Improvement of Atomization Characteristics of Spray by Multi-Hole Nozzle for Pressure Atomized Type Injector

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Abstract

The purpose of this study is to invent high-efficiency atomization enhancement nozzle, which the spray with large spray angle, short liquid core length and small droplet diameter is obtained. In the previous study, the single hole atomization enhancement nozzle, which excellent spray characteristics are obtained at relatively low injection pressure, was developed. In this study, it was investigated about atomization of the spray of the multi-hole atomization enhancement nozzle invented in this study, and aimed to improve atomization characteristics and to obtain excellent spray characteristics with shorter breakup length, larger spray angle and smaller droplet diameter. The effects of dimensions of the atomization enhancement nozzle such as hole number, the hole diameter, position of the nozzle hole on atomization of the spray and atomization characteristics were investigated. As a result, it was clarified that in case of the multi-hole atomization enhancement nozzle with hole number of N = 4, breakup length becomes short about 70 p.c. and spray angle becomes large about two times, droplets of the spray become considerably small compared with the single hole atomization enhancement nozzle. Atomization characteristics were improved considerably and uniform spray mass flux distributions are obtained by using the multi-hole atomization enhancement nozzle with hole number of N = 4.

Introduction

It is a matter of great urgency to reduce carbon dioxide caused by global warming. The final objects of this study are improvement of combustion characteristics of a direct injection Diesel engine, reduction of soot emission, progress of fuel consumption rate by improvement of spray characteristics. In the previous studies, it was cleared that cavitation phenomenon in the nozzle hole is considerably affected to atomization of the spray [1]-[13]. Moreover, it was developed the atomization enhancement nozzle [8], [13], which excellent spray characteristics with large spread angle of the spray, short breakup length and small droplet diameters, are obtained at relatively low injection pressure by cavitation in the nozzle hole. Furthermore, the effects of the atomization enhancement nozzle [14], [15] on atomization of intermittent spray at atmospheric and high-ambient pressure conditions and application to the actual Diesel injector were investigated. 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 direct injection Diesel nozzle. At previous results, 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 a previous single hole nozzle for direct injection Diesel injector at the intermittent spray under high-ambient pressure condition, and it was indicated possibility of application to the actual Diesel injector [15].

In this paper, the atomization enhancement nozzles [14], [15], which was installed in a direct injection Diesel injector and the multi-hole nozzle, which total sectional area of nozzle holes of the multi-hole nozzle is the same diameter as one of the single hole nozzle, were used. The effect of the developed injection nozzle on atomization of the spray was investigated. The effects of dimensions of the atomization enhancement nozzle such as hole number, hole diameter, pitch circle diameter of nozzle hole, gap diameter and 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 clarified that in case of the multi-hole atomization enhancement nozzle with hole number of N=4, breakup length becomes short about 70 p.c. and spray angle becomes large about two times, droplets of the spray become considerably small compared with the single hole atomization enhancement nozzle. Atomization characteristics were improved considerably and uniform spray mass flux distributions are obtained by using the multi-hole atomization enhancement nozzle with hole number of N=4.

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Experimental Apparatus and Method

Experimental apparatus is shown in Fig.1. Experimental apparatus consists of a high-pressure pump, a spark light source for taking photographs of the spray. Water at room temperature pressurized by the high-pressure pump was continuously injected under atmospheric pressure condition. Disintegration behavior of the spray was photographed by transmitted light, using a stroboscope. Breakup length of a liquid core, which is defined as distance from the nozzle exit to breakup point of the liquid core, was measured by electrical resistance method [2] in which a screen detector was used. Breakup length is defined as the liquid core length, which was injected from one nozzle hole. In case of the multi-hole nozzle, it is necessary to measure the liquid core length of the sprays injected from each nozzle holes. However, in case of the multi-hole nozzles invented in this study, when injection pressure increased over 0.1 MPa, the sprays injected from each nozzle holes are generated one spray. Therefore, breakup length was measured by previous measurement method and definition. Spray angle was defined as the spray boundary, and it was measured by images of photographed sprays.

