Effect of Cavitation in the Cylindrical Nozzle on the Liquid Breakup Process

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The objective of this study is to promote the disintegration of liquid jet by cavitation inside a nozzle. Using a cylindrical nozzle, the effects of the nozzle dimensions on the liquid breakup are investigated. When the length-diameter ratio L/D of a nozzle is low, cavitation bubbles are formed inside the nozzle and the breakup of the issuing jet is promoted.

1. Introduction

The atomization by pressure atomizers permits the promotion of atomization using high injection pressure of 100 MPa or higher, but the technique suffers from nozzle durability and the fact that the mean diameter of the spray cannot be reduced to below 15 μm. Therefore, if increases in drop size can be suppressed even at low pressures, the technique can potentially be beneficial from the standpoint of energy savings. As such, attempts have been made to promote the atomization process by exploiting the disturbance of liquid flow due to the cavitation within the nozzle. Shimizu et al.[1] used cylindrical nozzles having a nozzle length/nozzle diameter ratio of L/D=1-50 to investigate the cavitation and the breakup pattern of the liquid. They confirmed that, up to an injection pressure of 2.0 MPa, contraction flow and cavitation arise, and the contraction flow re-attaches to the nozzle wall. They also reported that the location of re-attachment moves toward the nozzle outlet as the injection pressure increases, and the atomization process is promoted accordingly. Tamaki et al.[2] used a nozzle equipped with a mesh at the nozzle inlet and a nozzle equipped with a ring-shaped groove inside the nozzle to examine the pattern of cavitation inside the nozzle and the pattern of breakup of the liquid over the range of L/D=1-20. They reported that in the case of a nozzle fitted with a mesh, as the L/D ratio increases, the breakup length increases and the spray angle decreases, with worsening atomization characteristics.
With the objective of studying the effect of the generation and collapse of cavitation in a nozzle on the breakup of liquid, we used cylindrical nozzles as a preliminary step to observe and discuss the effects of nozzle dimensions and geometrical configurations on the internal flow and the pattern of the breakup of the liquid.

2.Experimental Method

Figure 1 shows a schematic of a sample cylindrical nozzle constructed of transparent PMMA. Figure 1 (a) shows a configuration having a sharp corner part in the nozzle that facilitates the generation of contraction flow (S-Type) in the nozzle. Table 1 shows the dimensional specifications for the S-Type nozzle. We prepared a total of nine types of nozzles by fixing *L*/*D* at 3, 12 and 20; by fixing the nozzle diameter *D* at 0.5, 1.5 and 3 mm; and by determining the corresponding nozzle length *L*. In the present paper, we principally describe the results obtained using nozzles having a nozzle diameter *D* of 1.5 mm to 3 mm. Figure 1 (b) shows a nozzle with a round (*R*=3.5 mm) nozzle inlet (R-Type). Figure 1 (c) shows a tapered nozzle (T-Type) in which the nozzle diameter decreases monotonously.

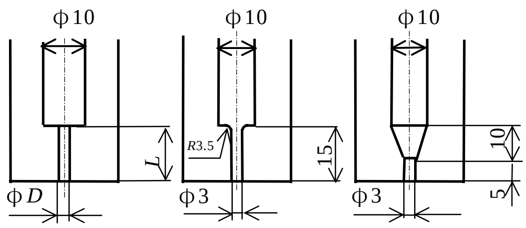
Figure 2 shows a schematic of the experimental apparatus. The liquid used is tap water. The pattern of liquid disturbance in the nozzle and the pattern in which the issued liquid film were photographed on a 35 mm still camera using transmission light based on a micro-flash light source. In the present study, the primary focus is the assessment of fundamental phenomena, including the observation of the generation of cavitation. For this reason, the absolute pressure of the injection was a low 0.2-0.8 MPa. The Reynolds number *Re* was defined according to the following equation, using the average velocity *U* and nozzle diameter *D*:

$$Re = \frac{UD}{\nu} \qquad (1)$$

3. Experimental Results and Discussion

3.1 Flow internal to the cylindrical nozzle and the pattern of liquid breakup

Figure 3 shows the internal flow within an S-Type nozzle (top) and the pattern of breakup of the issuing liquid (bottom) for an *L*/*D*=20 configuration. For *L*/*D* =20, cavitation does not generate in the sharp corner part of the nozzle when the injection pressure is 0.2-0.5 MPa (Fig. 3 (a)-(d)). The bottom photograph shows the behavior of the liquid flow around 200 mm downward from the nozzle outlet, which indicates that there is little atomization of the liquid jet. When the injection pressure rises above 0.6 MPa (Re=5.23×10^4-8.26×10^4) (Figs. 3 (e)-(g)), there is some cavitation due to the sharp corner section of the nozzle. However, these cavitation bubbles collapse as they form. Furthermore, although the issued liquid surface is disturbed, breakup is not promoted to an extent that is comparable to the case in which the injection pressure is higher than 0.8 MPa. This behavior may be due to the fact that even if disturbance occurs because of the collapse of cavitation bubbles, the large *L*/*D* value, i.e., the large nozzle length *L*, causes the disturbance to attenuate as the liquid flows



(a) S-Type (b)R-Type (c)T-Type

Fig.1 Test cylindalical nozzles

Table 1 Dimensional specifications for the S-Type nozzle

D (mm)	*L* (mm)	*L*/*D*
3	9	3
1.5	4.5	
0.5	1.5	
3	36	12
1.5	18	
0.5	6	
3	60	20
1.5	30	
0.5	10	

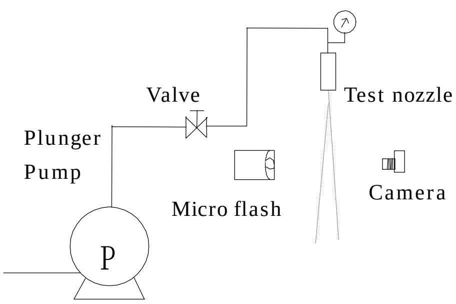
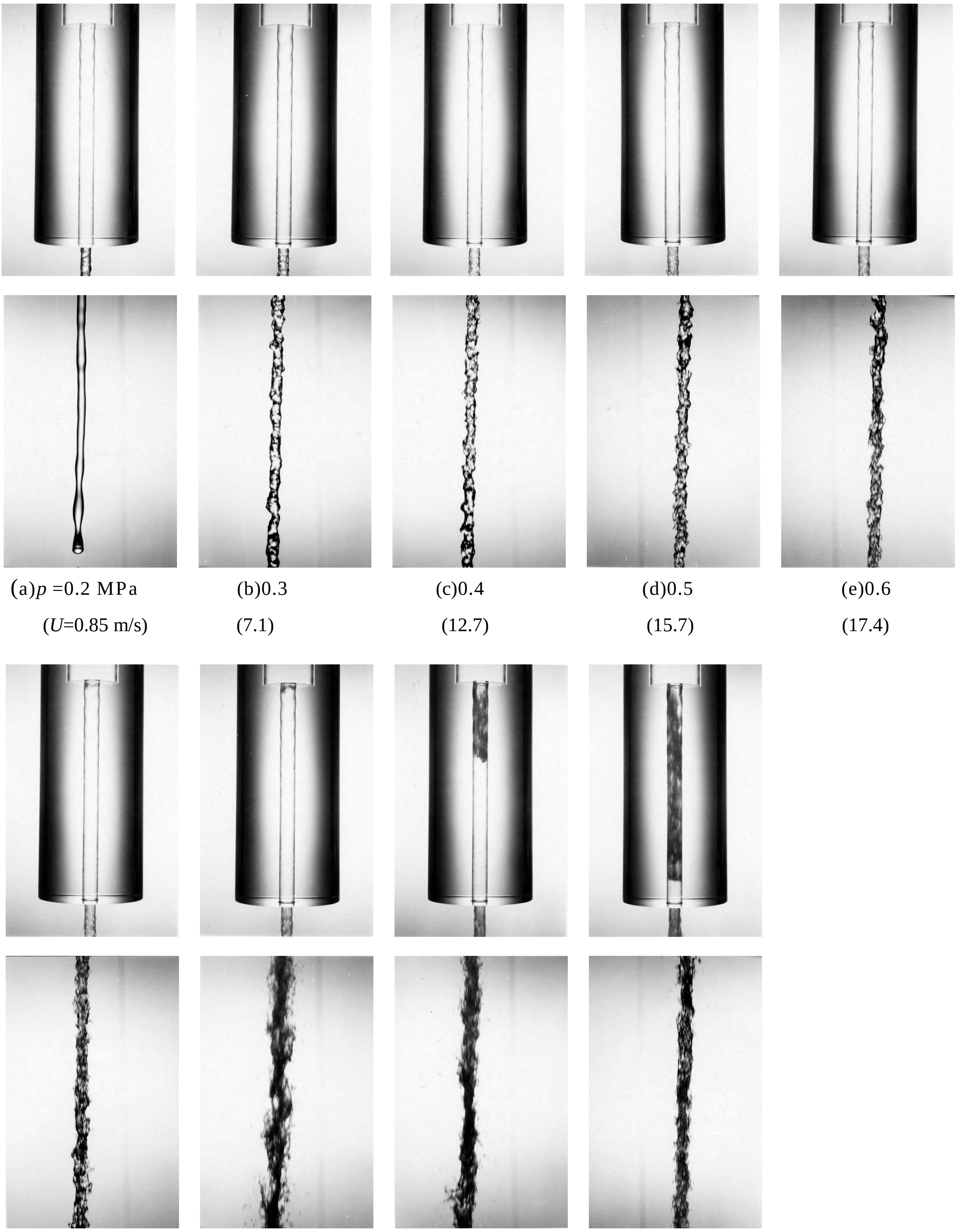


