Effect of Exhaust Gas Recirculation and Injection Pressure on Exhaust Emissions from a Diesel Engine

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ABSTRACT

To clarify optimal combination of high-pressure injection and exhaust gas recirculation (EGR) for simultaneous reduction of nitric oxides (NOx) and particulate (PM) emissions in the diesel engine exhaust, experimental and theoretical studies were performed on a single cylinder test engine. The measured tendencies of NOx and PM were evaluated in terms of spray characteristics under various injection conditions and of exhaust recirculation rate. The results suggest that enhancement of air entrainment and turbulent mixing effectively reduce the PM without deterioration of NOx at a high exhaust recirculation rate. From an analysis based on a stochastic diesel combustion model, this phenomenon is caused by a change of maximum temperature at which the mixture can arrive.

INTRODUCTION

Exhaust gas recirculation (EGR) is a useful means to reduce NOx emission from diesel engines. However, EGR has a disadvantage in that PM emission significantly increases when a higher EGR rate is used to obtain a lower NOx emission. This problem can be overcome by employing high-pressure injection because of its potential of introducing more oxygen into the spray. Therefore, the combination of EGR and high-pressure injection is thought to be a most useful technique for simultaneous reduction of NOx and PM$^{1,2}$.

To obtain sufficient reduction of the emissions, an adequate injection condition should be met. It is clear that entrainment of surrounding gas into a spray should be enhanced to suppress PM. This can be realized by the injection at an elevated injection pressure. However, an excessively high injection pressure may sacrifice the NOx reduction ability of EGR despite a lower PM. For this reason, reduction of the nozzle orifice size should be combined when high pressure injection is employed. However, it is not yet well known how to optimize nozzle orifice size and injection pressure when EGR is employed.

From this point of view, we aim at clarification of the strategy for determining the injection condition for low NOx and PM emission when using EGR at high loads in direct-injection diesel engines. For this purpose, effects of the spray characteristics on the measured emissions will be discussed. From the results it will be demonstrated that reduction of nozzle orifice size is essential to reduce the NOx emission without deterioration of the PM emission at a low EGR rate, and that elevation of injection pressure is advantageous to reduce PM emission without an increase in NOx emission at a high EGR rate. Explanations will be made for the EGR effect on combustion and emissions based on a stochastic diesel combustion model.

EXPERIMENTAL

The direct-injection four-stroke-cycle single-cylinder diesel engine with natural aspiration was used for experiments, with a KD-3 high-pressure injection system$^{3}$. The main specifications of the engine and the injection system are listed in Table 1. This engine has a deep-bowl toroidal type combustion chamber at a swirl ratio of 2.4. The engine was operated at a speed of 1800rpm and injection start timing of TDC using gas oil (JIS grade No.2) as fuel. The fuel was injected by a hole-type injector with four nozzle holes. The amount of injection was fixed to 41mg/stroke, which corresponded to equivalence ratio of 0.71 in the case of no exhaust gas recirculation. This condition is near the smoke limit when a conventional jerk-type injection system is employed. Eight sets of test were carried out for different nozzle orifice diameters $d_o$ and maximum injection pressures $p_{\text{max}}$ as shown in Table 2. $p_{\text{max}}$ is the maximum injection pressure measured at the inlet of injection nozzle holder. Test No.0 was taken as the baseline condition under which a relatively low injection pressure of 60MPa and large nozzle orifice of 0.24mm were used. In tests Nos.1 through 3, $d_o$ is reduced to 0.20mm and $p_{\text{max}}$ is raised to 80 to 120MPa. $d_o$ is further reduced to 0.18mm with higher injection pressure of 100 to 150MPa in tests Nos.4 through 6. In test No.7 the
smallest nozzle orifice of 0.16mm is used with injection pressure of 120MPa.

