Atomization behavior on the top of upward liquid jet

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Abstract

Fundamental behavior of an upward liquid jet was investigated experimentally. Atomization characteristics at the top of upward jet were controlled with the injection momentum and breakup process of the jet. Maximum height (top height) of the jet, breakup length and droplet size distributions dispersed from the top of upward liquid jet were measured at various conditions of injection velocity and nozzle diameter. The maximum height of upward liquid jet was agreed with the value calculated by Bernoulli's equation. In the case of a small diameter nozzle (D=1.0mm), the breakup length was equivalent to that of the downward liquid jet. However, SMD of the upward liquid jet spray was larger than that of downward liquid jet. In the case of relatively large diameter nozzle (D=3.0mm), SMD of the upward liquid jet spray became smaller compared with that of downward liquid jet, because the small droplets were formed by the collisions of droplets.

1. Introduction

Many theoretical and experimental works for the atomization phenomena of liquid jet were carried out [1, 2]. In these works, basics characteristics for downward liquid jet using many kinds of cylindrical nozzles have been investigated. Downward liquid jet is elongated to the downward direction by the effect of gravity. Then, the disintegration characteristics are greatly influenced by the gravity [3, 4]. Liquid column diameter of the downward jet became smaller and the wavelength of the surface wave became shorter. In the case of upward liquid jet, it seems that the jet diameter becomes large by the effect of gravity and the disintegration phenomena for the upward liquid jet was differed from that of downward liquid jet. However, there was little information about the atomization phenomena for the upward liquid jet. Experimental data of the upward jet are very important because there are many applications in the various industrial fields, such as sprinkler, jet of wind washer, liquid jet for fire extinguisher. In this paper, fundamental characteristics of the upward liquid jet were investigated experimentally.

2. Experimental setup and method

A schematic view of the experimental apparatus used in this study is shown in Fig.1. The experimental apparatus consisted of a water tank, an injection nozzle, a stroboscope, and a high-speed video camera system.

Cylindrical pipes were used as the injection nozzles to form the liquid jet. Inner diameters of the nozzles used here were D=1.0mm and 3.0mm. In order to make a fully developed velocity distribution at the nozzle exit, length of the nozzle was 50 times longer than the inner diameter of the nozzle. Tap water was used as a test liquid. Water was supplied to the nozzle from the water tank, which was pressurized by the air.

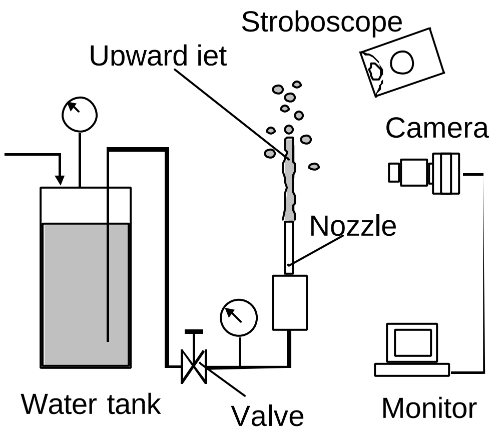

Fig.1 Experimental setup

Behaviors of the liquid jet were investigated by using a high-speed video camera. To discuss the quantitative characteristics of the liquid jet, some parameters shown in Fig.2 were defined. An origin of the vertical axis z was set on the nozzle tip, and the horizontal axis y was set as a radial direction from the z-axis. Maximum height L_{mz} and the breakup length L_{bz} were measured by the naked eye with a stroboscope. Sizes of many droplets were measured from video images and the droplet size distributions were derived.

Experiments of downward liquid jet were also carried out for the comparative study. The breakup length and the droplet size distribution were also measured for the downward liquid jet.

