ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-6-11

PRACTICAL STUDY ON HIGH-DISPERSION AND HIGH-PENETRATION DIESEL INJECTION NOZZLE (SECOND REPORT: ATOMIZATION OF INTERMITTENT SPRAY OF HIGH-DISPERSION ATOMIZATION ENHANCEMENT NOZZLE AT HIGH-AMBIENT PRESSURE)

N. Tamaki[1*], K. Morimoto[2], M. Chiba[2]

[1*]Department of Mechanical Engineering, School of Engineering, Kinki University, Hiroshima, JAPAN
Phone: +81-82-434-7000, Fax.: +81-82-434-7011, E-mail: tamaki@hiro.kindai.ac.jp
[2]Undergraduates, Department of Mechanical Engineering, School of Engineering, Kinki University

ABSTRACT

The purpose of this study is to develop high-efficiency Diesel injection nozzle, which is able to obtain the spray with high-dispersion and high-penetration. The atomization enhancement nozzle, which excellent spray with large spray angle and small Sauter mean diameter was obtained by occurrence of cavitation under low injection pressure of about 10 MPa, was used. In this paper, the effect of this atomization enhancement nozzle on atomization of the intermittent spray at high-ambient pressure condition and application to the actual Diesel injector were investigated. From these results, it can be seen that although the spray tip penetration of the atomization enhancement nozzle is short, spread of the spray becomes large considerably compared with a previous single hole nozzle for a D. I. Diesel injector and high-dispersion spray was obtained at the intermittent injection under high-ambient pressure.

1. 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. In the previous studies, it was clarified that disturbance of the liquid flow in the nozzle hole due to occurrence of cavitation has a dominant effect on atomization of the liquid jet [1]-[13].

It has developed the atomization enhancement nozzle, which excellent spray characteristics correspond to super-high injection pressure of 200 MPa are obtained at relatively low injection pressure of 10 MPa [14]. Cavitation has a dominant effect on atomization of the liquid jet. The purpose of this study is to develop the atomization enhancement nozzle which is obtained the spray with high-dispersion and high-penetration, and it is to improve the spray characteristics of a D. I. Diesel nozzle. At previous results, it has been developed that although the spray tip penetration of the atomization enhancement nozzle [14] invented in this study is short, spread of the spray becomes large considerably compared with a previous single hole nozzle for a D. I. Diesel injector at the intermittent spray [15].

In this paper, the effect of the atomization enhancement nozzle [14], which was invented in the previous study on atomization of the intermittent spray at high-ambient pressure condition and application to the actual Diesel injector, were investigated. The test nozzles were used a single hole nozzle and the atomization enhancement nozzle [14]. 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 the intermittent spray and atomization characteristics were investigated.

As a result, it was cleared that although the spray tip penetration of the atomization enhancement nozzle is short, spread of the spray becomes large considerably compared with the previous single hole nozzle at high-ambient pressure of 1.6 MPa at ambient temperature of 300 K.

2. EXPERIMENTAL APPARATUS AND METHORD

Schematic of the experimental apparatus is shown in Fig.1. It is consisted of high-pressure pump, microcomputer for control of injection time, injection duration and irradiation time of stroboscope, digital camera, stroboscope and pressure vessel. Light oil for fuel was intermittently injected under high-ambient pressure conditions 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_1=0.15 mm, $T_{inj.}$=0.7 ms for D_1=0.3 mm, and fuel injection quantity are

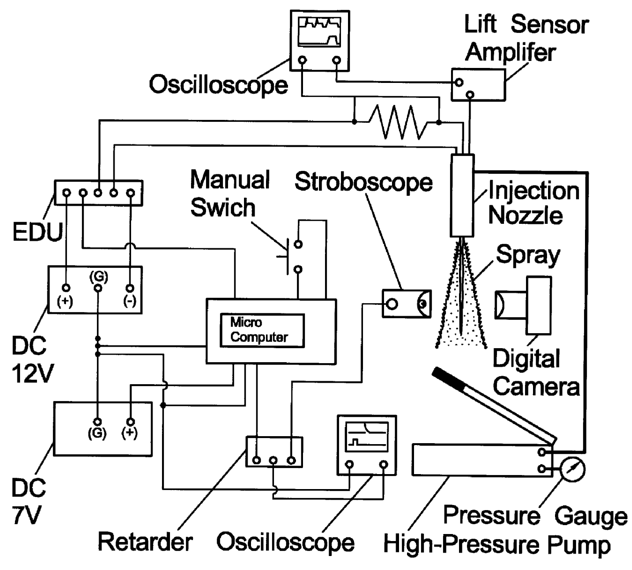


Fig.1 Experimental apparatus

from about 4 mg to 7 mg independent of the hole diameters D_1, D_2 except of the bypass number of n=4. The ambient pressures were varied from P_a=0.1 MPa to 1.6 MPa at the room temperature of T_a=300 K. 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 1.05 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 [14] which was invented in the previous study. Fuel injection quantity of test nozzles is shown in Table 2.

