Atomization Enhancement of the Spray and Improvement of the Spray Characteristics by Cavitation and Pin Inserted in the Nozzle Hole

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Abstract
The purpose of this study is improvement of the spray characteristics of the injection nozzles for internal combustion engines. Atomization enhancement of the spray was performed by utilizing the disturbance of a liquid flow due to cavitation and by giving the flow of the radial direction at the vicinity of the hole exit. The test nozzles were used a pressure atomized nozzle improved a single hole nozzle and the pin was inserted in the nozzle hole. The effects of existence and configuration of the pin, position of the pin and geometric shapes of the nozzle hole on atomization enhancement and formation of solid cone spray were investigated. As the results, the following conclusions were obtained. Existence and configuration of the pin are affected by atomization enhancement of the spray, when the nozzle with additional the convex pin was used, solid cone spray is obtained and spread of the spray becomes wide extremely. Moreover, configuration of the pin, position of the pin tip and hole diameter where the pin tip is located are greatly affected by formation of solid cone spray and atomization enhancement of the spray.

1. Introduction

A hole nozzle, which is used a direct injection Diesel engine, is demanded high-injection pressure in order to obtain excellent spray characteristics. From energy saving view point, it is important to obtain excellent spray and spray characteristics under low injection pressure. When a nozzle with additional the pin like that a pin-type nozzle is used, the spray with a large spray cone angle is obtained under low injection pressure comparing with the hole nozzle. However, the spray pattern is generally hollow cone spray. In order to control of exhaust emissions and unburned fuel, it is important to obtain solid cone spray which droplet size distributions and flow distributions at sectional area of the spray are uniformity and small. Experimental [1]-[14], numerical studies and modeling [15]-[18] concerned with cavitation in the nozzle hole, relationships between a nozzle internal flow and atomization of a liquid jet were investigated. Previous research, including that performed by the present authors, has clarified that the liquid flow in the nozzle hole and the disturbance of the liquid flow due to occurrence of cavitation are greatly affected by spray performance. It has developed the atomization enhancement nozzle which the same spray characteristics as ones at super-high injection pressure of 200 MPa is obtained under low injection

pressure of 10 MPa, based on the previous research [14].
The purpose of this study is improvement of the spray characteristics of the single hole nozzle. Moreover, it is to develop the atomization enhancement nozzle which spread of the spray is large, the breakup length is short, flow distributions at sectional area of the spray are uniformity, droplet size distributions are uniformity and small. In order to improve the spray characteristics of the single hole nozzle, the effects of existence and configuration of the pin, position of the pin and geometric shapes of nozzle on the spray characteristics, atomization enhancement and formation of solid cone spray were investigated.

2. Experimental Apparatus and Procedures

The experimental apparatus is shown schematically in Fig. 1. The equipment mainly consists of a liquid injection system with a high-pressure pump, a spark light source for taking photographs of the liquid flow in the nozzle hole and the spray. Water at room temperature pressurized by the high-pressure pump was continuously injected under atmospheric conditions. The nozzle internal flow and the disintegration behavior of the spray were photographed by transmitted light, using a stroboscope. The liquid core length i.e. the breakup length, which is defined as the distance from the nozzle exit to the breakup point of the liquid core, was measured by electrical resistance method [19] in which a screen detector was used. The spray angle was defined as the spray boundary. The spray pattern was investigated by inserting a needle detector inside the spray and by measuring flow distributions at sectional area of the spray.
The structures of test nozzles are shown in Fig. 2. The test nozzles are of three types. The atomization enhancement nozzle invented in the previous study is the sharp edged nozzle with additional the gap and the bypass, which was connected between the upstream chamber and the gap [Fig.2 (a)]. Another ones are the atomization enhancement nozzle which was inserted a columnar pin [Fig.2 (b)] and a convex pin [Fig.2 (c)]. The hole diameter upstream from the gap D_1 was constant of 3.0 mm and the hole diameters downstream from the gap D_2 were varied from 3.0 mm to 5.0 mm. The hole length upstream from the gap L_1 was 3.0 mm, and the hole length downstream from the gap L_2 were 2.0 mm and 10.0 mm independent of the hole diameters D_2. The structures of the pins are shown in Fig. 3. The pins are the convex pin of the pin tip diameter in 2 mm, length in 0.5 mm and axial diameter in 1 mm, and the columnar pin of axial diameter in 2 mm.