Fig.2 Schematic of experimental apparatus



(a)p =0.2 MPa (b)0.3 (c)0.4 (d)0.5 (e)0.6

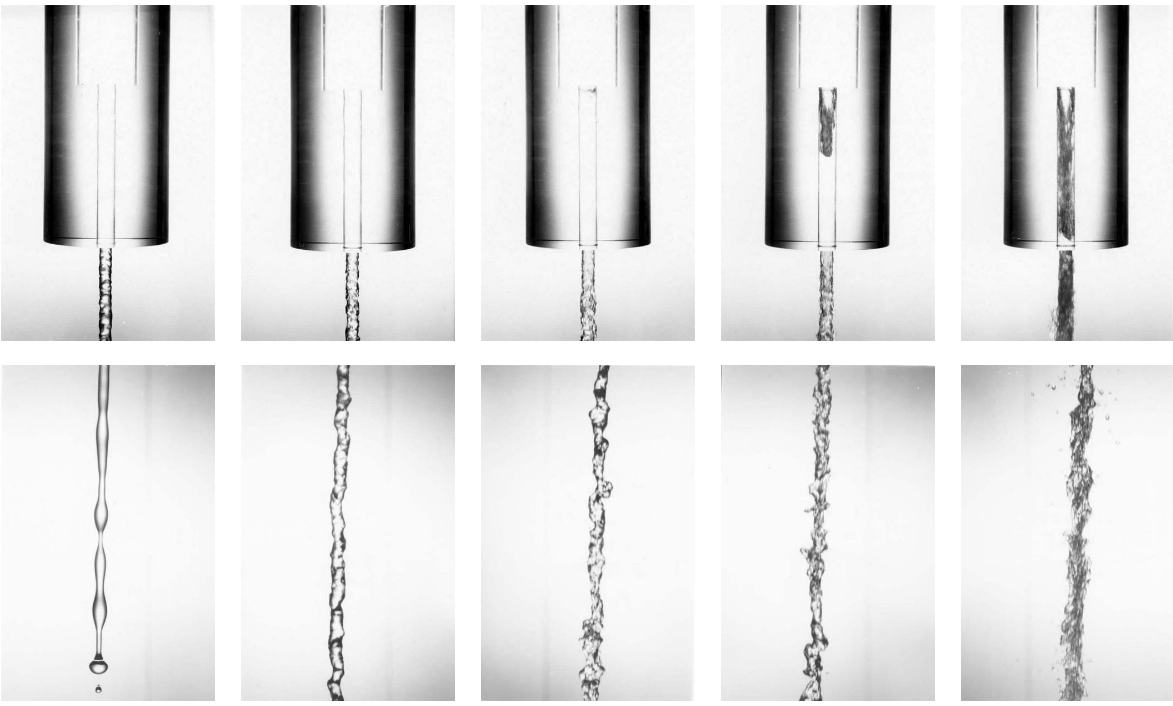
(U=0.85 m/s) (7.1) (12.7) (15.7) (17.4)

