Practical Study on High-Dispersion and High-Penetration Diesel Injection Nozzle
(1st Report, Effects of Geometric Shape of High-Dispersion Atomization Enhancement Nozzle on Atomization of Intermittent Spray)

N. Tamaki[1*], Y. Nishida[2] and T. Hosokawa[3]

[1*]Department of Mechanical Engineering, School of Engineering, Kinki University, Hiroshima, JAPAN
[2]Japan Steel Works, LTD., Hiroshima, JAPAN
[3]Japan Freight Railway Company, Tokyo, JAPAN

Abstract
The purpose of this study is to develop the nozzle, which is able to obtain the spray with high-dispersion and high-penetration and to apply the atomization enhancement nozzle developed in this study to an actual Diesel injector. In this paper, the effects of this atomization enhancement nozzle on atomization of intermittent spray and application to the actual Diesel injector were investigated. The results show that although the spray tip penetration of the atomization enhancement nozzle is short, the spread of the spray becomes large significantly compared with the single hole nozzle and high-dispersion spray was obtained at the intermittent injection.

Introduction

It is important to obtain excellent spray characteristics and combustion characteristics in order to reduce fuel consumption ratio and carbon dioxide for control of global warming. A hole nozzle, which is used a direct injection Diesel engine, is demanded high-injection pressure up to about 200 MPa (2000 bar) in order to obtain excellent spray characteristics. Moreover, it is necessary to obtain the spray with high-dispersion and high-penetration. Experimental studies [1]-[6] concerned with cavitation in the nozzle hole and atomization of the liquid jet were investigated. The disturbance of the liquid flow in the nozzle hole due to occurrence of cavitation has a dominant effect on atomization of the liquid jet. It has developed the atomization enhancement nozzle, which the spray characteristics at relatively low injection pressure of 10 MPa are equal to ones at super-high injection pressure of 200 MPa [7]. However, since these results were steady spray, application to the actual Diesel injector was not clear.

The purpose of this study is to develop the atomization enhancement nozzle, which is obtained the spray with high-dispersion and high-penetration. Moreover, it is to apply the atomization enhancement nozzle to the actual Diesel injector, and it is to improve the spray characteristics of a direct injection Diesel nozzle. In this paper, the effects of the atomization enhancement nozzle [7], which was invented in the previous study, on atomization of intermittent spray and application to the actual Diesel injector were investigated. The test nozzles were used a single hole nozzle and the atomization enhancement nozzle. The effects of geometric shape and dimensions of the atomization enhancement nozzle such as the hole diameter, the hole length, the gap diameter made at the nozzle hole, the bypass number which was connected between the upstream chamber and the gap on atomization of intermittent spray and atomization characteristics were investigated.

As a result, it was cleared that although the spray tip penetration of the atomization enhancement nozzle invented in this study is short, the spread of the spray becomes large considerably compared with the previous single hole nozzle at the intermittent spray.

Experimental Apparatus and Method

Schematic of the experimental apparatus is shown in Fig.1. It is consisted of high-pressure pump, microcomputer for controlling injection time, injection duration and irradiation time of stroboscope, digital camera and stroboscope. Light oil for fuel was intermittently injected under atmospheric pressure condition at the differential pressure of injection of P_i=100 MPa, the spray was photographed at the arbitrary time after start of injection. The injection duration of fuel was $T_{inj.}$=0.9 ms for the hole diameter of D_l=0.15 mm, $T_{inj.}$=0.7 ms for D_l=0.3 mm, and the injection amount of fuel is about from 4.5 to 6.9 mg

