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Practical Study on High-Dispersion Atomization Enhancement Nozzle

(Effects of Ambient Pressures on Atomization of Spray and Application to Actual Diesel Nozzle)

Nobushige Tamaki[1], Yoshiaki Ishida[2] and Akihiko Higashi[2]

[1] Associate Professor, Department of Mechanical Engineering, Kinki University, tamaki@hiro.kindai.ac.jp
[2] Undergraduate Students, Department of Mechanical Engineering, Kinki University

ABSTRACT The purpose of this study is to develop the atomization enhancement nozzle, which is able to obtain the spray with high-dispersion and high-penetration. Moreover, it is to apply the atomization enhancement nozzle to an actual Diesel injector, and it is to improve the spray characteristics of a direct injection Diesel nozzle. In this paper, the effects of the ambient pressures on atomization of the spray of the atomization enhancement nozzle and the effects on atomization of the spray at the intermittent injection were investigated. Moreover, the correlation of the atomization characteristics between an enlarged nozzle and an actual size nozzle were investigated. The results show that the atomization enhancement nozzle developed in this study was obtained the excellent spray and the spray characteristics, which the breakup length is short, the spray angle is large and the droplet diameter is small, and atomization of the spray and the spray characteristics were considerably improved. Moreover, it was clarified that the spread of the spray of this atomization enhancement nozzle at the high-ambient pressure condition is larger than the atmospheric pressure condition and this nozzle is able to obtain the excellent spray with large spray angle under the high-ambient pressure condition. Although the spray tip penetration of the atomization enhancement nozzle is short compared with one of the single hole nozzle, the spread of the spray of the atomization enhancement nozzle is larger than one of the single hole nozzle at the intermittent injection. It can be seen that atomization of the spray is enhanced considerably at the intermittent injection. Furthermore, approximate correlations between the enlarged nozzle and the actual size nozzle were obtained.

Keywords: Atomization, Fuel Injection, Diesel Engine, Atomization Enhancement, Cavitation, Spray Characteristics

1. INTRODUCTION

A direct injection Diesel injector is demanded the high-injection pressure up to about 100 MPa in order to obtain the excellent spray characteristics. It is important to obtain the excellent spray and the spray characteristics, which a liquid core length, that is, the breakup length is short, the spray angle is large and the droplet diameter is small, under the low-injection pressure from an energy saving view point. Experimental studies [1]-[11], numerical studies and modeling [12]-[16] concerned with cavitation in the nozzle hole, relationships between a nozzle internal flow and atomization of a 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. Based on this concept, the atomization enhancement nozzle, which the spray characteristics at relatively the low-injection pressure of 10 MPa are equal to ones at the super-high injection pressure of 200 MPa, was investigated in the previous study [17]. It is necessary to obtain the spray with high-dispersion, high-penetration and to obtain the fuel injection rate correspond with the super-high injection pressure of the actual Diesel engine.

The purpose of this study is to develop the nozzle of which the spray with high-dispersion and high-penetration is obtained and the spray characteristics and the flow characteristics are improved at the low-injection pressure condition.

In this paper, the effects of geometric shapes of the nozzle and the ambient pressures on atomization enhancement of the spray and application to the intermittent spray were investigated to apply the actual Diesel injector. Moreover, the correlation of the atomization characteristics between the enlarged nozzle and the actual size nozzle were investigated.

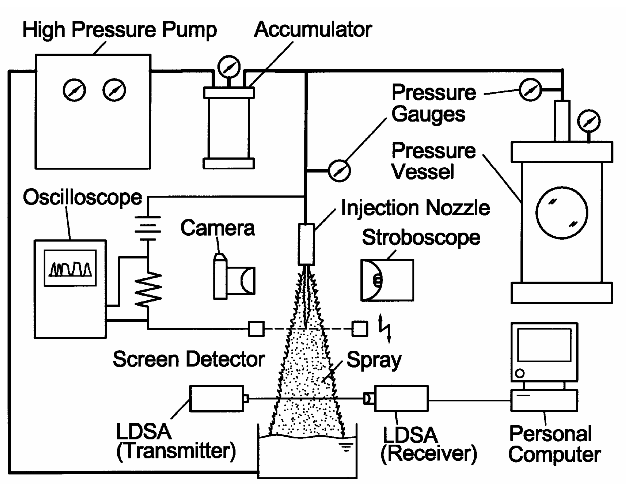
The results show that the spread of the spray of the atomization enhancement nozzle developed in this study becomes wide considerably under the high-ambient pressure of P_a=1.6 MPa at the room temperature. Moreover, it was clarified that this atomization enhancement nozzle is obtained the excellent spray with a large spread angle of the spray compared with the single hole nozzle at the intermittent spray. Furthermore, approximate correlations between the enlarged nozzle and the actual size nozzle were obtained.