(f)0.7 (g)0.8 (h)0.9 (i)1.0

(21.0) (23.7) (25.7) (27.5)

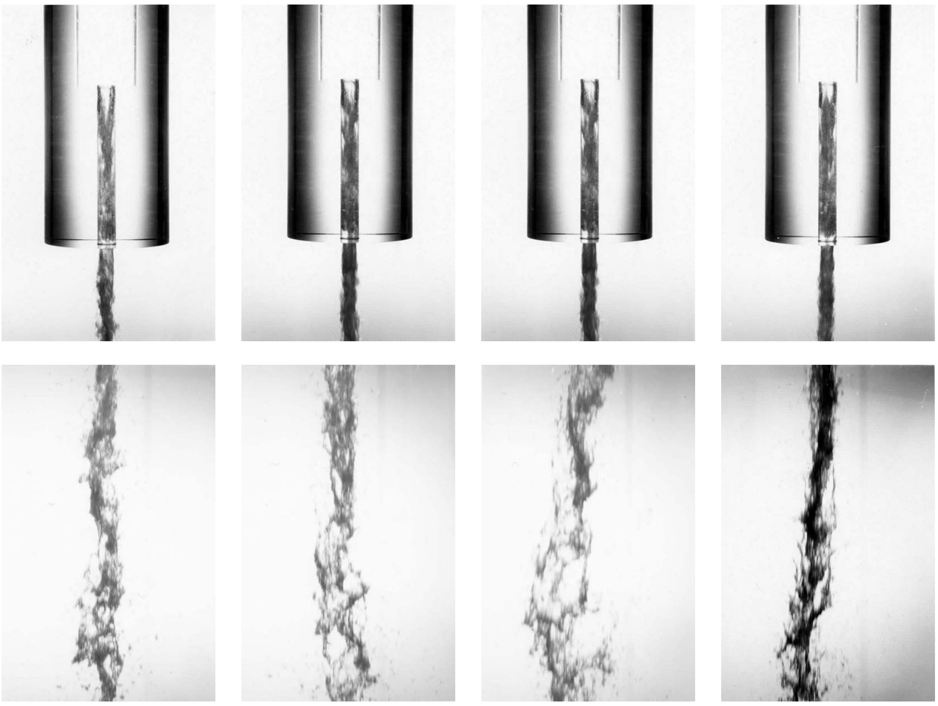
Fig.3 Internal flow and breakup phenomena (L/D=20, D=3mm)

(In Figs.3,4, and 5, the center of the bottom photograph was 200 mm below the nozzle outlet.)



(a)p =0.2 MPa (b)0.3 (c)0.4 (d)0.5 (e)0.6

(U=1.8 m/s) (7.3) (12.4) (15.3) (17.2)