In this study, cold EGR was employed to avoid influence of the change in the intake charge temperature at different EGR rates. Hot exhaust gas was cooled down to atmospheric temperature by using a heat exchanger, mixed with fresh air in a mixing tank, and then supplied to the engine. The EGR rate \( r \) was defined as being mole ratio of the recirculated gas to total charged gas introduced into the cylinder. \( r \) is determined by calculation from the CO\textsubscript{2} concentration measured for each gas.

RESULTS AND DISCUSSION

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Test conditions</th>
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<tbody>
<tr>
<td><strong>Test No.</strong></td>
<td>Maximum injection pressure ( P_{N\text{max}} \text{ MPa} )</td>
</tr>
<tr>
<td>0</td>
<td>60</td>
</tr>
<tr>
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<td>6</td>
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</tr>
<tr>
<td>7</td>
<td>120</td>
</tr>
</tbody>
</table>

Tendency of NO\textsubscript{x} and PM

Figure 1 shows the effects of EGR rate on exhaust emissions and engine performance obtained in tests Nos.0 through 3. The overall equivalence ratio increases from 0.71 to 0.83 when EGR rate changes from 0% to 25%. In the case of test No.0 (\( P_{N\text{max}}=60\text{MPa}, \ d_N=0.24\text{mm} \)), Bosch smoke reading, PM, THC and indicated specific fuel consumption \( b_i \) rapidly increase with EGR rate due to the decrease in the oxygen concentration in the charge. When the injection pressure is elevated at a smaller nozzle orifice of 0.20mm (Nos.1 through 3), PM emission is lowered at every EGR rate while NO\textsubscript{x} increases. In spite of high injection pressure, \( \Delta p/d\theta \text{max} \) is kept low due to the reduction of nozzle orifice size.

Fig.1 Effect of EGR rate on exhaust emissions and engine performances (Test Nos.0–3)
Figure 2 shows that, when the nozzle orifice diameter $d_n$ is further reduced to 0.18mm (tests Nos.4 through 7) or less, the reduction of PM becomes insufficient for the same injection pressure as in $d_n=0.20mm$. Even when the injection pressure is elevated to 150MPa (No.6), NOx and PM are only reduced to the same level as in the test No.1 (80MPa, 0.20mm). From Figs.1 and 2, it is also clear that insoluble fraction of particulates SOLID is mainly influenced by EGR while the soluble fraction SO is affected insignificantly.

**Effect of spray characteristics on emissions**

To discuss the effects of injection characteristics in a systematic way, spray characteristics are evaluated for each test based on a previous study\(^{(4)}\) by some of the present authors, and its relation to NOx and PM emission will be discussed.

**Spray characteristics**

Spray development and progress of turbulent mixing of fuel and air in the spray may strongly affect the heat release process and emissions. From this point of view, some characteristic values were calculated for each test condition. They are the amount of surrounding gas entrained into the spray $M$, power of generating turbulence $P_T$, microscopic mixing rate $\omega$, ratio of air and fuel flow rate $J_A/J_F$ and spray tip penetration $x$. These values can be linked to injection condition, i.e., injection pressure or injection velocity $u_F$ and nozzle orifice diameter $d_n$, on the basis of the momentum spray theory\(^{(5)}\) and the stochastic spray model\(^{(6)}\). These are given as follows.

\[
M/M_o = \left( \frac{u_F}{u_{F0}} \right)^2 \left( \frac{d_n}{d_{N0}} \right)^2
\]

\[
P_T/P_{T0} = \left( \frac{u_F}{u_{F0}} \right)^3 \left( \frac{d_n}{d_{N0}} \right)^{1/2}
\]

\[
\omega/\omega_o = J_A/J_F = \left( \frac{u_F}{u_{F0}} \right)^2 \left( \frac{d_n}{d_{N0}} \right)^{1/2}
\]

\[
x/x_o = \left( \frac{u_F}{u_{F0}} \right)^{1/2} \left( \frac{d_n}{d_{N0}} \right)^{1/2}
\]

All these values are normalized by a baseline condition denoted by subscript 0. It should be noted that $\omega$ and $J_A/J_F$ have the same sensitivity to $u_F$ and $d_n$.