2. EXPERIMENTAL APPARATUS AND METHODS

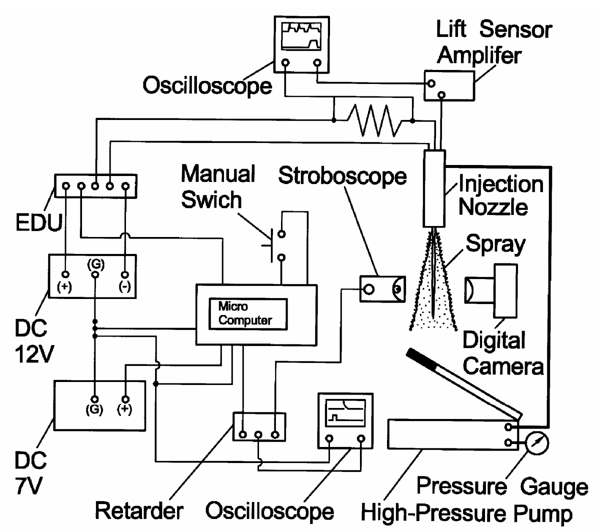
The experimental apparatus is shown schematically in Fig. 1. The equipment consists of liquid injection system with a high-pressure pump for the continuous injection [Fig.1 (a)] and with a high-pressure pump that is worked by hand for the intermittent injection [Fig.1 (b)], a spark light source for taking photographs of disintegration behaviors of the spray. The high-pressure pump for the continuous injection supplied water up to the injection pressure of P_i=20 MPa and it was continuously injected under the atmospheric and the high-ambient pressure of P_a=1.6 MPa at the room temperature. The high-pressure pump for the intermittent injection supplied light oil up to the injection pressure of P_i=100 MPa and it was intermittently injected under the atmospheric pressure condition. The disintegration behaviors of the spray were photographed by scattering light, using a stroboscope.

The breakup length of the liquid core, which is defined as the distance from the nozzle outlet to the breakup point of the liquid core, was measured by an electrical resistance method [18] in which a screen detector was used. The spread angle of the spray, that is, the spray angle was measured as the spray boundary by the photographs of the sprays. The droplet diameter and the droplet size distributions were measured by a narrow angle forward scattered method an LDSA particle analyzer at 150 mm downstream from the nozzle outlet. It gives the Sauter mean diameter that is spatially averaged along a line through the spray.

The structures of the test nozzles are shown in Fig. 2, and the configuration of the test nozzles is shown in Table 1. The test nozzles were of two types: the single hole nozzle [Fig.2 (a)], the enlarged and the actual size atomization enhancement nozzles developed in the previous study [Fig. 2 (b)] [17]. The atomization enhancement nozzle was the nozzle in which the gap was made at the nozzle hole and the bypass, which was connected between the upstream chamber of the nozzle hole correspond to the sac chamber

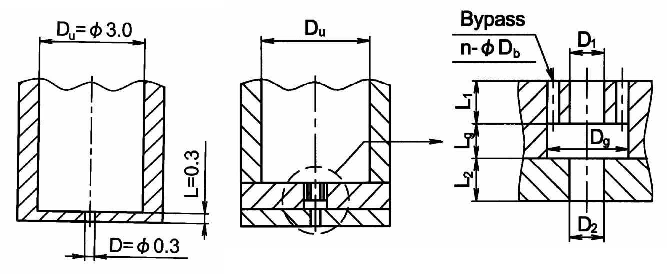


(a) Experimental apparatus for continuous injection



(b) Experimental apparatus for intermittent injection

Fig.1 Experimental apparatus



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

Fig.2 Test nozzles

Table 1 Configuration of test nozzles

(mm)

Nozzle types	D_u	L	D	
Single hole nozzle	Ø3.0	0.3	Ø0.3	
Atomization enhancement nozzle	n	D_u	L_1	D_1
	1, 4	Ø3.0	0.3	Ø0.15, Ø0.3
		Ø30	3.0	Ø3.0
	L_g	D_g	L_2	D_2
	0.3	Ø0.6, Ø0.8, Ø1.0	0.3, 0.9	Ø0.3
	3.0	Ø18	3.0	Ø3.0

of the actual Diesel injector and the gap, was installed.

