Experimental Study on a Diesel Spray of Multi-Stage Injection

M.Arai and K.Amagai

Faculty of Engineering
Gunma University
1-5-1 Tenjin-cho, Kiryu 376
Japan

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, break-up length [1,2] and size distribution [3] 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 τ_i (in this paper $i = 1,2$).

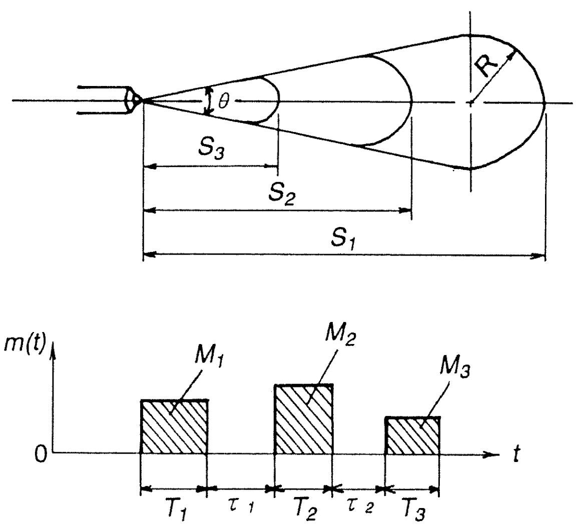

Fig.1 Model of multi-injected diesel spray

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 $M_t = \sum_i M_i$. And the total injection time is defined as $T_f = \sum_i T_i + \sum_i \tau_i$

As the case of $\tau_i = 0$, the injection pattern becomes single injection similar to the conventional diesel spray. When the τ_i is sufficiently larger than T_i, interaction between split sprays vanishes because the each spray grows independently. If we consider the case of $\tau_1 \neq 0$, τ_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, τ 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 following 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 installed in the injection pipes to defend an irregular injection. Injection timing of each split spray was controlled by the rotation phase shift between pumps. Injection rate patterns of the fuel were measured by using the Bosch type injection rate mater. The growth pattern 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_2 gas at 3.0MPa for all experiment. Single-hole type diesel injection nozzle was used. The diameter D and the length L of the nozzle hole were 0.27mm and 0.6mm ($D/L = 2.22$), respectively. The opening pressure of nozzle was 19.3MPa. The experimental conditions were shown in Table 1.

The spray tip penetration S_i of ith spray was measured from the photographs taken by the drum camera. The spray angle θ was also measured. Total spray volume V was evaluated by the simple model shown in Fig.1 and was calculated from S_1 and θ, as follows:

$$V = \frac{\pi R^2(S_1 - R)}{3} + \frac{4\pi R^3}{3}, \qquad (1)$$
$$R = \frac{S_1 \tan(\theta/2)}{1+\tan(\theta/2)},$$

where R indicates the radius of a hemisphere corresponding to the shape of spray tip.

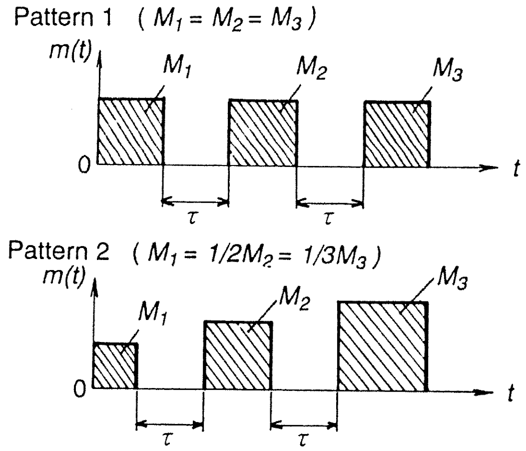

Fig.2 Test injection patterns.

