Reduction of Nitrogen Oxides of Diesel Engines by Exhaust-Gas-Selective Recirculation

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ABSTRACT

Exhaust-gas-selective recirculation is proposed for the purpose of reducing the emission of nitrogen oxides from diesel engines. In this method, either carbon dioxide or water is extracted from the exhaust gas and is fed directly into the intake air. These gases work to decrease the combustion temperature due to their greater heat capacities, thereby reducing the exhaust oxides of nitrogen remarkably. Therefore, it is expected that a diesel engine with exhaust-water-selective recirculation, EWR, may achieve a reduction in NO while maintaining thermal efficiency and exhaust particulates. In the case of exhaust-carbon-dioxide-selective recirculation, ECDR, a greater NO reduction might be attained with less amount of recirculating gas than EWR, although the ECDR requires a complicated system because of the difficulty in regenerating carbon dioxide.

INTRODUCTION

Diesel engines have higher thermal efficiency than most other heat engines and have beneficial advantages from the point of energy saving and mitigation of global warming. For this reason, they have been widely utilized in trucks and buses as well as ships and cogeneration systems. Because of the nature of diesel combustion, however, diesel engines emit more particulates and oxides of nitrogen, NOx, than other engines. To accomplish a low emission diesel engine, various attempts have been undertaken through many approaches including combustion modification, fuel improvement, and exhaust gas aftertreatment, but simultaneous reduction of both particulates and NOx is not very easy. For example, particulates traps and deNOx catalytic converters have been explored, but they are hampered by the problems in durability and reliability. The formation of NOx is a function of peak gas temperature and its residence time. Exhaust gas recirculation, EGR, is one of the effective methods to attain the reduction of combustion temperature, thereby decreasing the formation of NOx.

In this study, exhaust-gas-selective recirculation, which selectively recirculates either CO2 or H2O from the exhaust to the intake, is proposed and its effectiveness will be made clear.

EXHAUST-GAS-SELECTIVE RECIRCULATION

The exhaust gas recirculation, EGR, is a well established technique, which introduces a small portion of exhaust gas into the intake charge to reduce the combustion temperature. EGR is one of the effective methods to suppress the NOx formation and has been widely utilized in gasoline engines. In the case of a diesel engine, too much exhaust gas recirculation may decrease engine performance due to the deficiency of oxygen. EGR may be classified into three patterns, that is, hot EGR, in which exhaust gas is directly fed from the exhaust to the intake, cold EGR, in which exhaust gas is cooled down before recirculation, and selective EGR. The last one is what is to be proposed in this study and relies on the concept that CO2 or H2O is selectively recirculated. These gases are three-atomic having higher heat capacities, so that it is expected to suppress the NOx formation unless the recirculating gas is at an excessive concentration. It is known that this method is not associated with a great increase of exhaust soot.11,12

Figure 1 shows the result of an experiment carried out by one of the present authors.11 Test was undertaken on a single-cylinder four stroke-cycle direct-injection diesel engine having a cylinder bore of 90 mm, a stroke of 105 mm and a compression ratio of 15.7. The engine was operated at a constant speed of 1,800 rpm and a constant fuel injection quantity of 28.4 mg per shot. In the figure, brake specific fuel consumption, BSFC, NO concentration and smoke density are plotted against the fuel injection timing in the case when a part of intake air was replaced with CO2 or N2.

Even if either CO2 or N2 is substituted for a part of intake air, the NO concentration decreases with the increase in dilution gas. The NO reduction by CO2 is much greater than that in the case by N2 at the same dilution ratio because
of the greater heat capacity of CO\textsubscript{2}. Black smoke tends to increase with an increase in substitution by N\textsubscript{2}, whereas in the case of CO\textsubscript{2}, the increase in black smoke is not clearly been seen. This is because that CO\textsubscript{2}, which is distributed over the combustion chamber, restricts the formation of carbon through chemical equilibrium including Boudouard reaction. Hence a greater reduction in NO may be accomplished without an increase in soot emission. Optimum dilution ratio of CO\textsubscript{2} would be 10 \%, at which a remarkable NO reduction can be achieved with keeping the smoke and brake specific fuel consumption at baseline levels.