3. EXPERIMENTAL RESULTS AND DISCUSION

3.1 Effect of hole diameter upstream from gap on atomization of intermittent spray and spray tip penetration

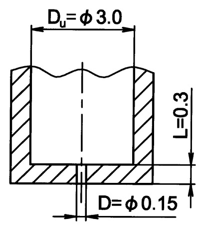
The effect of hole diameter upstream from the gap D_1 on atomization of the intermittent spray is shown in Fig.3. The hole diameter downstream from the gap D_2 is constant of 0.3 mm. The differential pressure of injection is P_i=100 MPa, and the ambient pressure is P_a=1.6 MPa at the room temperature of T_a=300 K. In case of the same fuel injection period, it is guessed that fuel injection quantity is different by the hole diameter upstream from the gap D_1. Therefore, the injection periods were changed $T_{inj.}$=0.70 ms and 0.90 ms. The injection period of D_1=0.15 mm is $T_{inj.}$=0.90 ms and one of D_1=0.3 mm is $T_{inj.}$=0.70 ms. Fuel injection quantity of the nozzle with D_1=0.15 mm and the bypass number of n=4 becomes large about 10 mg due to increase of fuel flow rate incoming from

Table 1 Specification of test nozzles (mm)

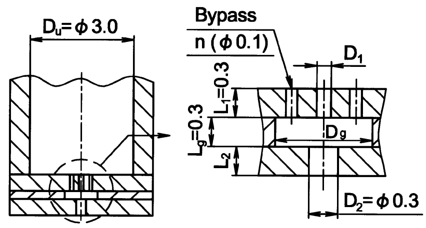
Nozzle Types	Dimensions			
Single Hole Nozzle	D_u	L	D	
	3.0	0.3	0.15	
Atomization Enhancement Nozzle	n	D_u	L_1	D_1
	0, 1, 4	3.0	0.3	0.15, 0.3
	L_g	D_g	L_2	D_2
	0.3	0.6, 0.8, 1.0	0.3, 0.9	0.15, 0.3

Table 2 Fuel injection quantity

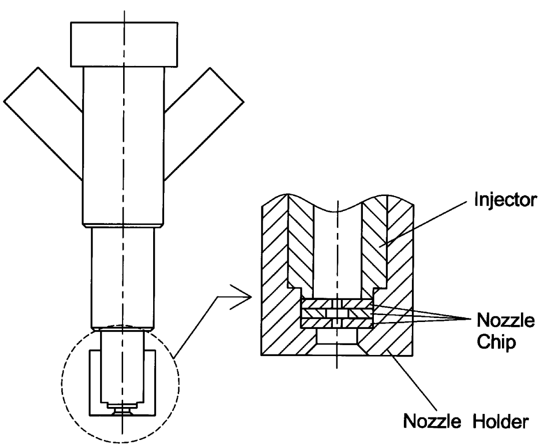
Test nozzles	Fuel injection quantity (mg)
Single hole nozzle L=0.3 mm, D=0.15 mm	4.14
n=1, L_1=L_g=L_2=0.3 mm, D_1=0.15 mm, D_2=0.15 mm, D_g=0.6 mm	4.94
n=1, L_1=L_g=L_2=0.3 mm, D_1=0.15 mm, D_2=0.3 mm, D_g=0.6 mm	6.74
n=1, L_1=L_g=L_2=0.3 mm, D_1=0.15 mm, D_2=0.3 mm, D_g=0.8 mm	6.56
n=1, L_1=L_g=L_2=0.3 mm, D_1=0.15 mm, D_2=0.3 mm, D_g=1.0 mm	6.86
n=1, L_1=L_g=L_2=0.3 mm, D_1=0.3 mm, D_2=0.3 mm, D_g=1.0 mm	6.06
n=0, L_1=L_g=L_2=0.3 mm, D_1=0.15 mm, D_2=0.3 mm, D_g=1.0 mm	4.44
n=4, L_1=L_g=L_2=0.3 mm, D_1=0.15 mm, D_2=0.3 mm, D_g=1.0 mm	9.86