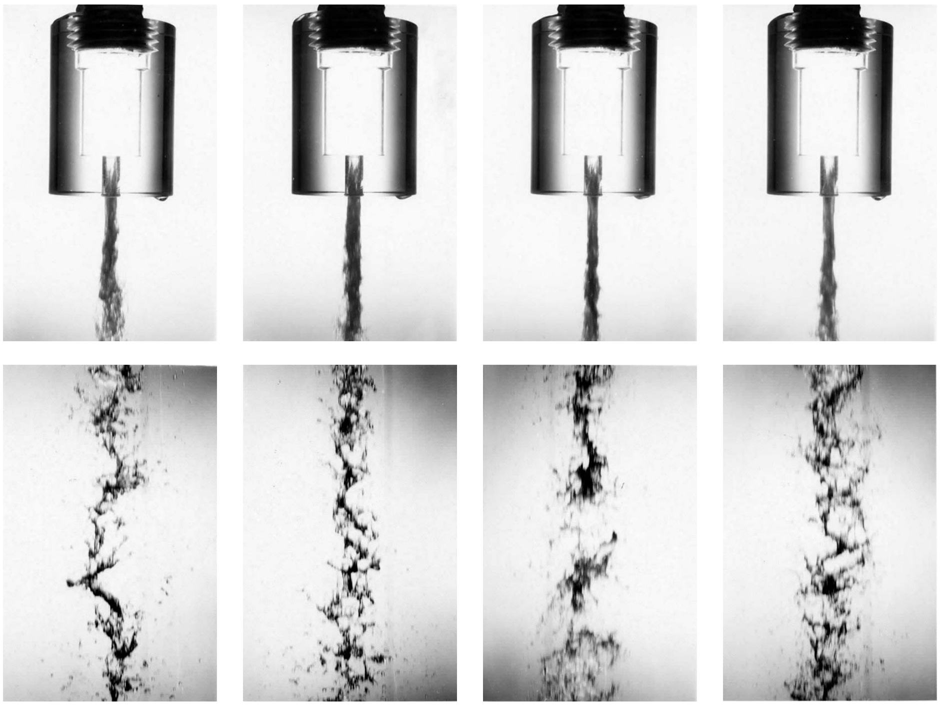
(f)0.7 (g)0.8 (h)0.9 (i)1.0

(19.6) (22.2) (24.6) (26.8)

Fig.4 Internal flow and breakup phenomena (L/D=12, D=3mm)

(a)p =0.2 MPa (b)0.3 (c)0.4 (d)0.5 (e)0.6

(U=1.8 m/s) (7.7) (12.4) (15.0) (16.5)



(f)0.7 (g)0.8 (h)0.9 (i)1.0

(19.0) (21.8) (23.3) (24.5)

Fig.5 Internal flow and breakup phenomena (L/D=3, D=3 mm) through the nozzle. In addition, the bubble disintegration point (the cavitation re-attachment point) associated with the increase in pressure moves downstream as the injection pressure increases, as illustrated in Figs. 3 (h) and (i), and this is consistent with the experimental results [1]. In such cases, the surface of the issued liquid is significantly disturbed, most likely due to disturbance of the liquid flow from the collapse of cavitation bubbles, with the figures confirming the manner in which droplets are dispersed in the surroundings.

Figure 4 also shows the internal flow in an S-Type nozzle (top) and the pattern of breakup of the issuing liquid (bottom), for an L/D=12. At an injection pressure of 0.9 MPa, the cavitation disappears inside nozzle for L/D=20 (Fig.3 (h)). In contrast, the liquid is issued without the cavitation disappearing for L/D=12 (Fig.4 (h)). This phenomenon may be due to the fact that, when the L/D value is large, the pressurized liquid must flow a significant distance before being released into the atmosphere, such that the pressure rises easily again to the value at which the cavitation bubbles collapse. In contrast, when the L/D value is reduced, the pressure is prevented from rising again due to the influence of the atmospheric pressure, therefore a tendency for bubbles not to collapse appears. The issued liquid flow is also significantly disturbed, in particular, the atomization is promoted when bubbles are issued from the nozzle without collapsing (Figs. 4(e)-(i)). In the present study, given the same nozzle diameter (D=3 mm) and the same injection pressure, the two nozzles, L/D=20 and 12, have virtually the same velocity inside the nozzle. However, compared to the L/D=20 configuration, the L/D=12 configuration produces cavitation at a lower injection pressure. One cause of this behavior may be that in the L/D=12 configuration with a small L value, a large pressure gradient exists from the contraction flow section to the nozzle outlet where the liquid flow is released to the surroundings, which facilitates the generation of bubbles in the upstream region .

Figure 5 shows the flow inside an S-Type nozzle (top) and the pattern of breakup of the issued liquid (bottom), for the L/D=3 configuration. In this case, cavitation generates in the entire nozzle even under the low injection pressure of 0.4 MPa (Fig. 5 (c)), the liquid flow is disturbed, and the breakup of the liquid jet is promoted. This phenomenon also occurs when a higher injection pressure is employed. In such a small L/D configuration, there is no possibility of the collapse of bubbles, and atomization is promoted by the disturbance of the liquid flow associated with the generation of bubbles.

