Effects of Cavitation in a Nozzle Hole on Atomization of Spray and Development of High-Efficiency Atomization Enhancement Nozzle

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Abstract

It is well known that cavitation in a nozzle hole is a dominant factor on atomization of a liquid jet. Although cavitation number is used to represent cavitating flow, the physical quantity at the region, where cavitation does not occur, is usually used. Moreover, in usual, observations in the nozzle hole and disintegration behavior of the liquid jet are used a magnified nozzle. In this study, it was investigated about the mutual relationships of the liquid flow in the nozzle hole and atomization of the spray between the magnified nozzle and the scaled-up nozzle. Moreover, mutual relationships between the pressure distribution in the nozzle hole and behavior of the liquid flow in the nozzle hole were studied, and cavitation pressure coefficient, that is, cavitation number was newly defined by using the static pressure in the nozzle hole where cavitation occurs. Furthermore, the effects of kinematic viscosity of a liquid on internal flow in the nozzle hole and atomization of the spray was studied. From these results, high-efficiency atomization enhancement nozzle, which excellent spray characteristics are obtained at low injection pressure independent of kinematic viscosity, was developed. The effects of this atomization enhancement nozzle on atomization of intermittent spray at high-ambient pressure condition and application to the actual Diesel injector were studied. Spread of the sprays of the atomization enhancement nozzle is wide considerably, compared with the single hole nozzle. 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.

Introduction

In early researches, it was believed that atomization of the liquid jet was caused by interfacial forces existing between the liquid jet and the ambient gas. Researchers, including the author, have reviewed the relationships between the internal flow with cavitating flow and disintegration behavior of the liquid jet [1]-[7]. As the results, it has been clarified that strong disturbance of the liquid flow in the nozzle hole due to occurrence of cavitation has a dominant effect on atomization of a liquid jet. Although almost all results about these relationships have been limited to the results concerning to a relatively large hole diameter and a low injection pressure, recently, Chaves [8] has been studied about cavitating flow in a real sized transparent VCO nozzle. It is guessed that the results and the tendency concerning to a magnified nozzle differ from ones of an actual size nozzle. Hence, it was investigated about the mutual relationships of the internal flow in the nozzle hole and atomization of the spray between a magnified nozzle and an actual size nozzle. Moreover, since the pressure in the nozzle hole is affected by occurrence of cavitation, mutual relationships between the pressure distribution in the nozzle hole and behavior of the liquid flow in the nozzle hole were studied. In order to represent the nozzle internal flow, cavitation pressure coefficient, that is, cavitation number was newly defined by using the static pressure in the nozzle hole where cavitation occurs. As the results, it can be seen that behavior of cavitation in the nozzle hole and atomization of the spray for a magnified nozzle are similar to an actual size nozzle, mutual relationships of these nozzles were obtained. Moreover, the newly defined cavitation pressure coefficient corresponds to behavior of the liquid flow in the nozzle hole.

The atomization enhancement nozzle that the excellent spray characteristics, which the liquid core length is short, the spray angle is large and the droplet diameter is small, is obtained at relatively low injection pressure was developed in the previous study. It is concerned that the liquid viscosity affects to behavior of the liquid flow in the nozzle hole, occurrence of cavitation and atomization of the spray. Moreover, this atomization enhancement nozzle was obtained the same excellent spray characteristics independent of kinematic viscosity.

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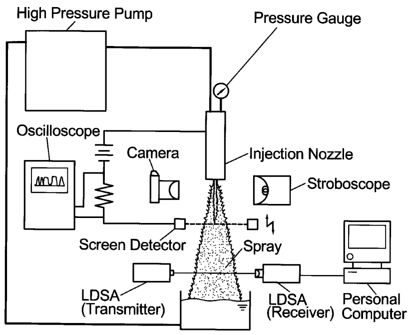
Furthermore, the effects of the atomization enhancement nozzle developed in this study [7] on atomization of the intermittent spray at high-ambient pressure condition and application to the actual Diesel injector were studied. Spread of the sprays of the atomization enhancement nozzle is wide considerably, compared with the previous single hole nozzle. 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.