Schematic of test nozzles are shown in Fig. 2. Test nozzles are the single hole atomization enhancement nozzle [Fig. 2 (a)], the multi-hole one [Fig. 2 (b)]. Total sectional area of nozzle holes of the multi-hole nozzle is constant of the single hole nozzle. Specification of test nozzles is shown in Table 1.

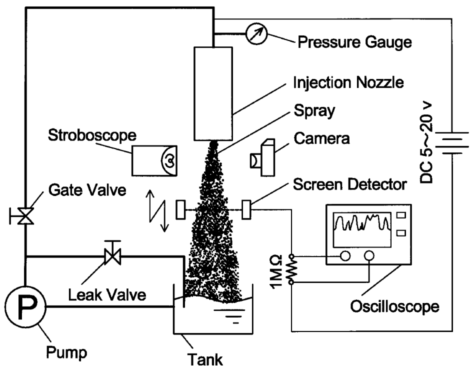
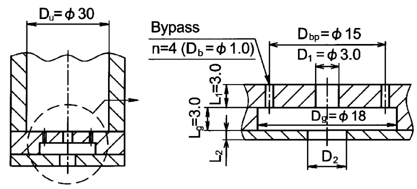
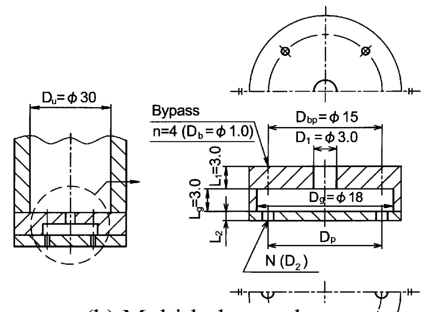


Figure 2. Schematics of experimental apparatus



(a) Single hole nozzle



(b) Multi-hole nozzle

Figure 2. Schematics of test nozzles

(b) Multi hole nozzle

Figure 1. Schematics of test nozzles

Table 1. Specification of test nozzles (mm)

Nozzle Types	Dimensions				
	N	**n**	**D_b**	**D_{bp}**	**D_1**
Atomization Enhancement Nozzle	1, 4, 5, 8	0, 1, 4	1.0	9.0, 15	3.0
	L_g	**D_g**	**D_2, D_{2c}**		**D_p**
	3.0	18	3.0 (N=1), 1.5 (N=4), 1.3 (N=5), 1.1 (N=8)		6.0, 9.0, 12, 15

Experimental Results and Discussion

Effect of Hole Number of Atomization Enhancement Nozzle

The effect of hole number of atomization enhancement nozzle on atomization of the spray is shown in Fig. 3. The hole diameter downstream from the gap D2 of the multi-hole nozzle is the same total sectional area as one of the single hole nozzle. Except of the pitch circle diameter of the bypass Dbp and the pitch circle diameter of the nozzle hole Dp, suitable measurements for atomization enhancement were used as the test nozzles. In case of the single hole nozzle, although ligaments exist in the spray, spread of the spray is small compared with the multi-hole nozzle, and small droplets generates little. To the contrary, in case of the multi-hole nozzle, spread of the spray of hole number of N=4 is the largest, high-dispersion spray is obtained, and a great number of small droplets exist in the spray in spite of magnified nozzle with large hole diameter. When hole number increases of N=8, spread of the spray becomes small and it is the smallest at the multi-hole nozzle. Although droplets become small like that N=4, density of the droplets becomes high in the spray. Moreover, in case of hole number of N=5,

