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ENHANCEMENT OF ATOMIZATION OF HIGH-VISCOUS LIQUID JET BY PRESSURE ATOMIZED NOZZLE

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Abstract

The purpose of this study is to develop the atomization enhancement nozzle, which is able to atomize high-viscous liquid jet under low injection pressure from resources saving view point. In this paper, we investigated the effects of kinematic viscosity of the injection liquid and geometric shapes of nozzle on atomization of the spray and spray characteristics of high-viscous liquid. Kinematic viscosity was varied from $0.66\text{x}10^{-6}$ m^2/s (0.66 cSt) deserved kerosene and water to $20\text{x}10^{-6}$ m^2/s (20 cSt) deserved heavy oil at liquid temperature of 303 K. The break up length and Sauter mean diameter of high-viscous liquid spray were measured in variation of the injection pressure up to 15 MPa (150 bar). The results show that the spray, which spread of the spray is large, the breakup length is short and Sauter mean diameter is small, was obtained, and enhancement of atomization of high-viscous liquid jet is possible under low injection pressure, using a pressure atomized nozzle. Moreover, almost the same spray characteristics were obtained independent of kinematic viscosity, using a nozzle improved a single hole nozzle.

Introduction

The recycling and effective use of waste materials are regarded as very important from resources saving view point. Moreover, if excellent spray characteristics were obtained at small energy independent of the fuel property, it is possible to have a wide range of application of the fuel. The purpose of this study is to develop the atomization enhancement nozzle, which is able to atomize high-viscous liquid jet under low injection pressure. This paper presents effective atomization of high-viscous liquid. In general, a twin fluid atomizer was used for atomization of high-viscous liquid [1]-[2]. However, the pressure atomized nozzle was used in this study from an energy saving view point and the application of this nozzle to a nozzle for direct injection diesel engine. The pressure atomized nozzle is necessary large energy i.e. high injection pressure in order to obtain excellent spray characteristics, and it is difficult to atomize high-viscous liquid.

Atomization of the liquid jet is affected by occurrence of cavitation in the nozzle hole [3]-[13], geometric shapes of nozzle, the injection pressure and the ambient pressure [14]. Especially, 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. The atomization enhancement nozzle, which cavitation occurs at relatively low injection pressure and excellent spray characteristics was obtained, was developed, and it was investigated about the application of high-viscous liquid to effective atomization.

Experimental Apparatus and Methods

The experimental apparatus is shown schematically in Fig. 1. The equipment consists of high-viscous 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 the droplet size distributions and Sauter mean diameter. Water at room temperature pressurized by the high pressure pump was continuously injected under atmospheric conditions. The internal flow and cavitation phenomena in the nozzle hole 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

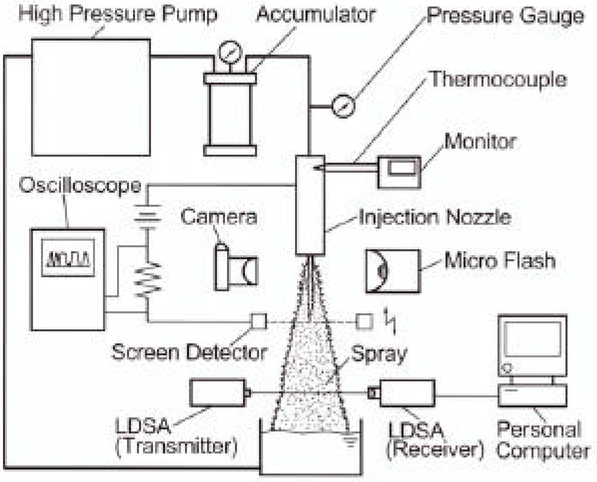


Figure 1. Schematic of experimental apparatus.

defined as the distance from the nozzle exit to the breakup point of the liquid core, was measured by electrical resistance method [3] in which a screen detector was used. The spread angle of the spray i.e. the spray angle was defined as the spray boundary. The droplet size distributions and Sauter mean diameter were 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.