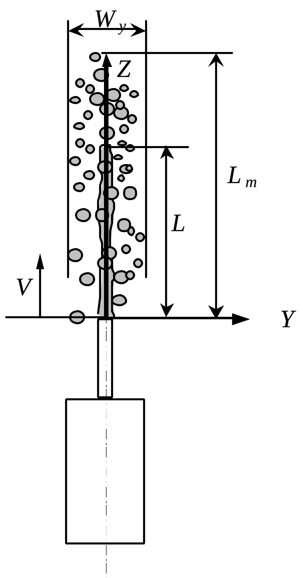

Fig.2 Definition of measurement parameters

3. Results and discussion

3.1. Maximum height and breakup length of upward liquid jet

The maximum height L_{mz} and breakup length L_{bz} were measured for the upward liquid jet under the various conditions of injection velocity. The results for a *D*=1mm nozzle are shown in Fig.3. The symbols (○) represent the maximum height and the symbols (△) represent the breakup length. Breakup length of the downward liquid jet was also measured in order to compare the data of upward and downward liquid jets. Solid circles (●) represent the data of downward liquid jet.

When the injection velocity was smaller than 2m/s, the liquid jet took the maximum height without disintegration of the liquid column. In the higher velocity condition, the jet was disintegrated and spray was formed between breakup point and maximum height. In other ward, this jet was penetrated upward after it being broken-up. In the case, which the velocity was higher than 2m/s, it could be observed that both breakup lengths of upward liquid jet and downward liquid jet are almost same.

The maximum height L_{mz} of the jet could be predicted by the energy balance based on the Bernoulli's equation. At this point, all the kinetic energy should be converted to the potential energy, then, the following equation can be obtained.

$$L_{mz} = \frac{V^2}{2g} \quad (1)$$

Here, V is the injection velocity of the liquid jet, and g is the acceleration of gravity. The solid line in Fig.3 represents the calculated value from Bernoulli's height using the mean velocity of jet injection *V*.

The dashed and dotted lines are the values calculated considering the radial velocity distribution of the liquid jet. The dashed line represents the Bernoulli's height calculated by the maximum center velocity of a fully developed turbulent flow. And the dotted line was calculated value from the maximum center velocity of laminar flow. From the comparison between predicted height and experimental one, it can be said that experimental data was almost agreed with that of the Bernoulli's height calculated by the mean injection velocity.

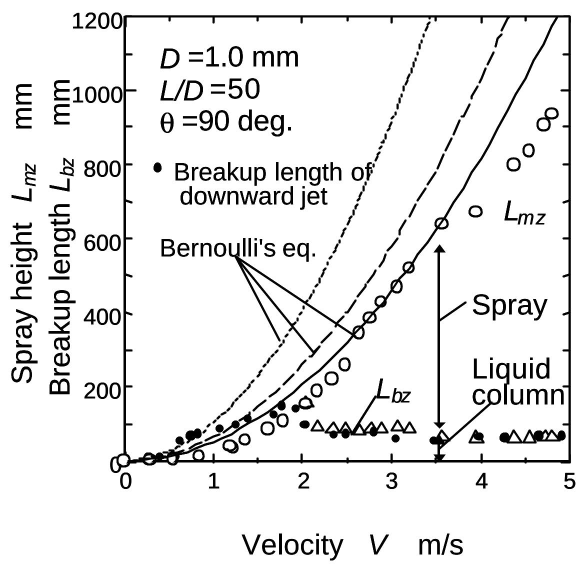

Fig.3 Spray height and breakup length (*D*=1.0mm)

The results for liquid jet for D=3mm nozzle are shown in Fig.4. The maximum height L_{mz} had the similar tendency with the result of Fig.3. Breakup length L_{bz} of the upward liquid jet was slightly short compared with that of downward liquid jet. This tendency was differed from the case of 1mm nozzle. The reason of this difference might be explained as follows. Breakup length of the liquid jet injected from the 3mm nozzle was longer than that of the jet injected from 1mm nozzle at the same injection velocity. Since the breakup length was relatively short for the 1mm nozzle jet, it seemed that the liquid column diameter was not changed at the high injection velocity conditions. Therefore, the breakup length of the upward liquid jet became equivalent to that of downward liquid jet.

In the case of 3mm nozzle, the breakup length of the liquid jet became relatively long. Therefore, the liquid column diameter of the upward liquid jet increased at near the breakup point by the effect of gravity. Namely, the liquid column was contracted vertically. On the other hand, the liquid column of downward jet was elongated vertically by the effect of gravity. Therefore, the breakup length of upward jet became shorter compared with that of downward jet.