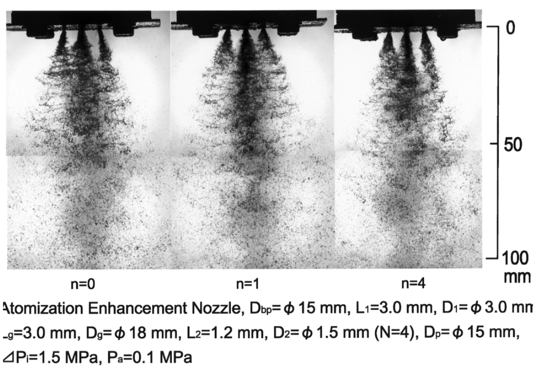


Figure 3. Effect of hole number of atomization enhancement nozzle on atomization of spray

although spread of the spray is relatively large, the spray, which was injected from nozzle center, atomizes little and the sprays, which was injected from the other nozzle holes, atomize like that the spray of N=4. From these results, it can be seen that the multi-hole nozzle with hole number of N=4 is the most effective to atomize of the spray and to obtain high-dispersion spray.

The effect of hole number on breakup length and spray angle are shown in Figs.4 and 5, respectively. As shown in Fig.4, breakup lengths of the multi-hole nozzles are shorter than the single hole nozzle. Especially, breakup lengths of hole number of N=4 and 8 are short at all injection pressures. Breakup lengths of N=4 and 8 become short about 70 p.c., its become short considerably. As shown in Fig.5, spray angle of the single hole nozzle of N=1 is the smallest, spray angle of the multi-hole nozzle of N=4 is the largest at all injection pressures. Spray angle of N=4 is over 60 degrees and two times as large as the single hole nozzle and other multi-hole nozzles.

The effect of hole number of atomization enhancement nozzle on spray mass flux distribution is shown in Fig.6. Spray mass flux except of hole number of N=4 are the largest at the nozzle center axis of x=0 mm, and spray mass flux at vicinity of the nozzle center axis, for instance, x=2.0 mm, it rapidly decreases and spray mass flux distribution does not becomes uniformity. In case of hole number of N=4 which was obtained excellent atomization characteristics, uniform spray mass flux distributions are obtained at wide ranges to radial direction of x=-15 mm and x=15 mm. Moreover, in case of the multi-hole nozzle of N=8, although relatively uniform spray mass flux distributions are obtained at vicinity of x=-5 mm and x=5 mm, when distance from spray center axis x becomes large, spray mass flux becomes rapidly little and it does not becomes uniformed distribution. In case of N=5, spray mass flux at the nozzle center axis is the largest, liquid core exists at vicinity of spray center axis, it can be seen that spray mass flux distribution of N=5 becomes considerably heterogeneous.

From these results, it can be seen that spread angle

of the multi-hole nozzle of N=4 is large, breakup length is short, relatively small droplets disperse wide range of the spray and atomization characteristics is improved compared with the single hole atomization enhancement nozzle.

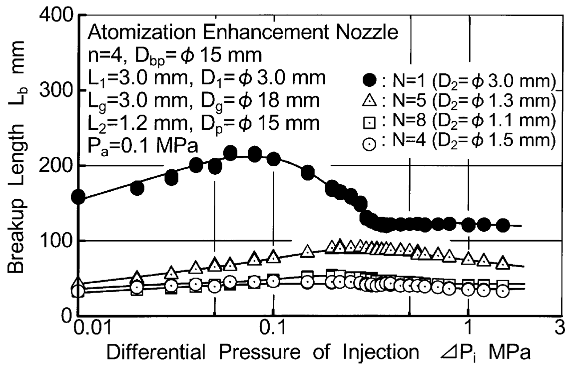


Figure 4. Effect of hole number of atomization enhancement nozzle on breakup length

