Feasibility of Improving the Atomization Characteristics with Wall Impingement for Steady Jet

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Abstract

In the present study, effects of wall impingement of a liquid steady jet on atomization characteristics were investigated, experimentally. Water is injected from a 0.3 mm-diameter nozzle, whose length-diameter ratio is 0.4, and a liquid column is formed. The liquid column impinges on a solid wall positioned 18 mm downstream from the nozzle exit, forming a thin liquid film. The impingement wall diameter was varied as 1.0, 3.0 and 10 mm. The impingement angle was varied as 30, 60 and 90 deg. The liquid film was visualized by an instantaneous shadowgraph. It is observed that the liquid film breaks into ligaments at the film tip and that the ligaments break into droplets. Velocity of the film was measured by PDPA. SMD of the droplets was measured by LDSA. It is shown that SMD of the droplets is determined by the film velocity and impingement angle, regardless of the injection pressure and impingement wall diameter. When the liquid film velocity is smaller than 300 m/s, smaller SMD is obtained compared with a free jet.

1. Introduction

Liquid atomization is a key technology in various practical combustors, such as gas turbines, jet engines, diesel engines, gasoline direct injection engines and so on. It is necessary to establish a liquid atomization technology that can obtain fine droplets with smaller injection pressure.

Wall impingement of a steady liquid jet is expected to be useful to form a thin liquid film, and it may possibly improve atomization characteristics due to breaking of the thin liquid film. Liquid film atomization is widely used in practical atomizers, such as fan spray nozzles [1-3] and rotating disk atomizers and so on. Inamura et al. [4-6] have been investigated effects 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. [7] have also been investigated effects of utilization of wall impingement on 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 works, it is shown that the wall impingement remarkably decrease the droplet diameter. However, in these practical works, liquid film geometries and experimental parameters are rather complicated, and it is difficult to extract dominant phenomena.

In the present study, a steady liquid jet emerging from a 0.3 mm-diameter nozzle is impinged on a solid wall. Three major parameters are investigated, such as (i) the injection pressure, (ii) the impingement wall diameter and (iii) the impingement angle. These are varied widely, and effects of them are investigated. Karasawa et al. [8] have investigated atomization characteristics of a free jet with the same nozzle as the present study. In their work, it is clearly shown that SMD of the droplets is determined by the jet velocity at the nozzle exit, regardless of the nozzle geometry and the injection pressure. Similar results would possibly be obtained in the present study. Therefore, as an additional parameter, (iv) the liquid film velocity is also investigated.

2. Experimental Setup

Figure 1 shows experimental setup in the present study. Water is injected from a 0.3 mm-diameter nozzle, whose length-diameter ratio is 0.4, and a liquid column is formed. The nozzle is so-called straight type [8]. The liquid column impinges on a solid wall positioned 18 mm downstream from the nozzle exit, forming a thin liquid film. The liquid column velocity is V_1, and the liquid film velocity is V_2. The solid wall is an end of a cylinder bar, and the wall diameter d was varied as d = 1.0, 3.0 and 10 mm. The impingement angle α was varied as α = 30, 60 and 90 deg. For the all impingement angles, the surface of the impingement wall is kept vertically, while the injection angle was changed. Therefore, the liquid film is formed within the vertical plane. The injection pressure was varied from 0.49 to 49 MPa. As pressure sources, bottled nitrogen for smaller pressure case and an oil pump for larger pressure case, were used. The origin of the coordinate system is set at the center of the impingement wall, and x axis is set vertically downward along the liquid film plane.

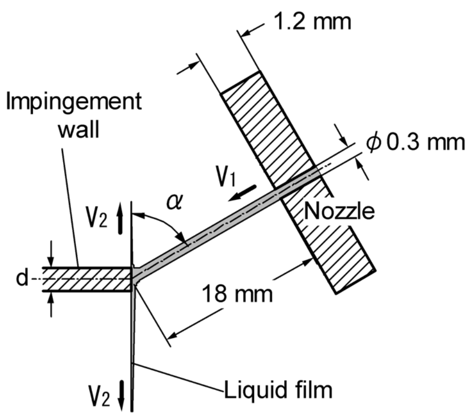


Fig. 1 Schematic of the experimental setup.