The hole diameters are almost the same diameter as the actual Diesel nozzle of D_2=Ø0.3 mm and about ten times as large as the actual Diesel nozzle of D_2=Ø3.0 mm. The upstream chamber diameters D_u were enlarged the hole diameter ten times, D_u were Ø3.0 mm for the actual Diesel nozzle and Ø30 mm for the enlarged nozzle in order to reduce the volume of the sac chamber. The hole diameter upstream from the gap D_1, the gap diameter D_g and the hole length downstream from the gap L_2 were varied as shown in Table 1.

3. EXPERIMENTAL RESULTS AND DISCUTION

3.1 The effects of the bypass number and the ambient pressures on the spray characteristics and the flow characteristics

The effects of the bypass number on the breakup length, the spray angle and the Sauter mean diameter are shown in Figs.3, 4 and 5, respectively. As shown in Figs.3 and 4, in case of the bypass number of n=1, the breakup length becomes short and the spray angle becomes large compared with ones of n=4 at all injection pressure regions. As shown in Fig.5, the Sauter mean diameter at the region of which the injection pressure P_i is greater than about P_i=5 MPa are almost the same values independent of the bypass number. Moreover, the small Sauter mean diameter of 10 to 20 microns are obtained at the region of which the injection pressure is greater than about P_i=10 MPa.

The effects of the bypass number and the ambient pressures on atomization of the spray are shown in Fig.6.

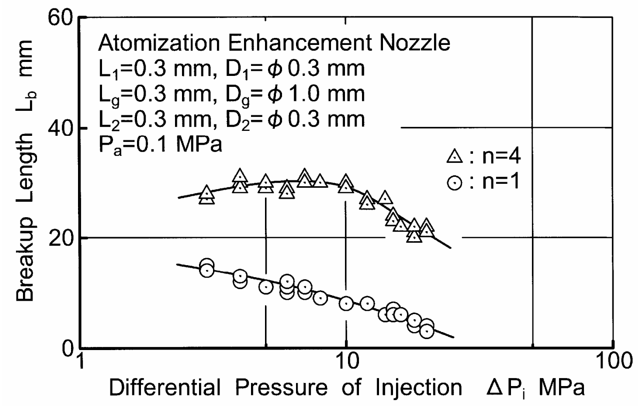


Fig.3 Effects of the bypass number on the breakup length

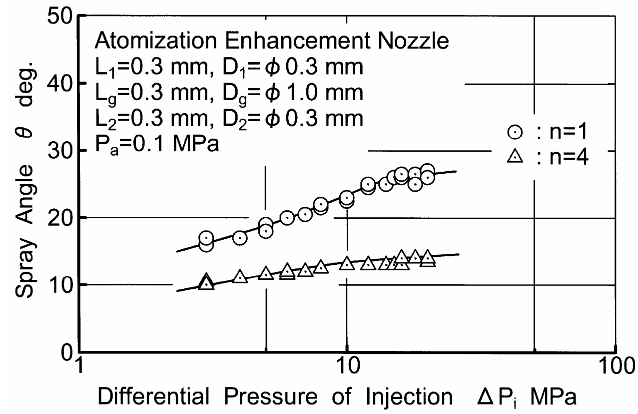


Fig.4 Effects of the bypass number on the spray angle

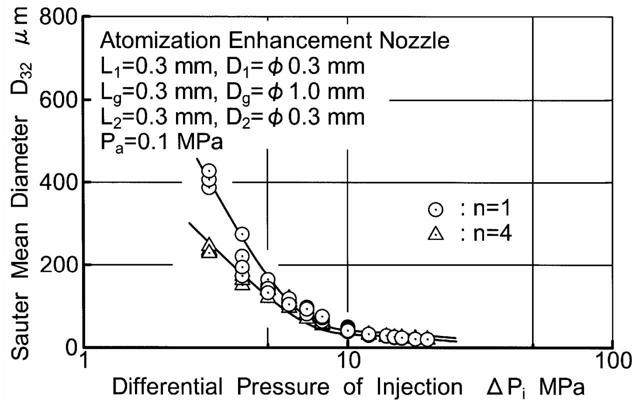
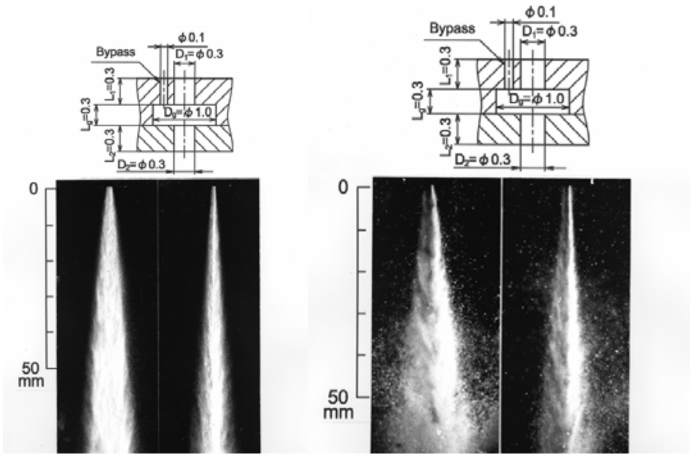