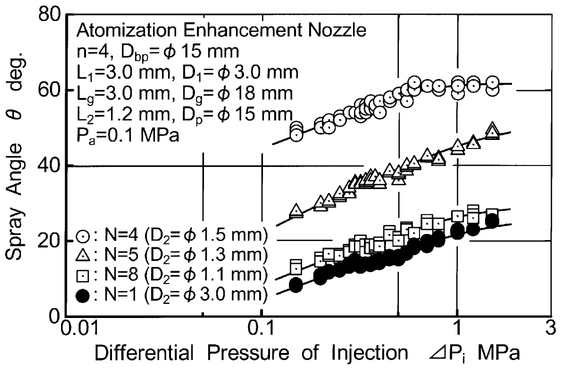


Figure 5. Effect of hole number of atomization enhancement nozzle on spray angle

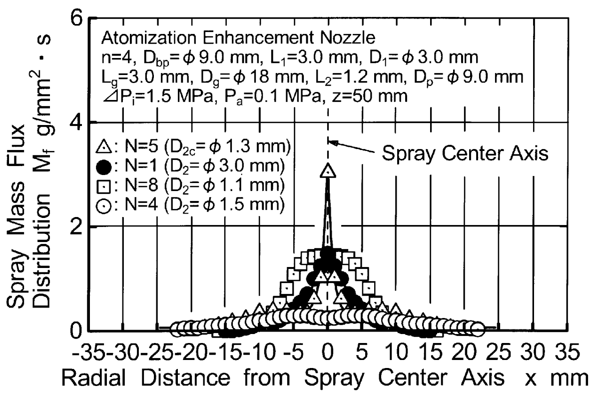


Figure 6. Effect of hole number of atomization enhancement nozzle on spray mass flux distribution

Effect of Bypass Numbers of Nozzle

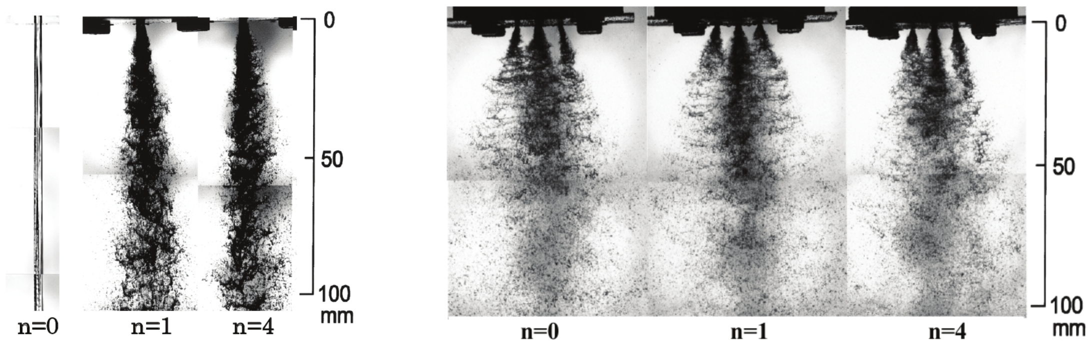
The effect of existence of bypass and bypass numbers on atomization of the spray is shown in Fig. 7. Figure 7 (a) is the single hole atomization enhancement nozzle, (b) is the multi-hole one. As shown in Fig.7 (a), in case of the nozzle without bypass (n=0), the liquid jet does not atomize at all. In case of the nozzle with bypass (n=1, n=4), spread of the spray becomes wide, and spread of the spray becomes small with an increase in bypass number.

It is considered that in case of the nozzle without bypass, since hydraulic flip, which the liquid flow in the nozzle hole separates from the inner wall of the nozzle hole, occurs in the nozzle hole like that the single hole nozzle and strong disturbance does not occur in the liquid flow in the nozzle hole, the liquid jet does not atomize. To the contrary, when bypass is installed, the static pressure in the gap increases and disturbance due to collapse of cavitation bubbles occur in the liquid flow, the spray atomizes. Moreover, it is guessed that when bypass number increases, the flow rate incoming from bypass increases, atomization of the spray is controlled. As shown in Fig.7 (b), in case of the multi-hole atomization enhancement nozzle, spread of the sprays are almost same independent of existence of bypass and bypass numbers, and it is considerably larger than the single hole atomization enhancement nozzle. It is not clear that the reasons which atomization of the spray is different by hole numbers at the nozzles without bypass and the same bypass numbers.