(a) Single hole nozzle for D. I. Diesel injector



(b) Atomization enhancement nozzle [14]



(c) D. I. Diesel injector with atomization enhancement nozzle

Fig.2 Test nozzles

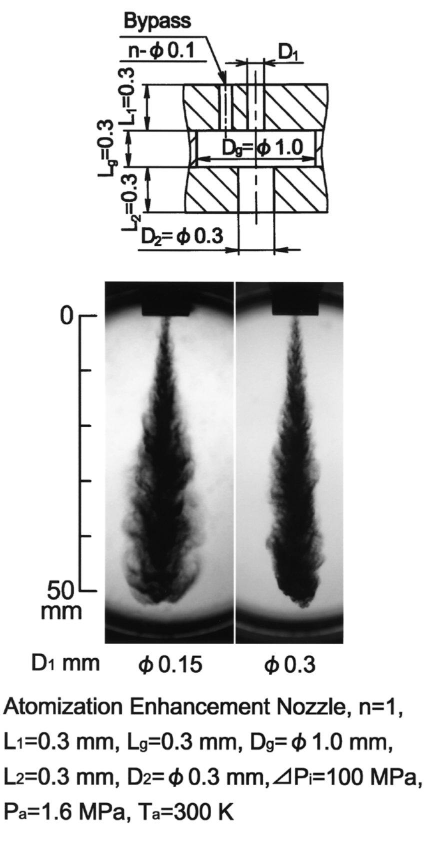


Fig.3 Effect of hole diameter upstream from gap on atomization of intermittent spray

the bypass. Spread of the spray of D_1=0.15 mm becomes large, atomization of the spray is enhanced and high-dispersion spray is obtained compared with the nozzle of D_1=0.3 mm. It is considered that when the hole diameter upstream from the gap D_1 is small, since the flow velocity becomes large, cavitation occurs easily compared with the nozzle with the large hole diameter D_1. As a result, spread of the spray becomes large and the spray atomizes considerably by using the nozzle with the small hole diameter upstream from the gap. Moreover, the spray length, which is indicated as a distance from outlet of the nozzle to the spray tip, is almost same independent of D_1.

It can be seen that although the hole diameter upstream from the gap D_1 little affects penetration of the spray, it affects dispersion of the spray, that is, spread of the spray, and high-dispersion spray is obtained by using the nozzle with the smaller hole diameter of D_1=0.15 mm for the hole diameter of D_2=0.3 mm.

3.2 Effect of hole diameter downstream from gap on atomization of intermittent spray and spray tip penetration

The effect of the hole diameter downstream from the gap D_2 on atomization of the intermittent spray is shown in Fig.4. The hole diameter upstream from the gap D_1 is constant of 0.15 mm, and the hole diameters downstream from the gap are changed as 0.15 mm and 0.3 mm. The injection period is 0.9 ms independent of D_2. Since the nozzle hole upstream from the gap, that is, the location where the fuel flows into the nozzle hole from the sac chamber of the injector is same diameter, it is guessed that fuel amount flowing into the nozzle hole is almost same values independent of D_2. However, as shown in Table 1, fuel injection quantity of D_2=0.15 mm is small compared with D_2=0.3 mm. Although fuel injection quantity is different by the hole diameter D_2, spread of the sprays and the spray lengths are almost same and the sprays atomize independent of D_2.

From these results, it can be seen that the spray, which spread of the spray is wide, is obtained by using the nozzle with the smaller hole diameter of D_1=0.15 mm for the large hole diameter of D_2=0.3 mm. Moreover, when the hole diameter D_1 is 0.15 mm, the spray lengths are almost same, and excellent spray, which spread of the spray is wide, is obtained independent of the hole diameter downstream from the gap D_2.