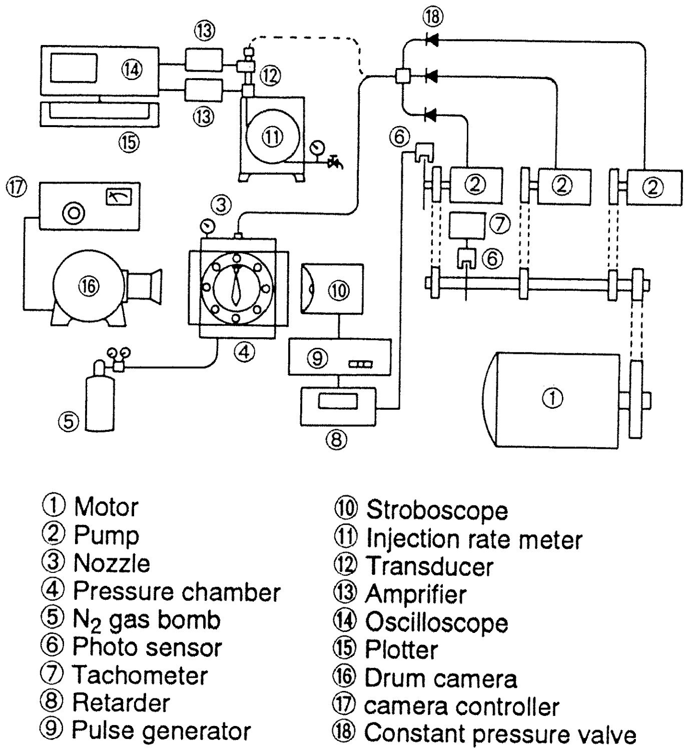

Fig.3 Schematic view of experimental apparatus

Table 1 Experimental conditions

Pump rotation speed	700rpm
Ambient pressure	3.0MPa
Ambient temperature	288K
Nozzle opening pressure	19.3MPa
Total injection mass M_t	15.5, 20.2, 25.5mg/st
Injection interval τ	0, 0.3, 0.6ms.

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 = 15.6mg/st. The single (τ = 0ms) injection spray was compared with the multi-stage injection (τ = 0.6ms). 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 = 3.2ms, 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 = 25.5mg/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 mg/st). However, the second split

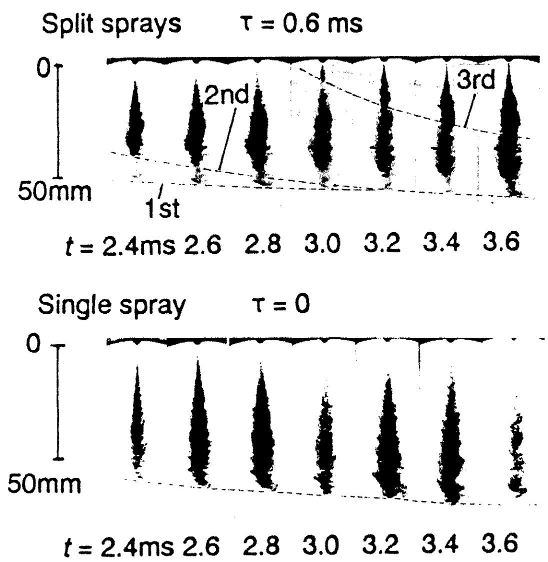

Fig.5 Photographs of spray
(Pattern 1, M_t = 15.6mg/st)

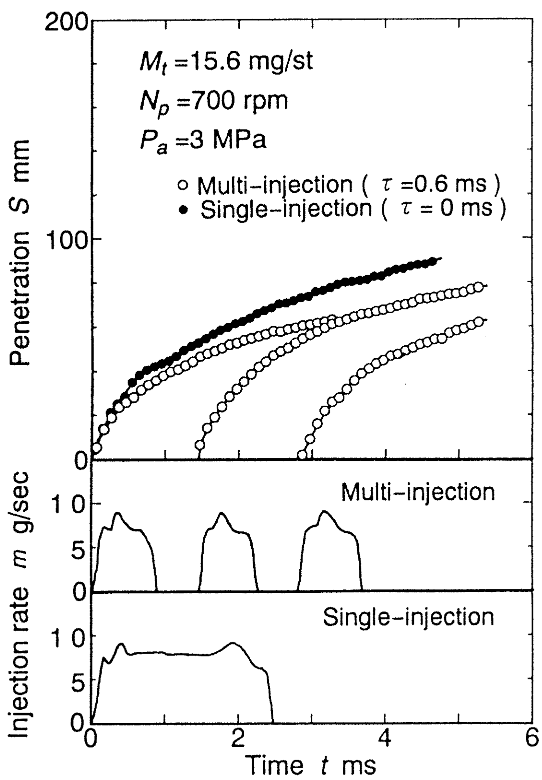

Fig.4 Spray tip penetrations
(Pattern 1, M_t = 15.6mg/st)