The effect of bypass number on breakup length at the multi-hole atomization enhancement nozzle is shown in Fig.8. Although atomization of the spray is almost same as shown in Fig.7 (b), breakup length of the nozzles without bypass (n=0) and bypass number of n=1 are short, and the nozzle with bypass number of n=4 is long. The reasons are considered as follows. The effect of bypass number on volumetric flow rate at the multi-hole atomization enhancement nozzle (N=4) is shown in Fig.9. As shown in Fig.9, volumetric flow rate of the nozzle without bypass (n=0) is the little and one of the nozzle with bypass number of n=4 is the largest, independent of the injection pressures. Generally, in case of the same injection pressure condition, it is guessed that since the spray hardly atomizes at large volumetric flow rate condition, atomization of the spray of bypass number of n=4 becomes wrong. From these results, it can be seen that existence of bypass and bypass number are not affected to atomization of the spray at the multi-hole atomization enhancement nozzle, the spray with large spread angle is obtained.

Effect of Hole Diameter Downstream from Gap

The effect of hole diameter downstream from gap; simply called the outlet hole diameter on atomization of the spray is shown in Fig.10. The effects of the outlet hole diameter on breakup length and spray angle are shown in Figs. 11 and12, respectively. Figures 10, 11, 12 (a) is the case of the single hole atomization enhancement nozzle, and (b) is the multi-hole one. As shown in Fig.10, in case the single hole atomization enhancement nozzle and the outlet hole diameter D_2 is larger than the hole diameter upstream from the gap D_1; simply called the inlet hole diameter, spread of the spray becomes large.



Atomization Enhancement Nozzle, D_{bp}=15 mm, L_l=3.0 mm, D_1=3.0 mm, L_g=3.0 mm, D_g=18 mm, L_2=1.2 mm, D_2=1.5 mm (N=4), D_p=15 mm, P_i=1.5 MPa, P_a=0.1 MPa

(a) Single hole nozzle (N=1) (b) Multi-hole nozzle (N=4)

Figure 7. Effects of existence of bypass and bypass numbers on atomization of spray

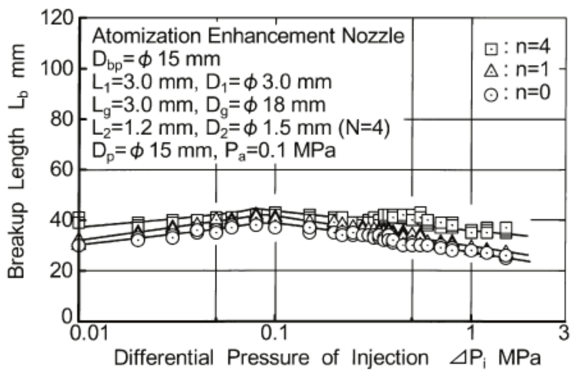


Figure 8. Effect of bypass number on breakup length

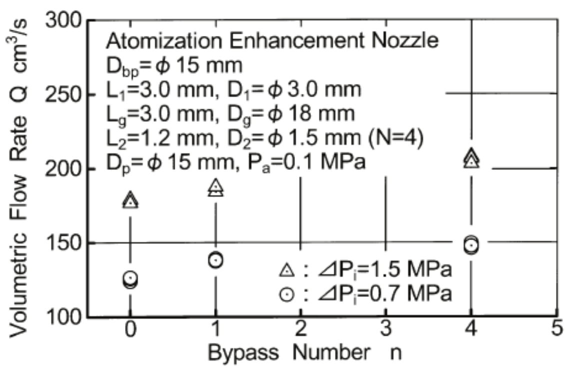
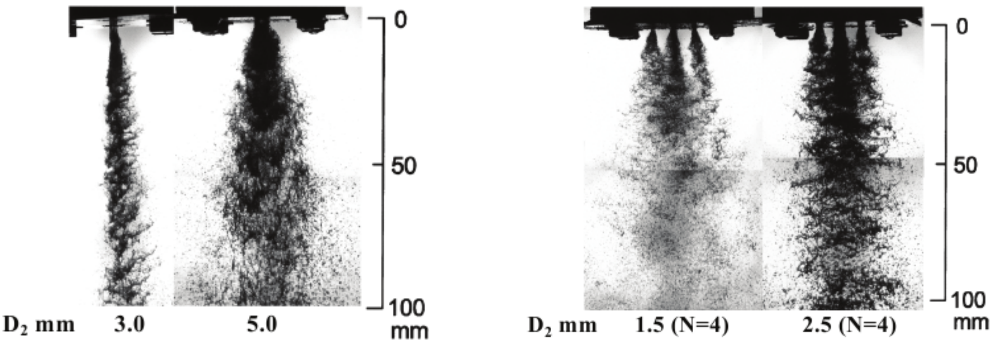


