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EFFECT OF NOZZLE DIAMETER ON THE ATOMIZATION CHARACTERISTICS OF A WALL IMPINGEMENT LIQUID JET

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ABSTRACT Utilizing wall impingement of a high speed liquid jet is expected to improve the liquid atomization characteristics, since it can produce thin liquid film. In the present study, in order to reveal the atomization mechanism, the nozzle diameter effect was examined experimentally. The nozzle diameter D was varied from 0.2 mm to 0.5 mm. The impingement wall diameter d was also varied from 0.8 mm to 2.0 mm. The impingement angle α was set at 30 deg and 90 deg, and the injection pressure P_{inj} was varied from 0.5 to 7.5 MPa. Distilled Water was injected from the nozzles. Before impingement the liquid jet was kept to be a liquid column, and it impinged on the wall positioned at 18 mm downstream of the nozzle exit. After the impingement, a liquid film was formed. The behavior was observed by a strobe light. The liquid jet velocity V_1 and the liquid film velocity V_2 were measured with an LDA. The droplet size (SMD) was measured with an LDSA. At the nozzle diameter of D = 0.2 mm, the injection pressure of P_{inj} = 7.5 MPa, and the impingement angle of α = 90 deg, about 18 μm of the SMD was obtained. Utilizing wall impingement of the liquid atomization, although SMD decreases with the decrease in nozzle diameter, the dependence of the SMD on the nozzle diameter becomes less.

Keywords: Liquid Atomization, Wall Impingement Jet, Nozzle Diameter, Liquid Film, Breakup Length, SMD

1. INTRODUCTION

In order to reduce the NOx emission level in jet engine combustion, Pre-vaporized and Pre-mixed Lean (PPL) combustion has been proposed. The improvement of the liquid atomization is one of the key technologies to realize the PPL combustion. It is desirable to obtain smaller droplets with lower injection pressures. As one of the methods to improve the atomization, utilizing wall impingement of a steady liquid jet is expected to be useful to form a thin liquid film. And it may possibly improve the atomization characteristics due to breaking of the thin liquid film.

Inamura et al. [1-3] have been investigating the effect of utilization of wall impingement on atomization characteristics of a gasoline direct-injection nozzle. And they reported that the wall impingement nozzle can produce rather fine droplets compared with that of conventional swirl nozzles. Shiga et al. [4] have also been investigating the effect of utilization of wall impingement on the atomization characteristics of air blasting fuel atomizer for jet engines. And they reported that it can produce rather fine droplets even with low air flow rate. From these experiments, it is shown that the wall impingement jet remarkably decreases the droplet diameter. However, in these practical works, the liquid film geometries and experimental parameters are complicated, and it is difficult to extract dominant phenomena. Araki et al. [5] have also been investigating the effects of the wall impingement of a steady liquid jet on the atomization characteristics. And they reported that the SMD is determined by the liquid film velocity and the impingement angle.

However, although the effect of nozzle size is quite improvement especially in practical applications, there are a few studies on the size effect even in a free jet at higher injection pressure, and no data is available for the liquid film atomization.

On the basis of this background, further investigation was carried out to reveal the effect of nozzle size and the underlying mechanism.

Three kinds of measurements were carried out in the present study, namely (i) flow visualization of the liquid film, (ii) measurement of liquid jet and liquid film velocities, and (iii) droplet diameter measurement. Results are given to discuss in comparison with those obtained in free jet.

2. EXPERIMENTAL SETUP AND PRODUCE

Figure 1 shows a schematic of the experimental setup. Distilled water was used as the test liquid. The water was pressurized by N_2 gas in a high pressure vessel, and it is introduced to the nozzle through a pipe. The injection pressure P_{inj} was measured with a pressure gage in the high-pressure pipe. The injection nozzle was installed in a nozzle holder. The water was injection from the nozzle in the atmosphere. The liquid jet impinges onto a solid wall positioned at 18 mm downstream of the nozzle exit. It was observed that, before the impingement, the liquid jet was a liquid column. After the impingement, a thin liquid film was formed.