Fig.5 Effects of the bypass number on the Sauter mean diameter

Figure 6 (a) is the ambient pressure of P_a=0.1 MPa, Fig.6 (b) is P_a=1.6 MPa at the room temperature. The spread of the sprays of the nozzle with the bypass number of n=1 are wide and the sprays atomize compared with the nozzle with the bypass number of n=4 independent of the ambient pressers.

The effects of the bypass number on the volumetric flow rate are shown in Fig.7. The volumetric flow rate is almost the same values independent of the bypass number compared with the arbitrary injection pressures, it can be seen that increasing of the bypass number is little affected to improvement of the flow characteristics.



n=1 n=4 n=1 n=4

Atomization Enhancement Nozzle, L_1=0.3 mm, D_1=Ø 0.3 mm, L_g=0.3 mm, D_g=Ø 1.0 mm, L_2=0.3 mm, D_2=Ø 0.3 mm, P_i=20 MPa, T_a=300 K

(a) P_a=0.1 MPa (b) P_a=1.6 MPa

Fig.6 Effects of the bypass number and the ambient pressures on atomization of the spray

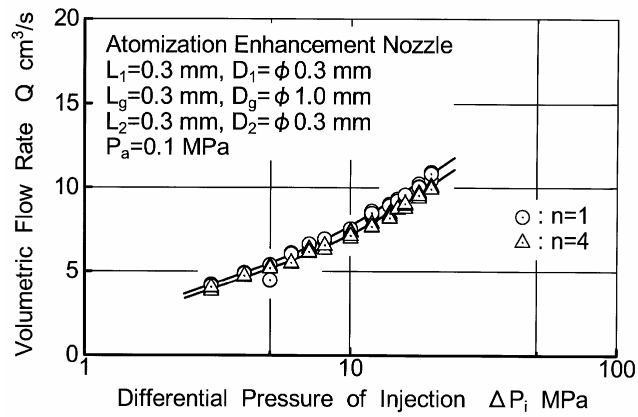


Fig.7 Effects of the bypass number on the volumetric flow rate

3.2 The effects of the hole length downstream from the gap and the ambient pressures on the atomization characteristics

The effects of the hole length downstream from the gap L_2 on atomization characteristics are shown in Fig.8. In case of the shorter hole length of L_2=0.3 mm, the breakup length becomes short and the spray angle becomes large compared with the longer hole length of L_2=0.9 mm at the arbitrary injection pressures.

The effects of the hole length downstream from the gap on atomization of the sprays are shown in Fig.9. Figure 9 (a) is the ambient pressure of P_a=0.1 MPa, Fig.9 (b) is P_a=1.6 MPa at the room temperature. As shown in Fig.9 (a), the spread of the sprays of the nozzle with the shorter hole length of L_2=0.3 mm become wide and the sprays atomize compared with the nozzle with the longer hole length of L_2=0.9 mm. As shown in Fig.9 (b), although the spray of the nozzle with the longer hole length of L_2=0.9 mm atomizes at P_a=1.6 MPa compared with P_a=0.1 MPa,

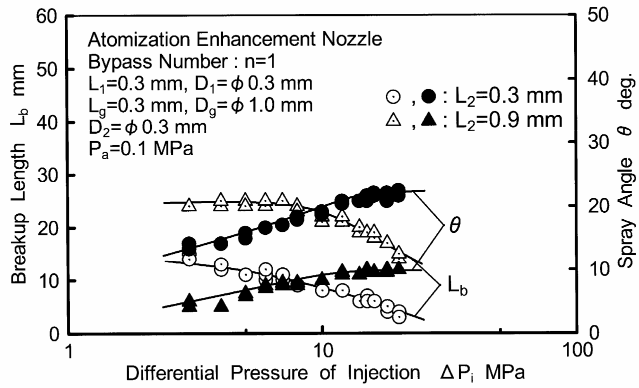


Fig.8 Effects of the hole length downstream from the gap on the atomization characteristics