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

The effect of the bypass number on atomization of the intermittent spray is shown in Fig.5. The differential pressure of injection is P_i=100 MPa and the time after start of injection is t=0.95 ms. Spread of the sprays are large independent of the bypass numbers and especially one of the bypass number of n=1 is the largest. In the previous study, it was clarified that spread of the spray of the nozzle without the bypass was the smallest at atmospheric pressure condition [15]. However, spread of the spray becomes large at high-ambient pressure condition. It is considered as follows; it is well known that in case of the nozzle without the bypass, cavitation does not occur in the nozzle hole at atmospheric pressure condition due to occurrence of hydraulic flip [4]. However, it is guessed that hydraulic flip does not occur in the nozzle hole at high-ambient pressure conditions due to increase of ambient density, and the spray of the nozzle without the bypass also atomizes. Moreover, although cavitation occurs independent of existence of the bypass and the bypass number, it is considered that magnitude of disturbance of the liquid flow

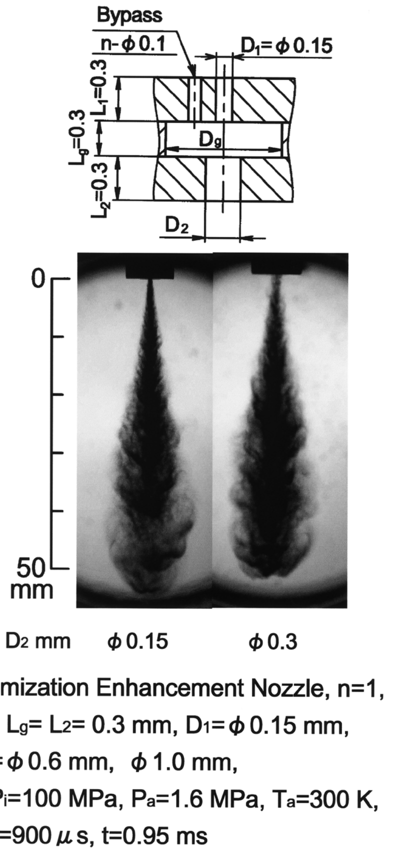


Fig.4 Effect of hole diameter downstream from gap on atomization of intermittent spray

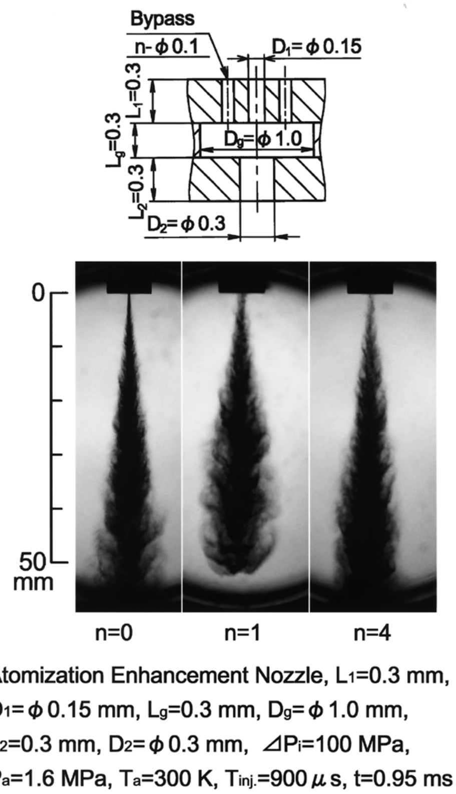


Fig.5 Effects of bypass number on atomization of intermittent spray

caused by occurrence of cavitation is different by existence of the bypass and the bypass number. Furthermore, in case of the bypass number of n=4, atomization of the spray is controlled due to increase the liquid flow from the bypass. Therefore, it is guessed that atomization of the sprays and spread of the sprays are different by existence of the bypass and the bypass number.

The effect of the bypass number on the spray tip penetration is shown in Fig. 6. The spray tip penetration becomes long with a passage in the time after start of injection. Although the spray tip penetration 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, increasing rate of the spray tip penetration becomes small independent of existence of the bypass and the bypass number. The spray tip penetrations of the nozzles without the bypass of n=0 and the bypass number of n=4 are long compared with one of n=1. The spray tip penetration of n=1 is the shortest and one of n=4 is the longest compared with arbitrary time after start of injection.

It can be seen that spread of the sprays are almost same independent of existence of the bypass and the bypass number, dispersion of the spray is a little affected by the bypass number. 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 high-penetration spray is not 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 like that atmospheric pressure condition [15].