Table 1 shows the experimental conditions. The injection pressure P_{inj} of the test water was varied from 0.5 to 7.5 MPa (Corresponding potential velocity V_{th} = 32 to 123 m/s). The nozzle is a hole nozzle of straight type

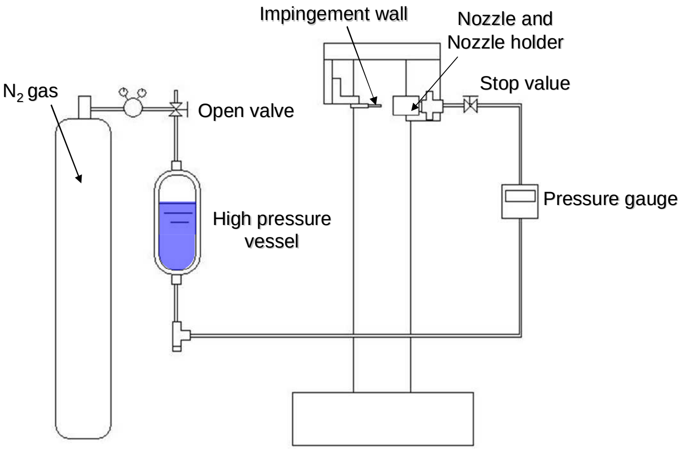


Fig.1 Schematic of experimental setup

Table 1 Experimental condition

Nozzle Diameter D [mm]	0.2, 0.3, 0.4, 0.5
Nozzle Type	Straight
L / D	4.0
Impingement Wall Diameter d [mm]	0.8, 1.0, 1.5, 2.0
d / D	3.0 to 4.0
Injection Pressure P_{inj} [MPa]	0.5 to 7.5
Impingement Angle α [deg]	30 and 90
Test Water	Distilled Water

whose length to diameter ratio (L/D) is 4.0. The nozzle diameter D was varied from 0.2 to 0.5 mm. The impingement angle α was set at 30 and 90 deg.

The impingement wall was kept to be vertical, while the impingement angle was changed. Therefore, the liquid film is usually formed in the vertical plane. According to a previous study [5], the ratio of the impingement wall diameter d and the nozzle diameter D (d/D) was set to be 3.0 to 4.0. Due to the viscous friction on the wall surface, the liquid film velocity slightly decreases. With the increase in the impingement wall diameter, the effect of the viscous friction becomes greater. In the present study, walls as small as possible were used (3.0 to 4.0 times as much as the liquid jet diameter), to minimize the effect of the viscous friction. As the impingement wall, the end of a cylinder bar of steel (High-speed tool steel ; HSS) was used, and the impingement wall diameter was varied from 0.8 to 2.0 mm.

Three kinds of measurements were carried out in the present study, namely (i) flow visualization of the liquid film, (ii) measurement of liquid jet and liquid film velocities, and (iii) droplet diameter measurement. A stroboscope light source (Sugawara Lab, MS-230A) was used for the flow visualization of the liquid film.

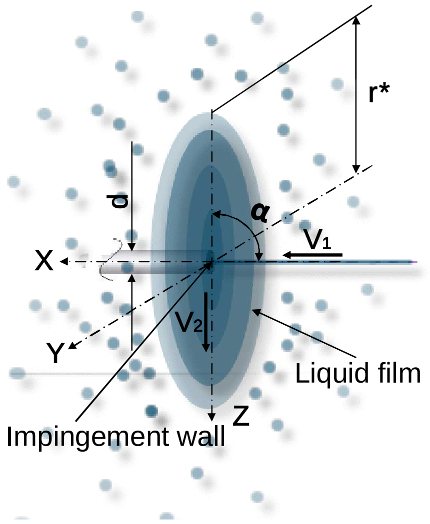


Fig.2 Schematic of the impingement wall and the liquid film

The pulse duration was about 1.6 μsec and it is short enough to freeze the image. A CCD video camera (Hamamatsu Photonics, C5405-50/-51) was used to obtain the instantaneous images. The images were acquired in a computer through an A/D converter.

Figure 2 shows a schematic of the impingement wall and the liquid film. The liquid jet velocity V_1 and the liquid film velocity V_2 were measured by an LDA (Laser Doppler Anemometry). The forward scattering optical system was applied. For the liquid jet, the velocity V_1 was measured at 18 mm downstream of the nozzle exit in X direction. For the liquid film, the velocity V_2 was measured at 5 mm downward from the impingement wall center in Y direction. No particles were seeded into the water to prevent the nozzle being damaged. During the LDA measurement, clear Doppler signals were observed. It is considered that, (i) small bubbles due to cavitation at the nozzle, (ii) fine surface waves on the liquid jet or film, and (iii) fine dusts in the water act as scatterers in the measurement.

The SMD of the droplets was measured by a narrow angle forward scattering method (Tohnichi Computer Applications, LDSA-1300A). The measuring position was 500 mm downward from the impingement wall center where the Transmittance (ratio of incident laser and permeability laser) is suitable [6].

3. RESULTS AND DISCUSSIONS

3.1. Flow Visualizations of Liquid Film

Figure 3 shows the visualized area in Figures 4 and 5. The liquid jet is coming from the right to left, and it impinges on the impingement wall. After the impingement, the liquid film was formed.

