Experimental Study on a Diesel Spray of Multi-Stage Injection

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ABSTRACT

The structure of multi-stage injection diesel spray was experimentally investigated. This multi-stage spray was formed by the three split sprays at one injection stage. The temporal and spatial characteristics of the spray were measured by using the drum camera or YAG laser visualization system. The spray tip penetration and spray angle were measured and the total spray volume and mean equivalence ratio were also evaluated under the various conditions of injection interval between split sprays. It was confirmed that the total volume and the mean equivalence ratio of the multi-stage injection diesel spray were affected by the injection interval.

INTRODUCTION

A large number of investigations had been made on the temporal and spatial structure of the diesel spray such as the spray tip penetration, spray angle, breakup length and size distribution of fuel droplets, because the structure of the spray plays an important role in the combustion performance and the emission of pollutants. From these previous works, it was clarified that the enhancement of the mixing process between fuel and air was important for the improvement of combustion process. In this report, we propose a new concept about a diesel spray of the multi-injection in order to control the spray structure. This multi-stage injection diesel spray includes, as the special cases, the conventional diesel spray and pilot injection spray.

CONCEPT OF A MULTI-STAGE DIESEL SPRAY

Figure 1 shows the simple model for the multi-stage diesel spray. This spray is formed by three split sprays in one injection stage. The injection rate pattern of this spray is simply described by following parameters:

1. fuel mass of ith injection $M_i$ (in this paper $i = 1, 2, 3$),
2. period of ith injection $T_i$ (in this paper $i = 1, 2, 3$),
3. injection interval between ith and $(i+1)$th injection $\tau_i$ (in this paper $i = 1, 2$).

Then the relation between $M_i$ and $T_i$ is described by $M_i = \int_0^{T_i} m_i(t) dt$, where $m_i(t)$ is an injection rate. However, since $M_i$ and $T_i$ could not control each other independently, we mainly controlled $M_i$. The total injection mass is defined as $M = \sum_i M_i$. And the total injection time is defined as $T = \sum_i T_i$.

As the case of $\tau_i = 0$, the injection pattern becomes single injection similar to the conventional diesel spray. When the $\tau_i$ is sufficiently larger than $T_i$, interaction between split sprays vanishes because the each spray grows independently. If we consider the case of $\tau_1 \neq 0$, $\tau_2 = 0$ and $M_1 << M_2 + M_3$, the pilot injection may be realized.

In this paper, we considered only $\tau_1 = \tau_2 = \tau$ as the most basic case shown in Fig.2. In order to make clear the effect of injection interval on spray structure, $\tau$ was controlled from 0 to 0.6ms. Two typical patterns about the injection rate were examined, i.e. pattern 1 is the case of $M_1 = M_2 = M_3$ and the pattern 2 is $M_1 = M_2/2 = M_3/3$.

As described here, the multi-stage diesel spray is suitable for investigation of the relationship between injection rate pattern and spray structure. We have follow-
ing expectation about the effects of multi-stage injection:

(1) Large unsteady motion with spray growth may create
due to the interaction between one split spray and others.
(2) Air entrainment into the spray may be enhanced by
the large vortex structure in the spray.
(3) Homogeneous mixing of fuel droplet and air may be
achieved over the all spray with increase in unsteady
motions.

Moreover, it includes the following fluid dynamically
interesting problems:

(4) Since the second split spray grows into the first split
spray, the internal structure in the first spray may be
analyzed from the observation of second spray behavior.
(5) Since the unsteady motion of the spray is enhanced
by the intermittent injection, relation between unsteady
motion and spray structure may be clarified.

EXPERIMENTAL APPARATUS AND
METHOD

Figure 3 shows the experimental apparatus and
measurement system. Fuel was supplied from three fuel
pumps. Three injection pipe lines connecting with three
pumps independently were joined to one inlet pipe of an
injection nozzle. The constant pressure valves were in-
stalled in the injection pipes to defend an irregular
injection. Injection timing of each split spray was con-
trolled by the rotation phase shift between pumps.
Injection rate patterns of the fuel were measured by using
the Bosch type injection rate meter. The growth pat-
tern of the spray was observed by the drum camera with
stroboscope. The cross sectional view of the spray was
visualized by the laser sheet method using a YAG laser
system.