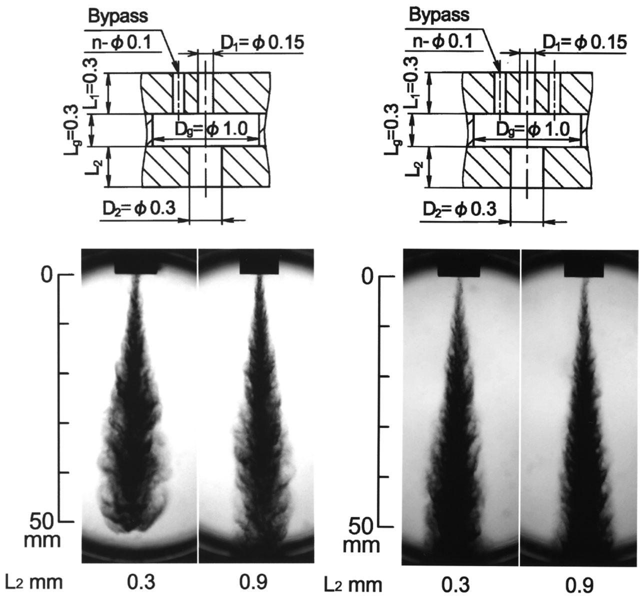
3.4 Effect of the hole length downstream from the gap on atomization of intermittent spray and spray tip penetration

The effect of the hole length downstream from the gap L_2; simply called the hole length on atomization of the intermittent spray is shown in Fig.7. As shown in Fig.7 (a), in case of the bypass number of n=1, spread of the spray of the shorter hole length of L_2=0.3 mm is large compared with one of the longer hole length of L_2=0.9 mm, the spray atomizes and high-dispersion spray is obtained. As shown in Fig.7 (b), in case of the bypass number of n=4, 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 the spray.

The effect of the hole length on the spray angle is shown in Fig.8. In case of the bypass number of n=1, the spray angle of the nozzle of L_2=0.3 mm is larger than one of the nozzle of L_2=0.9 mm. On the other hand, in cases of without the bypass of n=0 and the bypass number of n=4, the spray angles are almost same values and the spray angle is little affected to the hole length downstream from the gap.

It can be seen that 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 becomes considerably large and high-dispersion spray is obtained.

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 penetrations become long



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

Atomization Enhancement Nozzle, L_1=0.3 mm, D_1=0.15 mm, L_g=0.3 mm, D_g=1.0 mm, D_2=0.3 mm, P_i=100 MPa, P_a=1.6 MPa, T_a=300 K, $T_{inj.}$=0.9 ms, t=0.95 ms

Fig.7 Effect of hole length downstream from gap on atomization of intermittent spray

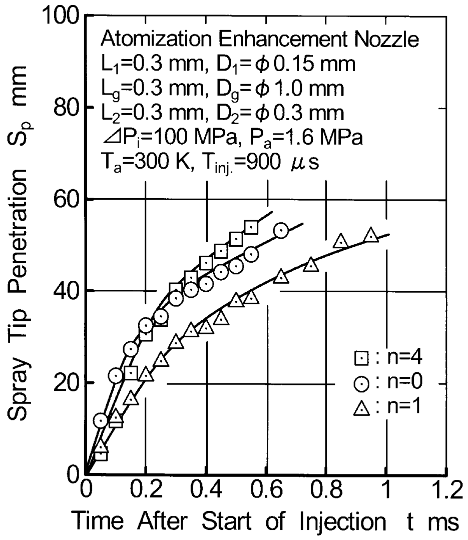


Fig.6 Effects of bypass number on spray tip penetration

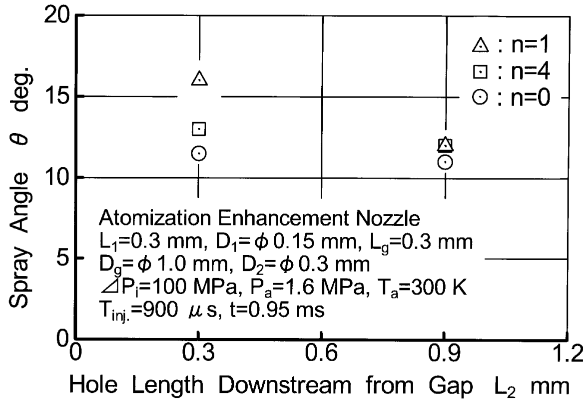
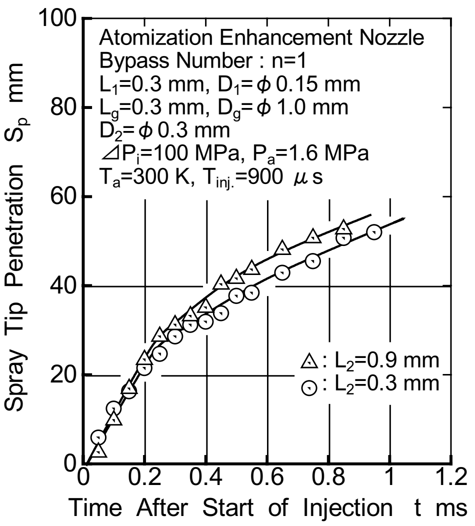