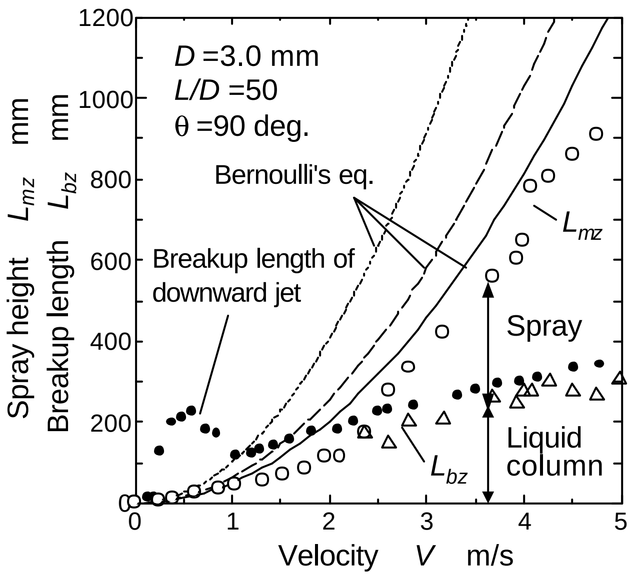

Fig.4 Spray height and breakup length (D=3.0mm)

3.2. *Droplet size distributions for upward liquid jets of D=1mm nozzle*

The diameters of many droplets produced in upward jet were measured from the high-speed video images. Droplet size distribution was derived from the data of several hundred droplets. Measuring area was set at top portion of the upward liquid jet. For the comparative study, the droplet size distribution of the downward jet was also derived. Measuring area of the downward jet was set at down stream of the breakup point.

Figure 5 shows the droplet size distributions for D=1mm nozzle at various injection velocity conditions for upward liquid jet. Injection velocity V was set at 2.6, 3.1 and 3.7m/s. Then the Reynolds numbers were Re=2600, 3100 and 3700, respectively. The droplet size distributions were broad in the cases of V=2.6m/s and 3.1m/s. In the case of V=3.7m/s, two peaks, were observed in the distribution.

Figure 6 shows the droplet size distributions for downward liquid jet. Injection velocities were set at same values in Fig.5. Clearer peak appeared in the size distribution compared with the results of Fig.5. Since the Reynolds number was around 3000, it seemed that the flow conditions were laminar or transient states. In these conditions, irregular breakup phenomena were observed but the regularity of the breakup frequency was relatively high. So the droplet size distribution has a peak as shown in Fig.6. However, in the case of upward liquid jet, the droplet size distribution was consisted of a broad components. The reason of it is explained later.

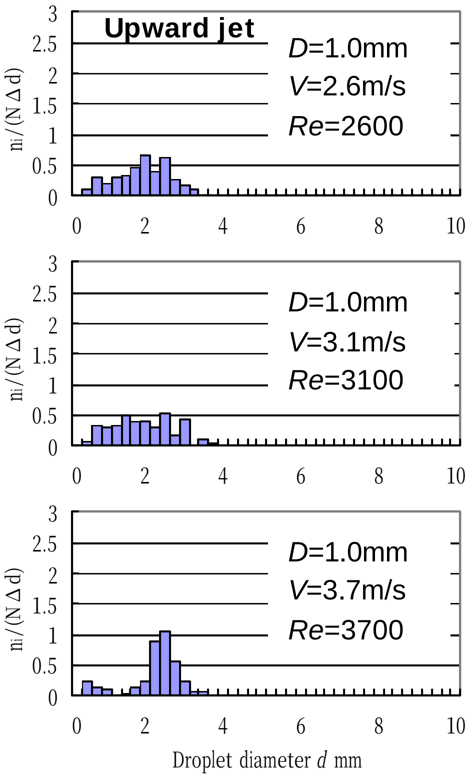

Fig.5 Droplet size distributions of upward jet (D=1.0mm)