The system of exhaust carbon-dioxide-selective recirculation, ECDR, if it were realized, would be effective to purify the diesel exhaust. Water injection is well known as a NO\textsubscript{x} reduction approach. If the system of exhaust-water-selective recirculation, EWR, may be achieved, it would be attractive as well because it does not need any auxiliary water tanks on a vehicle. Therefore, the feasibility of CO\textsubscript{2} and H\textsubscript{2}O selective recirculation was firstly investigated. Secondly, the effect of EWR on the combustion and exhaust emissions will be clarified.

**EXHAUST-WATER-SELECTIVE RECIRCULATION, EWR**

**Feasibility of the EWR System**

In the EWR system, water should be condensed by cooling the exhaust gas below dew point and then be introduced into the intake. Water at a room temperature can be directly recirculated, so that the reduction in NO\textsubscript{x} would be attained without a decrease in the volumetric efficiency. The approaches to reduce NO\textsubscript{x} by means of water include fuel-water emulsion,\textsuperscript{31} fuel-water-fuel injection\textsuperscript{31} and so on in addition to water injection. These methods are effective to decrease NO\textsubscript{x}, but, they imply the inconvenience to carry an extra water tank and the complexity of the fuel injection system. On the contrary, the EWR system can recirculate water not only derived from combustion but also injected into the intake. Hence a closed system can be accomplished without a supplementary water charge, and it is not necessary to install a large water tank on a vehicle. Accordingly, this system can be accepted regardless of whether engine is for stationary use or not.

The total amount of water, which can be provided to the intake, will be estimated here. In the EWR, as illustrated in Fig.2, air at mass flow rate, \( A \), and water at mass flow rate, \( W_s \), in a liquid state are introduced into engine, where \( W_s \) consists of water produced by combustion, \( W_c \), and water injected into intake air. Mass ratio between water and fuel, that is, the ratio of water to be supplied into the intake, \( W_s \), to the fuel consumption, \( F \), was calculated as shown in Fig.3. \( R_e \) is the volume ratio of exhaust gas to be served for condensation to the total exhaust gas, and condensation ratio, \( R_c \), is defined as the volume ratio of water to be condensed to the total exhaust water and determined by a vapor partial pressure. In the figure, the changes of \( W_s / F \) and \( R_e \) against the fuel-air equivalence ratio \( \phi \) are given when hydrocarbon fuel in C/H ratio of 0.5 is used and exhaust gas is cooled down until 30 °C. At an equivalence ratio \( \phi = 0.8 \), \( R_e \) reaches 60 \%, and if the whole exhaust gas is condensed (\( R_e = 1.0 \)), 1.93 times as much water as the fuel consumption can be obtained as symbolized by ● in the figure. Since NO\textsubscript{x} is effectively reduced at water-fuel ratio of 0.7 while minimizing an increase of exhaust hydrocarbons at high load,\textsuperscript{31} it would be enough to condense the 60 \% of whole exhaust gas. At low and middle loads, however, it is required to increase the amount of exhaust gas to be condensed.

It is found that EWR has a potential to be realized in an actual engine. With a view to evaluating the design
guideline of the EWR system, water injection was conducted and its effect on engine performance and exhaust emissions has been investigated. The NO concentration and Bosch smoke density were predicted when the EWR was adapted to a diesel engine.

Experimental Set-up and Procedure

Two water-cooled naturally aspirated single-cylinder four stroke-cycle direct-injection diesel engines have been used in this study. Table 1 summarizes the engine specifications and test conditions. Both engines have deep-bowl type combustion chambers, and engine 2 was specially prepared to measure exhaust particulate matter. Each fuel injection system consists of Bosch type fuel injection pump and hole-type nozzle.

To clarify the influence of the amount of water on engine performance and exhaust emissions, fresh water was injected into the intake pipe instead of using condensed water from the exhaust. Experiments were carried out at a constant engine speed using a JIS No.2 gas oil. Each exhaust gas concentration at engine 1 was determined on dry gas basis. The heated FID analyzer (Yanaco, EHF-710H) was used to measure total hydrocarbons. The measurement of nitrogen oxides was also performed by an NDIR (Horiba, AIA-23).

Water was injected at a fixed crank angle by using an electric fuel injector for gasoline engines and the amount of injection was changed by varying the valve opening period. The amount of water was kept constant for the same experiment. The mass fraction of water to fuel consumption, \( R_w \), at the load where brake specific fuel consumption reached the minimum at the base injection timing, was selected as an indicator of quantity of water injection.