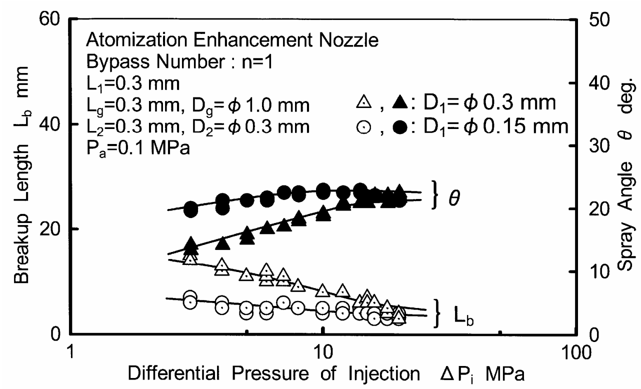
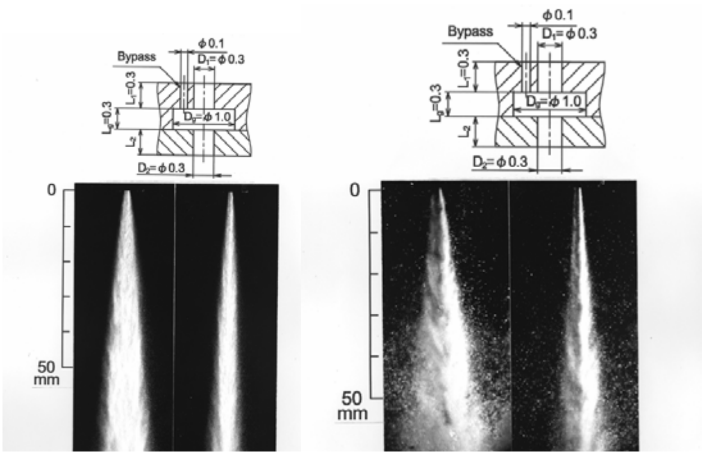


Fig.10 Effects of the hole diameter upstream from the gap on the atomization characteristics



L_2 mm 0.3 0.9 0.3 0.9

Atomization Enhancement Nozzle, L_1=0.3 mm, D_1=Ø 0.3 mm, L_g=0.3 mm, D_g=Ø 1.0 mm, L_2=0.3 mm, D_2=Ø 0.3 mm, P_i=20 MPa, T_a=300 K

(a) P_a=0.1 MPa (b) P_a=1.6 MPa

Fig.9 Effects of the hole length downstream from the gap and the ambient pressures on atomization of the spray

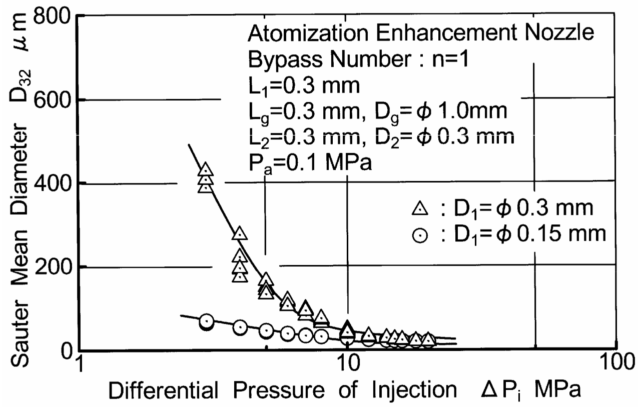


Fig.11 Effects of the hole diameter upstream from the gap on the Sauter mean diameter