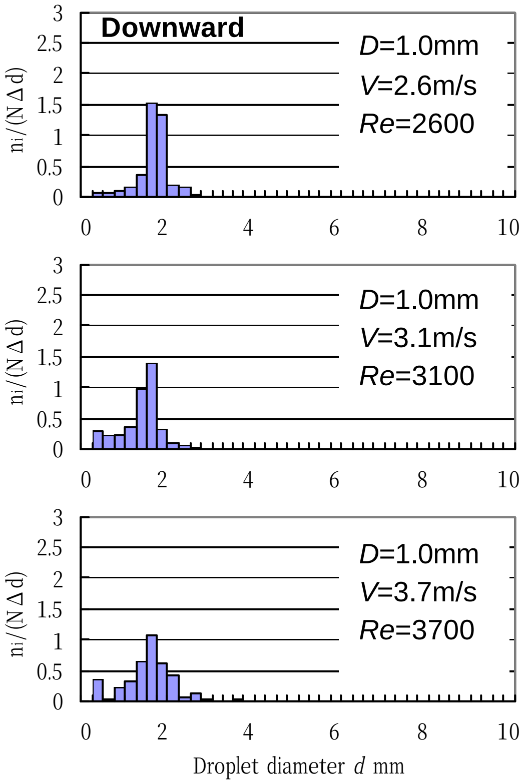

Fig.6 Droplet size distributions of downward jet (D=1.0mm)

Figure 7 shows a photographs of upward laminar liquid jet of 1mm nozzle at the injection velocity of V=2.3m/s. Droplet size around the breakup point was relatively uniform. However, the some different size droplets appeared around the top portion of the jet. From this photograph, it seemed that the coalescence of several droplets were occurred around the top portion of upward jet and the droplet size distribution became broader.

Sauter mean diameter, SMD, was derived from the droplet size distribution. SMD was calculated by $\sum_i n_i d_i^3 \Big/ \sum_i n_i d_i^2$ and the results were summarized in Fig.8. It was found that the SMD of upward liquid jet was larger than that of downward liquid jet. The reason of this result may be easily explained as follows. As shown in Fig.7, the coalescence of the droplets occurred in the upward liquid jet, whereas the coalescence was very few in the case of downward liquid jet. From the result of Rayleigh's instability theory of liquid column, the droplet size d is derived as 1.89D_l. Where, D_l is a liquid column diameter. If it was assumed that the liquid column diameter was same as the nozzle diameter, the droplet size of the liquid jet injected from 1mm nozzle was about 1.89mm. This value was close to the data of downward liquid jet.

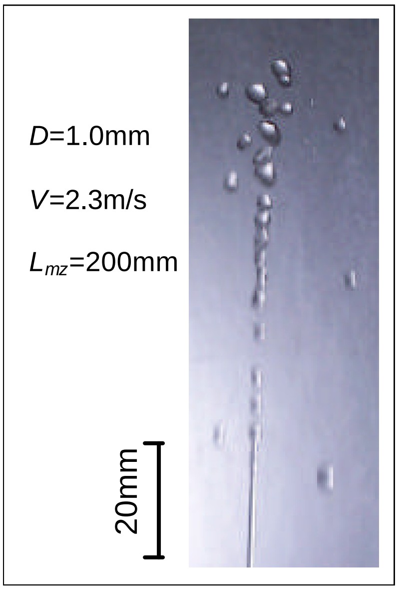

Fig.7 Photograph of upward liquid jet

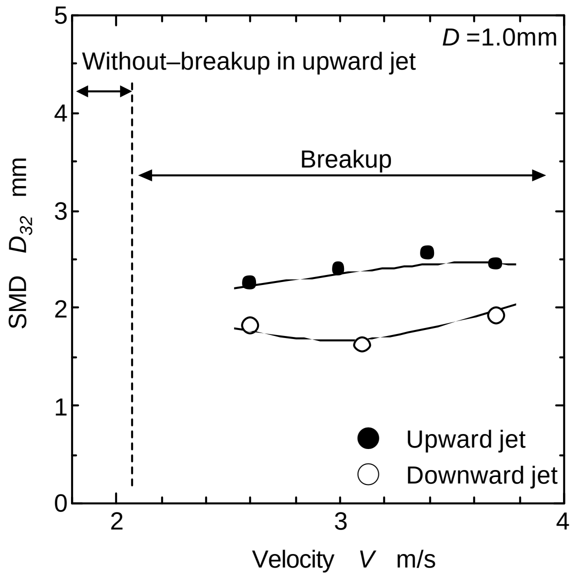

Fig.8 Comparison of SMD between upward and downward jets (D=1.0mm)

3.3. Droplet size distributions for upward liquid jets of D=3mm nozzle

Droplet size distributions for upward liquid jet of 3mm nozzle were derived as shown in Fig.9. In the both cases of V=2.6m/s and 3.7m/s, droplet size distributed in the very wide range from 0.2mm to 9mm. At higher injection velocity of 8.1m/s, many small droplets were observed in the droplet size distribution. The maximum peak was observed around 1mm.