Figures 4 and 5 show the instantaneous liquid film images, for the nozzle diameter D = 0.2 and 0.5 mm, respectively. The injection pressure P_{inj} is varied from 0.5 to 7.5 MPa, and the impingement angle α is set at 30 and 90 deg, respectively.

For the impingement angle α = 30 deg, regardless of the nozzle diameter and the injection pressure, it is observed that a fan shaped liquid film is formed. With the

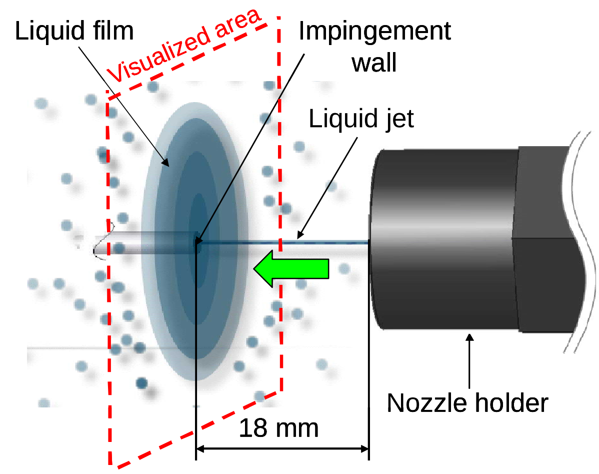


Fig.3 Visualized area in Figures 4 and 5

increase in the impingement angle α, the spread angle of the liquid film is increased. For the impingement angle α = 90deg, it is observed that a disk shaped liquid film is formed. For almost all cases observed in the present study, the atomization process is similar. First, fine waves appear on the liquid film, and the liquid film breaks into droplets at the film periphery.

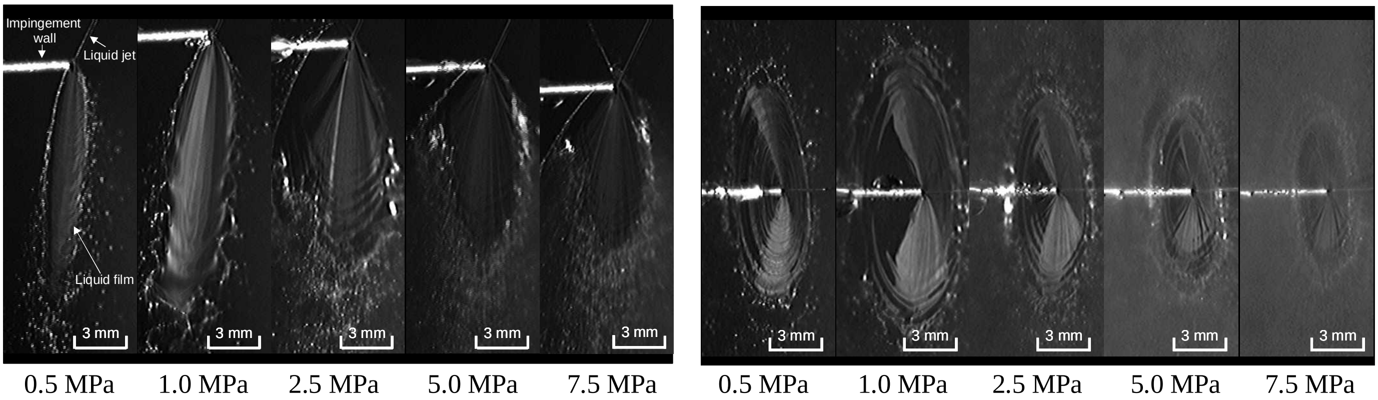
It is further observed that, with the increase in the injection pressure P_{inj}, the breakup length of the liquid film decreases. It means that, the breakup length becomes smaller with the increase in the liquid film velocity, while the mass flow rate of the water increases. It is thus considered that the liquid film breaks up when the inertia force of the liquid film exceeds the force by surface tension.

At the same injection pressure, with the increase in the nozzle diameter D, the breakup length of the liquid film becomes larger. It is considered that the thickness of the liquid film increases with the increase in the nozzle diameter D because of the increase in the mass flow rate, and that it takes longer distance to pinch the liquid film.

For the nozzle diameter D = 0.2 mm, and the injection pressure P_{inj} = 0.5 MPa, the liquid film diameter is smaller than that for P_{inj} = 1.0 MPa. Since the inertia force is smaller due to lower injection pressure and the force by surface tension becomes dominant, it is difficult to spread the liquid film widely.