Experimental Apparatus and Method

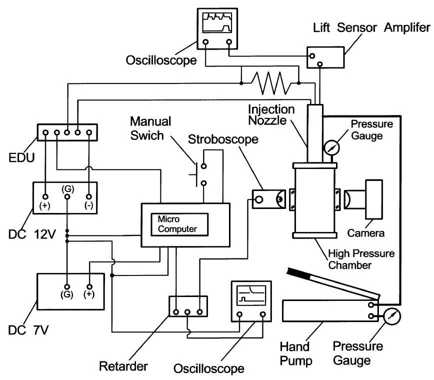
The experimental apparatus is shown schematically in Fig. 1. Figure 1 (a) is the apparatus for continuous injection and (b) is for intermittent injection. For continuous injection, equipment consists of liquid injection system with a high pressure pump, a spark light source for taking photographs of the liquid flow in the nozzle hole and the spray, and a narrow-angle forward scattering type LDSA particle analyzer for measurement of droplet and droplet size distributions. Water at room temperature pressurized by the high-pressure pump was continuously injected under atmospheric pressure condition. Cavitation structures prevailing in the nozzle hole and disintegration behavior of the liquid jet were photographed by transmitted light, using a stroboscope. The disintegration behavior of the spray was photographed by back diffusion light illumination method and transmitted light using a stroboscope. The breakup length of the liquid core, which is defined as the distance from the nozzle exit to the breakup point of the liquid core, was measured by electrical resistance method [1] in which a screen detector was used. The spread angle of the spray, that is, the spray angle was defined as the spray boundary. The droplet size distribution was measured by LDSA at 150 mm downstream from the nozzle exit. It gives Sauter mean diameter that is spatially averaged along a line through the spray.

For intermittent injection, equipment consists of high-pressure pump, microcomputer for controlling 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 condition at the differential pressure of injection of P_i=100 MPa. The spray was photographed at the arbitrary time after start of injection. The injection duration of fuel was $T_{inj.}$=0.9 ms. The ambient pressure was 1.6 MPa at room temperature. Injection fuel amount of test nozzles are from 5.6 mg to 6.9 mg.

The structures of the test nozzles are shown in Fig. 2. Test nozzles are the single hole nozzle (a), the atomization enhancement nozzle (b) and the direct injection Diesel injector with the atomization enhancement nozzle (c). The nozzle, which the inlet of the nozzle hole is sharp edged orifice, easily occurs contracted flow at vicinity of the inlet of the nozzle

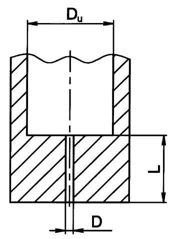


(a) For continuous injection

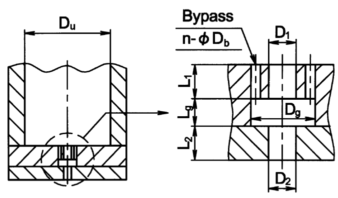


(b) For intermittent injection

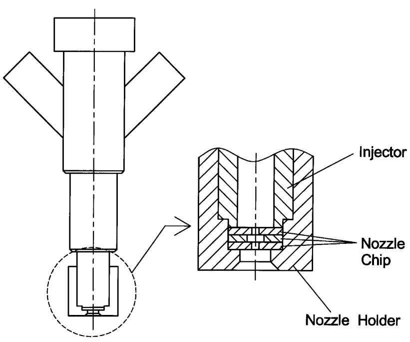
Figure 1 Schematic of experimental apparatus



(a) Single hole nozzle

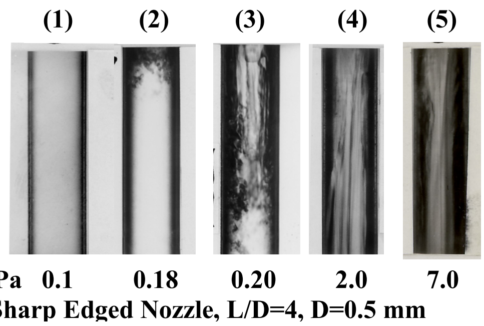


(b) Atomization enhancement nozzle

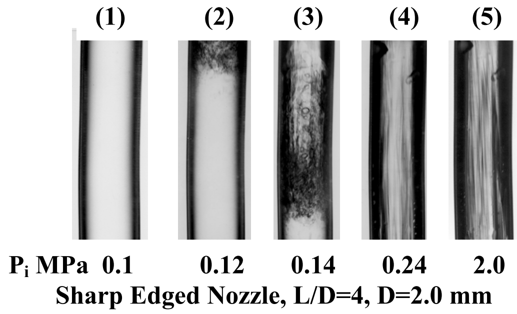


(c) Direct injection Diesel injector
(With atomization enhancement nozzle)

