Effect of Rich and High Turbulence Combustion on NOx and Particulate Emissions from a High Speed Direct-Injection Diesel Engine

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ABSTRACT

In this study it was tried to reduce NOx and particulate emissions simultaneously in a high speed direct-injection diesel engine by realizing fuel-rich combustion to reduce NOx emission at initial combustion stage and high turbulence combustion to reduce particulate emission at diffusion combustion stage. High squish combustion chambers were used to realize the reduction of NOx and particulate emissions. Experiments were carried out to investigate the effects of high squish combustion chambers with small throat and swirl ratio on combustion process and exhaust emissions. Results showed that high squish combustion chambers could reduce both NOx and particulate emissions with retarded injection timing and intensified squish. Further reduction of NOx emission could be realized by restraining initial burning.

In order to analyze the results, endoscopic high speed photography was employed to observe flame behavior. Photographs showed that flame development and combustion process were different in the original combustion chamber and high squish combustion chamber. Furthermore, Engine CFD code was used to simulate air-fuel mixture formation and combustion process. Calculations proved that air motion caused by combustion chamber geometry significantly affected air-fuel mixing and combustion process.

INTRODUCTION

The direct-injection diesel engine is the main power source for many applications because of its inherent high thermal efficiency and low CO₂ emission. However, with increasingly stringent emission regulations, reduction of NOx and particulate emitted from the direct-injection diesel engine is of urgent necessity. Many efforts such as pilot injection, EGR, and high pressure injection have been made to reduce emissions of DI diesel engines⁴⁻⁶⁻⁹. However, because of the trade-off relationship between NOx and particulate emissions, it is difficult to reduce both emissions simultaneously.

Authors previously reported that high squish combustion chamber was effective in reducing particulate emission, especially when injection timing was retarded, making it possible to reduce NOx and particulate emissions simultaneously⁴⁻⁹. It was also found that NOx emission decreased significantly under fuel-rich and strong swirl conditions at initial combustion stage⁹. Based on such findings, in this paper the attempt was made to realize fuel-rich condition at premixed combustion stage to reduce NOx emission and high turbulence condition at diffusion combustion stage to reduce particulate emission in a direct-injection diesel engine.

EXPERIMENTAL APPARATUS AND PROCEDURE

A 4-stroke single cylinder naturally aspirated direct-injection diesel engine was used in this research. Engine specifications were given in Table 1. JIS#1 diesel fuel (density 843kg/m³, lower heating value 44200kJ/kg) was used. Combustion chambers used in this study were shown in Fig.1 and Table 2. The STD piston had the original toroidal combustion chamber. The R35 piston had a high squish combustion chamber with throat diameter to bore diameter ratio of 35%. The R35S piston also had a high squish combustion chamber with the same throat diameter as the R35 chamber. The cavity volume of the R35S chamber was smaller than that of the STD and R35 chambers, which was assumed favorable for forming fuel-rich mixture inside the cavity. The R35S chamber was employed in two cases. For one case, the top clearance 8 was enlarged to maintain the same compression ratio as in the STD chamber. For the other

<table>
<thead>
<tr>
<th>Bore(mm) × Stroke (mm)</th>
<th>102 × 105</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard compression ratio</td>
<td>17</td>
</tr>
<tr>
<td>Standard combustion chamber</td>
<td>toroidal</td>
</tr>
<tr>
<td>Standard inlet port and swirl ratio</td>
<td>helical, 2.2</td>
</tr>
<tr>
<td>Type of fuel injection pump</td>
<td>Bosch PFR-IAW</td>
</tr>
<tr>
<td>Nozzle</td>
<td>150° - 4 × 0.29</td>
</tr>
</tbody>
</table>

Table 2 Characteristics of combustion chambers

<table>
<thead>
<tr>
<th>Cavity volume (cm³)</th>
<th>STD</th>
<th>R35</th>
<th>R35S</th>
<th>R35S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top clearance (mm)</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td>1.67</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17</td>
<td>17</td>
<td>19.5</td>
<td>17</td>
</tr>
</tbody>
</table>
submodel, spray submodel and $k-\varepsilon$ two-equation turbulence model. Combustion submodel assumes that at first the premixture of fuel and oxygen is formed and then premixed gas is consumed by a single step chemical reaction which is expressed by an irreversible reaction of an Arrhenius form. The spray submodel treats the spray as a quasi-steady gas jet. Air entrainment into the jet is represented at distributed sink zone. Flow rate of entrained air is calculated by momentum theory. Outflows of fuel, entrained air, momentum and other quantities are calculated at source zone.