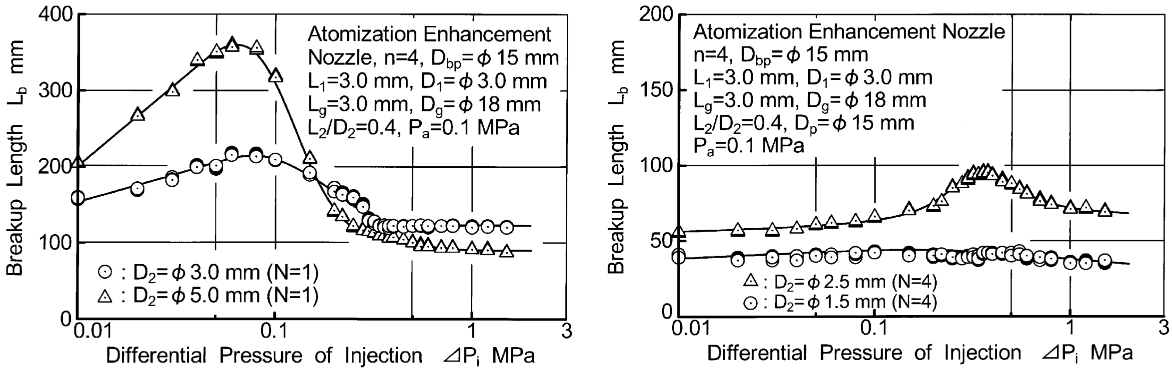
Figure 9. Effect of bypass number on volumetric flow rate



Atomization Enhancement Nozzle, n=4, D_{bp}=15 mm, L_1=3.0 mm, D_1=3.0 mm, L_g=3.0 mm, D_g=18 mm, L_2 / D_2=0.4, D_p=15 mm, P_i=1.5 MPa, P_a=0.1 MPa

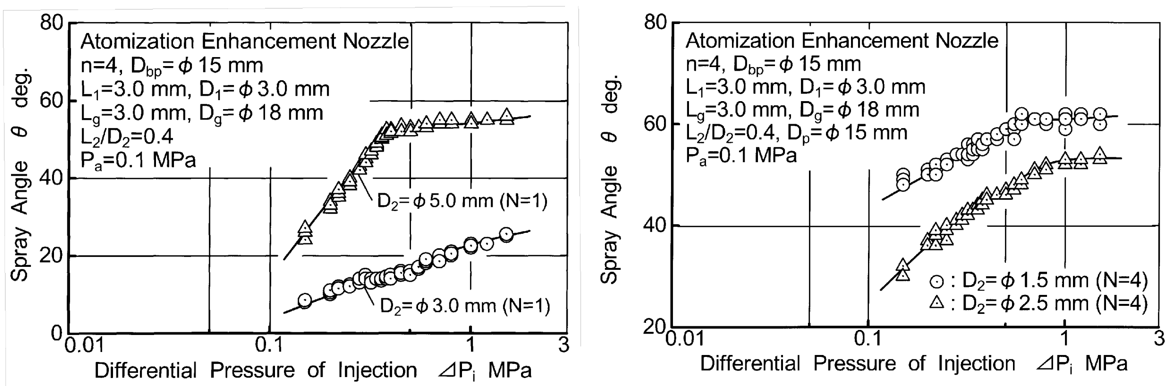
(a) Single hole nozzle (N=1) (b) Multi-hole nozzle (N=4)