3.2 Influence of nozzle shape

To consider the effect of nozzle dimensions on the breakup process, a classification of the R-Type and T-Type nozzles with respect to the pattern of liquid breakup (smooth jet, wavy jet, and spray) in terms of jet velocity is shown in Fig.6(a). In addition, in order to examine the transition of breakup patterns, Figs. 6 (b) and (c) show a classification of liquid breakup patterns in the S-Type nozzle in terms of L/D values. Smooth jet refers to a condition in which the liquid jet deforms due to an axisymmetric growth of wave motion and breaks up into droplets. Wavy jet refers to a condition in which macroscopic disturbances and deformations arise on the surface, and expand due to the action of the ambient gas. Finally, spray refers to a condition in which the action of the ambient gas increases as the flow velocity increases, leading to the generation of ligament, horn-like, and bag-like deformations, such that their breakup produces liquid droplets [3]. The pattern of breakup of liquid jets from a single-hole nozzle and the length of liquid breakup are often summarized using the following quantity: the jet number Je, which is a dimensionless number defined as follows;

$$Je = \frac{\rho_l U^2 D_e}{\sigma}\left(\frac{\rho_a}{\rho_l}\right)^{0.55} \tag{2}$$

Because the *L* of the S-Type nozzle (*L*/*D*=3, *L*=9 mm) is close to the length of the straight-tube section of the T-Type nozzle, we compare the two *L* values. In both the R-Type and T-Type nozzles (Fig. 6 (a)), the flow velocity at which a transition from wavy jet to spray occurs is greater than that for the S-Type nozzle (*L*/*D*=3) of similar nozzle length. This appears to be due to the fact that in the T-Type the change in the flow path cross-sectional area inside the nozzle is gradual, and thus any change in direction and flow velocity is gradual, which prevents the generation of cavitation, and which, in turn, prevents any promotion of disturbance. Although the generation of cavitation is suppressed in the R-Type nozzle compared with the S-Type nozzle, in the R-Type nozzle, cavitation is generated from the straight-tube nozzle inlet when the injection pressure reaches 0.6 MPa and the promotion of the breakup of liquid jet has been confirmed.

3.3 Transition of pattern of breakup

In the S-Type nozzle (Fig. 6 (b), (c)), the flow velocity of the transition from the wavy jet to spray declines as the value of *L*/*D* decreases. As shown in Fig. 5, this corresponds to the promotion of atomization due to the effect of a contraction flow resulting from the existence of a sharp corner part and the generation of cavitation bubbles. In contrast, as nozzle length increases, even if a contraction flow and disturbance due to cavitation exist, the resulting disturbance becomes stable in the flow path, which increases the transition velocity from the wavy jet to the spray.The flow velocity at which the liquid issued from the nozzle experiences a transition from smooth jet to wavy jet does not depend on *L*/*D* to the same extent as the transition from wavy jet to spray. This may be attributable to the fact that in the region in which the average flow velocity is low, no cavitation generates, and consequently, the transition is not affected by cavitation. With regard to the flow of a liquid jet from a single-hole nozzle, it has been reported that a transition from a smooth jet to a wavy jet occurs at a jet number of *Je*=10-15, and from a wavy jet to a spray occurs at a jet number of *Je*=400-500[4]. In the cylindrical nozzle used in the present study, for *Je*=15, the calculated flow velocity at which a transition from smooth jet to wavy jet occurs is 3.8 m/s for *D*=3 mm and 5.3 m/s for *D*=1.5 mm. In the case of the *L*/*D*=20, the calculated values are in good agreement with the experimental data, especially when *D*=1.5 mm, which is likely to be due to similarities with the single-hole nozzle. With regard to the calculated flow velocity at which a transition from wavy jet to spray occurs, for *Je*=400, the flow velocity is 19.5 m/s for *D*=3 mm, and 27.5 m/s for *D*=1.5 mm, which is in good agreement with the experimental results for the *L*/*D*=20.