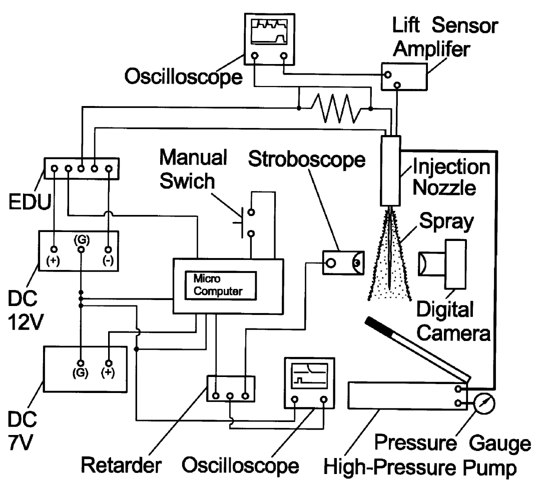


Fig.1 Schematic of experimental apparatus

independent of the hole diameters. The spray tip penetration was measured by images of the spray, which was photographed by back illumination light method using a stroboscope, until the maximum time after start of injection of 1.2 ms at intervals of 0.05 ms and 0.10 ms.

Schematics of the test nozzles are shown in Fig.2, and specification of the test nozzles is shown in Table 1. The test nozzles were used a single hole nozzle and the atomization enhancement nozzle which was invented in the previous study [7].

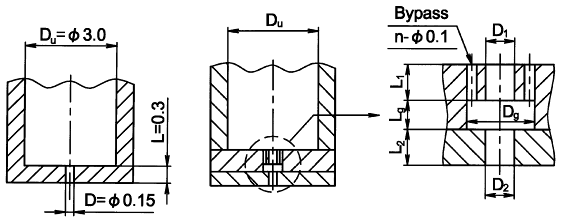
Experimental Results and Discussion

Effect of the bypass number on atomization of intermittent spray and spray tip penetration

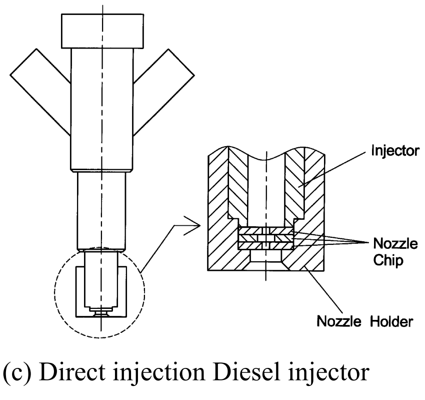
The effect of the bypass number on atomization of intermittent spray and the spray angle are shown in Figs.3, 4, respectively. The differential pressure of injection is P_i=100 MPa and the time after start of injection is $T_{inj.}$=0.40 ms. As shown in Fig.3, in case of

Table 1 Specification of test nozzles (mm)

<table>
<tr><th>Nozzle Types</th><th colspan="4">Dimensions</th></tr>
<tr><td rowspan="2">Single Hole Nozzle</td><td>D_u</td><td colspan="2">L</td><td>D</td></tr>
<tr><td>φ3.0</td><td colspan="2">0.3</td><td>φ0.15</td></tr>
<tr><td rowspan="4">Atomization Enhancement Nozzle</td><td>n</td><td>D_u</td><td>L_1</td><td>D_1</td></tr>
<tr><td>0, 1, 4</td><td>φ3.0</td><td>0.3</td><td>φ0.15, φ0.3</td></tr>
<tr><td>L_g</td><td>D_g</td><td>L_2</td><td>D_2</td></tr>
<tr><td>0.3</td><td>φ0.6, φ0.8, φ1.0</td><td>0.3, 0.9</td><td>φ0.3</td></tr>
</table>



(a) Single hole nozzle (b) Atomization enhancement nozzle



(c) Direct injection Diesel injector

Fig.2 Schematics of test nozzles

the bypass number of n=1 and n=4, spread of the sprays are wide and the sprays atomize compared with the nozzle without the bypass of n=0. Especially, the spread of the spray of n=1 is the largest, excellent spray is obtained. As shown in Fig. 4, the spray angle of the nozzle with the bypass number of n=1 are larger than the nozzle without the bypass of n=0 independent of the gap diameter D_g. In case of D_g=0.6 mm, the spray angle of n=1 and n=4 are almost same. In cases of D_g=0.8 mm and D_g=1.0 mm, the spray angle of n=1 is larger than one of n=4. From these results, it can be seen that when the nozzle with the bypass number of n=1 and the gap diameter of D_g=1.0 mm to the hole diameter downstream from the gap D_2=0.3 mm was used, the high-dispersion spray with the large spray angle is obtained.