Figure 10. Effect of hole diameter downstream from gap on atomization of spray



(a) Single hole nozzle (N=1) (b) Multi-hole nozzle (N=4)

Figure 11. Effect of hole diameter downstream from gap on breakup length



(a) Single hole nozzle (N=1) (b) Multi-hole nozzle (N=4)

Figure 12. Effect of hole diameter downstream from gap on spray angle

To the contrary, in case of multi-hole atomization enhancement nozzle and total sectional areas of the inlet hole diameter D_1 and the outlet hole diameter D_2 are same of D_1=3.0 mm, D_2=1.5 mm (correspond to the hole diameter of D_2=3.0 mm for the single hole atomization enhancement nozzle), spread of the spray becomes considerably large, droplets of the spray are considerably small from the spray image.

As shown in Figs.11, 12 (a), in case of hole number of N=1, breakup length of the outlet hole diameter D_2 of 5.0 mm (D_2>D_1) is short and spray angle is large at large injection pressure regions of P_i>0.5 MPa. As shown in Figs.11, 12 (b), in case hole number of N=4 and the total sectional areas of the inlet hole diameter D_1 and the outlet hole diameter D_2 are same of D_1=3.0 mm and D_2=1.5 mm (correspond to the hole diameter of D_2=3.0 mm for the single hole nozzle), breakup length becomes short and spray angle becomes large at all the injection pressure regions compared with the large outlet hole diameter of D_2=2.5 mm (correspond to D_2=5.0 mm for the single hole nozzle). These are considered as follows. In general, in case the injection pressure is the same, when volumetric flow rate is large, it seems that the spray hardly atomizes. Therefore, the spray of D_2=1.5 mm atomizes considerably compared with the nozzle of D_2=2.5 mm which volumetric flow rate is large.

Effect of Pitch Circle Diameter of Nozzle Hole Downstream from Gap

The effects of pitch circle diameter of nozzle hole downstream from gap on atomization of spray and breakup length are shown in Figs.13 and 14, respectively. When disintegration behavior of the spray was compared at arbitrary location downstream from the nozzle exit, the larger the pitch circle diameter, the larger the spread of the spray toward radial direction, and small droplets of the spray disperses widely. The droplets of the spray of the largest pitch circle diameter of D_p=15 mm become considerably small judging from the spray images at about 50 mm downstream from nozzle exit are considerably small and atomization of the spray is enhanced. As shown in Fig.14, breakup length becomes short with an increase in the pitch circle diameter of the nozzle hole downstream from the gap D_p, especially, breakup length of the nozzle with D_p=12 mm and 15 mm are short.

Thus, the reasons that when pitch circle diameter of nozzle hole is large, spread of the spray becomes large and atomization of the spray is enhanced, are considered as follows. The effect of position of the nozzle hole on atomization of the spray is shown in Fig.15. One of the nozzle holes of the multi-hole nozzle is selected. Distance from nozzle center to hole center L_0=0 mm, that is, in case the nozzle hole is on nozzle center axis, spread of the spray is narrow and relatively large droplets and ligaments are observed.

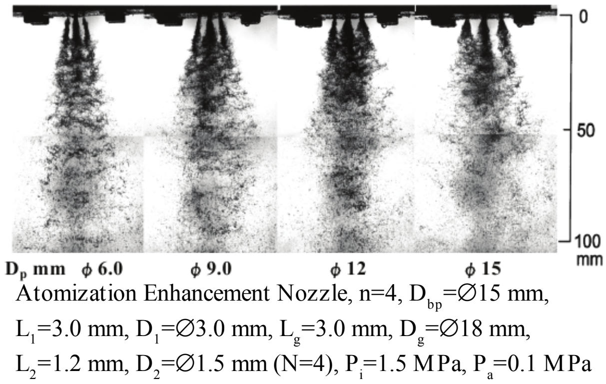


Figure 13. Effect of pitch circle diameter of nozzle hole on atomization of spray

