Observation and Calculation of the Combustion Characteristics of a HSDI Engine : Effects of Combustion Chambers and Injection Specifications

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ABSTRACT

The effects of combustion chambers and injection specifications on the combustion characteristics of a high speed DI (HSDI) engine was investigated by both combustion observation and multidimensional calculation. Two typical combustion chambers with different injector holes and injection pressures were tested for the exhaust emissions. To understand the reasons of testing results, first, a transparent engine was used to visualize the combustion processes based on the real combustion chambers to show the images and changes such as flame distribution and flame movement; second, a modified KIVA-II code was used to reveal the details such as rich mixture and high flame temperature histories. As a result, this study revealed the relationship between combustion characteristics observed and simulated with engine emissions, and some discussions were added. Moreover, the combustion chamber has large effect on the combustion characteristics, and the injector holes give different behavior depending on the chambers.

INTRODUCTION

To achieve the lower emission and higher performance of HSDI engines, much work is needed in fields of fuel injection equipment (FIE), combustion improvement, fuel quality improvement, exhaust gas after-treatment and so on. Recent years, the introduction and development of common rail injection system has resulted in great advantages of injection pressures, injection timing and multi-injection possibility. Also, the progress in after-treatment and reduction of sulfur contents in fuel has contributed to control the emissions. Together, combustion improvement is carried out by using visualizing diagnostic and multidimensional simulation with which more information is available for directing the development of new engines. However, in the case of using transparent engine for visualization, it is difficult to have a piston crown window with the same shape of production combustion chamber to reach the real phenomena. And to predict the changes of emissions by multidimensional simulation code, such as KIVA-II, much work is needed to modify current models or add new sub-models. To overcome such problems in visualization and simulation, we had used acrylic piston crown window to replace quartz glass to have the real combustion chamber shape in the transparent engine and modified the spray model in KIVA-II based on our measurements of liquid spray penetration and combustion process. All of these were applied to understand the combustion characteristics of HSDI engines for combustion improvement. In this paper, the emissions were tested for combustion chambers, injector holes and injection pressures. The emission differences were explained comprehensively by visualizing the combustion processes, analyzing the flame movement and by simulating the air/fuel mixture and temperature histories.

TEST AND ANALYSIS METHODS

A HSDI engine was used with common rail injection system for emission testing. Engine and injection system specifications are shown in table 1, and operating conditions in table 2. The geometry of combustion chambers are shown in Fig.1, the narrow entrance with deep bottom type is called type A, and the wide entrance with shallow bottom type is called type B. The visualization area covered the whole chamber and part of the squish area as shown in the same figure.
Table 1: Engine specifications

<table>
<thead>
<tr>
<th>Condition</th>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>Engine Speed</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Chamber Type</td>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
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<td>B</td>
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<tr>
<td>Injection Timing</td>
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<td>TDC</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Nozzle</td>
<td></td>
<td>φ0.18x5</td>
<td>φ0.18×6</td>
<td>φ0.14×8</td>
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<td></td>
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<tr>
<td>Fuel Amount</td>
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<td>35mm³/st(Excess Air Ratio 1.64)</td>
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<td></td>
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<tr>
<td>Injection Pressure</td>
<td></td>
<td>32MPa</td>
<td></td>
<td></td>
<td></td>
<td>80Mpa</td>
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</tr>
</tbody>
</table>

Figure 1: Chamber type

To visualize the combustion phenomena, a transparent engine was used as shown in Fig.2, which was modified from a single cylinder testing engine. The engine was a classic extended piston window type engine which has large bore than the testing engine for the reasons of observing the squish area [1] and has the acrylic resin transparent combustion chamber with the same shape of that of the testing engine. The area in the combustion chamber was illuminated by the 300W xenon lamp to visualize the image of combustion process. The operating conditions and the injection mass of fuel for each cycle are the same as the testing engine. All of the visualization were carried out at film speed of 6000 fps by an E-10 high speed camera of NAC, with shatter constant of 1/10, using Kodak 7250 color film. (As shown in table2) And the movement of flame which was acquired from the visualization images was measured by a cross-correlation processing method [2].

Multidimensional simulation was conducted by means of KIVA-II. The main modification was introduction of a liquid-phase core sub-model and modified with our liquid-phase length measurement [3]. This modification was effective to predict the trend of emission change relating to combustion chamber, injector holes and so on [4].