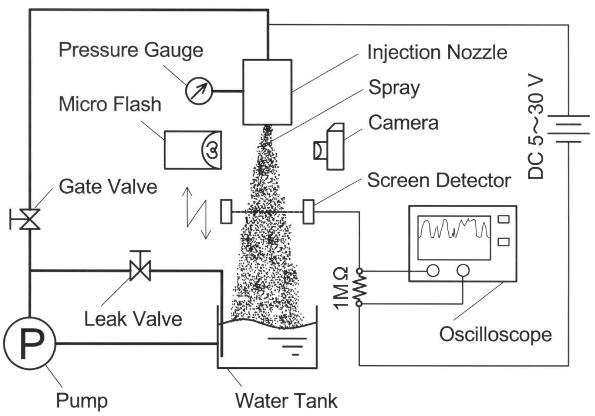


Fig. 1 Experimental apparatus

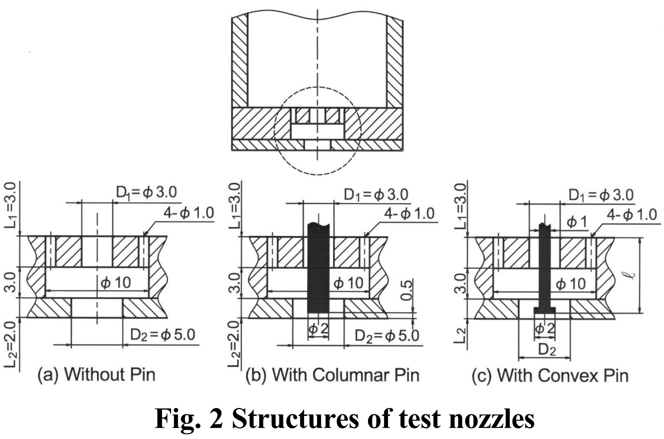
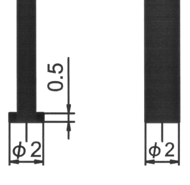


Fig. 2 Structures of test nozzles



(a) Convex pin (b) Columnar pin

Fig. 3 Structures of pins

3. Experimental Results and Discussions

3.1. Effects of existence and configuration of the pin on atomization of the spray

The effects of existence and configuration of the pin on atomization of the spray were investigated. The nozzle internal flow and the disintegration behavior of the spray at the maximum injection pressure of 1.5 MPa is shown in Fig. 4, and the effects of existence and configuration of the pin on the breakup length is shown in Fig. 5. Since the photographs of the nozzle internal flow are obtained by transmitted light, the interface between cavitation bubbles and the liquid, the inner wall of the nozzle hole appear in black. As shown in Fig. 4, cavitation takes place inside the nozzle hole, spread of the spray of the nozzle with additional the convex pin is larger than the nozzle in which the pin is not inserted. As shown in Fig. 5, in case of the nozzle with additional the convex pin, the breakup length is shorter than the nozzle in which the pin is not inserted. Moreover, as shown in Fig. 4 and Fig. 5, the disintegration behavior of the spray and the breakup length are affected by the configuration of the pin. In case of the nozzle with additional the columnar pin, although cavitation takes place inside the nozzle hole, spread of the spray is narrow and the breakup length is long, comparing with the nozzles with additional the convex pin and without the pin. Thus, when the columnar pin was inserted in the nozzle hole, atomization of the spray was restrained and fine spray characteristics do not obtain. From these results, it can be seen that when the convex pin was inserted in the nozzle hole, atomization enhancement and improvement of the spray characteristics can provide.