Figure 2 Schematic of test nozzles and injector hole and cavitation occurs in the nozzle hole. The hole diameters of the single hole nozzle D were changed from 0.3 mm to 3.0 mm, the hole length-to-diameter ratio L/D are 4 and 20. The atomization enhancement nozzle, which a gap, that is, space with large hole diameter was installed at middle of the nozzle hole, was used. The atomization enhancement nozzle is the sharp edged nozzle with additional a gap and a bypass, which was connected between the upstream chamber and the gap.



(a) Hole Diameter D=0.5 mm



(b) Hole Diameter D=2.0 mm

Figure 3 Internal flow in nozzle hole of actual size nozzle and magnified nozzle

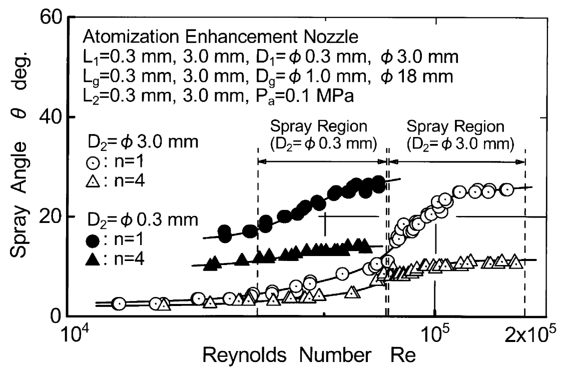


Figure 4 Effects of hole diameters on spray angle (Comparison between magnified nozzle and actual size nozzle)

Experimental Results and Discussion

Relationships between magnified nozzle and actual size nozzle

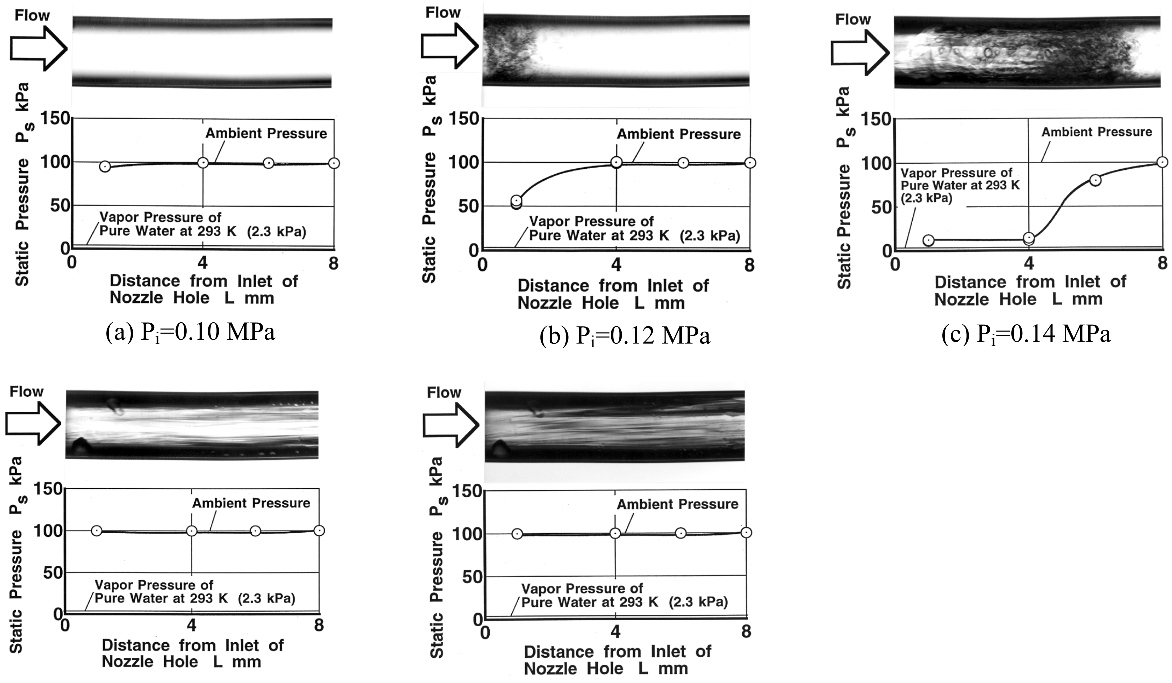
The nozzle internal flow between the scaled-up nozzle and the magnified nozzle are shown in Fig. 3. Since the photographs of the nozzle internal flow are obtained by transmitted light, the interface between cavitation bubbles and the liquid, the inner wall of the nozzle hole appears in black. When the differential pressure of injection P_i increases, behavior of the liquid flow in the nozzle hole, that is, inception of cavitation bubbles at the inlet of the nozzle hole (2), collapse of cavitation bubbles at the outlet of the nozzle hole (3), occurrence of hydraulic flip (4), (5) are almost same independent of the hole diameters.