On the contrary droplet size distributions for downward liquid jet of 3mm nozzle were shown in Fig.10. In the cases of V=2.6m/s and 3.7m/s, droplet diameter distributed in the relatively wide ranges. From the comparison between Figs.9 and 10 at the case of 8.1m/s, it was confirmed that the droplet size distributions for upward liquid jet were very differed from those for downward liquid jet.

SMD was also derived for 3mm nozzle jet and the results were summarized in Fig.10. SMD of downward liquid jet was independent of injection velocity. However, SMD of upward liquid jet decreased with increasing the injection velocity. When the injection velocity was lower than 6m/s, SMD of upward liquid jet was larger than that of downward liquid jet. This result may be explained as the droplet coalescence as described in Fig.8.

When the injection velocity became higher than 6m/s, SMD of upward liquid jet became smaller than that of downward liquid jet. In order to clarify the reason of this result, detail observations of the upward jet were carried out by using a high-speed video system. Figure 12 shows some photographs taken at various height of upward liquid jet under the condition of V=8.1m/s. As shown in the figure, relatively uniform size droplets were observed around the breakup point. However, the liquid sheet, which was formed by the collisions of droplets, was observed at the downstream portion of the breakup point. And it was observed that many small droplets were formed by the disintegration of the liquid sheet. Namely, secondly breakup phenomena by the inter-droplets collisions occurred in this condition of V=8.1m/s. By this secondly breakup, droplet size distribution shifted to the smaller side in the case of upward liquid jet.

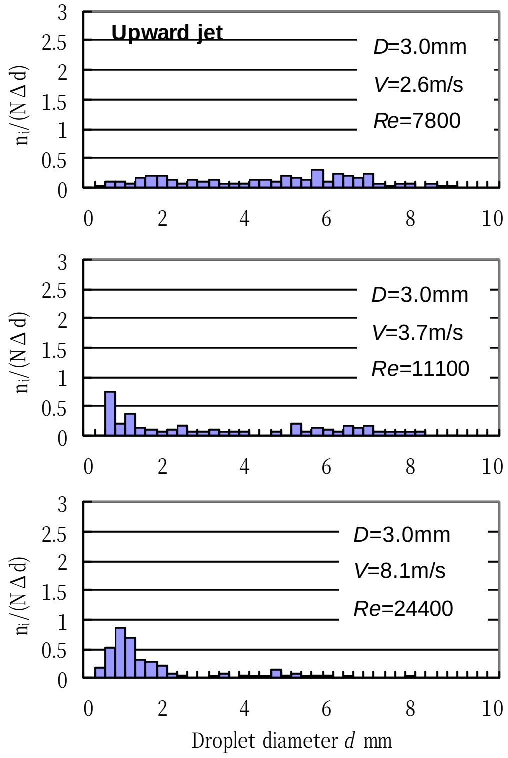

Fig.9 Droplet size distributions of upward jet (D=3.0mm)

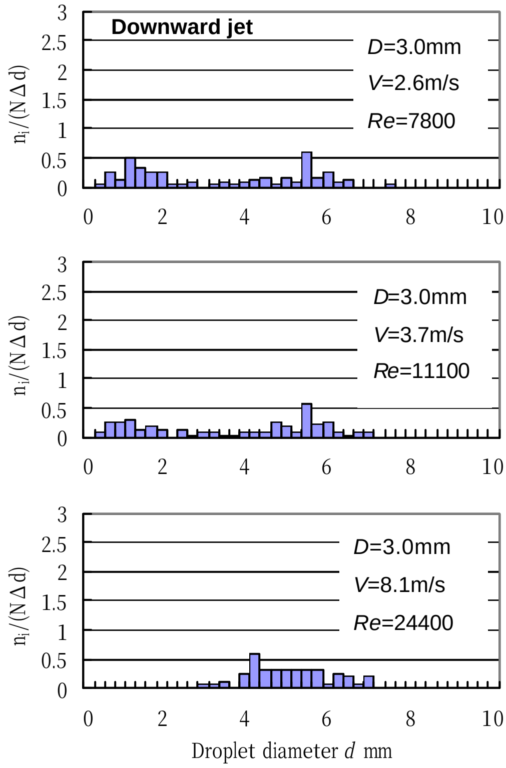

Fig.10 Droplet size distributions of downward jet (D=3.0mm)