RESULTS AND DISCUSSION

Effects of Combustion Chamber
The effect of combustion chamber shape on the relative emission changes of smoke and NOx (condition

Figure 2: Engine and visualization System

Figure 3: Comparison of emissions results between experiments and calculations for varying combustion chamber shape
No.3 of type A as 1) are shown in Fig.3 under the same injection timing and pressure of TDC and 32MPa. Clearly, comparing with type A, both testing and simulating show that type B chamber has worse smoke and lower NOx emissions. Fig.4 shows the comparison of combustion processes, by which it is found that in the case of type A chamber, the impingement of spray on the chamber wall promotes the distribution of flame inside and outside chamber, the whole chamber is full with flame around ATDC10°. Meanwhile in the case of type B chamber, there are still a regions without flame. Since the total air and fuel are the same for both chambers, therefore, in the viewpoint of air/fuel mixing, type A chamber has a good mixing than that of type B chamber. As a result, many visible soot clouds can be seen in the front area of the spray in type B chamber, which remain visible even in
Figure 4: Comparison of combustion processes between type A & type B chamber

Figure 5: Comparison of measured flame movement between chambers

Figure 6: Calculated rich mixture and high temperature region rate for varying combustion chamber shape

Figure 7: Comparison of emission results between experiments and calculations for varying nozzle hole numbers using type A chamber

Figure 8: Comparison of emission results between experiments and calculations for varying nozzle hole numbers using type B chamber

movement is considered to be caused by interaction among injection, combustion and air flow (swirl). Around the end of injection, in type A chamber, the vectors are larger than that in type B chamber. These results would be come from the stronger impingement reaction between spray and chamber wall in type A chamber, which can be find also in the direction of vectors. In later diffusion combustion stage, the direction of vectors in both chambers show strong effect of swirl, again, the swirl is stronger in type A chamber than type B if comparing each other. These strong effects of spray impingement and swirl are reasons for lower smoke and higher NOx emissions.

Simulated rich (ϕ > 2.5, is related to soot formation) mixture change and higher temperature volume (>=2000K, is considered to be the main reason of NOx formation) are shown in Fig. 6. These results show that type A chamber has a good mixing of air/fuel, giving a lower rich mixture fraction than type B, and the higher
Effect of Injection Hole

Keeping the same injection area while changing the holes, the testing and simulating results are shown in Fig. 7 and Fig. 8 for chamber type A and B respectively. Examination of the emissions behavior in both chambers, clearly, the trend of change differs from each other, that is, in type A chamber, increase of holes results in worse smoke and somewhat lower NOx, the reverse is in type B chamber.

Fig. 9 shows the comparison of combustion processes under different holes in type A chamber. Since 5 holes injector has always shown the good flame distribution inside chamber, increase of holes to 6 has contributed little to improve flame distribution, but if see the interference in the front part of spray, it is found that increase of holes really make such interference worse, represented by increased soot clouds around the front part of spray, and the unburned soot at later combustion stage. This can be considered as the main reasons to explain the worse smoke. The simulated results of rich mixture and temperature volume histories in Fig. 10 also indicate the same trend as in the visualized combustion processes.

In type B chamber, the combustion processes of Fig. 11 and simulated rich mixture and temperature volume histories of Fig. 12 are show that, increase of holes, the spatial distribution is improved, since type B has a wider entrance of chamber with weaker effect of impingement of spray on the wall, which is favorable to increase nozzle holes to improve air/fuel mixing without the negative effect of over interference among the impinged sprays as occurred in type A chamber. The rich mixture history is also shows the improvement of mixing with increase of holes in this case.
and for engineering development of new engines or improvement of current engines.

REFERENCES


CONCLUSIONS

An observation and simulation study has been carried out to explain the emission changes and understand more details of the combustion processes in a HSDI engine for the purpose of further improvement. These results of this study have shown the effective way of using both visualization and simulation methods to analyze combustion process. Through such a study, the complex of the combustion process, such as spray impingement on the wall, flame distribution inside and outside the chamber, the chamber shape depending combustion characteristics of holes and so on are revealed to some extent, and these information will be important for fully understand the whole phenomena of combustion.