The reason why the disintegration behaviors of the spray are different by the configuration of the pin is considered as follows. Schematics of the nozzle internal flows and the issuing sprays are shown in Fig. 6. As shown in Fig. 6 (a), in case of the convex pin, cavitation takes place inside the nozzle holes upstream and downstream from the gap. It is guessed that the strong disturbance caused by collapse of cavitation bubbles occurs

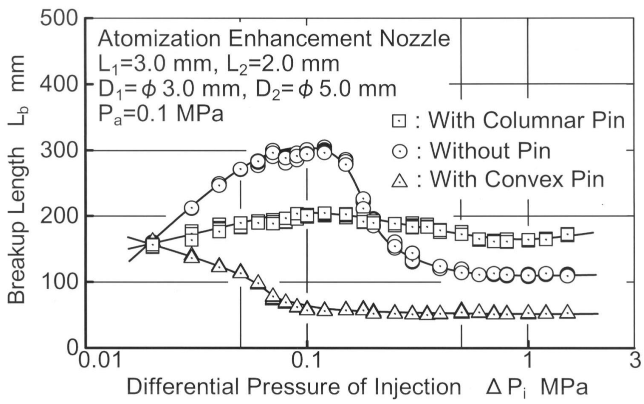


Fig. 5 Effects of existence and configurations of the pin on the breakup length

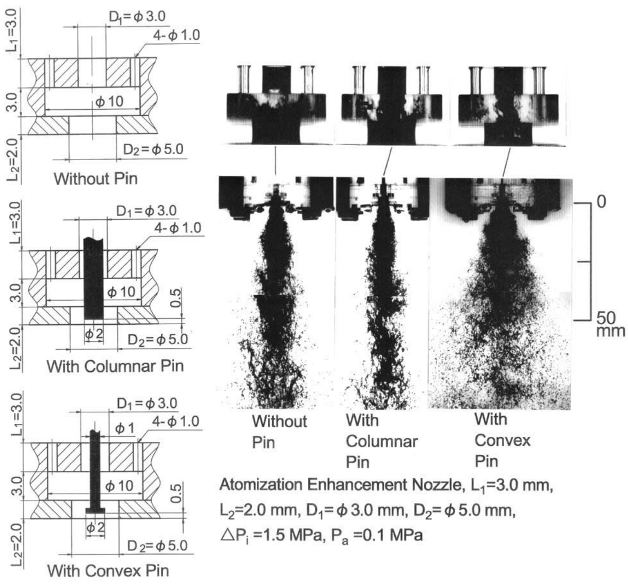
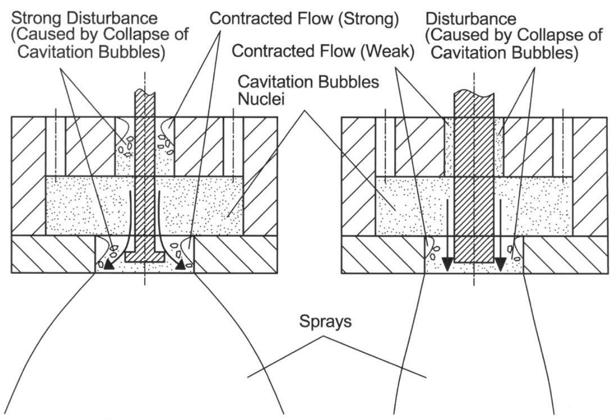


Fig. 4 Disintegration behavior of the spray



(a) Convex pin (b) Columnar pin

Fig. 6 Schematics of the nozzle internal flows and the issuing sprays

there. Moreover, the flow direction at the vicinity of the convex pin tip was changed in the radial direction toward the injection direction. As the results, the issuing spray spreads the radial direction and spread of the spray becomes large considerably by effects of both the strong disturbance caused by collapse of cavitation bubbles and the changing of the flow direction. To the contrary, in case of the columnar pin, it is guessed as follows. Since the axial diameter of the columnar pin is larger than one of the convex pin, intensity of contracted flow which is occurred at the hole inlet is weak. This opinion is clear from the results describing later that cavitation does not take place i. e. contracted flow occurs hardly with reduced the hole diameter under the same axial diameter of the pin. Therefor, intensity of the disturbance due to collapse of cavitation bubbles is weak comparing with one of the convex pin. Moreover, since the changing of the flow direction does not occur at the hole exit, spread of the spray is small.