The effect of the bypass number on the spray tip penetration is shown in Fig.5. The spray tip penetration of the bypass number of n=1 is the shortest and the penetration of the spray is weak except of the early injection. The spray tip penetrations of the nozzles without the bypass of n=0 and the bypass number of n=4 become long straightly with a progress in the time after start of injection. In case of the bypass number of n=1, although the spray tip penetration becomes long straightly until the time after start of injection of about

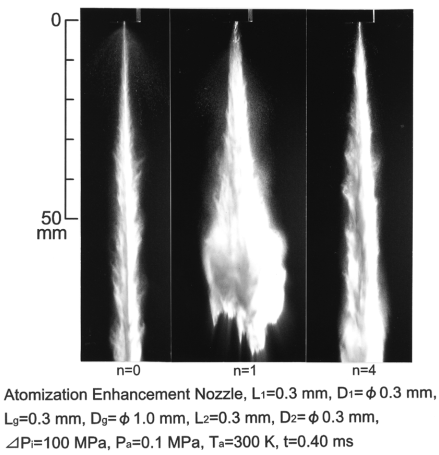


Fig.3 Effect of bypass number on atomization of intermittent spray

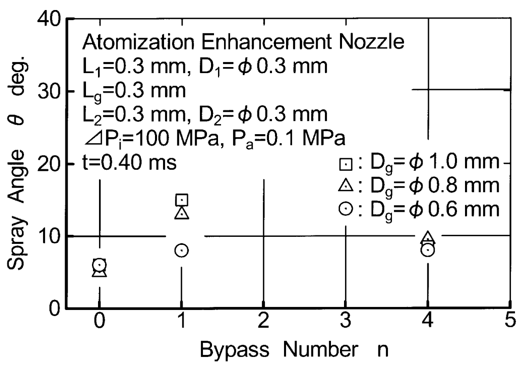


Fig.4 Effect of bypass number on spray angle

t=0.6 ms, when the time after start of injection excesses about t=0.6 ms, increasing rate of the spray tip penetration becomes small. The spray tip penetration of the nozzle without the bypass of n=0 is the longest, one of n=1 is the shortest compared with the same time after start of injection of t=0.7 ms.

The reasons why the disintegration behaviors of the sprays and the spray tip penetrations are different by existence of the bypass and the bypass numbers are considered as follows. Schematics of the internal flow in the nozzle hole and the issued spray are shown in Fig.6. As shown in Fig.6 (a), in case of the nozzle without the bypass of n=0, hydraulic flip [2], which the liquid flow in the nozzle hole is separated from the inner wall of the nozzle hole, occurs in the nozzle hole like that a single hole nozzle at the atmospheric pressure. Hence, it is guessed that even though the super-high injection pressure of 100 MPa, cavitation does not occur in the nozzle hole and the spray atomizes little at the intermittent injection. To the contrary, as shown in Fig.6 (b), in case of the bypass number of n=1, it is guessed that cavitation occurs in the nozzle hole like that the steady injection and atomization of the spray is enhanced due to disturbance of the liquid flow in the nozzle hole. Therefore, in case of n=1, the spread of the spray becomes wide and the penetration of the spray becomes weak, because the momentum toward the radial direction becomes large compared with the momentum toward the injection direction.