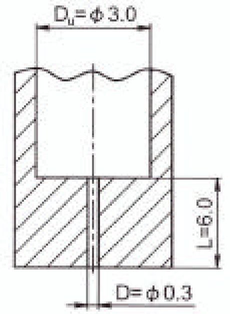
The structures of test nozzles are shown in Fig. 2. Test nozzle is the single hole nozzle [Fig. 2 (a)] which the inlet of the nozzle hole is sharp edge i.e. sharp edged nozzle. The atomization enhancement nozzle [Fig. 2 (b)] is the sharp edged nozzle with additional gap and the bypass, which was connected between the upstream chamber and the gap. Moreover, the round nozzle with additional inlet curvature [Fig. 2 (c)] was used to investigate about the effects of disturbance of the liquid flow caused by cavitation in the nozzle hole and the liquid flow from the bypass. The sharp edged nozzle easily causes a contracted flow at the inlet of the nozzle hole and cavitation takes place in the nozzle hole. The round nozzle does not take place cavitation.

Experimental Results and Discussions

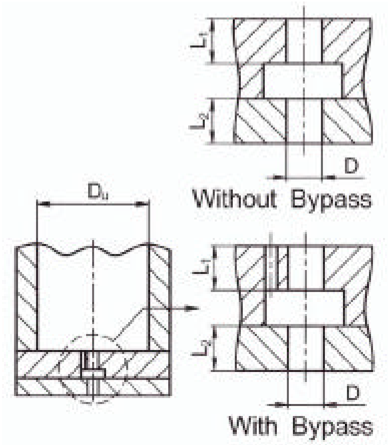
Effect of Configuration of Nozzle on Atomization of High-Viscous Liquid

In general, the single hole nozzle has mainly the following characteristics. High injection pressure is demanded to obtain an excellent spray characteristics, it is inapplicable to atomize of high-viscous liquid and secondary application to supply atomizing air does not need. Figure 3 shows the breakup length of the single hole nozzle under low-viscous liquid of 0.66x10^{-6} m^2/s. The breakup length becomes short with an increase in the hole length-to-diameter ratio L/D at the same injection pressure. It is clear that when the single hole nozzle of L/D=20 was used, relatively fine spray characteristics is obtained [8].

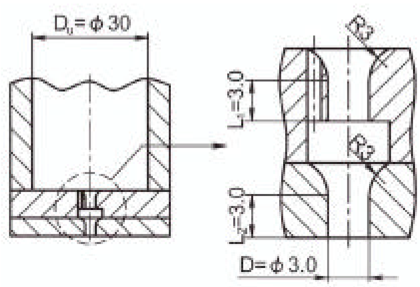
Figure 4 shows the comparison of the disintegration behaviors of high-viscous liquid between the single hole nozzle and the atomization enhancement nozzle invented in this study. The injection pressure is 15 MPa, kinematic viscosity is 20x10^{-6} m^2/s at 303 K and it deserves heavy oil. These results were taken under the hole diameter of D=0.3 mm, similar to a diesel nozzle. As shown in Fig. 4, in the case of the single hole nozzle, the liquid jet does not atomize at all under high-viscous liquid. To the contrary, in the case of the atomization enhancement nozzle, spread of the spray becomes extremely wide and the liquid jet was atomized considerably in spite of high-viscous liquid. Figure 5 shows the comparison of the breakup length between the single hole nozzle and the



(a) Single Hole Nozzle



(b) Atomization Enhancement Nozzle
(Nozzle-S, With Gap and Bypass)



(c) Round Nozzle
(Nozzle-R, With Gap and Bypass)

Figure 2. Schematics of test nozzles.

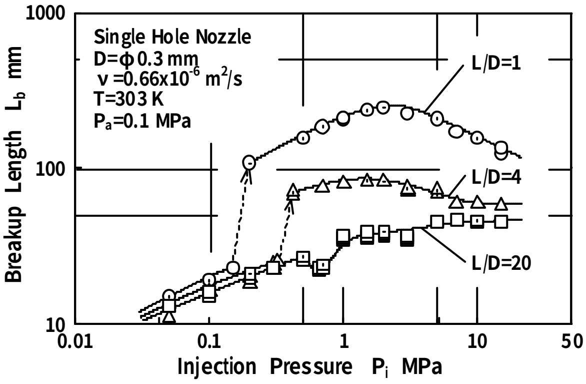


Figure 3. Variations of the breakup length of the single hole nozzle.

atomization enhancement nozzle. As shown in Fig. 5, the breakup length becomes long independent of configuration of the nozzle with an increase in the injection pressure up to about 3 MPa. In the case of the single hole nozzle, even though the injection pressure is more increased, the breakup length does not become short. The breakup length of the single hole nozzle is longer than the atomization enhancement nozzle, comparing with the same injection pressure of 15 MPa. To the contrary, in the case of the atomization enhancement nozzle, the breakup length becomes short rapidly after passing the maximum value of the breakup length. Moreover, when the injection pressure is over about 5 MPa, the breakup length of the atomization enhancement nozzle is the almost same one as the maximum injection pressure of 15 MPa. 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 of the single hole nozzle.