3.2. Effects of position of the pin inserted in the nozzle hole

The effect of position of the pin inserted in the nozzle hole on atomization of the spray and the spray pattern is shown in Fig. 7. The position of the pin l was indicated the distance from the hole inlet of upstream from the gap, it was varied from l=6.5 mm to 8.5 mm. Distance l=6.5 mm means that the convex pin tip is located at 0.5 mm below from the hole inlet of downstream from the gap, l=8.5 mm means that it is located at 0.5 mm below from the hole exit of downstream from the gap. As shown in Fig. 7, when the pin tip is traveled toward the hole exit, spread of the spray becomes wide. When the convex pin tip is located at 0.5 mm above from the hole exit (l is 7.5 mm), it is guessed from the photographs that solid cone spray is obtained. However, when the convex pin tip is just located at the hole exit (l=8.0 mm), it is guessed that hollow cone spray is obtained.
Thus, since it is difficult to decide the spray pattern clearly, judgement of hollow cone spray and solid cone spray was investigated by inserting the needle detector inside the spray. The schematic of the measurement method for the spray pattern is shown in Fig. 8. The equipment consists of a direct current circuit with a direct current power supply, a resistance, the needle detector and an oscilloscope. The impressed voltage was 30 v, the needle detector was inserted at sectional area of the spray. When the liquid core or the liquid film or the ligament or dense droplets is touched the needle detector tip, the circuit becomes turning on electricity. To the contrary, when they are not touched the needle detector tip, the circuit becomes the turning off electricity and the output signal of level off is appeared on the oscilloscope. Moreover, when they are touched and detached the needle detector tip, the circuit becomes the turning on and off electricity and the output signals like that spike wave is appeared.

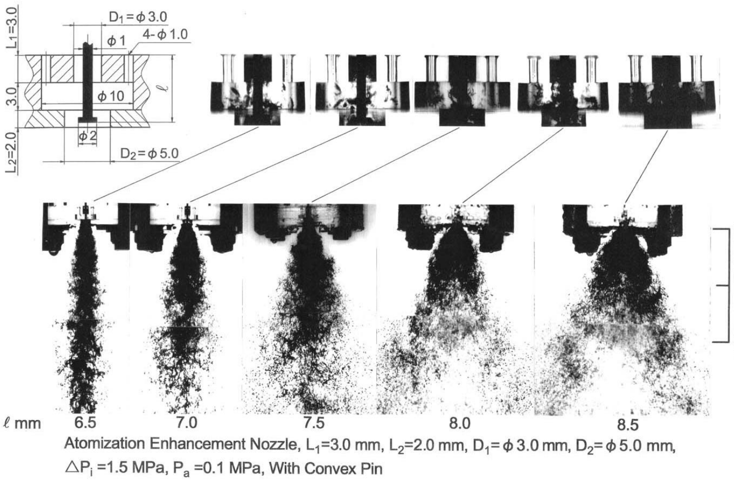


Fig. 7 Effect of position of the pin inserted in the nozzle hole on atomization of the spray and the spray pattern

