Effect of Fuel Injection Rate Shaping on Spray Combustion -Effect of the Slope of Injection Rate Rise on Combustion-

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ABSTRACT

This paper discusses the effect of fuel injection rate shaping on spray combustion, which is a promising technique for controlling emissions from diesel engines. Injection rate shaping with different slope of injection rate rise and drop maintaining same injection period and peak injection rate were examined by using the original electronically controllable fuel injection system. Fuel was injected into the high pressure and high temperature combustion chamber and the spray and combustion was investigated through the measurement of spray evolution, OH radical emission, luminous flame emission and the image analysis of flame by the two color method. It was shown that the slope of injection rate rise gives a larger effect especially on spray evolution, combustion period and the high temperature region in flame.

INTRODUCTION

Fuel injection rate shaping which is a temporal variation of injection rate in one combustion cycle has been considered to have a great influence on the formation of a combustible mixture, because it controls spray temporal and spatial distributions. Therefore it is believed that an optimization of the injection rate shaping will be a key to improve spray combustion and to reduce NOx and particulates.

Former researches have reported that it is important to reduce the amount of fuel injected during ignition delay to reduce NOx formation (1-3). Other researches have shown that a pilot injection (4,5) or a split injection (6,7) has beneficial effects on combustion and emissions. However a systematic study of the influence of injection rate shaping on diesel combustion has not been fully investigated yet.

In order to study this effect, we have developed an electronically controllable fuel injection system for variable injection rate shaping (8). In this study, by using this injection system, we examined the effect of the slope of fuel injection rate rise on spray combustion, flame temperature distribution and soot production. An OH radical emission, luminous flame emission and an image analysis by the two color method were utilized to obtain the ignition delay, combustion characteristics and the temperature and soot distribution.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Experimental apparatus consists of an injection system, a combustion chamber and an optical system. Figure 1 shows the schematic of a fuel injection system. In this system, fuel is always supplied at a constant pressure of 40.2 MPa. The actuator was attached on an extended pressure pin to control the sectional area of flow passage of fuel through the movement of needle lift and to obtain an arbitrary fuel injection rate shaping. From the requirement of higher

![Figure 1 Schematic of injection nozzle and actuator](image-url)
controllability and response, the actuator used is a multi-layer piezoelectric actuator with a stroke of 100 μm at 300 volts. In this injection system, a desired injection rate shaping can be obtained by controlling the voltage of the piezoelectric actuator by a personal computer.

Figure 2 shows the schematic of the experimental apparatus. The internal cavity of the combustion chamber is a circular cylinder of 80 mm in diameter and 2.2 liters in volume with two quartz observation windows of 80 mm in diameter. In the combustion experiment, a condition inside the combustion chamber was set to like a real diesel engine; gas pressure of 2.65MPa and gas temperature of 930K or those of 2.28MPa and 800K. The high pressure and high temperature ambient condition was accomplished by the combustion of hydrogen, nitrogen and oxygen mixture. The composition of mixture is set that the oxygen concentration after hydrogen combustion will be 21%. The fuel was injected from the top of the chamber and the spray combustion was investigated.

A bundled optical fiber was set at the side of the window to collect the light emission from spray flame. The fibers were divided into two branches, and one was equipped with a band pass filter of 310.3nm in center wavelength (FWHM:16.3nm) and photo multiplier tube to measure the intensity of OH radical emission and the other was equipped with a band pass filter of 601nm in center wavelength and photo diode to measure that of luminous emission. At the upper side of the window, one more photo diode was set to detect the luminous emission at the bottom part of the combustion chamber. The images of spray flame were obtained by the intensified CCD camera. The two color method (9) was used to evaluate the two dimensional flame temperature and soot distribution. To obtain two spray flame images on a CCD camera, we used a doubling prism and two different band pass filters; one was 488nm in center wavelength (FWHM:11.3nm) and the other was 634nm in center wavelength (FWHM:8.5nm).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Injection condition</th>
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<tbody>
<tr>
<td>Nozzle Type</td>
<td>Single Hole</td>
</tr>
<tr>
<td>Hole Diameter</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Fuel(Cetane No.)</td>
<td>JIS #2 Diesel Oil (55)</td>
</tr>
<tr>
<td>Injection Pressure</td>
<td>40.2MPa</td>
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<tr>
<td>Peak Injection Rate</td>
<td>10g/s</td>
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<tr>
<td>Injection Period</td>
<td>2.7ms</td>
</tr>
<tr>
<td>Injection Volume</td>
<td>16mm³</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