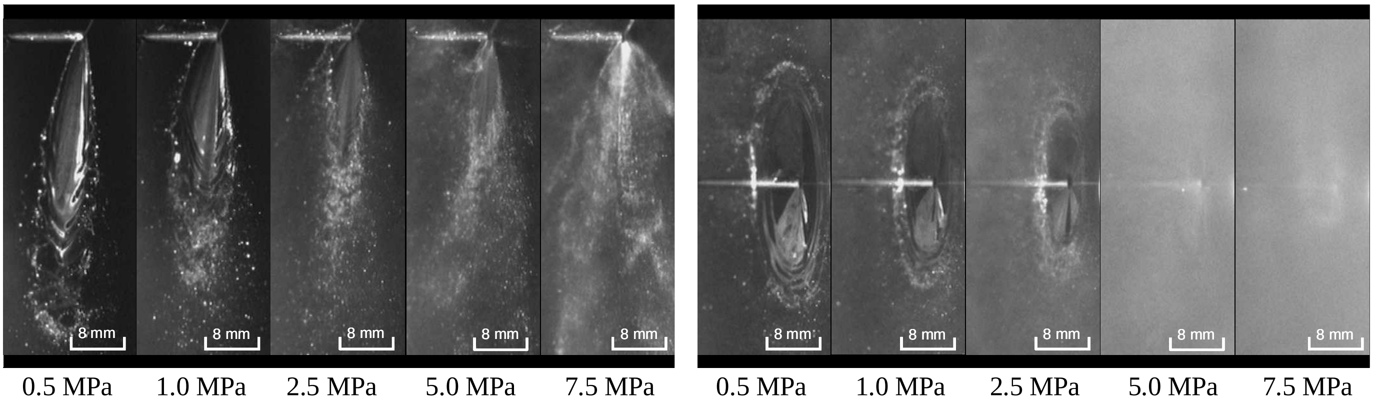
For the nozzle diameter D = 0.5 mm, the liquid film was not formed in the cases; α = 30 deg with P_{inj} = 7.5 MPa and α = 90 deg with P_{inj} = 5.0 and 7.5 MPa. For these cases, it is considered that, the inertia force is dominant, and that the water breaks into droplets immediately after the impingement.

Consequently, there are three regimes in the liquid film atomization, namely (i) a region of a smaller liquid film, at low velocities with smaller nozzles (surface tension is dominant), (ii) a region where the breakup length of the liquid film decreases with the increase in the velocity (surface tension and inertia force are comparable), and (iii) a region without liquid film at high velocities with large nozzles (inertia force is dominant). The effect of the



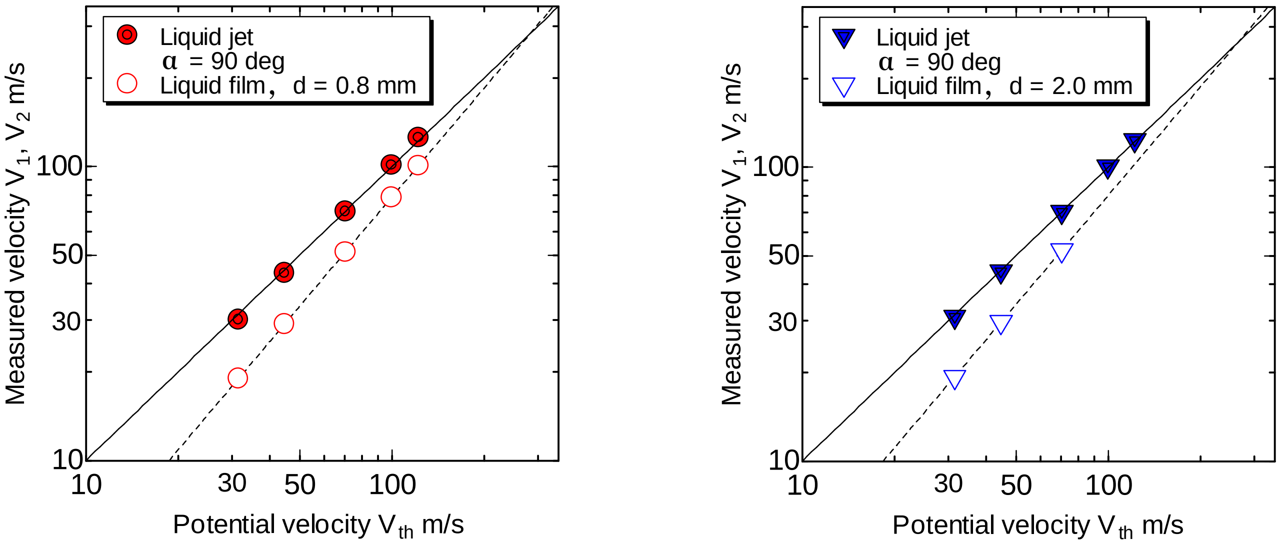
(a) α = 30 deg (b) α = 90 deg

Fig.4 Instantaneous liquid film images, for D = 0.2 mm



(a) α = 30 deg (b) α = 90 deg

Fig.5 Instantaneous liquid film images, for D = 0.5 mm



(a) D = 0.2 mm

(b) D = 0.5 mm

Fig.6 Comparison of the measured liquid jet and liquid film velocities V_1, V_2 with the potential velocity V_{th}