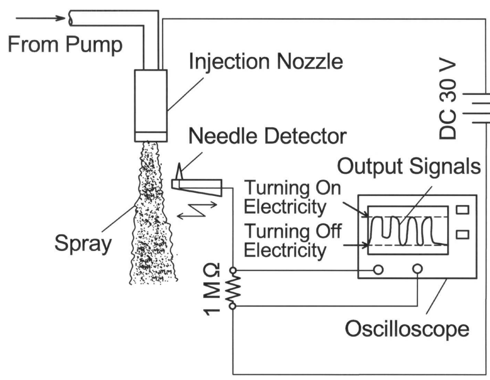
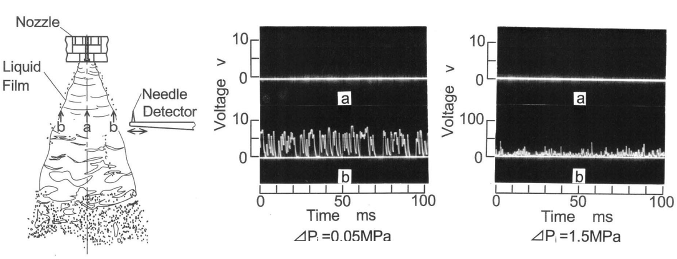


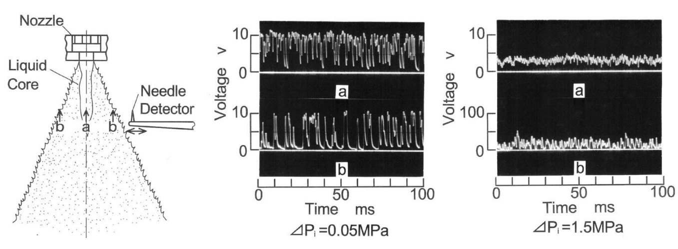
Fig. 8 Measurement method for the spray pattern

One of the output signals indicated by differences of the spray pattern is shown in Fig. 9. Figure 9 shows the typical output signals of liquid film breakup formed hollow cone spray and liquid column breakup formed solid cone spray. Figure 9 (a) shows the case of which the convex pin tip is protruded from the hole exit and hollow cone spray is formed. Figure 9 (b) shows the result of the atomization enhancement nozzle without the pin and the case of which the breakup pattern is liquid column breakup clearly. The higher voltage of spike wave indicated in the output signals shows the turning on electricity, and the lower one shows the turning off electricity. In case of hollow cone spray, when the needle detector is located at periphery of the spray (measurement points; b), the output signals indicated the turning on and off electricity are obtained as shown in Fig. 9 (a). This means that the liquid issued from the nozzle exists in the vicinity of the needle detector and it is repeating the touching and the detaching in the needle detector. When the needle detector is located inside the spray (measurement point; a), the output signals indicated the turning off electricity are obtained. This means that the liquid film, the liquid core, ligaments and droplets do not exist inside the spray. To the contrary, in case of solid cone spray, the output signals indicated the turning on and off electricity are obtained at both the periphery and inside the spray as shown in Fig. 9 (b). This is because the liquid column, ligaments and dense droplets exist inside the spray. The same tendencies are also obtained at higher injection pressure region. From these results, it is possible to grasp the spray pattern or the disintegration form by inserting the needle detector inside the spray.

The spray pattern was investigated by using this procedure. Figure 10 shows the spray pattern which was investigated by inserting the needle detector inside the spray shown in Fig. 7. Figure 11 shows flow distributions at sectional area of the spray. Figure 10 (a) and Fig. 11 (a) show the case of which it is located above 0.5 mm from the hole exit (*l*=7.5 mm), Fig. 10 (b) and Fig. 11 (b) show the case of which the convex pin tip is protruded from the hole exit (*l*=8.5 mm). As shown in Fig. 10 (a), the output signals indicated the turning on and off electricity are obtained independent of the locations at sectional area of the spray. Moreover, as shown in Fig. 11 (a), the volumetric flow rate at the vicinity of the hole exit (z= 10 mm) decreases at the spray center axis comparing with the other positions. However, the volumetric flow rate at the other sectional area of the spray increases at the vicinity of the spray center axis and it decreases with an increase in the distance from the spray center axis. Moreover, flow distributions at downstream from the hole exit becomes constant, it can be seen that the volumetric flow rate is almost uniformity. It is clear that