Fig.8 Effect of hole length downstream from gap on spray angle

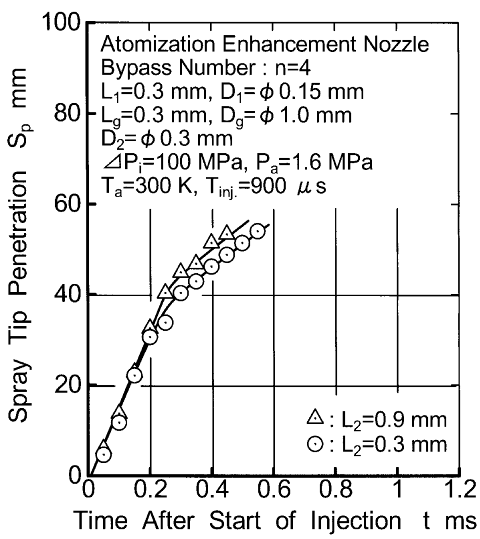
straightly with an passage in the time after start of injection until the time after start of injection of about t=0.3 ms. When the time after start of injection excesses about t=0.3 ms, increasing rate of the spray tip penetrations becomes small. Moreover, the spray tip penetration of L_2=0.9 mm is slightly longer than one of L_2=0.3 mm. 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.

In case of the longer hole length, it is guessed that behaviors of the liquid flow at the nozzle hole upstream from the gap little affects the liquid flow at the outlet of the nozzle hole. 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 outlet of the nozzle hole. Therefore, the nozzle with the longer hole length little affects geometric shapes and dimensions of the nozzle hole.

From these results, it can be seen that the hole length downstream from the gap little affects atomization of the spray and the spray tip penetration.



(a) Bypass number n=1



(b) Bypass number n=4

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

3.5 Effect of ambient pressures on dispersion of intermittent spray

The effect of the ambient pressures on dispersion of the spray is shown in Fig.10. Although the spray length at high-ambient pressure of P_a=1.6 MPa is short compared with low-ambient pressures, spread of the spray becomes large independent of the ambient pressures and high-dispersion spray is obtained. Moreover, the sprays, which spread of the sprays are almost same, are obtained at relatively high-ambient pressure conditions of P_a=1.1 MPa and 1.6 MPa.

From this result, it can be seen that the spray atomizes at relatively low-ambient pressure and spread of the spray are almost same, it is possible to inject at early time after start of injection at actual Diesel engine.

3.6 Comparisons of dispersion and penetration of spray of single hole nozzle for D. I. Diesel injector and atomization enhancement nozzle invented in this study

The disintegration behaviors of the intermittent sprays at the arbitrary time after start of injection are shown in Fig.11. The comparisons of atomization of the sprays of the single hole nozzle for a D. I. Diesel injector and the atomization enhancement nozzle invented in this study are shown in Fig.11. Figure 11 (a) is the single hole nozzle and Fig.11 (b) is the atomization enhancement nozzle. As shown in Fig.11, spread of the sprays of the atomization enhancement nozzle is large 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=0.75 ms, it seems that the spray length of the single hole nozzle become long compared with one of the atomization enhancement nozzle.

The spray tip penetrations of the single hole nozzle and the atomization enhancement nozzle is shown in Fig.12. As shown in Fig.12, the spray tip penetrations of the single hole nozzle are longer than one of the atomization enhancement nozzle compared with the same time after start of injection.

From these results, it can be seen that although the spray tip penetration of the atomization enhancement nozzle is short, spread of the spray becomes large considerably compared with the single hole nozzle and high-dispersion spray was obtained at the intermittent injection of the actual Diesel injector under high-ambient pressure.