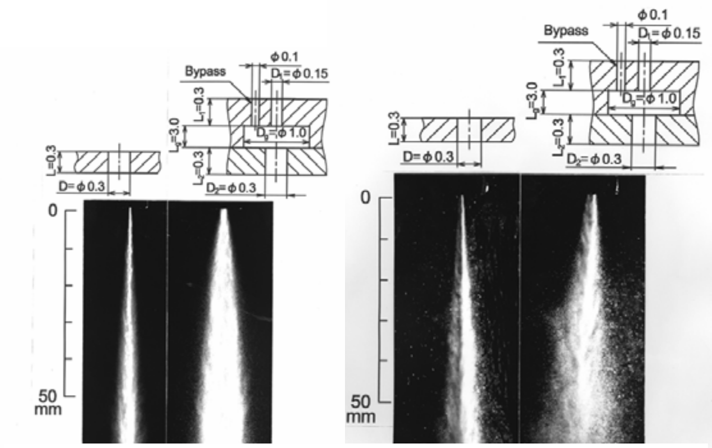
the spray of the nozzle with the shorter hole length of L_2=0.3 mm more atomizes and the same tendency is obtained independent of the ambient pressures. From this result, it can be seen that the shorter the hole length downstream from the gap is, the more the spray atomizes, the excellent atomization characteristics are obtained. Moreover, the sprays at the high-ambient pressure of P_a=1.6 MPa atomizes compared with the atmospheric pressure of P_a=0.1 MPa, the excellent spray is obtained at the high-ambient pressure condition.

3.3 The effects of the hole diameter upstream from the gap on the atomization characteristics

The effects of the hole diameter upstream from the gap D_1 on the atomization characteristics and the Sauter mean diameter are shown in Figs.10 and 11, respectively. As shown in Fig.10, when the hole diameter upstream from the gap D_1 is small of D_1=Ø0.15 mm for the hole diameter downstream from the gap of D_2=Ø0.3 mm, although the breakup length and the spray angle at the high-injection pressure regions greater than about P_i=15 MPa are almost the same values independent of D_1, the breakup length and the spray angle of D_1=Ø0.15 mm at the low-injection pressure regions are short and large, respectively. Moreover, the breakup length of D_1=Ø0.15 mm becomes short independent of the injection pressures, almost the same breakup length as the maximum injection pressure of P_i=20 MPa is obtained at relatively the low-injection pressure regions. As shown in Fig.11, when the injection pressure is low, the Sauter mean diameter of D_1=Ø0.15 mm becomes small considerably compared with one of D_1=Ø0.3 mm. When the injection pressure is greater than about P_i=10 MPa, almost the same Sauter mean diameter are obtained independent of the hole diameter upstream from the gap D_1. From this result, it can be seen that the excellent spray characteristics are obtained by using the nozzle with the smaller hole diameter upstream from the gap.

3.4 The effects of the geometric shapes and the ambient pressures on the spray characteristics

The effects of the geometric shapes of nozzle on atomization of the spray are shown in Fig.12. Moreover, the effects on the breakup length, the spray angle and the Sauter mean diameter are shown in Figs.13, 14 and 15, respectively. Figure 12 (a) is the ambient pressure of P_a=0.1 MPa, Fig.12 (b) is P_a=1.6 MPa at the room temperature. As shown in Fig.12, the spread of the sprays of the atomization enhancement nozzle become wide independent of the ambient pressures, the excellent spray is obtained at the high-ambient pressure condition. As shown in Figs. 13 and 14, the breakup length becomes short and the spray angle becomes large with an increase in the injection pressures. The breakup length of the atomization enhancement nozzle becomes short significantly at all injection pressure regions and the same breakup length as the maximum injection pressure of P_i=20 MPa is obtained as mentioned before. The spray angle becomes large considerably compared with the single hole nozzle. As shown in Fig.15, when the injection pressure is low, the Sauter mean diameter of the atomization enhancement nozzle are considerably smaller than one of the single hole nozzle. When the injection pressure P_i excesses about P_i=7 MPa, the Sauter mean diameter are almost the same values as the high-injection pressure regions independent of the geometric shapes of nozzle.



S.H.N. A.E.N. S.H.N. A.E.N.
L_1=0.3 mm, D_1=Ø 0.15 mm, L_g=0.3 mm, D_g=Ø 1.0 mm,
L_2=0.3 mm, D_2=Ø 0.3 mm, L=0.3 mm, D=Ø 0.3 mm,
P_i=20 MPa, T_a=300 K
(a) P_a=0.1 MPa (b) P_a=1.6 MPa

Fig.12 Effects of the geometric shapes of nozzle and the ambient pressures on atomization of the spray