The reason why high-viscous liquid jet atomizes at relatively low injection pressure is discussed as follows. Figure 6 shows the photographs of the nozzle internal flow and the sprays at kinematic viscosity of 20×10^{-6} m^2/s.

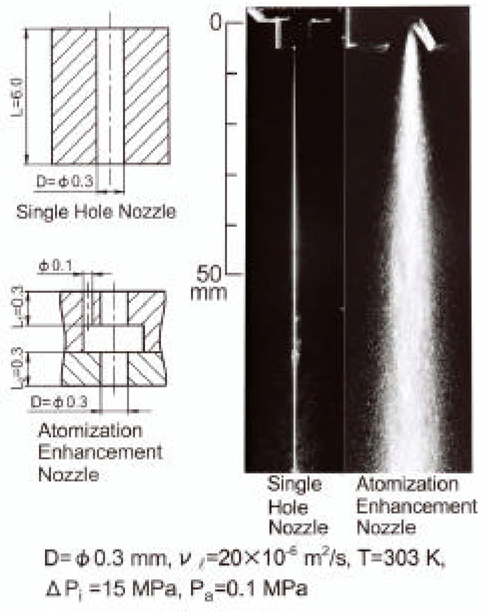


Figure 4. Comparison of disintegration behaviors of high-viscous liquid between the single hole nozzle and the atomization enhancement nozzle.

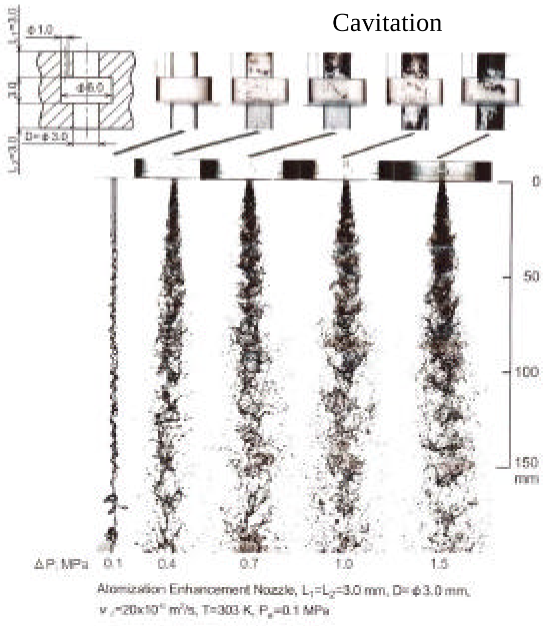


Figure 6. Photographs of the nozzle internal flow and the sprays of high-viscous liquid.

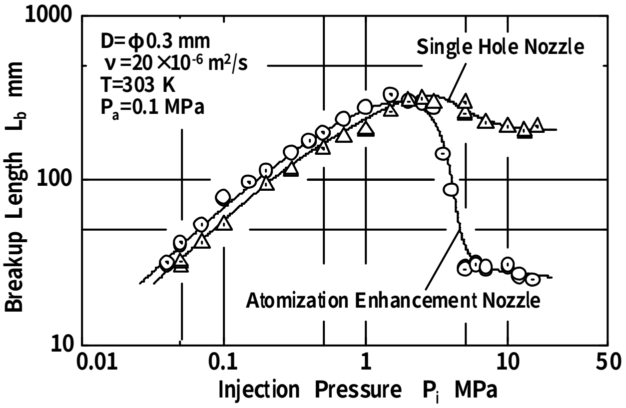
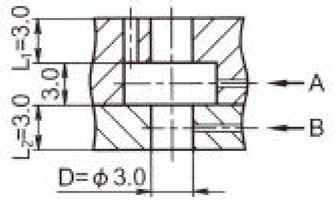


Figure 5. Comparison of the breakup length between the single hole nozzle and the atomization enhancement nozzle.