The effect of the hole diameters on the spray angle is shown in Fig. 4. Variations of the spray angle as a function of the Reynolds number are almost same tendencies and values at the spray region independent of the hole diameters at the bypass number of n=1and n=4. It can be seen that behavior of cavitation in the nozzle hole and atomization of the spray for the magnified nozzle are similar to the scaled-up nozzle, mutual relationships of these nozzles were obtained.

Relationships between nozzle internal flow and static pressure in nozzle hole

In the previous studies, it was clarified that when cavitation does not occure in the nozzle hole, even though with a considerably large increase to the injection pressure up to 200 MPa, the spread angle of the spray further down from the nozzle exit is small and the liquid jet atomizes little. To the contrary, when cavitation occurs in the nozzle hole, the spray atomizes considerably [5]. Thus, atomization of the spray is strongly affected by occurrence of cavitation.

The static pressures at vicinity of the inlet, the outlet and the middle of the nozzle hole were measured. The internal flow in the nozzle hole and the static pressure in the nozzle hole are shown in Fig. 5. When the nozzle hole is filled with the liquid and cavitation does not occur (a), the static pressures are almost constant values of atmospheric pressure of P_s=101.3 kPa. When cavitation bubbles are generated vicinity of the hole inlet (b), that is, inception of cavitation bubbles, the static pressure at vicinity of the inlet of the nozzle hole becomes low. It is guessed that the static pressure at nearest of the inlet of the nozzle hole becomes considerably low until the vapor pressure of the test liquid. When cavitation bubbles collapse at vicinity of the outlet of the nozzle hole (c), the static pressures, where collapse of cavitation bubbles occurs, are considerably low until the vapor pressure of the test liquid. When hydlaulic flip occurs in the nozzle hole (d), the static pressure increases atmospheric pressure of P_a=101.3 kPa. Moreover, even though the differential pressure of injection P_i increases, the static pressures are constant of atmospheric pressure of P_a=101.3 kPa. Thus, it can be seen that the pressure



(a) P_i=0.10 MPa (b) P_i=0.12 MPa (c) P_i=0.14 MPa

(d) P_i=0.24 MPa (e) P_i=2.0 MPa

Figure 5 Behavior of liquid flow in single hole nozzle and pressure distributions in nozzle hole

distributions in the nozzle hole corresponds to behaviors of cavitating flow in the nozzle hole.

Cavitation pressure coefficient

Cavitation number often uses to represent cavitation phenomena in the nozzle hole. In general, using the chamber pressure upstream from the nozzle hole, that is, the injection pressure, vapor pressure and the ambient pressure, or the dynamic pressure defines cavitation number. Since almost all these pressures are not the pressures at the region where cavitation occurs, it is considered that generally used cavitation number does not represent behavior of the liquid flow in the nozzle hole which cavitation occurs. In this study, cavitation pressure coefficient was newly defined by $C_p=(P_n-P_v)/(P_a-P_n)$, using the static pressure P_n at the region where cavitation occurs.

Variation of the cavitation pressure coefficient as a function of the differential pressure of injection is shown in Fig. 6. Test nozzle is the atomization enhancement nozzles with sharp edged and round inlet shapes. It is well known that in case of sharp edged nozzle, cavitation occurs easily, and in case of round inlet nozzle, cavitation does not occur in the nozzle hole. Although cavitation pressure coefficient becomes small with an increase in the differential pressure of injection in spite cavitation does not occur in the nozzle hole, when the differential pressure of injection excesses about P_i=0.5 MPa, cavitation pressure coefficient becomes small nearly equal to zero and one of high-viscous liquid of 20 x 10^{-6} m^2/s bacomes small. When cavitation occurs in the nozzle holes, cavitation pressure coefficient becomes small and constant. From this result, it can be seen that newly defined cavitation pressure coefficient, which is used the pressure at the region where cavitation occurs, corresponds to behavior of the liquid flow in the nozzle hole.