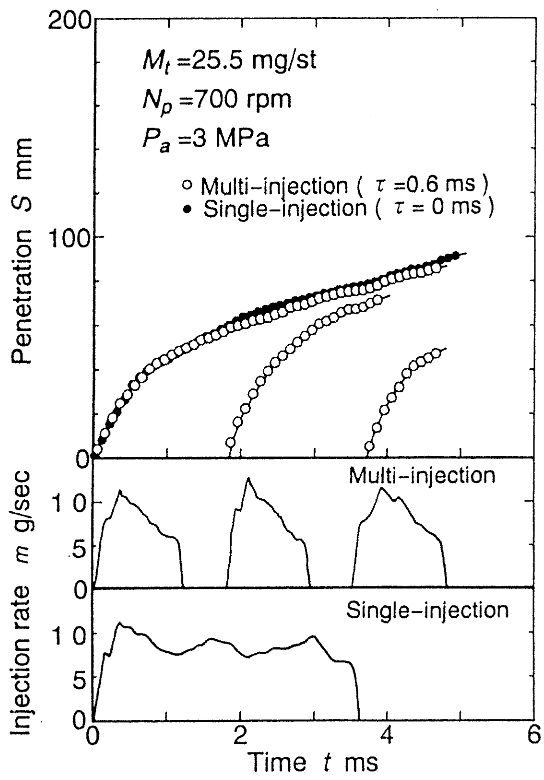

Fig.6 Spray tip penetrations
(Pattern 1, M_t = 25.5mg/st)

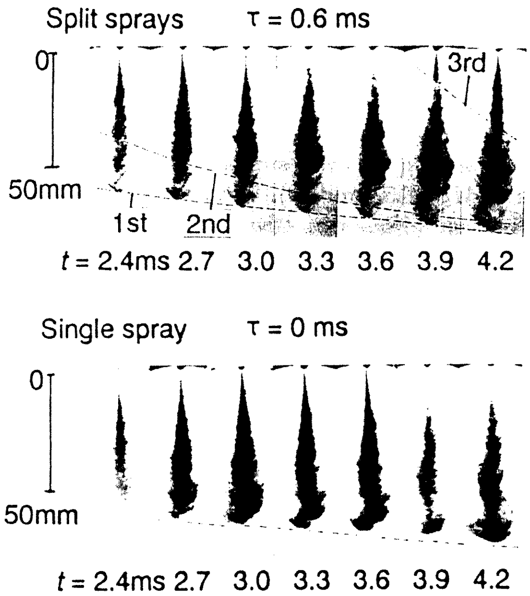

Fig.7 Photographs of spray (Pattern 1, M_t = 25.5mg/st)

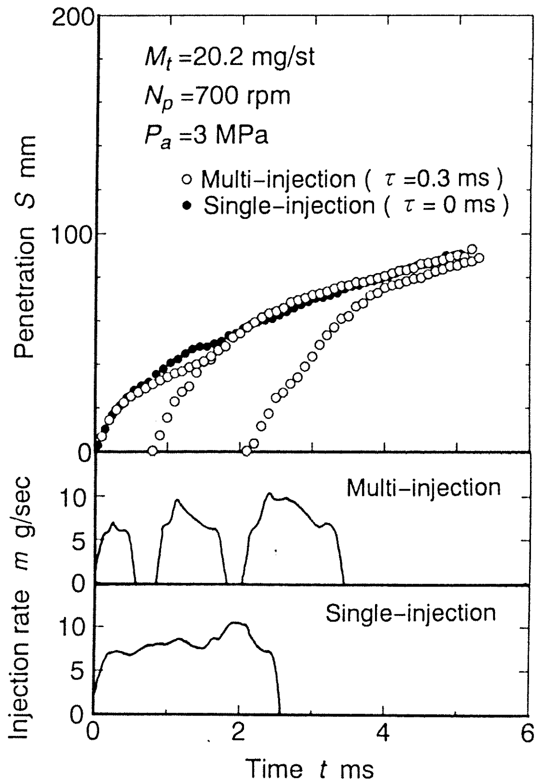

Fig.8 Spray tip penetrations (Pattern 2, M_t = 20.2mg/st)

spray was pushed away by the third split spray (same as pattern 1, M_t = 25.5 mg/st). The difference of interactions between split sprays can be explained by the stagnation timing of each split spray. That is, when the first split spray has small momentum, the second spray grows into the stagnated flow of the first spray. On the other hand, when the first split spray has the relatively