Measurement Point

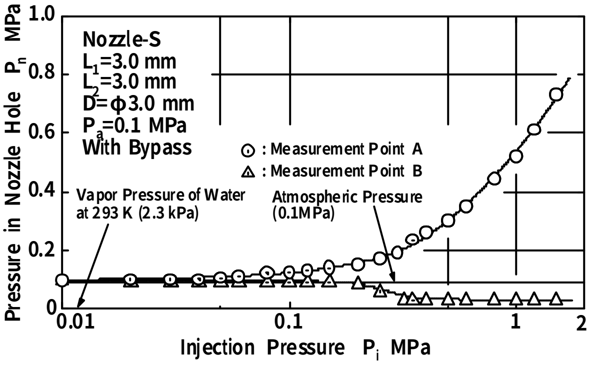


Figure 7. Variations of the static pressure in the gap and nozzle hole downstream from the gap.

This result is the hole diameter of D=3.0 mm. 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. When the injection pressure was increased to 0.7 MPa, cavitation takes place in the nozzle hole upstream from the gap and spread of the spray becomes wide. When the injection pressure was more increased to 1.0 MPa, cavitation takes place in the nozzle hole upstream and downstream from the gap and the spray atomizes considerably. When the injection pressure is over about 1.0 MPa, the disintegration behavior of the spray and spread of the spray are the almost same ones as the maximum injection pressure of 1.5 MPa.

Figure 7 shows variations of the static pressure in the gap and the nozzle hole downstream of the gap as a function of the injection pressure. The static pressure in the gap at measurement point A increases monotonically with an increase in the injection pressure, due to the influence of high pressure in the upstream chamber. When the injection pressure is over about 0.3 MPa, the static pressure in the nozzle hole at measurement point B decreases to the vapor pressure. From this result, it is clear that cavitation takes place in the nozzle hole, and it is considered that the bypass contributes to increasing the static pressure in the gap. In general, collapse of cavitation bubble occurs at the region where the static pressure is recovered from the vapor pressure. Therefore, it is considered that collapse of cavitation bubble occurs in the gap, a large number of cavitation bubble nuclei exists in the gap and cavitation takes place easily at the nozzle hole downstream from the gap.

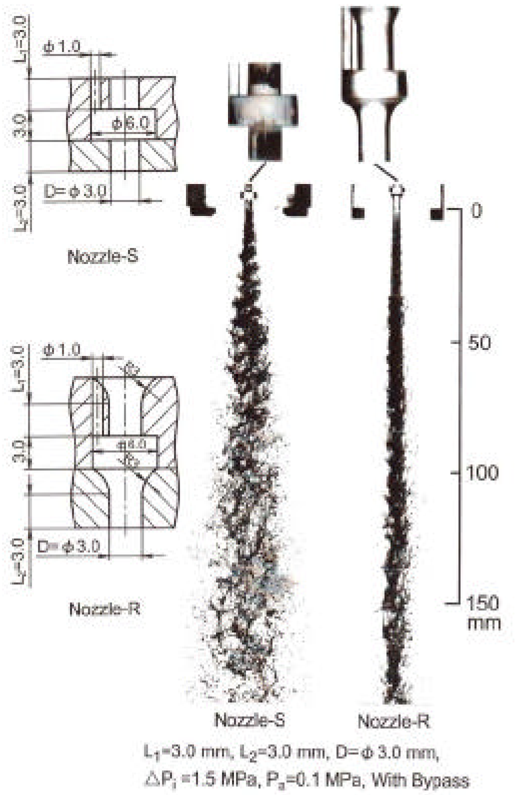


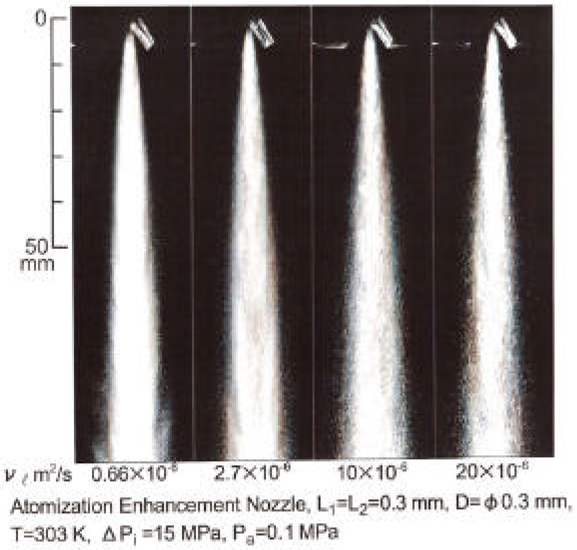
Figure 8. Effects of disturbance caused by cavitation and the liquid flow from the bypass on the disintegration behavior of the liquid jet.