Effect of configuration of nozzle on atomization of high-viscous liquid

In general, the single hole nozzle has mainly the following characteristics. High-injection pressure is demanded to obtain excellent spray characteristics, it is inapplicable to atomize of high-viscous liquid and it is necessary to supply atomizing air as the secondary application. Figure 7 shows the comparison of the disintegration behaviors of high-viscous liquid between the single hole nozzle of L/D=20 and the atomization enhancement nozzle invented in this study. The injection pressure is 15 MPa, kinematic viscosity is 20x10^{-6} m^2/s at 313 K and it deserves heavy oil. These results were taken under the hole diameter of D=0.3 mm. As shown in Fig. 7, in case of the single hole nozzle, the liquid jet does not atomize at all under high-viscous liquid. To the contrary, in case of the atomization enhancement nozzle, spread of the spray becomes wide and the spray atomizes in spite of high-viscous liquid. From this result, it can be seen that it is possible to atomize high-viscous liquid at relatively low injection pressure, using the atomization enhancement nozzle in which the gap was made and the bypass was installed at the nozzle hole.

The reason why high-viscous liquid atomizes by using pressure atomized type nozzle are considers as follows. Figure 8 shows the nozzle internal flow and the sprays at different kinematic viscosity from $0.66\text{x}10^{-6}$ m^2/s to $20\text{x}10^{-6}$ m^2/s. These test liquids correspond from gasoline to heavy oil. In general, when the pressure atomized nozzle was used, high-viscous liquid atomizes little and high-injection pressure is demanded to obtain the excellent spray, as mentioned before. As shown in Fig. 8, cavitation occurs in the nozzle hole and the spray atomizes considerably, independent of kinematic viscosity.

Figure 9 shows variations of the static pressure in the gap and the nozzle hole downstream from the gap as a function of the differential pressure of injection. As shown in Fig. 9, the static pressure in the gap at measurement point A increases monotonically with an increase in the differential pressure of injection, due to influence of high-pressure in the chamber upstream from the nozzle hole. When the injection pressure is over about 0.7 MPa, the static pressure in the nozzle hole at measurement point B decreases to near the vapor pressure. From this result, it is clear that cavitation occurs in the nozzle hole, and it is considered that the bypass contributes to increasing the static pressure in the gap.

Figure 10 shows the effects of kinematic viscosity on spray characteristics at the injection pressure of 15 MPa. This result was taken under the hole diameter of 0.3 mm. As shown in Fig.10, the breakup length becomes slightly long, the spray angle becomes slightly small and Sauter mean diameter becomes slightly large, with an increase in kinematic viscosity. However, the differences of the spray characteristics appear little between low-viscous liquid of $0.66\text{x}10^{-6}$ m^2/s and high-viscous one of $20\text{x}10^{-6}$ m^2/s. Therefore, it can be seen that it is possible to atomize and obtain excellent spray characteristics independent of kinematic viscosity of a liquid.

Atomization of intermittent spray at high-ambient pressure and application to actual Diesel injector

The effect of the atomization enhancement nozzle invented in this study on atomization of intermittent spray at high-ambient pressure condition is shown in Fig. 11. Spread of the sprays of the atomization enhancement nozzle is wide considerably, compared with the single hole nozzle. The penetration of the spray of the single hole nozzle is long compared with the atomization enhancement nozzle. 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.

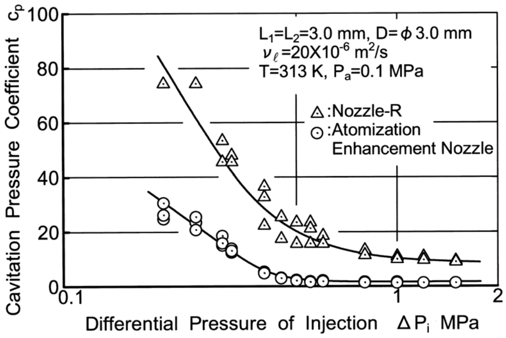


Figure 6 Variations of cavitation pressure coefficient as a function of differential pressure of injection