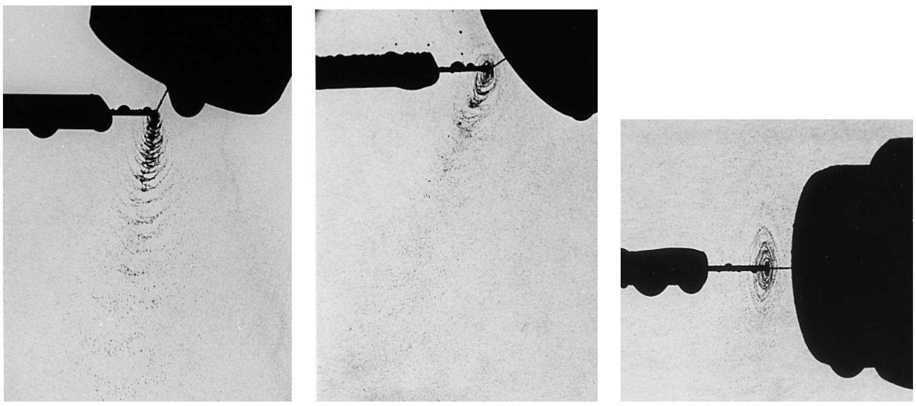
The liquid film was visualized by an instantaneous shadowgraph. The light source was a flash light. The pulse duration is short enough to freeze the image. The liquid film velocity V_2 was measured by PDPA. The measuring position was x = 4 mm. In the present study, for comparison, free jet velocity V_1 was also measured. The measuring position was along the jet center axis and 18 mm downstream from the nozzle exit. SMD of the droplets was measured by LDSA. The measuring position was x = 1000 mm. The position was decided according to Karasawa et al. [8], for direct comparison of SMD with the free jet.

3. Results and Discussions

3. 1. Flow Visualizations

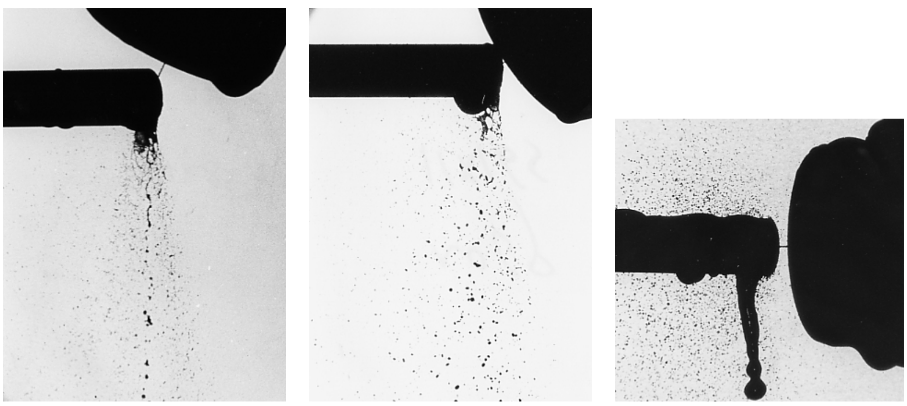
Figures 2 (a) to (c) show instantaneous shadowgraph images, for the impingement wall diameter d = 1.0 mm and the injection pressure P_0 = 1.0 MPa. Figs. 2 (a), (b) and (c) shows the images for the impingement angle α = 30, 60 and 90 deg, respectively. Large shadow on the right side of the images is the nozzle holder. Small shadow on the left side of the images is the impingement wall. For the impingement angle α = 30 deg, it is observed that a fan shaped liquid film is formed. With the increase in the impingement angle α, the spread angle of the liquid film is increased. For the impingement angle α = 90 deg, 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 film breaks into ligaments at the film tip. Second, the ligaments break into droplets. These atomization processes are observed in experiments of Tanasawa et al. [9].

Figures 3 (a) to (c) show instantaneous shadowgraph images, for the impingement wall diameter d = 10 mm and the injection pressure P_0 = 1.0 MPa. Figs. 3 (a), (b) and (c) shows the images for the impingement angle α = 30, 60 and 90 deg, respectively. When the impingement wall diameter d = 10 mm and the impingement pressure is small, it is observed that some part of impinged liquid sticks onto the impingement wall surface, and drips from it.