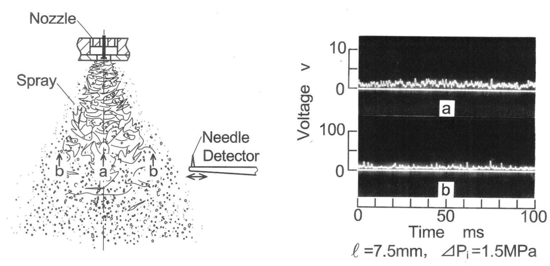


(a) Hollow Cone Spray

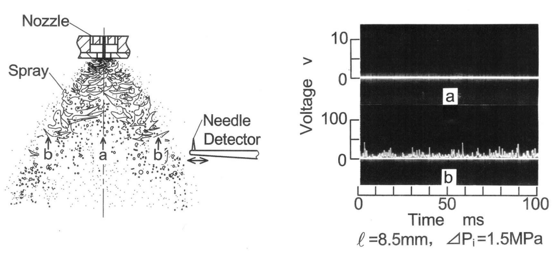


(b) Solid Cone Spray

Fig. 9 Output signals from needle detector inserted in the spray

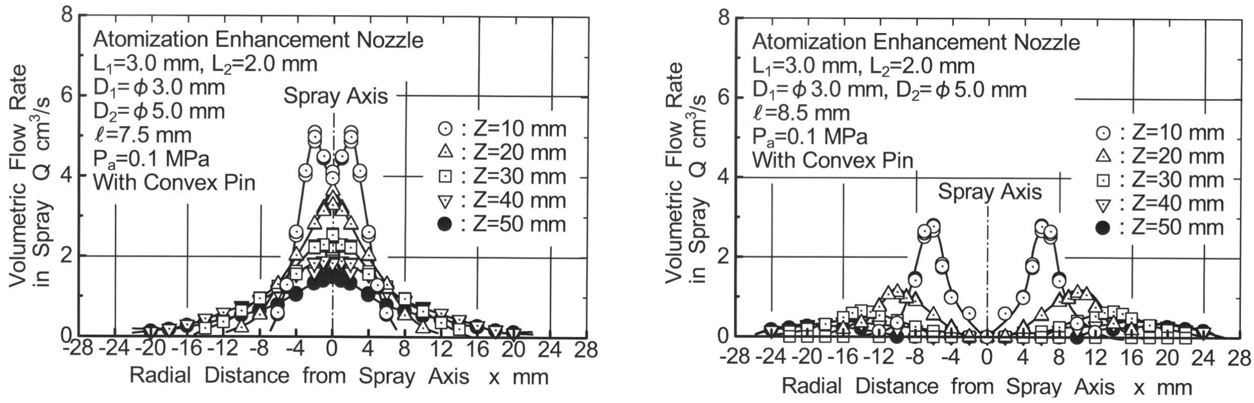


(a) *l*=7.5 mm



(b) *l*=8.5 mm

Fig. 10 Output signals from needle detector inserted in the spray



(a) *l*=7.5 mm **(b) *l*=8.5 mm**

Fig. 11 Flow distributions at sectional area of the spray

a large number of droplets and ligaments exist inside the spray at *l*=7.5 mm indicated in Fig. 7 and solid cone spray is formed.

To the contrary, as shown in Fig. 10 (b), the output signals indicated the turning off electricity are obtained at the vicinity of the spray center (measurement points; a), and ones of the turning on and off electricity are obtained at the vicinity of periphery of the spray (measurement points; b). As shown in Fig. 11 (b), flow distributions is not uniformity, the volumetric flow rate at the vicinity of the spray center is little, it increases with increasing the distance from the spray center axis. It can be judged that the spray at *l*=8.5 mm indicated in Fig. 7 is formed hollow cone spray.

From these results, when the atomization enhancement nozzle, which the hole diameter D_2 is 5.0 mm to the convex pin tip of 2.0 mm and the convex pin tip is located at 0.5 mm above from the hole exit, was used, it was clarified that solid cone spray was obtained and more atomization enhancement was possible.