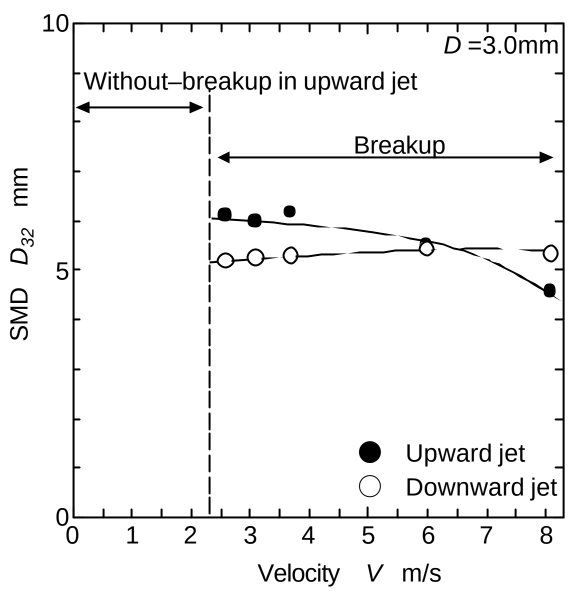

Fig.11 Comparison of SMD between upward and downward jets (D=3.0mm)

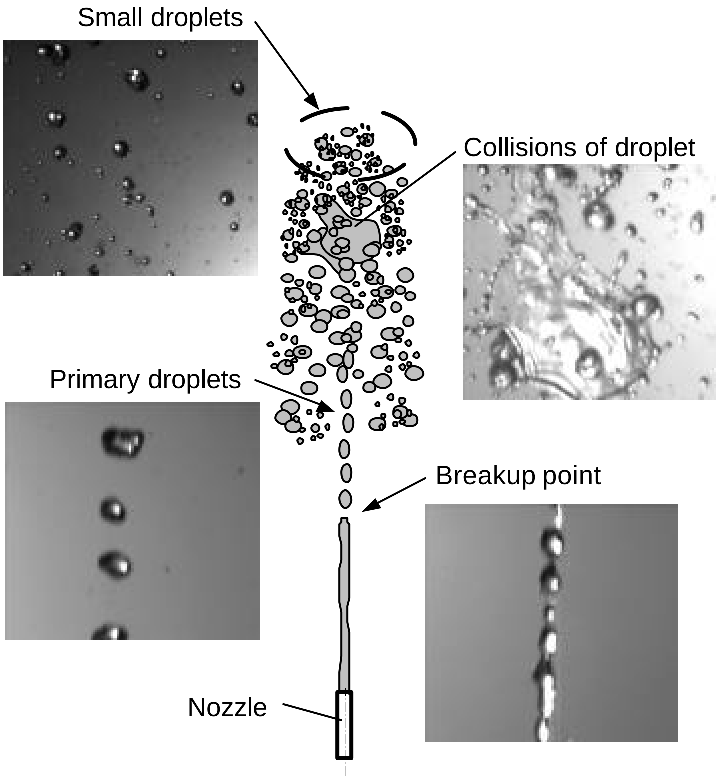

Fig.12 Structure of upward jet (D=3.0mm)

4. Conclusions

1. The maximum height of upward liquid jet was almost the same to the height predicted by Benoulli's equation using the mean injection velocity.
2. The Sauter mean diameter of the upward liquid jet was larger than that of downward liquid jet for small diameter nozzle (D=1.0mm).
3. In the case of relatively large diameter nozzle (D=3.0mm), the Sauter mean diameter of upward liquid jet became smaller with an increase of injection velocity. Collision of droplets in the upward jet was observed in the upward liquid jet. And it was found that the decrease of SMD was caused by the droplet collision in the condition of V=8.1m/s

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