Injection Rate Shaping and Spray Characteristics

Figure 3 shows the fuel injection rate shaping used in this study. Injection condition is presented in Table 1 and injection rate was measured by the momentum method at atmospheric condition. Injection period and injection rate peak were set to the same values of 2.7ms and 10g/s, and the slopes of injection rate rise and drop were changed to three typical patterns. We named them Pattern A, Pattern B and Pattern C in the order of injection rate rise.

Figure 4 and 5 show the temporal variations of a spray tip penetration and a spray volume with these injection rate shaping in an air of 1.07MPa. Spray volume was calculated by dividing the spray image into many parts in the direction of spray axis and summing the volume of disks whose diameter was the spray width at each part. As shown in these figures, the slope of injection rate rise gives a great effect on the spray evolution at initial stage. The spray tip penetration and the spray volume develop rapidly as the slope of injection rate rise becomes steeper.

To investigate this spray characteristics, a numerical calculation was performed. The outline of calculation model is as follows. Fuel injection period was divided into 30 equal periods. The injected fuel during each period, called parcel, injects at an initial velocity calculated from a measured injection rate and flights according to the experimental equations (10).

Figure 6 illustrates the calculated flight traces of injected fuel parcels at each period. In Pattern A, fuel parcels are
Fig. 4 Effect of injection rate shaping on spray tip penetration

Fig. 5 Effect of injection rate shaping on spray volume

distributed widely throughout the axis of spray. This is because later and lower injection velocity parcels cannot catch up with and overtake previously injected parcels. On the other hand, in Pattern C, fuel parcels concentrate around the spray tip because parcels injected later often catch up with and overtake former parcels due to its higher injection velocity. It is supposed that these higher injection velocity and interactions between parcels give a large effect on combustion.

Analysis of the Light Emission from Flame

Figure 7 shows the typical results of the measurement of light emission intensity from OH radical, $V_{OH}$, and luminous flame, $V_L$, at initial stage of combustion. OH radical emission can be thought as an indication of combustion reaction and luminous emission as that of diffusive combustion. As shown in this figure, at first, light emission from OH radical appears and diffusive combustion starts with a short time lag. In this study, we defined a period from a start of injection to that of OH radical emission as the ignition delay, $\tau_{d}$, and the period from a start of OH radical emission to that of luminous flame emission as the luminous flame delay, $\tau_{f}$, as indicated in Fig. 7.

Figure 8 shows the effect of fuel injection rate shaping on

Figure 6 Flight traces of injected parcels (Pa=1.07MPa)

ignition delay at two ambient temperatures of 930K and 800K. The horizontal axis indicates the time that the injection rate becomes maximum at each pattern. In case of 800K, ignition delay becomes slightly shorter as the slope of injection rate rise becomes steeper. The reason of this tendency is thought to be that a mixture formation at initial stage is enhanced as the initial injection rate is higher as shown in Fig. 4 and 5, so that physical delay due to an evaporation and a mixture formation becomes shorter.
Figure 7 Typical result of light emission from flame and definition of ignition delay, $\tau_{id}$, and luminous flame delay, $\tau_l$.

Figure 8 Effect of injection rate shaping on ignition delay.

On the other hand, the tendency of ignition delay in 930K is contrast to that in 800K and the ignition delay of the Pattern C is a very short period of 0.4ms. Though the reason of this tendency is not explored at the moment, these short ignition delay indicates that ignition occurred at incomplete spray.