Since the oxygen concentration in the surrounding gas is low, a decrease in $M$ increases PM. $P_T$ is kinetic energy per mass of fuel injected, which may be converted to turbulent energy in the spray. Sufficiently high $P_T$ ensures fuel-air mixing by generating turbulence in the shear layer in the spray. $\omega$ is the dissipation rate of turbulence, which is regarded as being microscopic mixing rate. A high $\omega$ is needed to quickly eliminate heterogeneity of temperature and concentration, which may lead to lower NOx and PM emissions. $J_A/J_F$ indicates capability of making the mixture leaner. Lack of the penetration $x$ causes poorer utilization of air existing in the combustion chamber.

**Relation between spray characteristics and emissions**

The above characteristic values were calculated for injection conditions tested. Here $u_F$ was calculated from the measured injection duration on the assumption that the injection mass rate was constant during injection. The test
Fig 3  Spray characteristics for injection conditions tested

No.0 was selected for the baseline condition. Figure 3 shows the results. The group of $d_o = 0.20 \text{mm}$ (Nos 1 through 3) have higher values of $M$, $P_r$, $\omega$, $J_s/J_f$ and $x$ than the baseline, and these values increase with injection pressure. When $d_o$ is reduced to 0.18mm or less (Nos 4 through 7), $M$ becomes less than the baseline. Using this figure, the reason for change of NOx and PM emission with injection conditions will be clarified below.

Figure 4 shows the NOx versus PM relation for each EGR rate $r$. In the case without EGR ($r=0$), PM is much reduced from the baseline case of No.0 as the injection pressure is increased as seen in Nos.1 through 3 ($d_o = 0.20 \text{mm}$). This is due to the increase in $M$, $P_r$, $\omega$ and $J_s/J_f$. However, the increase in the injection pressure increases NOx. This is well-known tendency when a high-pressure injection is used. On the other hand, Nos.4 through 7 with smaller orifice sizes of $d_o \leq 0.18 \text{mm}$ give lower NOx level than the greater ones of tests Nos 1 through 3. Among them, No.4 has lower NOx than No.0 with a slight increase in PM. There is a significant decrease in $M$ and $x$, while only $\omega$ and $J_s/J_f$ are higher than those of No.0 as shown in Fig.3. This result may indicate that reduction of nozzle orifice size is effective for lowering NOx. In this case, it is assumed that explosive combustion is prevented due to the decrease in air entrainment, whereas enhancement of micromixing or dilution contributes to eliminate fuel-rich mixture that could be the origin of PM.

In the case No.7, which has greater $M$, $P_r$, $\omega$ and $J_s/J_f$ than in the case of No.4, PM decreases only slightly and NOx increases. Similarly, further increase in these characteristic values in Nos.5 and 6 reduces PM but increases NOx.

When EGR is employed, the NOx sensitivity to spray characteristics is weakened as EGR rate $r$ is increased. At $r=10\%$, emissions tendency is qualitatively similar to that at $r=0\%$, but the range of NOx level is still broad. When $r$ is raised to 20 or more, the difference in the spray characteristic values only slightly changes NOx, although a significant effect on PM is noted. Thus it may be safely stated that the increase in $M$, $P_r$, $\omega$ and $J_s/J_f$ reduces PM without causing a significant increase in NOx.

In the case of No.3, mass of entrained gas is about 1.5 times greater than in the case of No.0 as shown in Fig.3. This means that even at $r=25\%$ the spray inhales more oxygen per unit time than the baseline at $r=0\%$. It may be suggested that the NOx level would be so high if this increase in oxygen directly leads to increase in heat release rate. In fact, the NOx changes only slightly. The detail of this reason will be discussed in the next section.

Mechanisms of NOx reduction by EGR

To better understand the above results, theoretical investigation was carried out on the NOx formation in combustion with EGR, based on the stochastic diesel combustion model. For the details of the model, refer to previous papers.