It can be seen that the bypass number affects considerably the dispersion and the penetration of the spray. Although the nozzle with the bypass number of n=1 is obtained the spray with large spread angle, that is, high-dispersion spray, the spray tip penetration becomes short and the spray with high-penetration is not obtained. To the contrary, in cases of the nozzles without the bypass of n=0 and the bypass number of n=4, although the spread angle of the spray is small and high-dispersion spray is not obtained, the spray tip penetration becomes long and high-penetration spray is obtained. From these results, it can be seen that in case of the nozzle with the bypass number of n=1, although the penetration of the spray is weak, high-dispersion spray is obtained.

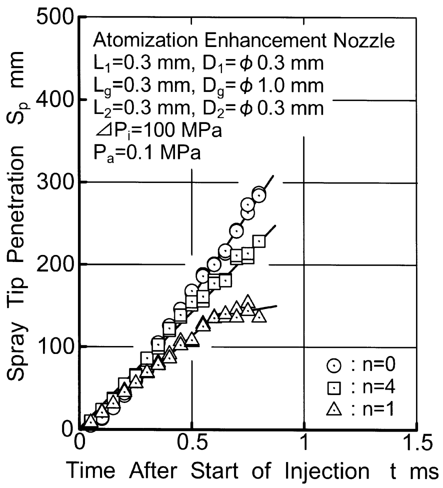
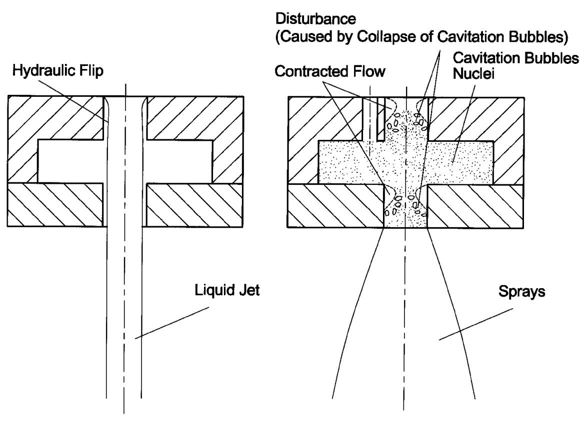


Fig.5 Effect of hole length downstream from gap on spray tip penetration



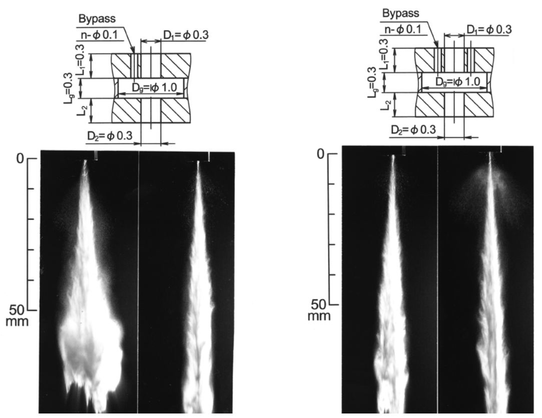
(a) Without bypass (n=0) (b) With bypass (n=1)

Fig.6 Schematics of internal flow in nozzle hole and issued jet

Effect of the hole length on atomization of intermittent spray and spray tip penetration

The effect of the hole length downstream from the gap; simply called the hole length on atomization of intermittent spray is shown in Fig.7. As shown in Fig.7 (a), in case of the bypass number of n=1, the spread of the spray of the shorter hole length of L_2=0.3 mm is large considerably compared with L_2=0.9 mm, the spray atomizes significantly. As shown in Fig.7 (b), in case of the bypass number of n=4, the spread of the spray of L_2=0.3 mm is slightly large compared with one of L_2=0.9 mm, the hole length is little affected to atomization of intermittent spray.