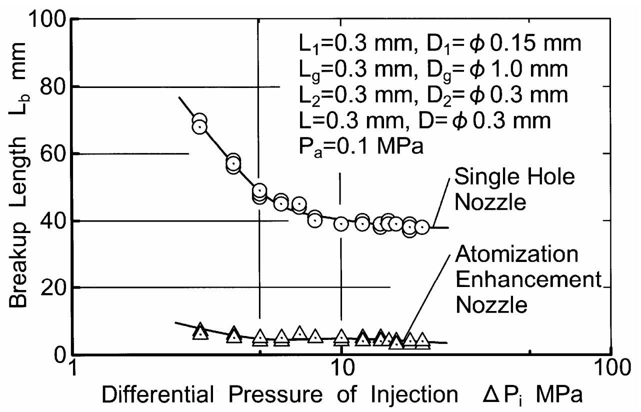


Fig.13 Effects of the geometric shapes of nozzle on the breakup length

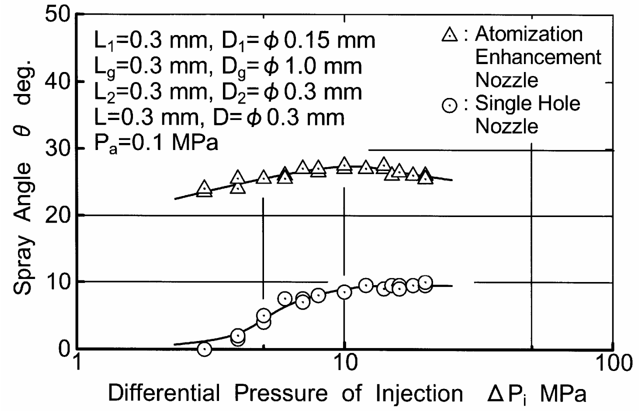


Fig.14 Effects of the geometric shapes of nozzle on the spray angle

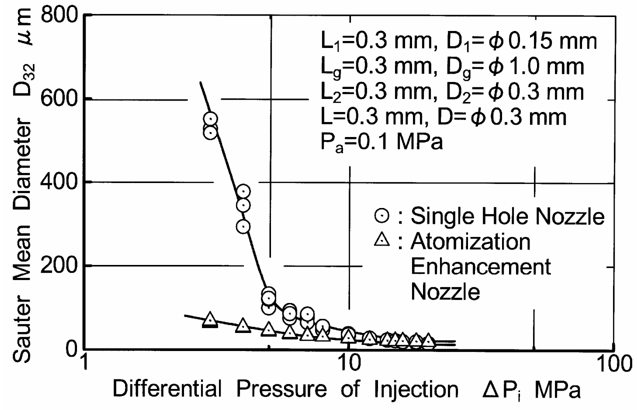


Fig.15 Effects of the geometric shapes of nozzle on the Sauter mean diameter

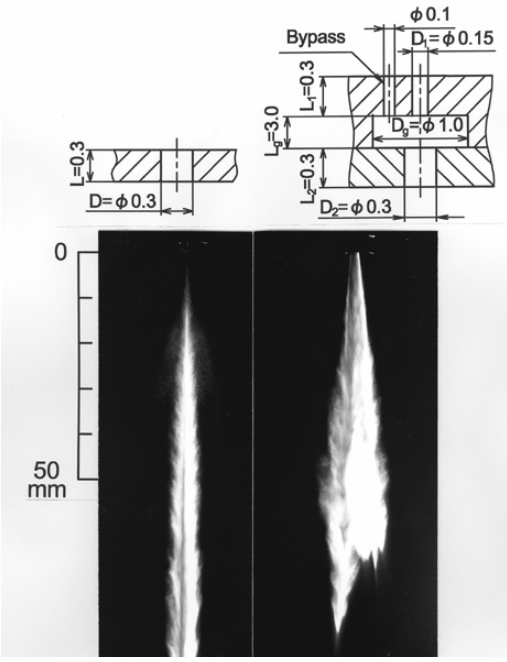
From these results, it can be seen that the atomization enhancement nozzle developed in this study is able to obtain the excellent spray characteristics under the low-injection pressure. Moreover, the breakup length of the atomization enhancement nozzle becomes short at all injection pressure regions and the spray angle becomes large compared with the single hole nozzle, the spray characteristics are improved significantly.

3.5 Application to the intermittent spray

Since these results are atomization of the spray of the atomization enhancement nozzle concerning to the continuous injection, it is not clear atomization of the spray under the intermittent injection and application to the actual Diesel injector. The photographs of the intermittent sprays of the single hole nozzle and the atomization enhancement nozzle are shown in Fig.16. The atomization enhancement nozzle, which the most excellent spray was obtained at the continuous injection, was used. The time after start of injection is constant of t=0.40 ms and the injection pressure is P_i=100 MPa. Although the spray tip penetration of the atomization enhancement nozzle is short compared with one of the single hole nozzle, the spread of the spray of the atomization enhancement nozzle is larger than the single hole nozzle. It can be seen that atomization of the spray is enhanced considerably at the intermittent injection like that the continuous injection.