This model characterizes the main process of diesel
combustion as being a process from the initially separated fuel and air into the mixed homogeneous state through turbulent mixing. This process is simulated by the heat and mass exchange between many fluid particles through their collisions. Frequency of the collision \( f \), which corresponds to turbulent mixing intensity, is inversely proportional to turbulent kinetic energy \( k \) and is proportional to its dissipation rate \( \varepsilon \). \( \varepsilon \) increases with \( k \) but decreases with \( L \), the characteristic scale of turbulence. Using these relations, \( f \) can be obtained from either \( k \) and \( L \) or \( k \) and \( \varepsilon \).

It is important to estimate the amount of fuel-air mixture formed during the ignition delay and turbulent energy generated in the spray until ignition. In this spray process, mixing is considered to take place between injected fuel particles and entrained air particles. The entrained air amount is determined based on the momentum theory. In this process, \( k \) is supplied by injection power \( P_r \) and turbulence energy generated by spray-swirl interaction. \( k \) decays by turbulence dissipation in the rate of \( \varepsilon \) with constant scale \( L \) and also by the spray mass growth.

After ignition takes place the mixing region is expanded over the whole volume of the combustion chamber. Also, in this combustion process, \( P_r \) generates turbulence energy as long as the injection lasts, but after the injection period, decay of \( k \) is accelerated by the expansion of the combustion chamber volume.

On the assumption that most of NOx is NO, the NO concentration during combustion is estimated by extended Zeldovich mechanism with equilibrium of heat release related species. Soot concentration is also considered to be free solid carbon produced in a manner as described by Boudourd equilibrium reaction.

Figure 5 shows the effect of EGR rate and injection velocity on the exhaust NO and PM (as carbon) emission. Here the nozzle orifice diameter is fixed to \( d_n = 0.20 \) mm and the injection velocity is changed in accordance with the injection pressure. For simplicity, the ignition delay is kept at a constant. As may be seen from the figure, the tendencies of NO and PM qualitatively coincide to measured results. The PM reduction without NOx deterioration due to high injection velocity is particularly well reproduced at higher EGR rates. The reason for this phenomenon can be explained by analyzing the tendency of the NO production rate in Figures 6 and 7.

In Figure 6 the calculated NO production rate \( d\text{NO}/dt \) on mole concentration per unit mass of mixture and temperature \( T \) in every fluid particle are plotted against equivalence ratio \( \phi \) for \( u_r = 270 \) m/s and \( r = 0 \)%. It should be noted that the temperature \( T \) of each fluid particle stands for the equilibrium temperature corresponding to the chemical composition. Therefore the temperature shows its maximum when \( \phi \) is around unity, where \( d\text{NO}/dt \) also reaches maximum. At a crank angle of \( \theta = 15 \) CA, when the average temperature \( T_2 \) tends to increase, the number of particles with \( \phi = 1 \)
temperature reduction by EGR significantly suppresses the NO production. This mechanism is thus confirmed at relatively high equivalence ratio. At a lower equivalence ratio, higher EGR rate is available due to excess oxygen leading a large reduction in NOx with a relatively small PM deterioration.

CONCLUSION

For determination of the optimal condition of injection for low NOx and PM emission when EGR is used, effects of spray characteristics on measured tendency of NOx and PM emission were discussed. The results show that reduction of nozzle orifice size is most important to reduce NOx emission without deterioration of PM emission at a low EGR rate. At a high EGR rate, enhancement of entrainment air into the spray and mixing by increasing the injection pressure is useful to reduce PM emission without increase in NOx emission. The reason has been elucidated through the investigation of EGR effect on combustion process and emissions by using a stochastic diesel combustion model. The increased heat capacity of mixture by EGR limits the temperature at which the mixture can arrive. This keeps the NO production rate lower even when the fuel-air mixing is much enhanced by high pressure injection.

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REFERENCES