The effect of the hole length on the spray angle is



L_2 mm 0.3 0.9 0.3 0.9

P_i=100 MPa, P_a=0.1 MPa, $T_{inj.}$=0.7 ms, t=0.40 ms

(a) Bypass number n=1 (b) Bypass number n=4

Fig.7 Effect of hole length downstream from gap on atomization of intermittent sprays shown in Fig.8. The spray angle of the nozzle without the bypass of n=0 becomes large a little, one of n=1 becomes small with an increase in the hole length L_2. The spray angle of the bypass number of n=4 are almost same values independent of the hole length L_2. Moreover, in case of the nozzle with the bypass number of n=1 and the shorter hole length of L_2=0.3 mm, the spray angle is the largest, in case of the nozzle without the bypass of n=0, the spray angle is the smallest.

The effect of the hole length on the spray tip penetration is shown in Fig.9. As shown in Fig.9 (a), in case of the bypass number of n=1, the spray tip penetration of the hole length of L_2=0.9 mm becomes long straightly with an passage in the time after start of injection. Moreover, when the time after start of injection excesses about t=0.5 ms, the spray tip penetration of L_2=0.9 mm is longer than one of L_2=0.3 mm, high-penetration spray is obtained. As shown in Fig.9 (b), in case of n=4, the spray tip penetrations are almost same length and are long independent of the hole length L_2, high-penetration sprays are obtained.

It is considered that even though the grade of the disturbance of the liquid flow at both the gap and the nozzle hole upstream from the gap are different by the bypass number, the liquid flow in the nozzle hole downstream from the gap is commutated due to the longer hole length. Therefore, in case of the longer hole length, it is guessed that behaviors of the liquid flow vicinity of the exit of the nozzle hole are almost same, the bypass number is little affected to the spray tip penetration. Moreover, it is considered that the disturbance of the liquid flow caused by occurrence of cavitation at the inlet of the nozzle hole is reduced at the nozzle hole downstream from the gap. Therefore, the nozzle with the longer hole length is little affected to geometric shapes and dimensions of the nozzle hole.

Moreover, the reasons why the spray tip penetration of the hole length of L_2=0.3 mm becomes short compared with the nozzle of L_2=0.9 mm are considered as follows. It is guessed that the disturbance of the liquid flow, which is caused by collapse of cavitation bubbles, occurred in the nozzle hole downstream from the gap. In case of the nozzle of L_2=0.3 mm, the disturbance of the liquid flow strongly affects to the issuing spray. To the contrary, in case of the nozzle of L_2=0.9 mm, it is guessed that the disturbance of the liquid flow in the nozzle hole downstream from the gap reduces and the disturbance little affects to the issuing spray. Therefore, it is considered that the momentum of the spray toward the injection direction is larger than the momentum toward the radial direction and the spray tip penetration becomes long.

From these results, it can be seen that the hole length downstream from the gap strongly affects to atomization of the spray and the spray tip penetration. Moreover, it can be seen that although the penetration of the spray is weak, high-dispersion spray is obtained,

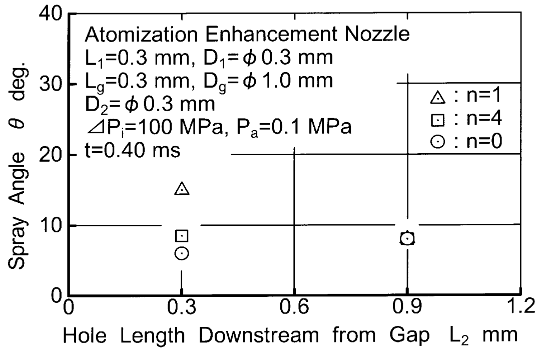
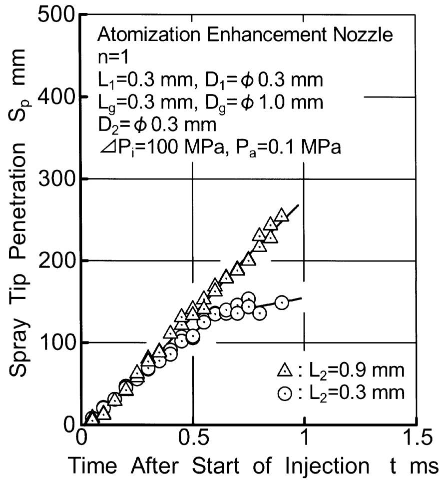
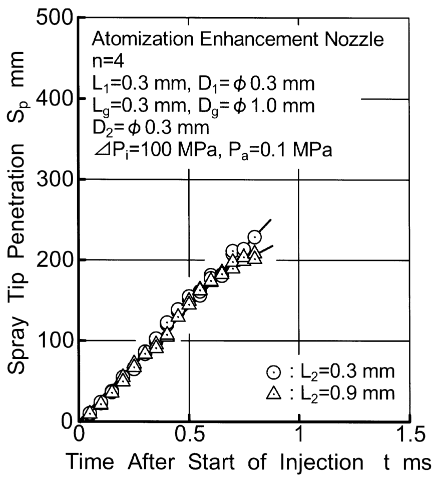