surface tension and the inertia force will be discussed in the later part of this article using the results of this liquid film velocity measurement.

3.2. Liquid Jet and Liquid Film Velocity Measurement

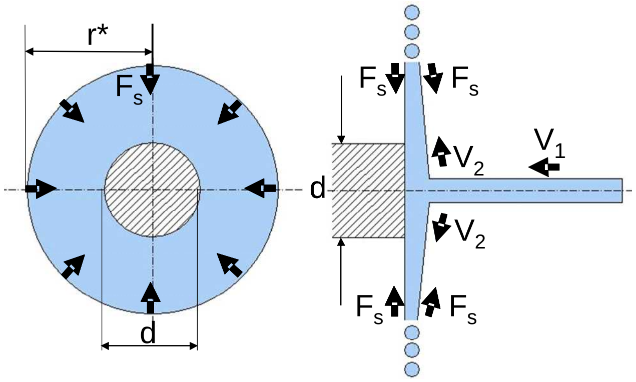
Figures 6 (a) and (b) show comparison of the measured liquid jet and liquid film velocities V_1, V_2 with the potential velocity V_{th} for the nozzle diameter D = 0.2 and 0.5 mm, respectively. The impingement angle α = 90 deg. The vertical axis is the liquid jet velocity V_1 and the liquid film velocity V_2 measured by LDA. The horizontal axis is the potential velocity V_{th} estimated by using Bernouilli's equation from the injection pressure P_{inj}. For the nozzle diameter D = 0.5 mm and the injection pressure P_{inj} = 5.0 and 7.5 MPa, the liquid film velocities were not be measured since the liquid film was not formed.

The liquid jet velocity V_1 is exactly the same as the potential velocity V_{th}. It is considered that the test water is injected from the nozzles without loss. The liquid film velocity V_2 should become equal to the liquid jet velocity V_1, if there is no loss. However, for each nozzle, the liquid film velocity V_2 is smaller than the liquid jet velocity V_1. And, with the increase in the injection pressure P_{inj}, the liquid film velocity V_2 is approaching to the value of the liquid jet velocity V_1.

Figure 7 shows the effect of the surface tension on the liquid film velocity V_2. At the breakup point, the force by the surface tension acts in the radial direction of the liquid film. The force by the surface tension F_s is

$$F_s = 4\pi\sigma r^* \qquad (1)$$

where σ is the surface tension and r* is the breakup length. The force by surface tension F_s is proportional to the breakup length of the liquid film. In Fig. 6, it is observed that, with the decrease in the potential velocity, i.e. the decrease in the injection pressure, the deceleration of the liquid film becomes larger. At low injection pressures, it is observed that the liquid film diameter becomes larger. It is considered that, at low injection pressures, the force by the surface tension becomes dominant and that deceleration of the liquid film velocity V_2 became large.



(a) Front view

(b) Side view

Fig.7 Effect of surface tension on the liquid film velocity V_2

3.3. Droplet Size of Free Jet Atomization and Liquid Film Atomization

Figure 8 shows the SMD variation with the liquid jet velocity V_1 in free jet atomization. The vertical axis is the SMD measured by LDSA. The horizontal axis is the liquid jet velocity V_1 measured by LDA. Results of free jet atomization obtained with an immersion method by Tanasawa et al. [7] are also available in the figure.

Under all conditions, with the increase in the liquid jet velocity, the SMD is decreased. Moreover, for all the nozzles in the present study, the SMD is almost the same as that by reported Tanasawa et al. [7]. For high injection pressures, the SMD in the present study is less than those reported by Tanasawa et al. [7]. Since the data obtained by Tanasawa et al. [7] was measured with immersion sampling method, it would be difficult to measure smaller droplets of the order of 10 μm.