3.3. Effects of the hole lengths downstream from the gap L_2 on atomization of the spray

From the above results, when the nozzle with the convex pin is used and the convex pin tip is located at 0.5 mm above from the hole exit (*l*=7.5 mm), excellent spray with larger spread angle and shorter breakup length and solid cone spray is obtained. However, it is not clear that when the convex pin tip is always located at there, such excellent spray is obtained or not. Hence, the disintegration behavior of the spray was observed fixing with the convex pin tip at 0.5 mm above from the hole exit. The effects of the hole lengths downstream from the gap L_2 on atomization of the spray is shown in Fig. 12. The hole lengths L_2 were used 2.0 mm and 10.0 mm. As shown in Fig. 12, cavitation takes place inside the nozzle hole independent of the hole length L_2. However, when the hole length L_2 is long of 10.0 mm, spread of the spray is small and the spray does not atomize as much comparing with the nozzle of 2.0 mm in the hole length L_2. Thus, even though cavitation takes place inside the nozzle hole and the flow direction is changed at the vicinity of the hole exit, spread of the spray is relatively small and atomization of the spray is greatly affected by the hole length L_2. The changing of the flow direction at the vicinity of the convex pin tip is affected a little by atomization of the spray. It can be seen that when the hole length L_2 is long, atomization of the spray is influenced by cavitation rather than the changing of the flow direction by the convex pin.

The reason is considered as follows. Schematics of the nozzle internal flows and the issuing sprays are shown in Fig. 13. As mentioned before, when the hole length L_2 is short, the strong disturbance caused by collapse of cavitation bubbles in addition to the changing of the flow direction occur at the hole exit. Therefor, spread of the spray becomes wide and atomization of the

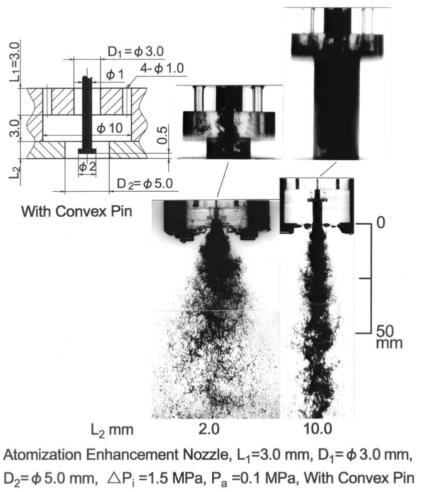
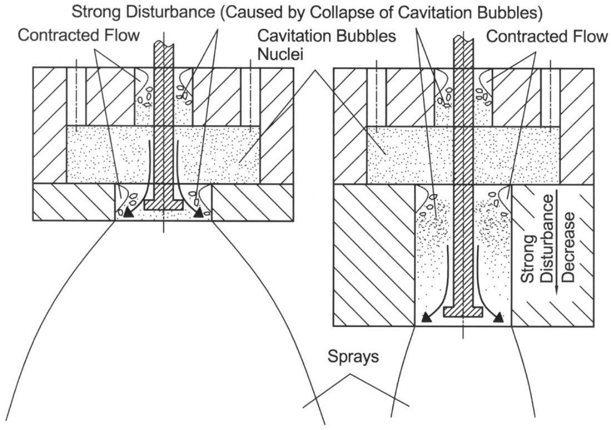


Fig. 12 Effects of the hole lengths L_2 on atomization of the spray



(a) Hole length L_2 is short. **(b) Hole length L_2 is long.**

Fig. 13 Schematics of the nozzle internal flows and the issuing sprays

spray is enhanced considerably. To the contrary, when the hole length L_2 is long, it is guessed that the intensity of the disturbance of the liquid flow caused by collapse of cavitation bubbles is reduced with approaching the hole exit, the disturbance occurred at the vicinity of the hole inlet is not contributed to atomization of the spray.