Fig.8 Effect of hole length downstream from gap on spray angle



(a) Bypass number n=1



(b) Bypass number n=4

Fig.9 Effect of hole length downstream from gap on spray tip penetration

using the nozzle with the bypass number of n=1 and the shorter hole length of L_2=0.3 mm.

Effect of the hole diameter on atomization of intermittent spray and spray tip penetration

The effect of the hole diameter upstream from the gap; simply called the hole diameter on the spray angle is shown in Fig.10. In case of the bypass number of n=1, the spray angles are almost same values independent of the hole diameter. In cases of without the bypass of n=0 and the bypass number of n=4, the spray angle, which the hole diameter is small of D_1=0.15 mm for the hole diameter downstream from the gap of D_2=0.3 mm, becomes large. Moreover, the spray angle of n=1 is the largest and one of the nozzle without the bypass of n=0 is the smallest.

The effect of the hole diameter on the spray tip penetration of the nozzle with the bypass number of n=1 is shown in Fig.11. The spray tip penetrations become long in proportion to the time after start of injection until about t=0.4 ms independent of the hole diameters. When the time after start of injection excesses about t=0.4 ms, the spray tip penetration of D_1=0.3 mm becomes longer than one of D_1=0.15 mm, penetration of the spray becomes strong.

Comparisons of dispersion and penetration of the spray of the single hole nozzle and the atomization enhancement nozzle

The disintegration behaviors of the intermittent sprays at the arbitrary time after start of injection are shown in Fig.12. Figure 12 (a) is the single hole nozzle and Fig.12 (b) is the atomization enhancement nozzle. As shown in Fig.12, the spread of the spray of the atomization enhancement nozzle is wide considerably at all the time after start of injection, compared with the single hole nozzle. Moreover, although the spray tip of the single hole nozzle are not photographed within the observation sight at the time regions of which the time after start of injection excesses t=0.25 ms, it seems that the spray length of the single hole nozzle become long compared with one of the atomization enhancement nozzle. The spray length of the single hole nozzle becomes long in proportion to the process of the time after start of injection.

The comparisons of the spray angle and the spray tip penetration between the single hole nozzle and the atomization enhancement nozzle are shown in Figs.13 and 14, respectively. As shown in Fig.13, the spray