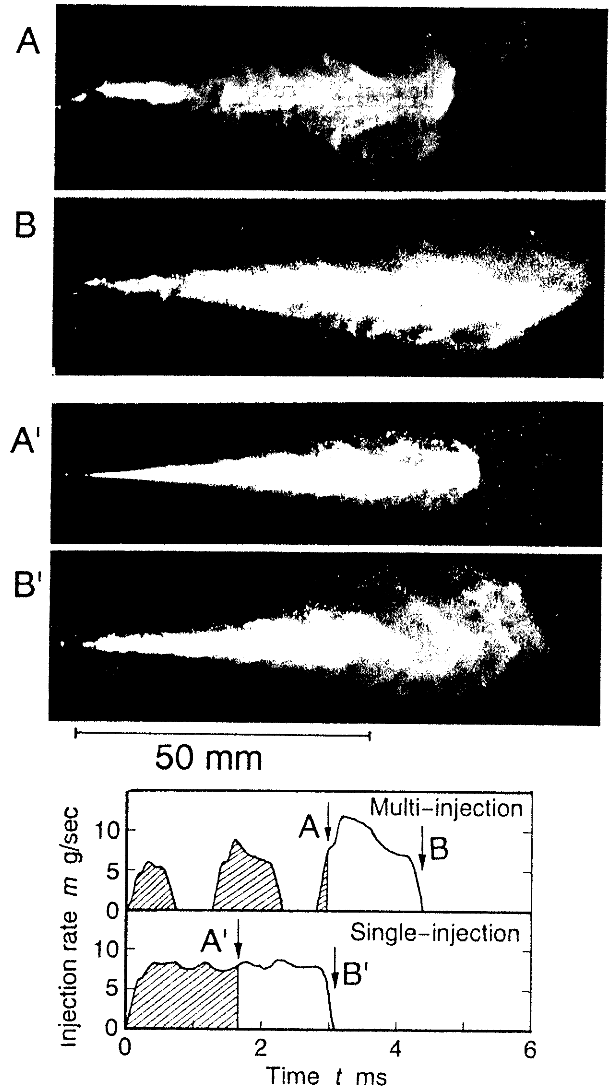

Fig.9 Cross sectional views of sprays
A,B: multi-injection, A',B': single injection
(N_p =650rpm, M_t =20.3mg/st)

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 τ on the spray volume and mean equivalence ratio is evaluated. 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 21deg., 25deg. and 18deg. for τ = 0ms, 0.3ms and 0.6ms, respectively. Table 3 indicates the averaged spray angle about various condition of pattern 1. Largest spray angle was observed at τ = 0.3ms. 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 τ =0.3ms, the total volume becomes larger than the other condition. The reasons why the spray angle and volume have the maximum values at τ =0.3ms may be explained as follows. When the injection interval τ =0ms, the spray structure is roughly the same as steady injection spray except the spray tip. On the other hand, when the case of τ =0.6ms, the interaction between split sprays reduces. At the case of τ =0.3ms, the interaction between split sprays becomes large.

Figures 12 and 13 shows the equivalence ratio ϕ

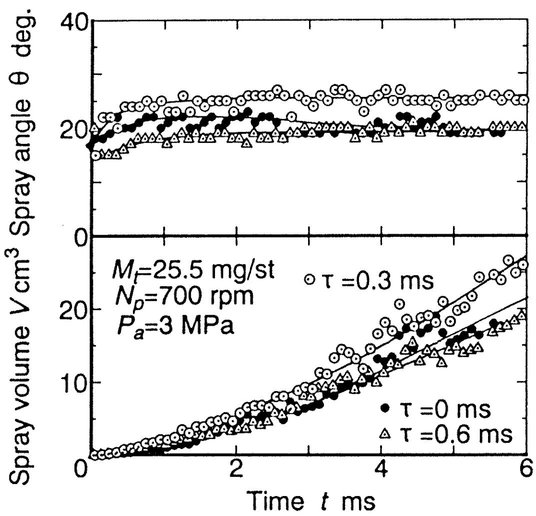

Fig.10 Spray angle and volume (Pattern 2)

Table 2 Mean spray angle (pattern 1)

τ M_t	15.6mg/st	20.2mg/st	25.5mg/st
0 ms	16 deg.	18 deg.	17 deg.
0.3 ms	23 deg.	23 deg.	23 deg.
0.6 ms	23 deg.	19 deg.	19 deg.

