engine speeds at higher load regions caused slight decrease in equivalence ratio.

The data in Fig. 9 were too widely scattered to be processed based on equivalence ratio alone, and thus had to be reorganized with each engine load as a parameter. As shown in the figure, increased load regions resulted in greater variation in equivalence ratio, and increased equivalence ratio contributed to gentle increase in NOx emissions. While it was found in the authors' previous studies (Bae, 1999; Bae et al., 1999) that the maximum equivalence ratio was measured between 0.74 and 0.8 at zero reduction rate in NOx emissions, the present study showed a considerably increased equivalence ratio of 1.1. This result is similar to that of the previous study (Bae et al., 1995) on the theoretical calculation: increased EGR rate led to increase in equivalence ratio, which resulted in fuel-rich regions, bringing about reduction in NOx emissions due to lower burned gas temperature, caused by insufficient oxygen concentration.

3.5 Soot emissions

At the engine speeds of 1800, 2800, and 3800 rpm, the engine load was employed as a parameter to measure soot concentration as affected by EGR rate variations. Shiozaki et al. (1990) have showed that a lowered intake oxygen concentration with the increase of EGR rate would lead to larger ignition delay, which in turn could prolong the combustion duration, resulting in considerably higher soot emissions. Machacon et al. (1994) have reported that while soot emissions drastically increased with elevating EGR rates, advancing injection timing at lower engine loads would suppress soot formation.

To generalize the results of this study, heavier loads combined with higher EGR rate led to greater soot emissions, with EGR rate having a significantly greater effect at higher loads rather than lower engine loads. A widely accepted explanation for the increase of soot emissions with greater EGR rate is that higher EGR may lead to reduced intake oxygen concentrations available to be premixed with the fuel injected before the combustion, which may contribute to increase in soot emissions. Furthermore, the reduced intake oxygen concentration may decrease the oxygen amount necessary for soot oxidation during the expansion stroke, and there-

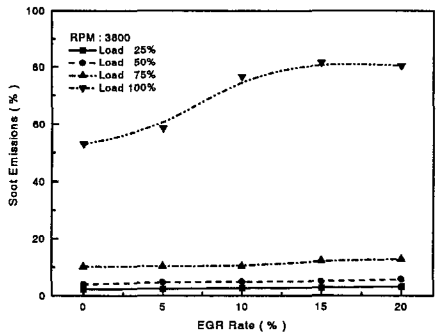


Fig. 10 Effects of EGR rate on soot emissions as a parameter of engine load at an engine speed of 3800 rpm

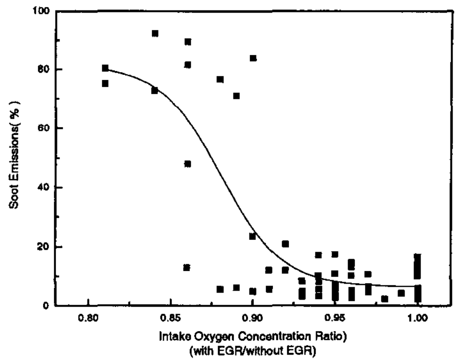


Fig. 11 Effect of intake oxygen concentration (with EGR/without EGR) soot emissions

by may abruptly increase soot formation. This means that the EGR application amount may be very limited in a highly loaded diesel combustion engine (Plee, et al., 1981).

Figure 10 shows the characteristics of soot emissions as affected by EGR rate variation at the engine speed of 3800 rpm. As is shown in the figure, soot emissions increase with higher EGR rate at the same engine load; within less than 75% of the engine load, EGR rate variation has no significant effect, but it does have a considerable effect at 100% of the engine load. In addition, at the same EGR rate, increased engine load results in greater soot emissions, with 100% of the engine load producing drastic increase in soot emissions.

To clarify the effect of intake oxygen concentration on soot emissions from the EGR system with scrubber, complete data obtained from the experiment are presented in Fig. 11, where an abscissa refers to the ratio of intake oxygen concentrations between EGR-application and non-EGR at all engine speeds and loads. As shown in the figure, higher EGR rates led to decrease in intake oxygen concentration ratio, resulting in greater soot emissions. Though some of the soot emissions would be eliminated with the scrubber, a considerable amount of soot emissions due to recirculated exhaust gas may be formed with increasing EGR rate. This tendency is qualitatively consistent with the results of the previous studies applying EGR alone (Bae, et al., 1999) and the previous findings (Bae, 1999) on the scrubber EGR system in a diesel engine.