Experimental Results and Discussions

In Fig.4, the brake specific fuel consumption, BSFC, Bosch smoke density, and concentrations of total hydrocarbons, THC, and NO are indicated against brake mean effective pressure, BMEP, for different degrees of water injection, in the case of injection timing of \( \theta_s = 12^\circ \) BTDC. The amount of water injection is described by water to fuel ratio, \( R_w \), at BMEP=0.664 MPa. NO decreases with an increase of water injection and reaches about a half the baseline concentration when a mass of water injection equals to the fuel consumption \( (R_w=1.00) \). This result is identical to that given by Marshall et al.\(^{10} \) Further increase in water injected brings about a further reduction in NO at a higher load. Although BSFC and Bosch smoke density show slight increases with the amount of water injection, degrees of their deterioration are not very significant compared to the conventional EGR. Exhaust gas temperature, \( T_e \), drops slightly with the amount of water injection.

Cylinder pressure, \( P \), and heat release rate, \( Q_h \), at different amounts of water injection under the same condition are illustrated in Fig.5. Ignition lag becomes longer with an increase in water injection and accordingly initial rate of heat

<table>
<thead>
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<th>Table 1 Engine specifications and test conditions</th>
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<td>Engine type</td>
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![Fig.4](effect_water_injection_performance_emissions.png)  Effect of water injection on engine performance and exhaust emissions

![Fig.5](cylinder_pressure_heat_release_rate.png)  Comparison of cylinder pressure and heat release rate at different degrees of water injection
release increases, whereas the NO concentration does not increase as shown above. The reason of this combustion characteristic can be explained as follows: The reduction of compression gas temperature owing to the heat of evaporation of water, the reduction of oxygen concentration, and the large heat capacity of water, all of which restrict the rise of combustion temperature and eventually limit the formation of NO.

In Fig.6, engine performance and exhaust emissions at BMEP=0.664 MPa are compared against the water to fuel mass ratio, W/F. NO decreases in proportion to an increase of water addition regardless of injection timing. Therefore, NO can be reduced by the retardation of injection as well as water introduction into the intake port. But the reduction rate in NO becomes smaller at the area where W/F exceeds 1.2, and SMOKE, BSFC and THC exhibit an increasing tendency. Since the deterioration of the volumetric efficiency, \( \eta_v \), is small in spite of an increase of water injection, increases of SMOKE and BSFC are less than those at the ordinary EGR, \( \eta_v \), however, declines slightly as W/F is increased, and this might imply that water injected into the intake air evaporates during the intake and compression strokes and is distributed as vapor in the combustion chamber. Compression gas temperature is dropped due to the greater heat of vaporization of water, resulting in a longer ignition lag \( \tau \) with an increase of water injection.

Figure 7 shows the result of exhaust particulates at different degrees of water addition at engine 2. Particulates, PART, were sampled by using a mini-dilution tunnel with the same procedure as that already shown elsewhere,\(^{19}\) and the particulates were separated into insoluble and soluble fractions, SOLID and SOF, respectively. Although the SOLID fraction decreases slightly with advancing fuel injection, total particulates increase with the advancement because of the increase of SOF. An increase of water injection brings about a longer ignition delay and also a bigger amount of fuel-air mixture formed during this period. This results in an increase in unburned fuel that is exhausted as HC or SOF. It can be concluded that water injection is more effective when the injection timing is retarded.

Prediction of the NO Concentration

The NO concentration was predicted by using a series of test results when the EWR was installed on an actual diesel engine. In Fig.8, contour map of NO on BMEP and water-fuel mass ratio, W/F, is given together with SMOKE. The water-fuel mass ratio that can be recirculated is indicated by EWR in the figure. It is possible to provide water at middle and high loads, and at a higher load it can be supplied more water than fuel consumption. The quantity of water injection becomes naturally smaller at a lower load where NO concentration is low. Consequently, this characteristic protects water from entering into lubricant.

Fig.6  Effect of water-fuel ratio on engine performance and exhaust emissions

Fig.7  Effect of water injection on particulate emission

Fig.8  Contour map of NO and Bosch smoke number on BMEP and water-fuel ratio
through combustion chamber when the average cycle gas temperature is low.

Estimated NO concentration and Bosch smoke number are shown against BMEP in Fig.9. The NO concentration might be reduced to approximately one forth that of the baseline if the engine was operated at the combination of retarded fuel injection and water injection. In order to reduce NO to the same concentration with the EWR at retarded injection by the replacement of intake air with N₂, nearly 15% of exhaust gas should be substituted from Fig.1, which inevitably leads to a drastic increase in smoke. It is expected that a diesel engine equipped with both EWR and retarded fuel injection may achieve less exhaust smoke than that with ordinary EGR. If a diesel engine with EWR is operated with load-dependent water injection and optimum retardation of fuel injection, the NO concentration is selectively reduced without a large sacrifice of thermal efficiency.