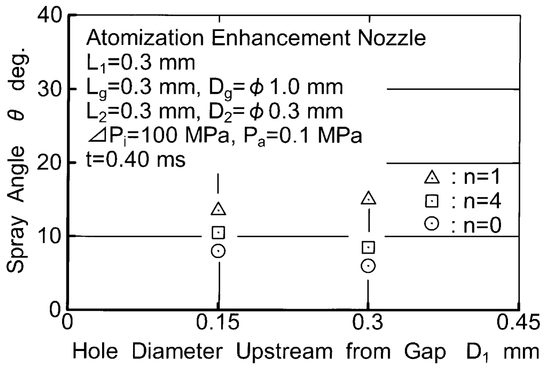


Fig.10 Effect of hole diameter upstream from gap on spray angle

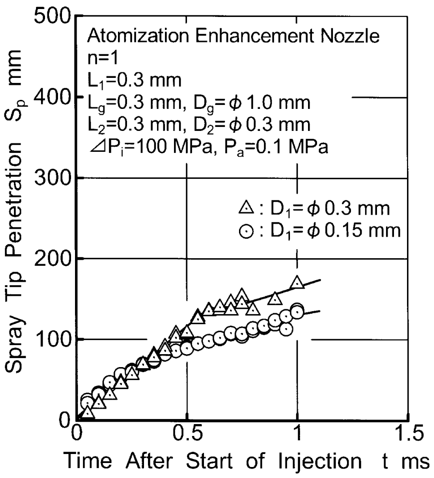
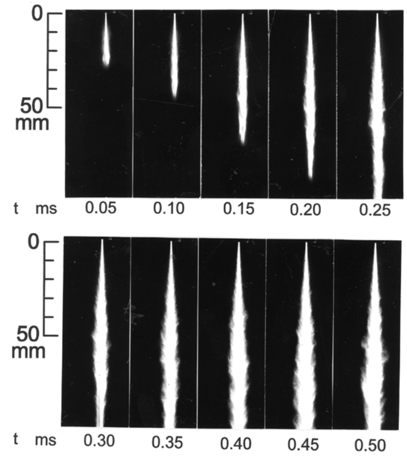
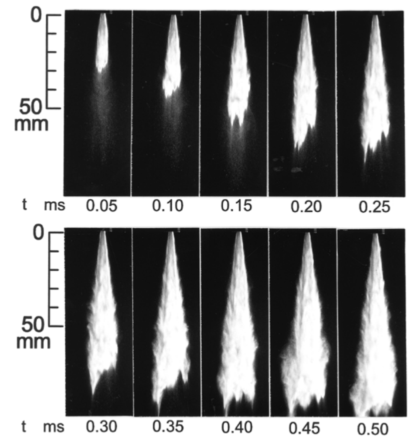


Fig.11 Effect of hole diameter upstream from gap on spray tip penetration



(a) Single hole nozzle



(b) Atomization enhancement nozzle

S. H. N. : L=0.3 mm, D=0.15 mm

A. E. N. : n=1, L_1=0.3 mm, D_1=0.15 mm, D_g=1.0 mm, L_2=0.3 mm, D_2=0.3 mm, P_i=100 MPa, $T_{inj.}$=0.9 ms

Fig.12 Effect of geometric shape of nozzle on atomization of intermittent spray

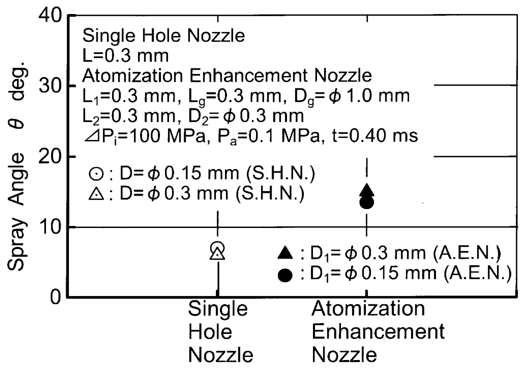


Fig.13 Comparisons of spray angle of single hole nozzle and atomization enhancement nozzle

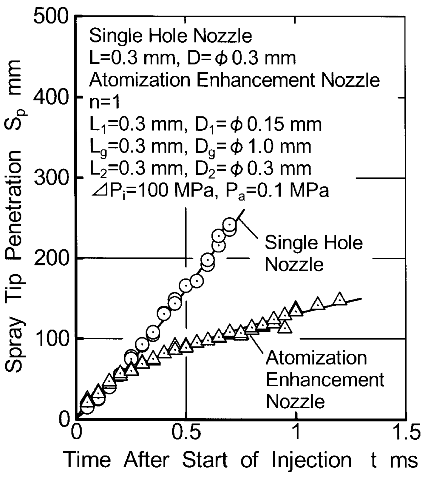


Fig.14 Comparisons of spray tip penetration of single hole nozzle and atomization enhancement nozzle