EXPERIMENTAL RESULTS

Effect of Combustion Chamber Geometry

The effect of combustion chamber geometry on engine performance and emissions was investigated at the injection timing of $-5\degree$ ATDC and swirl ratio of 2.2. As shown in Fig. 2, for the R35 chamber, smoke S and particulate PART emissions are improved compared with the STD chamber owing to the intensified turbulence created by the squish lip. However, in the R35 chamber, NOx emission is much higher than in the STD chamber. On the other hand, the R35S chamber with large top clearance exhibits an apparent tendency to suppress NOx emission. Nevertheless, smoke and particulate emissions deteriorate at high load because of weak squish intensity and unfavorable fuel distribution caused by large top clearance. In the R35S chamber with the same top clearance as in the STD and R35 chambers, smoke and particulate emissions decrease to the same level as in the R35 chamber. NOx emission is slightly lower than in the R35 chamber, but the degree of NOx reduction is still inadequate. The effect of combustion chamber geometry on fuel consumption is negligibly little, except the combustion chamber R35S with large top clearance which shows higher fuel consumption at high load. For the R35S chamber, because of the poor performance and worse particulate emission at high load as top clearance is enlarged, only the R35S chamber with the same top clearance as in the STD and

![Fig. 2 Effect of combustion chamber geometry on emissions](image-url)
R35 chambers is used in the following research.

Figure 3 shows cylinder pressure $p$ and heat release rate $Q$ of different combustion chambers at conditions identified in Fig.2. For the R35 and R35S chambers, heat release rate at diffusion combustion stage is higher, and combustion duration is shorter than in the STD chamber, resulting in lower smoke and particulate emissions. In the R35 chamber, heat release rate at premixed combustion stage is much higher than in other combustion chambers because a large amount of combustible mixture is available at initial combustion stage due to intensified air motion, which agrees with high NOx emission in this combustion chamber. In the combustion chamber R35S, heat release rate at initial combustion stage is as low as nearly half that of the R35 chamber because of fuel-rich combustion and short ignition delay caused by high compression ratio. In this chamber, it could be considered that the restrained premixed combustion caused by fuel-rich condition and the promoted diffusion combustion caused by high squish intensity are achieved. Nevertheless, NOx emission was not as low as expected. It is assumed that the lack of homogeneity of fuel-air mixture negates partly the effect of fuel-rich combustion. Another reason is the high temperature in combustion chamber due to high compression ratio.

![Fig.3 Cylinder pressure and heat release rate for different combustion chambers](image)

**Effect of Swirl**

The effect of swirl on engine performance and emissions of STD, R35 and R35S combustion chambers was investigated at injection timing of -5° ATDC. Swirl ratio $r_s$ was changed over the range from 1.8 to 4. Figure 4 shows, for all combustion chambers tested, the particulate emission and fuel consumption are achieved minimum when swirl ratio is from 2 to 3. Inadequate air motion at low swirl level and over mixing at high swirl level are considered to be the reasons of increased fuel consumption and particulate emission. THC emission does not change obviously as swirl is varied. The effect of swirl on NOx emission exhibits essentially different tendency for different combustion chambers. For the STD chamber, NOx emission increases with strengthened swirl. In opposite, for the R35 and R35S chambers, NOx emission decreases as swirl level is raised. For chamber R35S, the swirl ratio 3.1 at which not only particulate and fuel consumption but also NOx emission is at low level is employed in the following experiments.

![Fig.4 Effect of swirl on emissions](image)

**Effect of Injection Timing**

The effects of injection timing on emissions and performance for STD, R35 and R35S chambers at high load $P_e=0.7$MPa and low load $P_e=0.2$MPa are shown in Figs.5 (a) and (b) respectively. NOx emission decreases with retarded injection timing for all combustion chambers tested under both load conditions. When injection timing is retarded later than TDC, decrease of NOx emission becomes slow. In spite of high compression ratio in the R35S chamber, NOx emission is lower than that of the R35 chamber. Fuel consumption increases for each combustion chamber as injection timing is retarded, while combustion chamber R35S exhibits a tendency to mitigate the sacrifice in fuel consumption. At high load, particulate emission dominated by solid shows a trend similar to smoke density. For the STD chamber, smoke and particulate emissions increase unacceptably with retarded injection timing. In contrast, for combustion chambers R35 and R35S, smoke and particulate emissions show a decrease tendency at retarded injection timing. At low load, particulate emission dominated by SOF exhibits a trend similar to THC emission. In the R35 chamber, THC and particulate emissions increase dramatically when injection timing is retarded later than TDC. In the R35S chamber, THC and particulate emissions are much lower than in the R35 chamber. The results above indicate that it is possible for the R35S chamber to achieve low NOx and low particulate emissions at retarded injection timing with less sacrifice of fuel consumption and less deterioration of THC and SOF emissions at low load. Figure 6 shows the effect of injection timing on combustion characteristics of different combustion chambers. It is found that, as injection timing is retarded, maximum heat release rate $Q_{max}$ at initial burning
stage decreases for the R35 and R35S chambers. Combustion duration $\Delta \theta_{\text{burn}}$ of the R35 and R35S chambers is shorter than in the STD chamber, which indicates that it is possible for the R35 and R35S chambers to achieve low particulate emission at late injection timing.