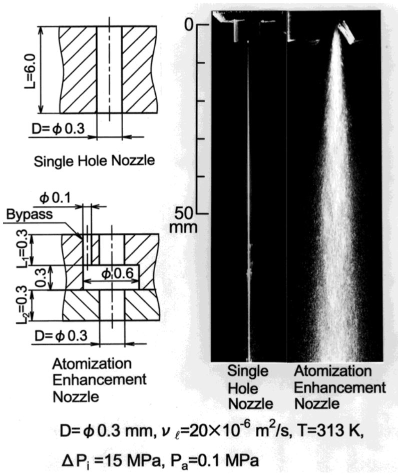


Figure 7 Effect of geometric shapes of nozzle on atomization of spray at high-viscous liquid

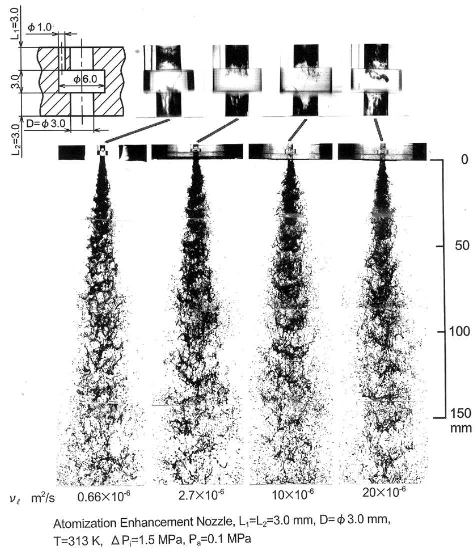


Figure 8 Effect of kinematic viscosity on nozzle internal flow and spray

Conclusions

(1) The mutual relationships between the magnified nozzle and the actual size one concerning the nozzle internal flow and cavitation phenomena were obtained.
(2) The pressure distributions in the nozzle hole correspond to behaviors of cavitating flow in the nozzle hole.
(3) The newly defined cavitation pressure coefficient, which was used the pressure in the nozzle hole, corresponds to behaviors of the liquid flow in the nozzle hole.
(4) Excellent spray and spray characteristics were obtained independent of kinematic viscosity of a liquid.
(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.

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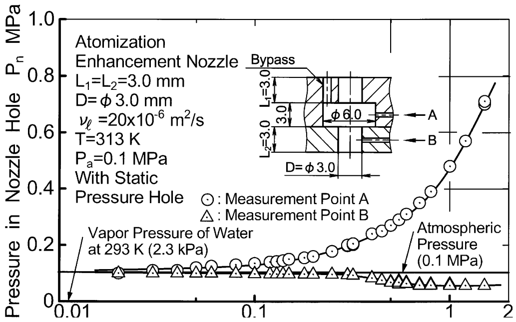

Figure 9 Variations of static pressure in gap and nozzle hole downstream from gap as a function of differential pressure of injection

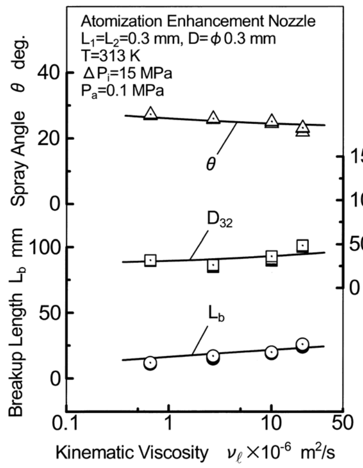

Figure 10 Effects of kinematic viscosity on spray characteristics

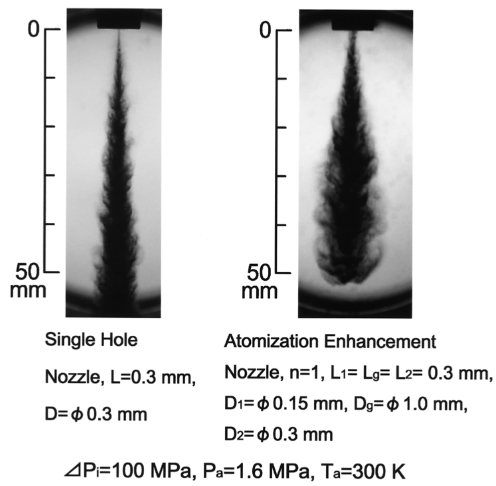

Figure 11 Effect of atomization enhancement nozzle on atomization of intermittent spray at high-ambient pressure condition