In order to realize the pressurized atmosphere same
to the actual engine, the pressure vessel (220mm × 199mm
× 280mm large) was used. The pressure vessel had the
windows (120mm in diameter) for visualization of the
events. The pressure was controlled by N\textsubscript{2} gas at 3.0MPa
for all experiment. Single-hole type diesel injection no-
zle was used. The diameter D and the length L
of the nozzle hole were 0.27mm and 0.66mm (D/L = 2.22),
respectively. The opening pressure of nozzle was 19.3MPa.
The experimental conditions were shown in Table 1.

The spray tip penetration \( S_t \) of ith spray was meas-
ured from the photographs taken by the drum camera.
The spray angle \( \theta \) was also measured. Total spray volume
\( V \) was evaluated by the simple model shown in Fig.1 and
was calculated from \( S_t \) and \( \theta \), as follows:

\[
V = \frac{\pi R^2 (S_t - R)}{3} + \frac{4\pi R^3}{3},
\]

\[
R = \frac{S_t \tan(\theta/2)}{1 + \tan(\theta/2)},
\]

where \( R \) indicates the radius of a hemisphere correspon-
ding to the shape of spray tip.

![Fig.2 Test injection patterns.](image)

![Fig.3 Schematic view of experimental apparatus](image)

<table>
<thead>
<tr>
<th>Table 1 Experimental conditions</th>
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<tbody>
<tr>
<td>Pump rotation speed</td>
</tr>
<tr>
<td>Ambient pressure</td>
</tr>
<tr>
<td>Ambient temperature</td>
</tr>
<tr>
<td>Nozzle opening pressure</td>
</tr>
<tr>
<td>Total injection mass ( M_t )</td>
</tr>
<tr>
<td>Injection interval ( \tau )</td>
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</table>
RESULTS AND DISCUSSION

Visualization on the spatial structure of spray

Figure 4 shows the spray tip penetrations of split sprays in the pattern 1 at the case of $M_t = 15.6\, \text{mg/st}$. The single ($\tau = 0\, \text{ms}$) injection spray was compared with the multi-stage injection ($\tau = 0.6\, \text{ms}$). The penetration of single spray tended to become more longer than that of multi-stage spray. From the data of multi-stage injection, it seems that the spray tip of second split spray catch up with the first spray at 3.2ms. It is found that the growth rate of second split spray is larger than that of first split spray, because the second split spray grows up into the axial flow induced by the first split spray. Mean velocities of the spray tip during 1ms after starting of injection were 19.6m/s, 23.3m/s and 21.7m/s for first, second and third split sprays, respectively. Figure 5 shows the photographs of the sprays corresponding to Fig.4. It is observed that the second split spray grows up into the first split spray. At $t = 3.2\, \text{ms}$, the tip of second one catch up with the first.

Figure 6 shows the spray tip penetrations of the split sprays of pattern 1 and the case of $M_t = 25.5\, \text{mg/st}$. In this case, since the sprays have the large momentum, the penetration of the first split spray consists with the single injection spray. Figure 7 shows the photographs of these sprays. From the Figs.6 and 7, it seems that the tip of the second split spray does not catch up with the first one. Then the tip of first split spray is pushed away by the second split spray. From the comparison between Fig.4 and Fig.6, it is confirmed that there are two types of spray growth pattern in the multi-stage injection spray, i.e. (i) catch up type like Fig.5 and (ii) push away type like Fig.7.

Figure 8 shows the time variation of the spray tip penetration of the pattern 2. The relation between first and second split sprays was similar to the catch up type (pattern 1, $M_t = 15.6\, \text{mg/st}$). However, the second split

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**Fig.5 Photographs of spray (Pattern 1, $M_t = 15.6\, \text{mg/st}$)**

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**Fig.6 Spray tip penetrations (Pattern 1, $M_t = 25.5\, \text{mg/st}$)**
large axial velocity (not stagnated), the second split spray can’t catch up to the first one.