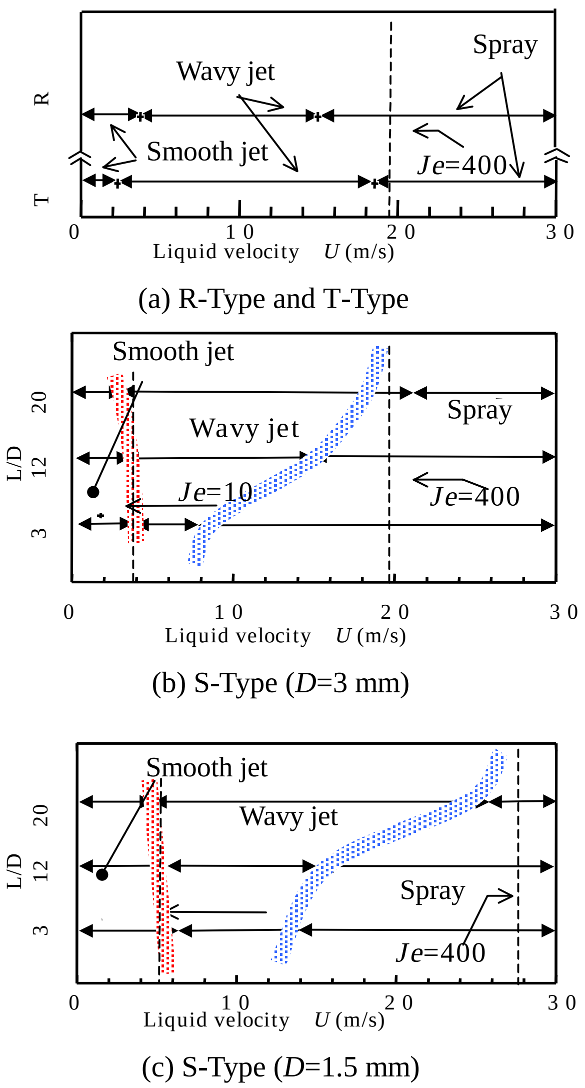


Fig.6 Transition of breakup phenomena

For similar Reynolds numbers (Re=3.12×10^4-3.74×10^4), (Fig. 3 (c), Fig. 4 (c), Fig. 5 (c)), no cavitation generates in the nozzle for the case of the *L*/*D*=20 and 12 configurations, and there is no discernible disturbance in the nozzle. However, the *L*/*D*=3 configuration exhibits severe disturbance of liquid flow in the nozzle, with the disturbance continuing to the nozzle outlet. Although the results are not presented in this paper, for cylindrical nozzles with *D*=1.5 mm, with a 1/2 nozzle diameter scale, the nozzle has been confirmed to exhibit the same trends in terms of the re-attachment of cavitation and a shift in the re-attachment point.
In addition, flow observed inside a nozzle (*L*/*D*=3, *D*=1.5 mm) has been confirmed to be highly consistent with numerical analysis calculations of the flow inside a 2D nozzle (*L*/*D* = 4, *D* =2 mm) by Sou et al.[5] regarding the generation of a contraction flow and a circulating flow from the sharp corner part and the behavior in which cavitation bubbles arise and collapse in the vicinity of a wall surface. Therefore, such disturbance of the liquid flow inside a nozzle, as indicated by these analytical results, plays a significant role in the promotion of atomization. The fact that the atomization process is promoted as the *L*/*D* ratio is reduced, meaning that the atomization is promoted even under a low flow velocity, seems to be significant from an application point of view. However, the question of whether the promotion of atomization is principally attributable to a disturbance in the liquid flow field due to the generation of cavitation or to shock-induced disturbance of liquid flow due to the collapse and disintegration of bubbles is yet to be answered.

4.Conclusion

With the objective of promoting the atomization of liquid jet, the present study used cylindrical nozzles to examine the influence of injection pressure, nozzle dimensions (*L*/*D*), and nozzle shape on the issued liquid. The results are summarized as follows:
(1) As the injection pressure increases, cavitation is confirmed to be generated inside nozzle, which promotes atomization.
(2) With a large *L*/*D* ratio, the disturbance occurring inside nozzle disintegrates as it flows through the nozzle, which does not promote atomization of the issuing liquid jet.
(3) With a small *L*/*D* ratio, cavitation, which is not susceptible to the effect of the downstream flow, is generated even under low injection pressures, which promotes the breakup of the issuing liquid jet.
(4) With a small *L*/*D* ratio, all transitions are affected by the generation and collapse of cavitation, and consequently the flow velocity at which a transition from wavy jet to spray occurs diminishes.
(5) Compared to S-Type nozzles of similar nozzle length (*L*/*D*=3), for R-Type and T-Type nozzles, any change in the direction or flow velocity inside the nozzle is gradual, which inhibits the generation of cavitation and, consequently, does not promote atomization.

References

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