According to Bae's experimental study on the scrubber EGR system in a diesel engine (Bae, 1999), the characteristics of soot emissions were determined by ignition delay, burned gas temperature, heat release rate (the peak values of premixed and diffusion combustions) and combustion duration; increased EGR rate caused lower intake oxygen concentration, resulting in negative effects on such combustion characteristics as ignition and mixing. Though it might be tempting to assume that greater ignition delay would increase fuel consumption amount burned during premixed combustion, decreased intake oxygen concentration instead resulted in reduced oxygen concentration for combustion, decreased combustion rate in premixed phase, lower combustion temperature, and shortened combustion duration, all of which would lead to increase in soot emissions.

Figure 12 shows the effect of exhaust oxygen concentration with EGR on soot emissions. As can be seen from the figure, soot emissions decreased markedly with the increase of exhaust oxygen concentration. In this figure, increased exhaust oxygen concentration means decrease in EGR rate, which may have been due to the fact that relatively higher oxygen concentration necessary for combustion contributed to decrease in soot emissions. These data may be applied to construct a feasible control device for the EGR system.

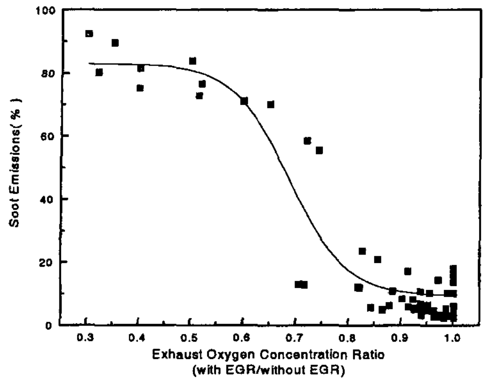


Fig. 12 Effect of exhaust oxygen concentration (with EGR/without EGR) on soot emissions

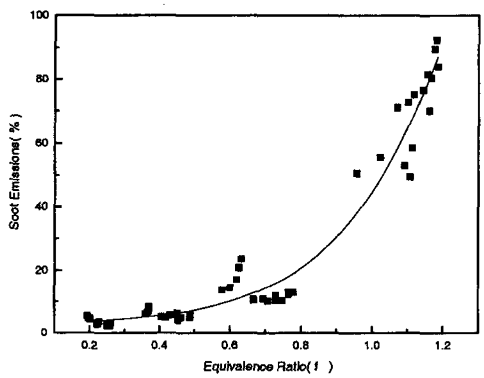


Fig. 13 Effect of equivalence ratio with EGR on soot emissions

Bae et al. (1994) suggested in their study on premixed combustion that the soot formation was considerably affected by the equivalence ratio because the heavy hydrocarbons, the precursor of soot, showed greater increase than the light ones as the equivalence ratio was elevated. Though diesel combustion is basically defined as diffusion, it may be considered locally as a mass of premixed combustion, leading to the same phenomena.

Figure 13 presents the correlation between the equivalence ratio(ϕ) and soot emissions. As shown in the figure, soot emissions are less than 20% in the lean mixture regions of below $\phi=0.8$, above which soot emissions increase drastically; above the theoretical equivalence ratio, soot emissions increase almost linearly to more than 50%. Most of the soot is formed because the duration of diffusion combustion is prolonged by decrease in ignition delay due to high temperature combustion during the compression stroke. The oxygen concentration in residual gas here plays an important role in the reburning of soot emissions. Therefore, it can be suggested from the results of this study that the increase of equivalence ratio with the EGR rate makes a contribution to the soot formation process because of relative deficiency in oxygen concentration, thus leading to an inevitable increase in soot emissions.

4. Conclusion

A four-cycle, four-cylinder, water-cooled, swirl chamber type diesel engine operating at engine speeds of 1800, 2800, and 3800 rpm was experimentally investigated with the engine load as a parameter, in order to clarify the effect of EGR rate on NOx and soot emissions, and to discuss the relationship between intake and exhaust oxygen concentrations, and equivalence ratio. The major findings obtained are summarized as follows:

(1) The soot removal efficiency in the scrubber was approximately 20 to 70%, though it showed a little variation depending on the engine speeds and loads.

(2) The variation in specific fuel consumption as affected by EGR rate increase was within 2 to 3% in the experimental range.

(3) As for the heat release rate, the ignition delay and the peak value of premixed combustion increased with EGR rate. In particular, their variations at the EGR rate of 20% at 100% engine load were significant

(4) As the intake and exhaust oxygen concentrations (increased EGR rate) decreased, NOx emissions decreased remarkably, but soot emissions increased.

(5) NOx emissions decreased steeply with the increase of equivalence ratio, in particular, greater decrease occurring in the lean mixture regions

of low engine load. Soot emissions increased with equivalence ratio, especially, an equivalence ratio of more than 0.9 producing remarkably greater soot emissions.

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