Figure 7 shows NOx-particulate relationships of different combustion chambers under high and medium load conditions. The STD chamber shows a typical trade-off relationship between NOx and particulate emissions under both load conditions. In the R35 and R35S chambers, NOx-particulate trade-off relationships do not occur. NOx and particulate emissions decrease simultaneously at retarded injection timing. Especially in the R35S chamber, NOx emission is further reduced compared with the R35 chamber.

![Fig. 7 Correlation of NOx and particulate emission](image)

**Fig. 7** Correlation of NOx and particulate emission

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**ANALYSIS OF COMBUSTION PROCESS**

Figure 8 shows the arrangement of endoscope in combustion chamber. Figure 9 shows view field and high speed photographs. The view field is at 0° ATDC in which nozzle tip and two of sprays are visible. Cavity edge of the R35S and STD chambers appears in the upper area near the nozzle in the view field after 18° ATDC and 24° ATDC respectively. For the STD chamber, the first luminescent flame is observed at 6° ATDC. After ignition, flame propagates in the direction of swirl. At 22° ATDC the bowl is filled with brilliant flame. The high luminosity flame corresponding to fuel-rich mixture tends to spread out of the cavity and the central pip is covered by flame. After 28° ATDC, the flame in the bowl burns out rapidly, while lumps of fuel-rich mixture burn slowly over the piston crown, where temperature is low and air motion is weak, causing insufficient oxidization and large amount of particulate emission. For the R35S chamber, ignition occurs at 4° ATDC, earlier than in the STD chamber because of intensified air motion and high compression ratio. Then the flame sweeps over the chamber in the direction of swirl. The
central pip is visible until 22° ATDC, possibly implying the high luminosity flame originating from fuel-rich mixture is kept beneath the squish lip until middle combustion stage. It indicates that the squish lip effectively prevents the fuel-rich mixture from spreading out of the cavity. After 28° ATDC, low luminosity flame spreads out over the piston crown. The mixture outside the bowl is dispersed by violent swirl and reversed squish and burns up rapidly. At the last burning stage, the uniform mixture oxidizes inside the bowl where relatively high temperature and air motion intensity are favorable for oxidation. The above phenomenon may be the reason of the low particulate emission in high squish combustion chambers.

Combustion process was simulated by CFD calculation. Figure 10 shows distributions of gas velocities $u_\text{m}$ and turbulent intensities $u'$ for a cross section including cylinder axis. Calculation was conducted under the condition of injection timing $0°$ ATDC and $P_e=0.7\text{MPa}$ for the STD and R35S chambers. At 20° ATDC, the diffusion combustion stage, strong reversed squish is seen for the R35S chamber and expansion flow in the cavity caused by combustion is also strong for the R35S chamber. As a result, high turbulence forms at the inlet edge and inside the cavity for the R35S chamber. Strong air motion and high turbulence promote fuel-air mixture formation and diffusion combustion. Figure 11

![Fig.8 Arrangement of endoscope in combustion chamber](image)

![Fig.9 Comparison of flame behavior for different combustion chambers](image)

![Fig.10 Gas velocity and turbulence intensity](image)

![Fig.11 Variation of unburned fuel in the cavity and clearance volume](image)

$n=1500\text{rpm}$  \quad $P_e=0.5\text{MPa}$  \quad $\theta_i=0°$  \quad ATDC
shows the time histories of total mass of unburned fuel. $M_{fb}$ is the ratio of unburned fuel mass in the cavity to injected fuel and $M_{bc}$ is the ratio of unburned fuel mass in the clearance volume to injected fuel. It is found that the R35S chamber keeps fuel in the cavity for a relatively long time and the amount of unburned fuel flowing out to the clearance volume is less than that for the STD chamber. It is suggested that in the R35S chamber, fuel is consumed mainly in the cavity because of strong air motion and high turbulence caused by combustion chamber geometry, which results in low particulate emission.

CONCLUSION

The original combustion chamber (STD) and two kinds of high squish combustion chambers (R35, R35S) are compared in terms of engine performance, exhaust emissions as swirl intensity and injection timing are varied. Results show:

1. Particulate emission is improved for the high squish combustion chambers. The high squish combustion chamber with small cavity volume exhibits potential possibility to reduce NOx emission by restraining the initial burning.

2. The absence of fuel-rich mixture out of the cavity and the oxidization of mixture with adequate air motion and temperature inside the cavity at diffusion burning stage may be the reason of the low particulate emission for the high squish chamber.

3. For the original and high squish combustion chambers, particulate emission and fuel consumption are achieved minimum with a swirl ratio range from 2 to 3. However, when swirl level is raised, NOx emission increases for the original combustion chamber, but decreases for the high squish combustion chambers.

4. For the high squish combustion chambers, with retarded injection timing, not only NOx but also particulate emission decreases. Particularly, the high squish combustion chamber with small cavity volume shows less sacrifice of fuel consumption and less deterioration of THC and SOF emissions at low load.

5. It is possible to reduce NOx and particulate emissions simultaneously by restraining premixed combustion and promoting diffusion combustion in direct-injection diesel engines.

ACKNOLEGEMENT

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REFERENCE