Figure 9 shows the effect of fuel injection rate shaping on luminous flame delay. Luminous flame delay is within 0.1ms and has a tendency to increase as the ambient temperature decreases and the slope of injection rate rise becomes steeper. It is supposed that higher injection rate, i.e., Pattern A, and longer ignition delay at lower temperature result in a larger amount of mixture, which delayed the start of diffusion combustion.

Intensity of luminous flame can be thought as a measure of combustion rate. So, the start of main combustion was defined as the time the luminous flame emission reached to one tenth of the peak value, and the end of main combustion was defined as the time the emission dropped to one tenth of the peak value. As shown in Fig. 10, main combustion tend to start early as the ambient temperature decreases and the slope of injection rate rise becomes steeper. This reason is that higher injection rate and lower temperature result in a large amount of injected fuel within ignition delay.

Figure 11 expresses the effect of injection rate shaping on main combustion period. In these patterns, that of Pattern B is the shortest at both ambient temperatures. This reason may be as follows. In Pattern A, lower injection velocity parcels in late injection period have a lower ability of air entrainment, which may cause longer main combustion period. In Pattern
C, although the favorable effects were expected through the investigation of spray characteristics, the combustion period was rather longer. This may be due to the facts that later fuel parcels were injected into a developing spray flame where flame itself prevents air entrainment, which elongates the combustion period.

**Effect on Flame Temperature**

Figure 12 illustrates the flame temperature distribution in ambient temperature of 930K. The data of half part of flame is presented in figure. The temperature range was divided into 5 bands between 2100K and 2900K that covered the temperature range of interest in diesel combustion. It is shown that, as the slope of injection rate rise becomes steeper, flame propagates rapidly in the directions of the spray axis and the spray width, and the area of high temperature region becomes larger. To investigate this tendency quantitatively, Figure 13 shows the temporal variations of high temperature area whose temperature was higher than 2500K. As described above, in Pattern A, higher temperature area is larger than other patterns at initial stage of combustion and lasts for a longer period. This may be due to the larger amount of fuel injected during the ignition delay. This tendency may result in an increase in the NOx emission.

**Effect on Soot Production**

Figure 14 and 15 show the effect of injection rate shaping on KL factor, which is a measure of soot production. Figure 14 shows the temporal change in a spatial integration of KL factor of flame within a view of window, and Figure 15 shows those of a spatial average of KL factor in ambient temperature.
Figure 15 Temporal variation of average KL factor of flame of 930K. At initial stage of combustion, the integration of KL factor in Pattern A is larger than those in other patterns. This is due to the larger amount of injected fuel and the larger volume of flame at initial stage of injection. Although the average KL factor in Pattern A at initial stage of combustion was expected to be lower due to the enhanced air entrainment, it was larger as shown in Fig.15. This may indicate that the mixture formation was not enhanced microscopically by the steeper injection rate rise.

In the latter stage of combustion, in Pattern A, the large amount of soot exists relatively longer period because of the lower mixture formation in late injection period. Though the soot production in Pattern B and C appears to be lower than that in Pattern A, the total amount of soot may not be so small because the fuel combusts mainly at the bottom of the combustion chamber at later period.

CONCLUSIONS

In order to study the effect of fuel injection rate shaping on spray combustion, the analysis of the light emission from flame and the image analysis by the two color method were performed using an electronically controlled fuel injection system for variable injection rate shaping. Following results were obtained.

1. Injection rate shaping has a great influence on a spray evolution. The steeper slope of injection rate rise enhances the spray evolution in the directions of the spray axis and the spray width, results in an enhanced air entrainment.
2. The effect of fuel injection rate shaping on ignition delay may depend on an ambient temperature.
3. The start of main combustion after ignition becomes earlier as the slope of injection rate rise becomes steeper and the ambient temperature becomes lower. This results from the larger amount of fuel injected within ignition delay.

4. The steeper slope of injection rate rise causes the production of many high temperature regions from the initial stage of combustion. These high temperature regions last for a longer period, which may result in an increase of NOx emission.
5. Within the condition of this study, the enhancement of air entrainment by the steeper injection rate rise could not improve the soot production at initial stage.

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