Figure 8 shows the effects of disturbance of cavitation in the nozzle hole and the liquid flow from the bypass on the disintegration behavior of the liquid jet. In the case of the sharp edged nozzle with the gap and the bypass (Nozzle-S), cavitation takes place in the nozzle hole, spread of the spray becomes wide and the liquid jet atomizes considerably. To the contrary, in the case of the round nozzle with the gap and the bypass (Nozzle-R), cavitation does not take place in the nozzle hole, the liquid jet atomizes little compared with Nozzle-S. It is clear that the disturbance due to the liquid flow from the bypass does not contribute to atomization of the liquid jet, the disturbance caused by occurrence of cavitation is the most dominant factor of atomization.

Effects of Kinematic Viscosity of a Liquid on Atomization of the Liquid Jet

Figure 9 shows the sprays at different kinematic viscosity from 0.66×10^{-6} m^2/s to 20×10^{-6} m^2/s. Figure 10 shows the effects of kinematic viscosity on spray characteristics at the injection pressure of 15 MPa. As shown in Fig. 9, spread of the sprays becomes wide and the excellent sprays are obtained, and the sprays at each kinematic viscosity have a similar disintegration behavior independent of kinematic viscosity of a liquid. Moreover, as shown in Fig. 10, the breakup length, the spray angle and Sauter mean diameter become slightly long, small and large respectively from a microscopic view point, with an increase in kinematic viscosity. However, the differences of the spray and spray characteristics appear little between low-viscous liquid jet of 0.66×10^{-6} m^2/s and high-viscous one of 20×10^{-6} m^2/s. Therefore, it can be seen that it is possible to atomize and obtain the excellent spray and spray characteristics independent of kinematic viscosity of a liquid. From this photograph, it can be seen that cavitation takes place in the nozzle hole, and the almost same phenomena take place in the nozzle hole. Therefore, the disintegration behaviors of the spray are the almost same, spread of the spray becomes wide and the spray atomizes considerably, independent of kinematic viscosity.

The reason why the disintegration behaviors of the spray and the spray characteristics are independent of kinematic viscosity is discussed as follows. Figure 11 shows the nozzle internal flow and the sprays at different kinematic viscosity of 0.66×10^{-6} m^2/s and 20×10^{-6} m^2/s at the injection pressure of 1.5 MPa. Figures 12 and 13 show the effects of kinematic viscosity on the breakup length and the spray angle, respectively. 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. 11, cavitation takes place in the nozzle hole and the spray atomizes considerably, independent of kinematic viscosity. Moreover, as shown in Figs. 12 and 13, when the injection pressure is over about 0.7 MPa, the breakup length and the spray angle are the almost same ones as the maximum injection pressure of 1.5 MPa independent of kinematic viscosity, respectively.



Atomization Enhancement Nozzle, $L_1=L_2=0.3$ mm, D= ϕ 0.3 mm, T=303 K, ΔP_i =15 MPa, P_a=0.1 MPa

Figure 9. Photographs of the sprays at different kinematic viscosity.

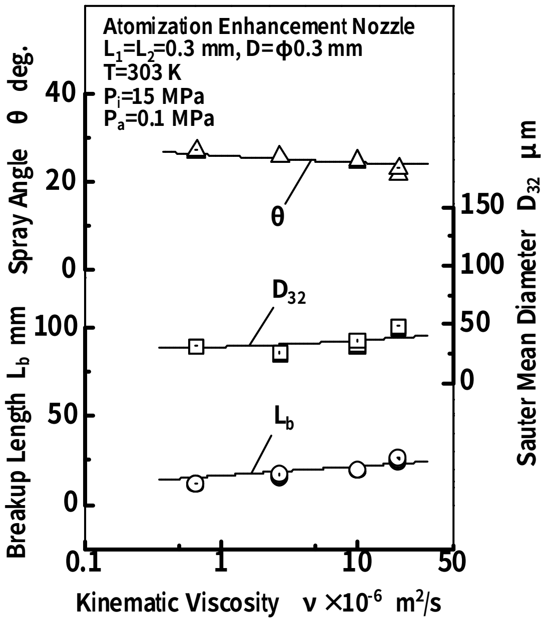
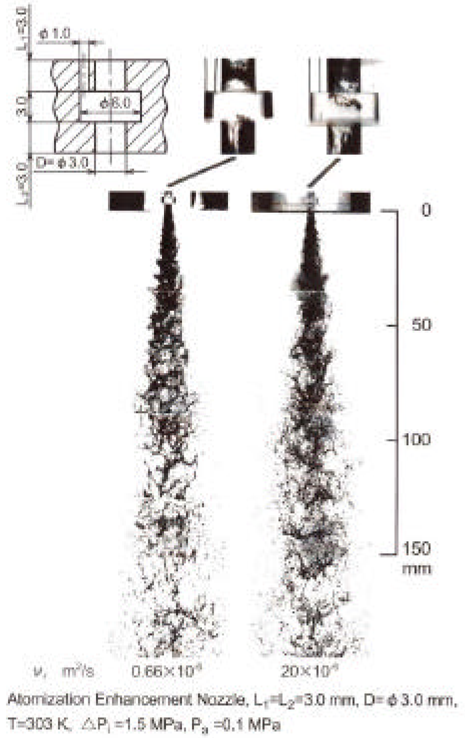