3.6 Correlation between the enlarged nozzle and the actual size nozzle

It is important to clarify the correlation of the spray characteristics between the enlarged nozzle and the actual size nozzle from the pint of view of nozzle design, because



S.H.N. A.E.N.
L_1=0.3 mm, D_1=Ø 0.15 mm, L_g=0.3 mm, D_g=Ø 1.0 mm, L_2=0.3 mm, D_2=Ø 0.3 mm, L=0.3 mm, D=Ø 0.3 mm, P_i=100 MPa, P_a=0.1 MPa, T_a=300 K, t=0.40 ms

Fig.16 Photographs of the intermittent sprays of the single hole nozzle and the atomization enhancement nozzle

it is possible to apply the characteristics of the enlarged nozzle to the actual size nozzle. Therefore, the correlation of the atomization characteristics between the enlarged nozzle and the actual size nozzle were studied by using the nozzles of which the hole diameter was enlarged ten times as large as the actual size nozzle and geometric shapes of nozzle and the measurements ratio are same. The spray angle of the nozzles with the hole diameters downstream from the gap of D_2=Ø3.0 mm and D_2=Ø0.3 mm were divided by D_2, and the results were simply indicated as the spray angle.

The effects of the hole diameter on the spray angle is shown in Fig.17. In case of the bypass number of n=1, the spray angle becomes large compared with the nozzle with the bypass number of n=4 independent of the hole diameter downstream from the gap D_2. Hiroyasu et al [2] termed the region where the breakup length and the spray angle become constant with an increase in the injection velocity the spray region of a single hole nozzle. This spray region is guessed that the injection pressure is greater than about P_i=0.5 MPa for the hole diameter of D_2=Ø3.0 mm and about P_i=5 MPa for D_2=Ø0.3 mm. Variations of the spray angle as a function of the injection pressures are almost the same tendencies, and almost the same spray angle are obtained independent of the hole diameter downstream from the gap D_2.

From this result, it can be seen that the tendency obtained at the enlarged nozzle is almost the same as the actual size nozzle, approximate correlations between the enlarged nozzle and the actual size nozzle were obtained.

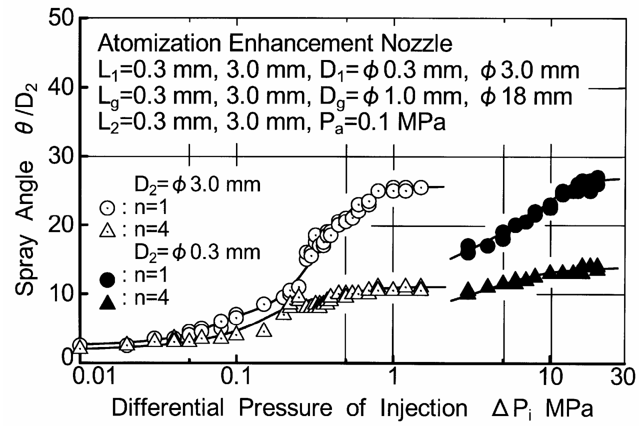


Fig.17 Correlation between the enlarged nozzle and the actual size nozzle (Effects of the hole diameter on the spray angle)

4. CONCLUSIONS

(1) The atomization enhancement nozzle with the bypass number of n=1, the shorter hole length downstream from the gap and the smaller hole diameter upstream from the gap are the most effective to atomization enhancement of the spray.
(2) The atomization enhancement nozzle atomizes considerably at the high-ambient pressure condition.
(3) The intermittent spray of the atomization enhancement nozzle atomizes considerably compared with the single hole nozzle, the atomization enhancement nozzle is able to apply the actual Diesel injector.
(4) Approximate correlations between the enlarged nozzle and the actual size nozzle were obtained.

NOMENCLATURE

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]
D_{32}	Sauter mean diameter	[μ m]
L	hole length	[mm]
L_b	breakup length	[mm]
L_1	hole length upstream from gap	[mm]
L_2	hole length downstream from gap	[mm]
n	bypass number	[-]
P_a	ambient pressure	[MPa]
P_i	injection pressure	[MPa]
Q	volumetric flow rate	[cm^3/s]
t	time after start of injection	[ms]
T_a	atmospheric temperature	[K]
θ	spray angle	[deg.]
θ /D_2	spray angle	[deg.]

SUBSCRIPTS

a	ambient, atmospheric
b	breakup
g	gap
i	injection, droplet
u	upstream

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