In the free jet atomization, it is shown that the SMD dose not depend on the nozzle diameter. In the present

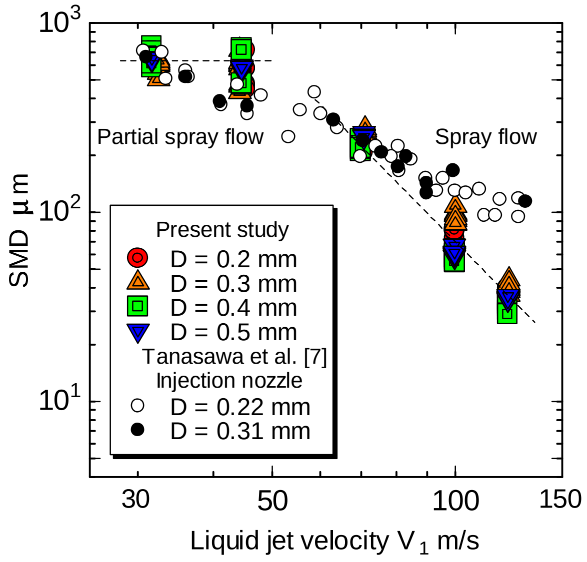


Fig.8 SMD variation with the liquid jet velocity V_1 in free jet atomization

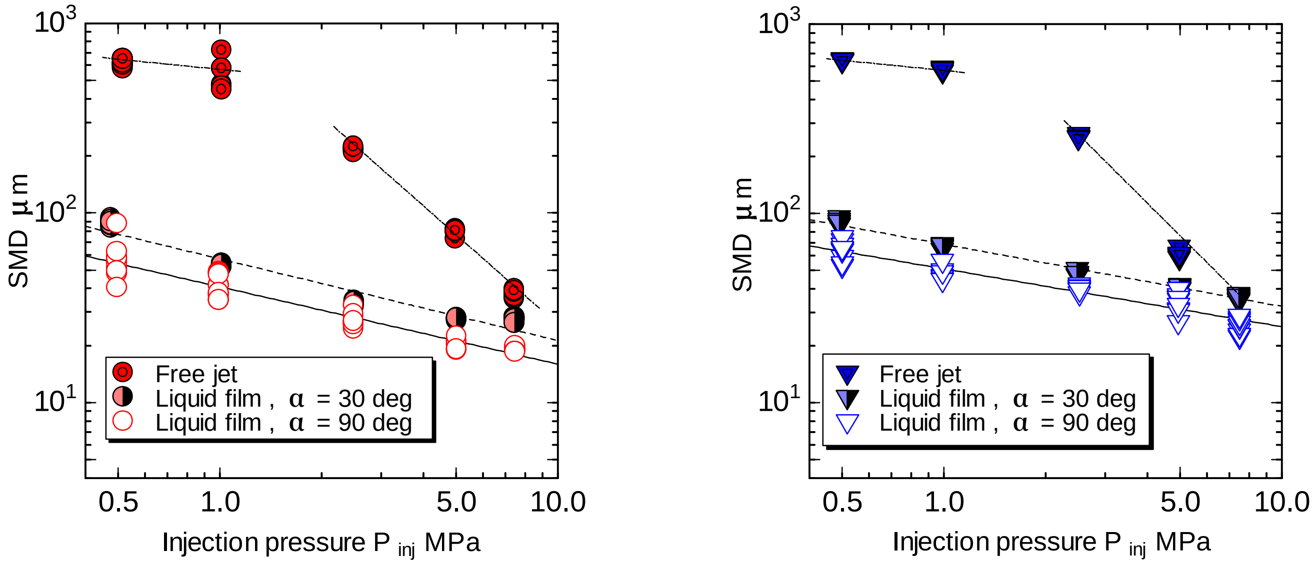
study, it is considered that, for the liquid jet velocity V_1 = 30 to 50 m/s, the phenomenon is the partial spray flow, and for the liquid jet velocity beyond V_1 = 50 m/s, the phenomenon becomes the developed spray flow, respectively.

Figures 9 (a) and (b) show the SMD variation with the injection pressure P_{inj} of the free jet atomization and the liquid film atomization for the nozzle diameter D = 0.2 and 0.5 mm, respectively. The vertical axis is the SMD measured by LDSA. The horizontal axis is the injection pressure P_{inj}.

For both cases, it is shown that with the increase in the injection pressure, the SMD was decreased. In the liquid film atomization, the SMD is smaller than the free jet atomization. In lower injection pressure for the liquid film atomization, the SMD becomes about 1/10 of the free jet atomization. In the spray flow, the distance from the jet surface to the core is important. It is considered that, in the liquid atomization, the distance from the jet surface to the core is smaller than the free jet atomization. Therefore, it is effective to use the liquid film atomization, in relatively lower injection pressure.