angle of the atomization enhancement nozzle is large independent of the hole diameters upstream from the gap D_1. As shown in Fig.14, the spray tip penetration of the single hole nozzle becomes long in proportion to progress of the time after start of injection. The spray tip penetration of the atomization enhancement nozzle becomes long straightly until the time after start of injection of about t=0.3 ms. When the time after start of injection excesses about t=0.3 ms, the increasing rate of the spray tip penetration becomes small. The spray tip penetrations of the atomization enhancement nozzle become short significantly as mentioned before, compared with one of the single hole nozzle at the time regions of which the time after start of injection excesses about t=0.3 ms.

From these results, it can be seen that the spray tip penetrations of the atomization enhancement nozzle are short and the spread of the spray of one becomes wide considerably, compared with the single hole nozzle. It was cleared that although atomization of the spray of the atomization enhancement nozzle is improved significantly, the spray tip penetration of one becomes short, the penetration of the spray is weak.

Conclusions

(1) The bypass number strongly affects of dispersion and penetration of the spray. In case of the bypass number of n=1, although penetration of the spray is weak, the spray angle becomes wide and excellent spray is obtained.
(2) In case of the nozzle with the bypass number of n=1 and the shorter hole length of L_2=0.3 mm, the spray angle is the largest. Moreover, in case the nozzle with the longer hole length, the spray tip penetration becomes long and penetration of the spray becomes strong.
(3) In case of the bypass number of n=1, the spray angle are almost same values independent of the hole diameter upstream from the gap. In cases of the nozzle without the bypass of n=0 and the bypass number of n=4, the spray angle of the nozzle with the smaller hole diameter of D_1=0.15 mm for the hole diameter downstream from the gap of D_2=0.3 mm becomes large.
(4) Although the spray tip penetration of the atomization enhancement nozzle is short compared with the single hole nozzle and penetration of the spray is weak, the spread of the spray of the atomization enhancement nozzle is considerably large and atomization of the intermittent spray is improved.

References

1. **Bergwerk, W.**, Flow Pattern in Diesel Nozzle Spray Holes, *Proc. Inst. Mech. Eng.*, Vol. 173, No. 25, (1959), pp. 655-660.
2. **Hiroyasu, H., Arai, M. and Shimizu, M.**, Break-up Length of a Liquid Jet and Internal Flow in a Nozzle, *Proc. Fifth International Conference on Liquid Atomization and Spray Systems*, (1991), pp.275-282.
3. **F. Ruiz**, A Few Useful Relations for Cavitaing Orifices, *Proc. Fifth International Conference on Liquid Atomization and Spray Systems*, (1991), pp. 595-602.
4. **Soteriou, C., Andrews, R. and Smith, M.**, Direct Injection Diesel Sprays and the Effect of Cavitation and Hydraulic Flip on Atomization, *SAE Technical Paper*, No. 950080, (1995), pp. 27-52.
5. **Chaves, H, Knapp, M., Kubitzek, A., Obermeier, F. and Schneider, T.**, Experimental Study of Cavitation in the Nozzle Hole of Diesel Injectors Using Transparent Nozzles, *SAE Technical Paper*, No. 950290, (1995), pp. 645-657.
6. **Badock, C., Wirth, R., Kampmann, S. and Tropea, C.**, Fundamental Study of the Influence of Cavitation on the Internal Flow and Atomization of Diesel Sprays, *Proc. Thirteenth Institute for Liquid Atomization and Spray Systems-Europe*, (1997), pp. 53-59.
7. **Tamaki, N., Shimizu, M. and Hiroyasu, H.**, Enhancement of the Atomization of a Liquid Jet by Cavitation in a Nozzle Hole, *Atomization and Sprays*, Vol. 11, No.2, (2001), pp. 125-137.