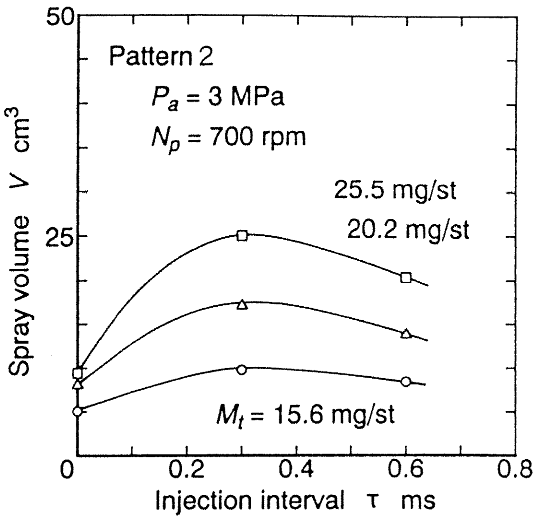

Fig.11 Spray volume vs. injection interval (Pattern 2)

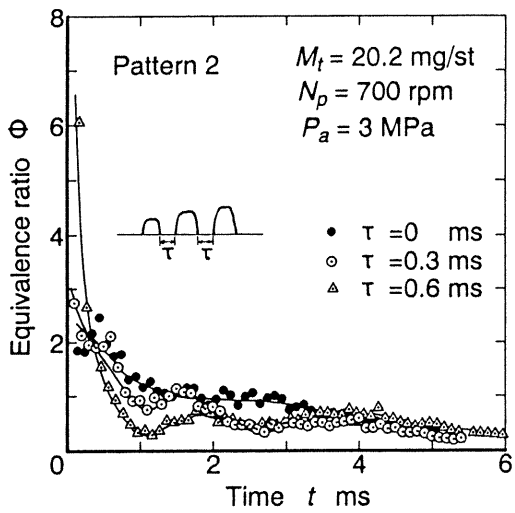

Fig.12 Equivalence ratio vs. time (Pattern 2)

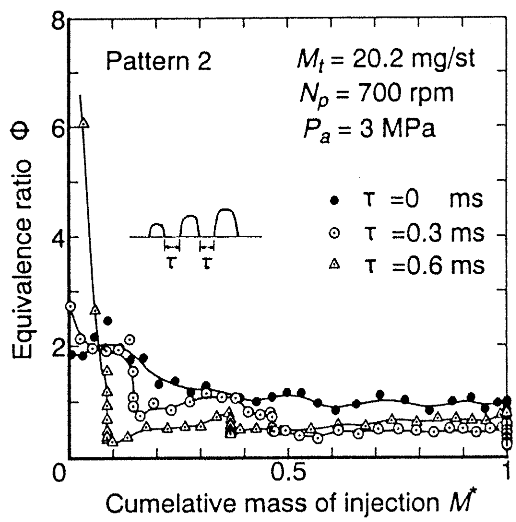

Fig.13 Equivalence ratio vs. cumulative mass of injection

versus time t and cumulative mass M^* defined as following equation:

$$M^* = \frac{\int_0^t m(t)dt}{M_t}, \quad 0 < t < T_f, \qquad (2)$$

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 ϕ shows a tendency to be small as increases of τ. 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.

Acknowledgement The authors would like to thanks Mr. N.Tanami, Mr. N.Honma and Mr. T.Maeda for carrying out the experimental works. This study was partially supported by the Research Committee of the Japan Society of Mechanical Engineers (RC-107, JSME)

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
θ = mean spray angle, deg.
τ = injection interval, ms
ϕ = mean equivalence ratio

REFERENCES

1. Arai,M., Shimizu,M. and Hiroyasu,H., "Breakup Length and Spray Angle of High Speed Jet", Proc. 3rd. Int. Conf. on Liquid Atomization and Spray Systems (ICLASS), London, Paper IB/4/1, 1985.
2. Hiroyasu,H. and Arai,M., "Structure of Fuel Sprays in Diesel Engines", SAE paper No.900475, 1990.
3. Hardalupas,Y., Taylor,A.M.K.P and Whitelaw, J.H., "Characteristics of the Spray from a Diesel Injector", Int. J. Multiphase Flow, Vol.18, No.2, pp.159-179, 1992.