Figure 9 shows the cross-sectional view of the sprays about multi and single injections by the laser sheet method. In this figure, points A and A’ have the same condition about the injected mass from the start of injection. Points B and B’ correspond to the end of injections. The large coherent structures are observed in the split sprays (A and B) on account of the unsteady jet by the multi-injection. The axial velocity in the multi-stage spray varied with injection rate and it fell to zero at the interval between one split spray and other. In consequence of this pulsed axial velocity, large coherent structures was created in the spray.

**Effect of the injection interval on the spray volume and equivalence ratio**

In this part, the effect of injection interval $\tau$ on the spray volume and mean equivalence ratio is evalu-
ated. Figure 10 shows the time variation of the spray angle and volume for the case of pattern 2 at various intervals. Averaged spray angles were 21 deg., 25 deg., and 18 deg. for \( \tau = 0 \text{ms} \), 0.3 ms and 0.6 ms, respectively. Table 3 indicates the averaged spray angle about various condition of pattern 1. Largest spray angle was observed at \( \tau = 0 \text{ms} \). It is confirmed that the increase in the spray angle and volume in multi-stage spray was caused by the coherent structures as shown in Fig. 9. Since the coherent structure in the multi-stage spray was enlarged, it caused the stretch of the shear flow region between the spray and surroundings and caused the increase in spray volume.

Figure 11 shows the effect of injection interval on the spray volume \( V \) evaluated at the time of injection finish. When the injection interval \( \tau = 0 \text{ms} \), the total volume becomes larger than the other condition. The reason why the spray angle and volume have the maximum values at \( \tau = 0 \text{ms} \) may be explained as follows. When the injection interval \( \tau = 0 \text{ms} \), the spray structure is roughly the same as steady injection spray except the spray tip. On the other hand, when the case of \( \tau = 0.6 \text{ms} \), the interaction between split sprays reduces. At the case of \( \tau = 0.3 \text{ms} \), the interaction between split sprays becomes large.

Figures 12 and 13 shows the equivalence ratio \( \phi \)

### Table 2  Mean spray angle (pattern 1)

<table>
<thead>
<tr>
<th>( \tau )</th>
<th>( M_t )</th>
<th>( 15.6 \text{mg/st} )</th>
<th>( 20.2 \text{mg/st} )</th>
<th>( 25.5 \text{mg/st} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ms</td>
<td>16 deg.</td>
<td>18 deg.</td>
<td>17 deg.</td>
<td></td>
</tr>
<tr>
<td>0.3 ms</td>
<td>23 deg.</td>
<td>23 deg.</td>
<td>23 deg.</td>
<td></td>
</tr>
<tr>
<td>0.6 ms</td>
<td>23 deg.</td>
<td>19 deg.</td>
<td>19 deg.</td>
<td></td>
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</tbody>
</table>
versus time $t$ and cumulative mass $M^*$ defined as following equation:

$$M^* = \frac{\int_0^t m(t) dt}{M_t}, \quad 0 < t < T_f,$$

(2)

where, $T_f$ is a time of injection end. It is found that the equivalence ratio of the multi-injection becomes smaller than that of the single injection. In the early period of the injection, equivalence ratio $\phi$ shows a tendency to be small as increases of $\tau$. But the final part of the injection, the case of $\tau = 0.3$ms fall down to the lowest value.

CONCLUSIONS

This paper introduces a concept of the multi-stage injection diesel spray and presents the basic data of spray structure. The results are summarized as follows:

(1) Two typical interaction patterns between split sprays were observed, i.e. simply called as catch up type and push away type. The catch up type was observed when the momentum of split spray was relatively small.
(2) The injection interval of the split sprays affected the spray angle and total spray volume.
(3) The equivalence ratio of the multi-stage spray became smaller than that of the single spray.
(4) Large coherent structures were observed in the multi-stage diesel spray rather than the single spray.

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NOMENCLATURE

$m =$ injection rate, g/s
$M^* =$ cumulative mass of injection
$M_t =$ total injection mass per stroke, mg/st
$N_p =$ pump rotation speed, rpm
$P_a =$ ambient pressure, MPa
$S =$ spray tip penetration, mm
$t =$ time, ms
$V =$ mean spray volume, cm$^3$
$\theta =$ mean spray angle, deg.
$\tau =$ injection interval, ms
$\phi =$ mean equivalence ratio

REFERENCES