For the liquid film atomization, the SMD for the impingement angle α = 90 deg is decreased to about 1/3 of the SMD for the impingement angle α = 30 deg, for all injection pressures. In Figs. 4 and 5, it is shown that, for the impingement angle α = 90 deg of the liquid film, the liquid film spreads in 360 deg, but for the impingement angle α = 30 deg of the liquid film, it spreads in thereabout 180 deg. Therefore, in the same injection pressure, since the liquid film thickness at the breakup point at the impingement angle α = 90 deg becomes thinner than the case of the impingement angle α = 30 deg, the finer ligament is produced, and thus the SMD is decreased. Throughout the experimental conditions in the present study, it is shown that the case of the impingement angle α = 90 deg is the most desirable for better atomization. For the nozzle diameter D = 0.2 mm, the impingement angle α = 90 deg and the injection pressure P_{inj} = 7.5 MPa, 18 μ m of the SMD could be obtained.

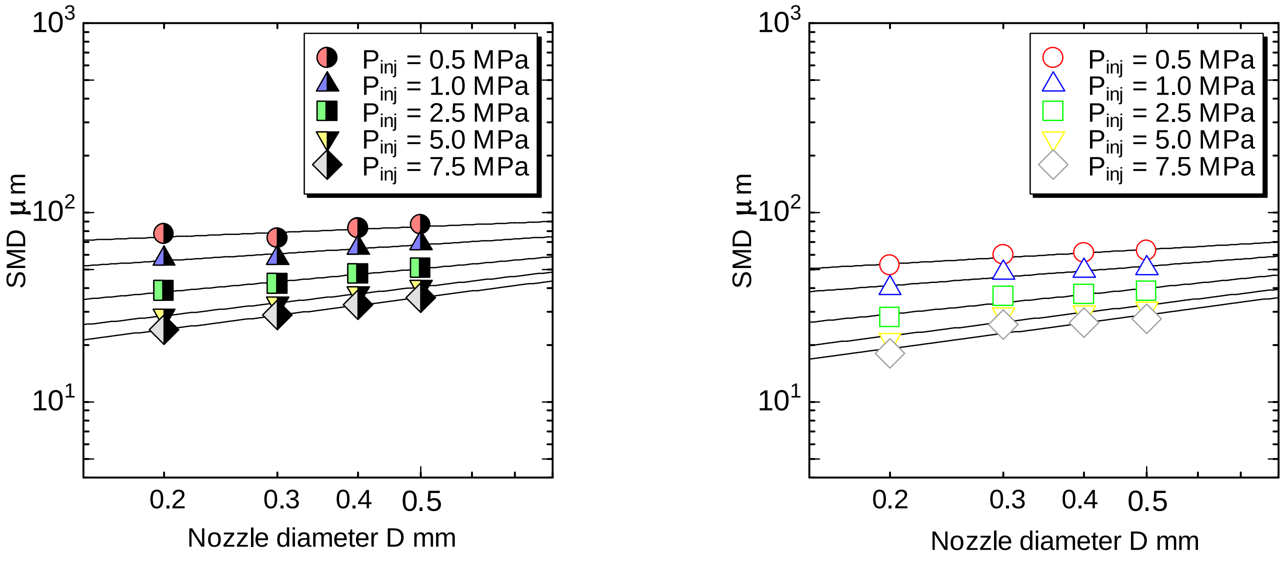
The dependence of the SMD on the injection pressure in the liquid film atomization is less than that of the free jet atomization. Thus, the advantage becomes less with the increase in the injection pressure, and then the lines for the free jet and the liquid film would intercept at a certain injection pressure. At would be about P_{inj} = 12.0 and 14.0 MPa for D = 0.2 mm at α = 30 and 90 deg respectively, and about P_{inj} = 7.0 and 9.0 MPa and for D = 0.5 mm at α = 30 and 90 deg respectively. It is considered that the SMDs for the free jet atomization and the liquid film atomization possibly intercept. In Figs. 4 (b) and 5 (b), with the increase in the injection pressure, the breakup length r* of the liquid film decreases. At the injection pressure P_{inj} = 7.0 to 14.0 MPa, since the liquid film is not formed, it is considered that there is an upper limit of the injection pressure in the liquid film atomization.