(a) α = 30 deg. (b) α = 60 deg. (c) α = 90 deg.

Fig. 2 Instantaneous shadowgraph images, for P_0 = 1.0 MPa and d = 1.0 mm.



(a) α = 30 deg. (b) α = 60 deg. (c) α = 90 deg.

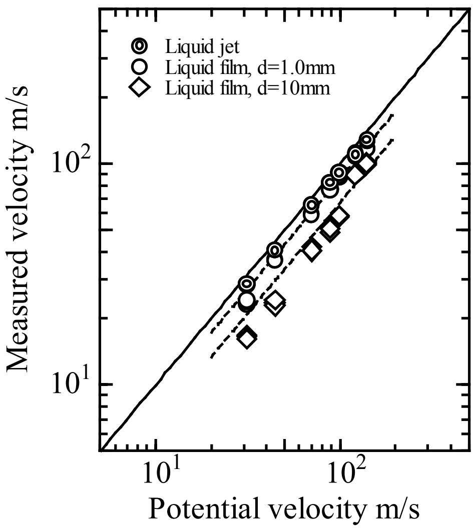
Fig. 3 Instantaneous shadowgraph images, for P_0 = 1.0 MPa and d = 10 mm.

It is considered that the liquid losses the momentum when flowing over the wall surface because of viscous friction. Therefore, it is considered, for the case of dripping, that the data should be treated carefully.

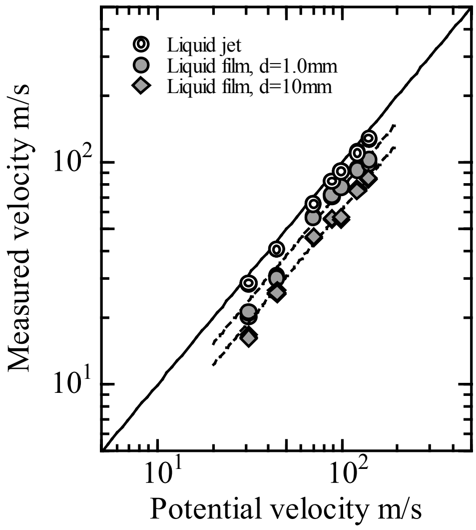
3. 2. Film Velocity Measurements

Figures 4 (a) and (b) show typical results of the film velocity measurements, for α = 30 and 90 deg, respectively. The measured film velocity is shown as a function of the calculated potential velocity by the Bernoulli's equation. The measured free jet velocity is also shown in the figures.

The free jet velocity V_1 is very close to the potential velocity. It is shown that, for the free jet case, the liquid emerges from the nozzle and reaches the maximum velocity without losses, especially for a straight type nozzle [8]. On the other hand, for wall impingement jet cases, the liquid film velocity is rather smaller than the potential velocity. From the Bernoulli's equation, it is predicted that the liquid jet velocity and the liquid film velocity are the same. However, in the present study, with the increase in the impingement wall diameter d, the film velocity decreases. And with the increase in the impingement angle α, the film velocity decreases. Therefore, two aspects are considered, such as (i) friction when flowing over the solid wall surface and (ii) friction when changing the flow direction.



(a) α = 30 deg.



(c) α = 90 deg.

Fig. 4 Liquid jet and Liquid film velocities.