In this study, it has been discussed that the condensed water is supplied to the intake by water injection. From the point of practical application, it is necessary to neutralize water containing sulfur compounds before injection, and the injection of temporarily stored exhaust water by engine requirement is another way for EWR to be more effective. Fuel-water emulsion or fuel-water-fuel injection might also be possible for feeding water to the engine. The possibilities of application of these methods to a diesel engine may be left to studies in the future.

EXHAUST-CARBON-DIOXIDE-SELECTIVE RECIRCULATION, ECDR

Outline of the ECDR System

Chemical absorption of CO₂ can be made by using amine type organic solvent such as monoethanolamine, MEA. MEA is employed as an absorber in this study because of the highest rate of absorption. The CO₂ absorption reaction by MEA is mainly the formation reaction of amine carbamate, R-NHCOONH₂-R, and the reaction rate reaches the maximum at a temperature of about 40 °C. MEA solution releases CO₂ at a temperature between 100 and 120 °C.

Figure 10 shows a schematic illustration of the ECDR system. All exhaust gas is introduced into the regenerator and cooled down to 100 - 120 °C there. At the neutralizer, exhaust gas containing sulfur is neutralized and also cooled down to 40 °C, and then fed to the absorber. Exhaust gas contacts MEA sprays there and CO₂ is selectively absorbed. MEA solution with absorbed CO₂ circulates through engine water jacket and the regenerator so as to receive heat for recycling CO₂. The MEA solution liberates CO₂ at the separator and flows in the absorber again.

Feasibility of the ECDR System

The feasibility of the ECDR system has been examined theoretically and experimentally. The heat necessary to release CO₂ from the MEA solution, Qₓ, consists of heat of endothermic reaction and latent heat. The heat available, Qₐ, is gained from both the coolant and the exhaust of engine. In Fig.11 the result of calculation are shown against the fuel-air equivalence ratio Ø in the case of recirculation ratio R/A=0.05 and 0.1. D/A represents the ratio of CO₂ flow rate, D, to the intake air flow rate, A, in the case of the recirculation, and increases with an increase of Ø.

Qₓ increases with Ø due to the rise of exhaust gas flow rate and temperature. On the contrary, Qₓ does not vary because the flow rate of MEA solution and CO₂ are not affected at a constant R/A. The ECDR system will be made effective if Qₓ exceeds Qₓ, for example, equivalence ratio over 0.4 is required in the case of R/A=0.05. Consequently, ECDR may be useful for reduction of NO at a relatively higher load. This system can be applied to the engine running at a constant speed such as marine and cogeneration purposes, although ECDR requires a fairly complicated system.

Next, feasibility of the ECDR system was analyzed by adapting it to a diesel engine. Test engine was the same direct-injection diesel engine which was used in Fig.1.
to regenerate CO₂ is one of the most serious problems. In this study, the ECDR system can not recycle CO₂ enough to reduce the formation of NOₓ, nevertheless the results may suggest the direction for future study.

SUMMARY

The exhaust-gas-selective recirculation has been proposed and its feasibility and effectiveness are explored. The results can be summarized as follows:

1) Exhaust-gas-selective recirculation, which recirculates either CO₂ or H₂O from the exhaust to the intake, works to decrease the combustion temperature due to their greater heat capacities, reducing nitrogen oxides remarkably.

2) Exhaust-water-selective recirculation, EWR, which recirculates the condensed water from the exhaust to the intake, might be accomplished in an actual engine without feeding a supplementary water. EWR is not associated with an increase in the volumetric efficiency, so that the increases in particulates, Bosch smoke number and brake specific fuel consumption are not significant compared to the ordinary EGR. The EWR system has the tendency to increase the amount of water with increase of load, thereby greatly reducing NO at higher loads and also preventing water from entering into lubricating oil at lower loads.

3) Exhaust-CO₂-selective recirculation, ECDR, which recycles CO₂ by monoethanolamine solution, was proposed. A great deal of NO reduction might be achieved by less amount of recirculate gas than that at EWR, although the ECDR requires a complicated system. Maintaining the heat necessary to regenerate CO₂ is the crucial factor from the point of practical application.

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