(a) D = 0.2 mm

(b) D = 0.5 mm

Fig.9 SMD variation with the injection pressure P_{inj}



(a) α = 30 deg (b) α = 90 deg

Fig.10 SMD variation with the nozzle diameter D

Table 2 SMD variation with the nozzle diameter D, for α = 30 deg

Injection Pressure P_{inj} [MPa]	Variation with SMD and nozzle diameter D
0.5	$\mathrm{SMD} \propto D^{0.14}$
1.0	$\mathrm{SMD} \propto D^{0.21}$
2.5	$\mathrm{SMD} \propto D^{0.31}$
5.0	$\mathrm{SMD} \propto D^{0.38}$
7.5	$\mathrm{SMD} \propto D^{0.43}$

Table 3 SMD variation with the nozzle diameter D, for α = 90 deg

Injection Pressure P_{inj} [MPa]	Variation with SMD and nozzle diameter D
0.5	$\mathrm{SMD} \propto D^{0.19}$
1.0	$\mathrm{SMD} \propto D^{0.26}$
2.5	$\mathrm{SMD} \propto D^{0.34}$
5.0	$\mathrm{SMD} \propto D^{0.41}$
7.5	$\mathrm{SMD} \propto D^{0.45}$

3.4. Parameters Determining the Droplet Size

Figures 10 (a) and (b) show variation of the SMD with the nozzle diameter, for α = 30 and 90 deg, respectively.

Tables 2 and 3 show the dependence of the SMD on the nozzle diameter in each injection pressure, for α = 30 and 90 deg, respectively. It is shown that the SMD is proportional to $D^{0.14\text{ to }0.43}$ for the impingement angle α = 30 deg, and $D^{0.19\text{ to }0.45}$ for the impingement angle α = 90 deg, respectively. At the same injection pressure, with the decrease in the nozzle diameter, the SMD becomes smaller. It is considered that the liquid film thickness at the breakup point decreases with the decrease in the nozzle diameter. Then, with the decrease in the injection pressure, the dependence of the SMD on the nozzle diameter becomes smaller. Thus, in the liquid atomization, although the SMD decreases as the nozzle diameter decreases, the dependence of the SMD on the nozzle diameter is small.

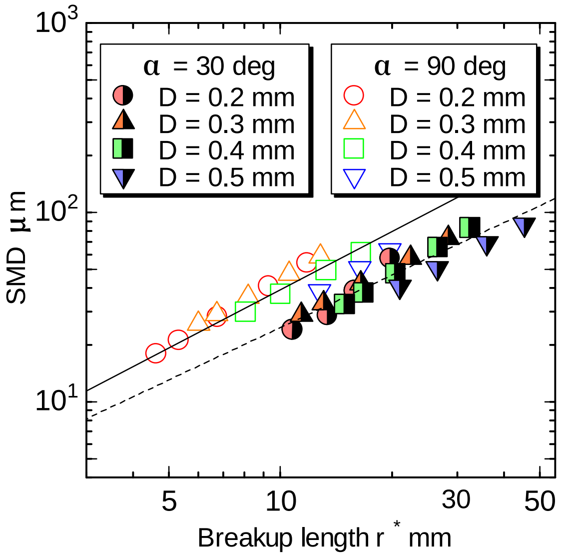


Fig.11 Variation of SMD with the breakup length r*

Figure 11 shows the variation of the SMD with the breakup length r* for the impingement angle α = 30 deg and 90 deg, respectively.

It is shown that, for each impingement angle α, the SMD gathers onto one line as a function of the breakup length r*, regardless of the injection pressure and the nozzle diameter. Therefore, it is believed that the SMD is affected by the breakup length r*. When the breakup length r* is same, the force by the surface tension is same. Thus, in the liquid film atomization, it is believed that the breakup length r* is one of the most important parameters.

4. CONCLUSIONS

Effects of nozzle diameter on the atomization characteristics of a wall impingement liquid jet were investigated experimentally. The nozzle diameter, the injection pressure and the impingement angle were varied. Results are summarized as follows:

1. The liquid jet velocity V_1 is almost the same as the potential velocity V_{th}.
2. The liquid film velocity V_2 decelerates due to the force by surface tension and it becomes smaller than the potential velocity V_{th}.
3. In low injection pressures, the SMD of the liquid film atomization is much smaller than the free jet atomization.
4. In the liquid film atomization, when the nozzle diameter D = 0.2 mm, the injection pressure P_{inj} = 7.5 MPa, and the impingement angle α = 90 deg, about 18 μm of the SMD is obtained.
5. In the liquid film atomization, for the impingement angle α = 30 deg, the SMD is proportional to $D^{0.14 \text{ to } 0.43}$.
6. In the liquid film atomization, for the impingement angle α = 90 deg, the SMD is proportional to $D^{0.19 \text{ to } 0.45}$.
7. In the liquid film atomization, although the SMD decreases as the nozzle diameter decreases, the dependence of the SMD on the nozzle diameter is small.
8. In the liquid film atomization, it is believed that the breakup length r* is one of the most important parameters.

5. ACKNOWLEDGEMENTS

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