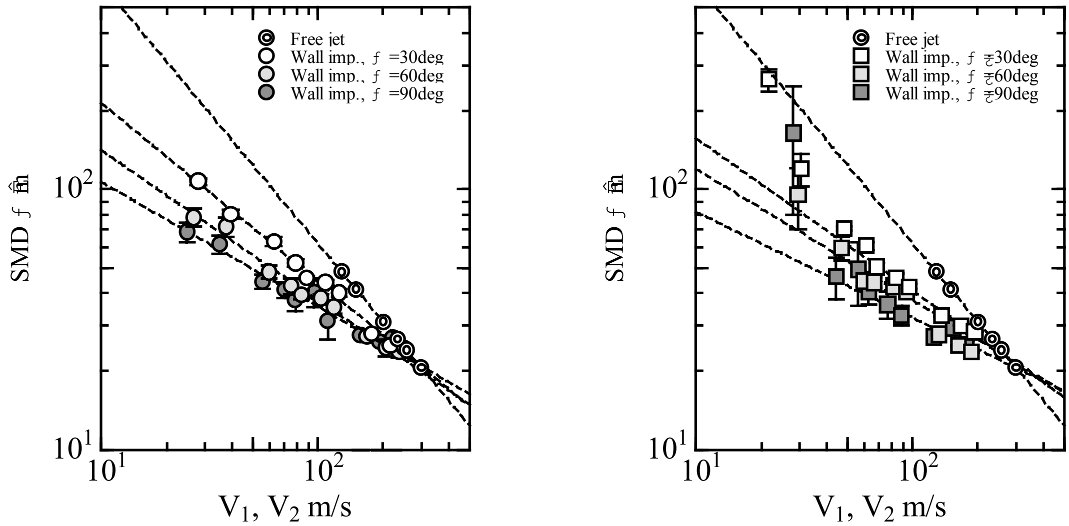
3. 3. Droplet Size Measurements

3. 3. 1 Impingement Wall Diameter Effects on Droplet Size

Figure 5 (a) shows SMD as a function of the film velocity V_2, for the impingement wall diameter d = 1.0 mm. Results of the free jet by Karasawa et al. [8] are also shown in the figure. SMD for the free jet are shown as a function of free jet velocity V_1. Error bars in the figures are estimated from standard deviations of the sets of measurements. For all cases, it is shown that with the increase in the liquid jet and liquid film velocities, SMD decreases lineally.

However, the slope is different. For wall impingement jet cases, with the decrease in the impingement angle α, the slope becomes steeper, getting closer to the results of the free jet. It is considered that the case of the impingement angle α = 0 deg may correspond to the free jet.

Figure 5 (b) shows SMD as a function of the film velocity V_2, for the impingement wall diameter d = 10 mm. The results are similar to Fig. 5 (a). However, in the small velocity region, some differences are seen. With the decrease in the liquid film velocity V_2, especially bellow $V_2 \approx 30$ m/s, SMD suddenly increases. It is considered that this rapid change in SMD attributed to the dropping mentioned above.



(a) d = 1.0 mm.　　(b) d = 10 mm.

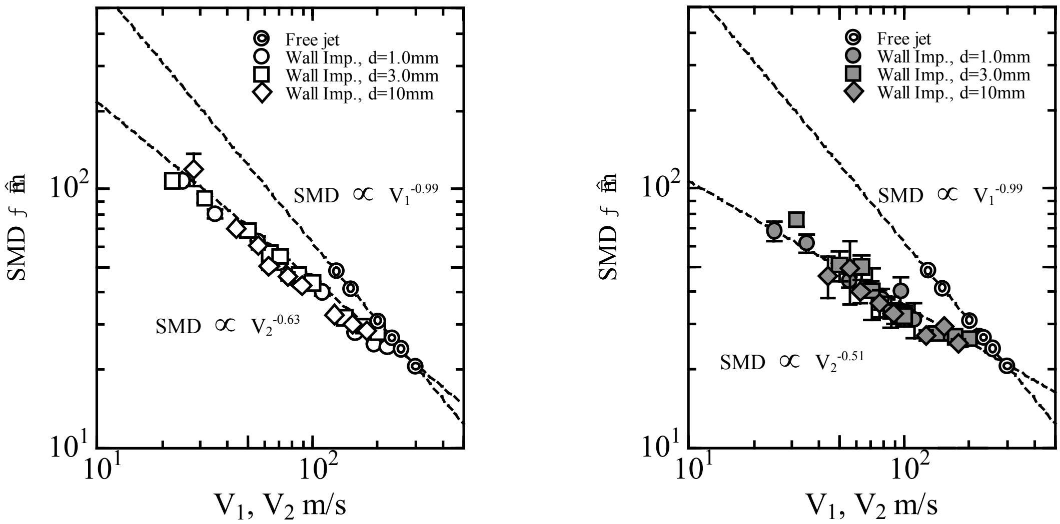
Fig. 5 SMD as a function of liquid jet and liquid film velocities.

3. 3. 2 Velocity and Impingement Angle Effects on Droplet Size

Figures 6 (a) and (b) show SMD as a function of the film velocity V_2, for all the impingement wall diameter conditions. Figs. 6 (a) and (b) shows the results for α = 30 and 90 deg, respectively. Plots affected by the dripping are omitted from the figures. In the figures, four important features are seen, which will be discussed bellow.