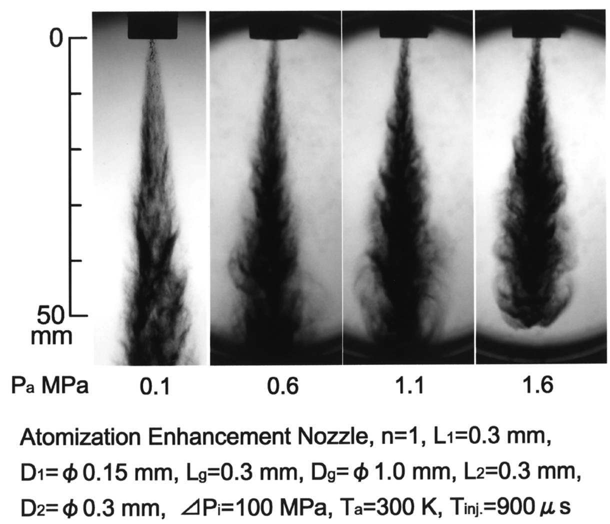
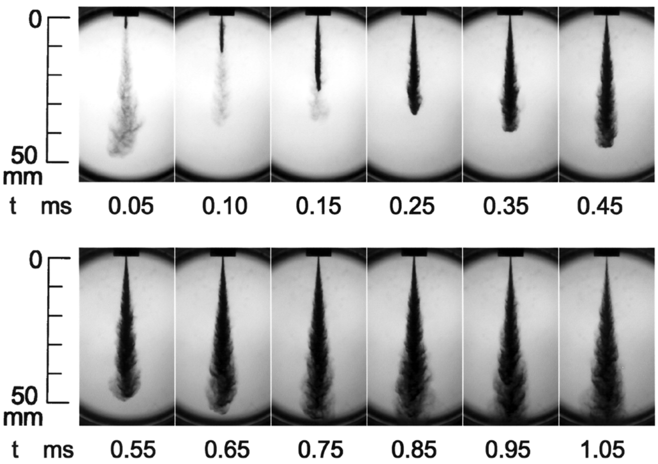
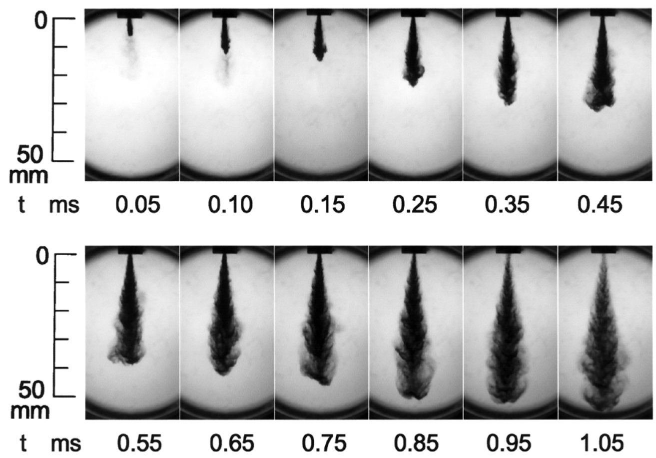


Fig.10 Effect of ambient pressures on dispersion of spray



(a) Single hole nozzle for D. I. Diesel injector



(b) Atomization enhancement nozzle

Fig.11 Disintegration behaviors of intermittent sprays at arbitrary time after start of injection

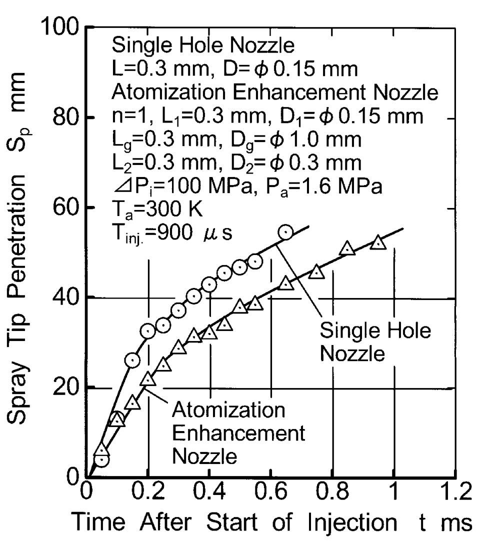


Fig.12 Spray tip penetrations of single hole nozzle for D. I. Diesel injector and atomization enhancement nozzle