Figure 10. Effects of kinematic viscosity on the spray characteristics.



Atomization Enhancement Nozzle, $L_1=L_2=3.0$ mm, D= ϕ 3.0 mm, T=303 K, ΔP_i =1.5 MPa, P_a =0.1 MPa

Figure 11. Photographs of the nozzle internal flow and the sprays at different kinematic viscosity.

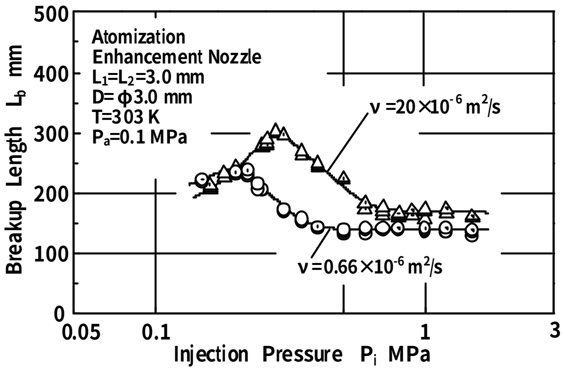


Figure 12. Effects of kinematic viscosity on the breakup length.

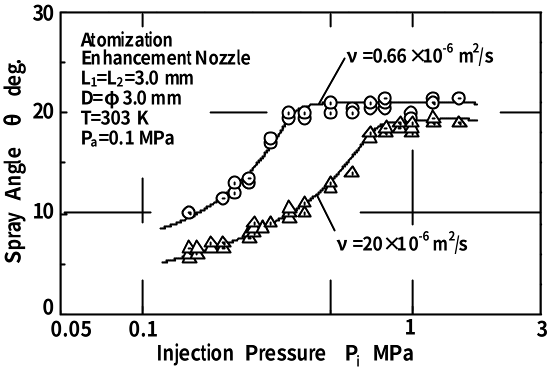


Figure 13. Effects of kinematic viscosity on the spray angle.

Since cavitation takes place in the nozzle hole similar to low-viscous liquid, it is able to atomize high-viscous liquid at relatively low injection pressure.

As a consequence of this study, it has been clarified that the atomization enhancement nozzle invented in this study is possible to atomize high-viscous liquid at relatively low injection pressure, and the excellent spray and spray characteristics were obtained independent of kinematic viscosity of a liquid.

Conclusions

The following conclusions are obtained in this study.

(1) The atomization enhancement nozzle invented in this study is able to atomize high-viscous liquid at low injection pressure.

(2) The excellent spray and spray characteristics, which spread of the spray is wide, the breakup length is short and Sauter mean diameter is small, were obtained independent of kinematic viscosity of a liquid.

Nomenclature

D	*Hole diameter*
D_{32}	Sauter mean diameter
L	*Hole length*
L_1	*Hole length of upstream from gap*
L_2	*Hole length of downstream from gap*
L_b	*Breakup length*
P_a	*Atmospheric pressure*
P_i	*Injection pressure*
P_n	*Pressures in gap and nozzle hole*
T_a	*Atmospheric temperature*
v_i	*Injection velocity*
θ	*Spray angle*
ν_l⁇	*Kinematic viscosity*

Subscripts

a	atmospheric
b	breakup
i	injection
l	liquid
n	nozzle

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