First, it is clearly shown, for each impingement angle α, that SMD gathers onto one line as a function of the liquid film velocity V_2. Therefore, it is considered that SMD is determined by the liquid film velocity and impingement angle, regardless of the injection pressure and impingement wall diameter. As mentioned above, with the change in the impingement wall diameter, liquid film velocity changes. Therefore, at the same time, the thickness of the film changes due to the mass conservation law. However, the effects of the thickness variation do not appear in the figure. From the mass conservation law, the change in the film thickness due to the impingement wall diameter, is about 30 % at the maximum. It is considered that the film thickness may have small effects on SMD.

Second, it is shown that gradients of the lines for the impingement angle α = 30 and 90 deg, are –0.63 and –0.51, respectively. For free jets, similar results were reported by Tanasawa



(a) α = 30deg. (c) α = 90deg.

Fig. 6 SMD as a function of liquid jet and liquid film velocities.

et al. [10] for the velocity region from 50 to 150 m/s, and by Karasawa et al. [8] for the velocity region from 100 to 300 m/s. It is shown from these studies that, for the free jets, SMD is expressed as the following equation,

$$\mathrm{SMD} \propto \mathrm{U}^{-1.0}, \qquad (1)$$

where U is liquid jet velocity. For impingement jets, Tanasawa et al. [9] reported similar results, for the velocity region from 10 to 50 m/s. They conducted atomization experiments using a liquid-liquid impingement jet. In their study, it is shown that, for the normal impingement case, that corresponds to α = 90 deg in the present study, SMD is expressed as the following equation,

$$\mathrm{SMD} \propto \mathrm{U}^{-0.5}, \qquad (2)$$

where U is the liquid jet velocity. Because the liquid jet velocity is proportional to the liquid film velocity, the relationship above is valid for the present study. In the present study, it is shown that the relationship above is valid for further wide range of the film velocity.

Third, it is shown, for α = 30 deg, that the gradient takes the value between –1.0 and –0.5. It is considered, for this case, that characteristics of both of the free jet and impingement jet are included. As mentioned above, it is considered that the case of α = 0 deg corresponds to the free jet. It means the two-dimensional liquid film with the spread angle of zero. The spread angle of the liquid film may play an important role. With the increase in the spread angle of the liquid film, the geometry becomes axisymmetric film rather than two-dimensional film. The spread of the liquid film may induce stretch of the film. It is considered that such stretch process may reduce the droplet size in the small velocity region. It is shown that the case of α = 90 deg is the most desirable for liquid atomization with smaller injection pressure. For example, it is shown that over 75 % reduction in SMD at the velocity $V \approx 20$ m/s, compared with the free jet.

Forth, it is shown, for all the impingement angle cases, that all the fitted lines intersect at $V \approx 300$ m/s. Wall impingement is no more effective on liquid atomization beyond $V \approx 300$ m/s, while the detail is not clear so far.

Consequently, to obtain fine droplets with wall impingement of a liquid steady jet, it is necessary (i) to use a small impingement wall, (ii) to impinge the liquid jet onto the wall normally, (iii) to be sure that there is an intersection point.

4. Conclusions

Effects of wall impingement of a liquid steady jet on atomization characteristics were experimentally investigated, by changing the injection pressure, impingement wall diameter and impingement angle. Conclusions are follows:

1. With the increase in the impingement wall diameter, the film velocity decreases.
2. With the increase in the impingement angle, the film velocity decreases.
3. SMD of droplets is determined by the liquid film velocity and impingement angle, regardless of the injection pressure and impingement wall diameter.
4. When the impingement angle is 90 deg, SMD of droplets is proportional to $V^{-0.51}$.
5. When the impingement angle is 30 deg, SMD of droplets is proportional to $V^{-0.63}$.
6. When the film velocity is smaller than 300 m/s, by wall impingement, SMD of droplets become smaller compared with a free jet.

5. Acknowledgements

The present study was carried out as a cooperative research between National Aerospace Laboratory of Japan and Gunma University. The authors thank H. Yamamoto of Gunma University for his help and suggestions in experiments.

6. References

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