4. CONCLUISIONS

(1) In case the hole diameter upstream from the gap is smaller than the hole diameter downstream from the gap, spread of the spray is wide and high-dispersion spray is obtained.
(2) Spread of the sprays are large independent of the bypass numbers and especially one of the bypass number of n=1 is the largest. In case of the bypass number of n=1, although the penetration of the spray is weak, high-dispersion spray is obtained.
(3) 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 becomes considerably large and high-dispersion spray is obtained. The spray tip penetrations are almost same length and are long independent of the hole length, high-penetration sprays are obtained.
(4) Spread of the spray becomes wide at relatively low-ambient pressure of P_a=0.6 MPa, and the spray, which corresponds to high-ambient pressure of P_a=1.6 MPa was obtained.
(5) Although the spray tip penetration of the atomization enhancement nozzle invented in this study is short, spread of the spray becomes large considerably compared with the single hole nozzle and high-dispersion spray was obtained at the intermittent injection of the actual Diesel injector under high-ambient pressure.

NOMENCLATURE

Symbol	Quantity	SI Unit
D	Hole diameter	mm
D_g	Gap diameter	mm
D_u	Upstream chamber diameter	mm
D_1	Hole diameter upstream from gap	mm
D_2	Hole diameter downstream from gap	mm
L	Hole length	mm
L_g	Gap length	mm
L_1	Hole length upstream from gap	mm
L_2	Hole length downstream from gap	mm
n	Bypass number	number
P_a	Ambient pressure	MPa
P_i	Differential pressure of injection	MPa
t	Time after start of injection	ms
T_a	Ambient temperature	K
$T_{inj.}$	Injection duration	ms

REFERENCES

[1] **Bergwerk, W.**, Flow Pattern in Diesel Nozzle Spray Holes, *Proc. Inst. Mech. Eng.*, Vol. 173, No. 25, pp. 655-660, 1959.

[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*, pp.275-282, 1991.

[3] **F. Ruiz**, A Few Useful Relations for Cavitaing Orifices, *Proc. Fifth International Conference on Liquid Atomization and Spray Systems*, pp. 595-602, 1991.

[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, pp. 27-52, 1995.

[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, pp. 645-657,

1995.
[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*, pp. 53-59, 1997.
[7] **Schmidt, D. P., Rultand, C. J. and Corradini, M. L.**, A Numerical Study of Cavitating Flows Through Various Nozzle Shapes, *SAE Paper*, No. 971597, 1997.
[8] **Tamaki, N., Nishida, K., Shimizu, M. and Hiroyasu, H.**, Effects of Cavitation and Internal Flow on Atomization of a Liquid Jet, *Atomization and Sprays*, Vol. 8, No. 2, pp. 179-19, 1998.
[9] **Chaves, H. and Obermeier, F.**, Correlation between Light Absorption Signals of Cavitating Nozzle Flow within and outside of the Hole of a Transparent Diesel Injection Nozzle, *Proc. Fourteenth Institute for Liquid Atomization and Spray Systems-Europe*, pp. 224-229, 1998.
[10] **Badock, C., Wirth, R., Fath, A. and Leipertz, A.**, Investigation of Cavitation in Real Size Diesel Injection Nozzles, *International Journal of Heat and Fluid Flow*, Vol. 20, pp. 538-544, 1999.
[11] **Henry, M. E. and Collicott, H.**, Visualization of Internal Flow in a Cavitating Slot Orifice, *Atomization and Sprays*, Vol. 10, No. 6, pp.545-563, 2000.
[12] **Arcoumanis, C. and Gavaises, M.**, Cavitation in Diesel Injectors: Modeling and Experiment, *Proc. Fourteenth Institute for Liquid Atomization and Spray Systems-Europe*, pp. 248-255, 1998.
[13] **Yule, A. J. Dalli, A. M. and Yeong, K. B.**, Transient Cavitation and Separation in a Scaled-up Model of a VCO Orifice, *Proc. Fourteenth Institute for Liquid Atomization and Spray Systems-Europe*, pp. 230-235, 1998.
[14] **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, pp. 125-137, 2001.
[15] **Tamaki, N., Nishida, Y. and Hosokawa, T.**, 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, *Proc. 21st Institute for Liquid Atomization and Spray Systems-Europe*, CD-R, 6 pages, 2007.