3.4. Effects of the hole diameters downstream from the gap D_2 on atomization of the spray

The effects of the hole diameters downstream from the gap D_2 on atomization of the spray, the breakup length and the spray angle are shown in Fig. 14 and Fig. 15, respectively. The diameter of the convex pin tip is constant of 2.0 mm, and the hole diameters D_2 were varied from 3.0 mm to 5.0 mm. From the results that the most effective method for atomization enhancement of the spray is to use the nozzle with shorter hole length L_2, the hole length downstream from the gap L_2 was constant of 2.0 mm independent of the hole diameters D_2. As shown in Fig. 14, when the hole diameter D_2 is 3.0 mm, cavitation does not take place inside the nozzle holes upstream and downstream from the gap, spread of the spray is small and the liquid jet atomizes little. When the hole diameter D_2 is 4.0 mm, cavitation takes place at the vicinity of the pin tip only, spread of the spray becomes wide a little. To the contrary, when the hole diameter D_2 is 5.0 mm, cavitation takes place inside the nozzle holes upstream and downstream from the gap and at the vicinity of the pin tip. It is shown that spread of the spray becomes wide to the radial direction with increasing

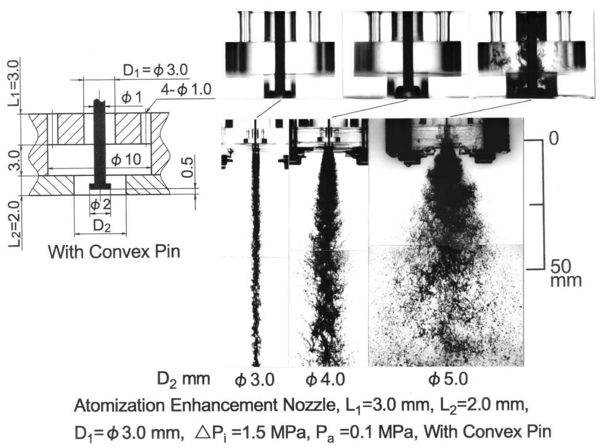


Fig. 14 Effects of the hole diameters D_2 on atomization of the spray

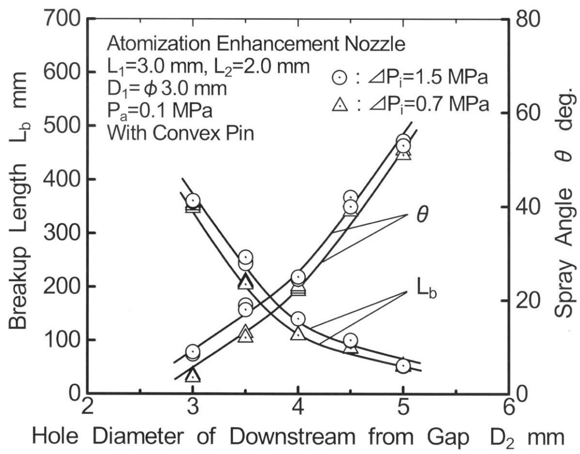


Fig. 15 Effects of the hole diameters D_2 on the breakup length and the spray angle

the hole diameters D_2. The excellent spray, which spread of the spray is wide extremely and droplets are very small and uniformity, is obtained and the spray atomizes considerably. Moreover, as shown in Fig. 15, the breakup length becomes short, and the spray angle becomes large with increasing the hole diameters D_2. From these results, it can be seen that the hole diameter downstream from the gap D_2 is influenced considerably atomization enhancement of the spray. When the nozzle with larger hole diameter D_2 and the nozzle inserted the convex pin was used, the excellent spray can be obtained.

4. Conclusions

The following conclusions were obtained in this study.

(1) When the convex pin tip is located at 0.5 mm above from the hole exit, it is the most effective to atomization enhancement of the spray and formation of solid cone spray.

(2) The configuration of the pin is greatly affected by atomization of the spray, when the nozzle with the convex pin was used, atomization enhancement of the spray is possible.

(3) The hole diameter where the convex pin tip is located is greatly affected by atomization enhancement of the spray, when the nozzle with the hole diameter of 5.0 mm to the convex pin tip of 2.0 mm was used, solid cone spray is formed and spread of the spray becomes wide considerably.

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