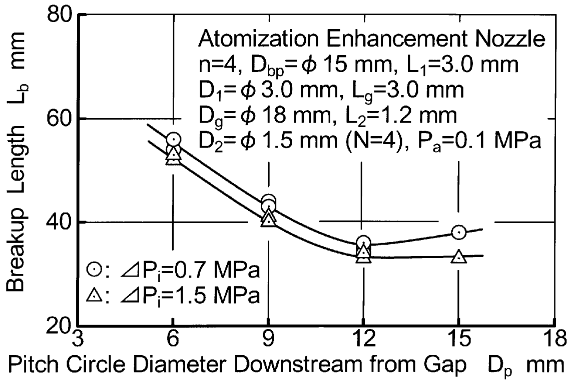


Figure 14. Effect of pitch circle diameter of bypass on atomization of spray

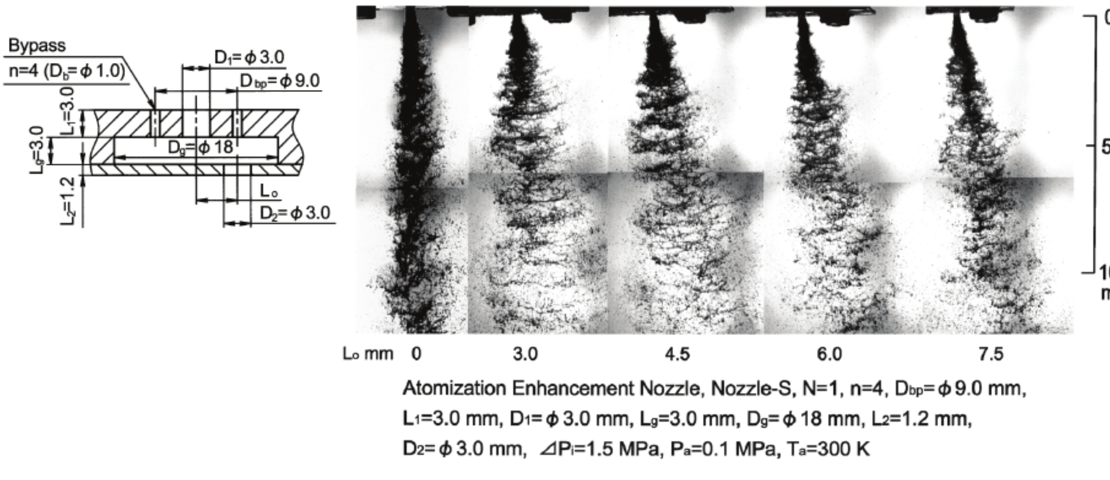


Figure 15. Effect of position of nozzle hole on atomization of spray

When the nozzle hole is located at L_o=3.0 mm, 4.5 mm, spread of the spray becomes wide and a large number of small droplets are generated. Moreover, when the nozzle hole is located at far from the nozzle center of L_o=6.0 mm, 7.5 mm, spread of the spray becomes narrow, and inclined angle of the spray becomes large. Based on these results, it is guessed that when the pitch circle diameter of nozzle hole is small corresponded with L_o=3.0 mm, 4.5 mm, droplets density at vicinity of nozzle center becomes high, relatively large droplet and liquid core exists at the spray center. To the contrary, when pitch circle diameter of nozzle hole is large corresponded with L_o=6.0 mm, 7.5 mm, it is possible to disperse the spray wide range due to issue inclining from the hole exit.

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Conclusions

1. In case of the multi-hole atomization enhancement nozzle, spread of the spray becomes large and breakup length becomes short compared with the single hole atomization enhancement nozzle. Moreover, uniform spray mass flux distributions are obtained.

2. In case of the multi-hole nozzle, it is little affected to atomization of the spray, and the spray with large spread angle was obtained.

3. In case total sectional area of the upstream and the downstream hole diameters from the gap are the same [D_1=3.0 mm, D_2=1.5 mm (N=4)], spread of the spray becomes considerably wide, breakup length becomes short, spray angle becomes large and droplets of the spray become considerably small, compared with larger downstream hole diameter of D_2=2.5 mm (N=4).

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