Effect of Cavitation in the Two-dimensional Nozzle on Liquid Breakup Process

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Using the 2D nozzle, the effects of the nozzle dimensions on the liquid breakup are investigated. When the L/W of the 2D nozzle is low, contraction flow generates upstream in the nozzle, and the disturbance inside the nozzle and the issuing jet are both promoted. Similarity between the cylindrical nozzle and the 2D nozzle are found with respect to the disturbance inside the nozzle and the breakup of the liquid.

1. Introduction

In pressure atomizers, if an increase in drop size can be suppressed even at low injection pressures, the result can be beneficial from the standpoint of energy savings. Therefore, attempts have been made to promote atomization by exploiting the disturbance in liquid flow due to the generation of cavitation inside the nozzle. Shimizu et al. [1] and Tamaki et al. [2] have demonstrated that nozzle dimensions and configuration have a significant effect on the generation of cavitation inside the nozzle and on the induced disturbance in the nozzle. The authors [3] examined the effect of the dimensions and configuration of a cylindrical nozzle on the internal flow and on the pattern in which the issuing liquid breaks up, for the case of relatively low injection pressure. However, because in cylindrical nozzles, cavitation appears and disappears almost uniformly around the circumference, observing the nozzle in detail from outside has been a difficult task. Therefore, in the present paper, we examine the internal flow and the breakup pattern using a nozzle having a rectangular cross-section (a 2D nozzle), for ease of observation. In this manner, we compare the effect of the generation and disappearance of cavitation on the breakup of the liquid as observed for a cylindrical nozzle and investigate the influence of the pressure distribution/variation in a 2D nozzle on the liquid breakup.

2. Experimental Method

Figure 1 shows the configuration of a 2D nozzle. The 2D nozzle, which is made of transparent PMMA, is designed to generate cavitation only at the right and left sharp corners. The cross-sectional configuration of the nozzle is fixed (t=2 mm, flow-path width W=6 mm), and the nozzle length L is allowed to vary, such that the ratio L/W varies from 0.6 to 10. In order to facilitate comparison with the results of the cylindrical nozzle, the value of W is set such that the equivalent diameter D_e of the 2D nozzle is equal to that of the cylindrical nozzle. Thus, the equivalent diameter D_e is defined as;

$$D_e = \frac{4A}{S} = \frac{2Wt}{W+t} \qquad (1)$$

where the cross-sectional area and the circumferential length of the 2D nozzle are A and S, respectively. Therefore, the cylindrical nozzle with D=3 mm and the 2D nozzle with W=6 mm and t=2 mm are equal with respect to equivalent diameter. Table 1 shows the dimensions of the 2D and cylindrical nozzles. Given the same type of liquid and flow rate, the breakup pattern in the cylindrical and 2D nozzles can be compared where L/D_e = 20 and 3.

The experimental apparatus is almost as same as that in a previous work[3]. The sample liquid used is tap water. The pattern of the liquid disturbance in the 2D nozzle, and the pattern of liquid film were photographed using a digital camera. Since the main focus was on the assessment of fundamental phenomena, the injection pressure was low, in the range of 0.2-0.8 MPa absolute pressure. The average velocity U was in the range of 0.85-27.5 m/s. The Reynolds number Re for the 2D nozzle was defined as;

$$Re = \frac{UD_e}{\nu} \quad (2)$$

The pressure inside the nozzle was measured using a strain gauge pressure sensor, and two types of nozzles, L/W=10 and 6, were used in pressure determinations. The locations at which measurements were taken were as follows: with a reference point (x=0) at the sharp corner part, near the nozzle inlet (x=2 mm) where contraction flow generated, at a middle point (x=L/2 mm), and near the outlet (x=(L-10) mm). For the L/W=10 nozzle, measurements were also taken at x=4 mm.

3. Observation of the Flow Inside the Nozzle

3.1 Flow inside the 2D nozzle and the pattern of liquid breakup

Figures 2 and 3 show photographs of the generation and disappearance of cavitation inside the 2D nozzle (top row), together with the breakup of the issuing liquid (bottom row). For comparison, photographs of results with cylindrical nozzles having the same L/D_e value are shown on the left. When L/D_e=20 (Fig. 2), cavitation arises in the sharp corner part in the nozzle, followed by disappearance, when the injection pressure is in the range 0.4-0.8 MPa (Re=4.2×10^4-6.15×10^4). The position at which the cavitation bubbles disappear is virtually constant for the pressure range. However, the region (black area in the photo) in which the cavitation bubbles exist widens as the pressure is increased. The reason for this is that as the injection pressure increases, the low-pressure region of the flow that has passed through the sharp corner part broadens toward the center line of the flow path. The liquid surface after being issued from the 2D nozzle is similar to the wavy jet issued from the cylindrical nozzle [3], and the scale of the disturbance does not change significantly even when the injection pressure increases.

When the nozzle length L is relatively short, L/D_e=3 (Fig. 3), under all injection pressures, the cavitation that arises in the sharp corner does not re-attach to the nozzle wall and does not disappear. As a result, a sufficiently disturbed liquid film is issued. When L/D_e=3, the liquid is

Table1 The values of L/D_e

Nozzle Type	Equivalent Diameter, D_e	L/D_e		
Cylindrical Nozzle	3 mm (D = 3 mm)	20 (L/D=20)	3 (L/D=3)	—
2D Nozzle	3 mm (W = 6 mm)	20 (L/W=10)	3 (L/W=1.5)	1.2 (L/W= 0.6)

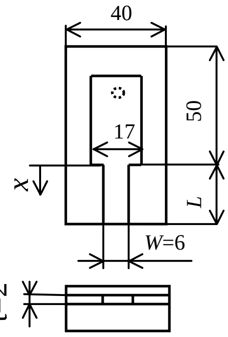
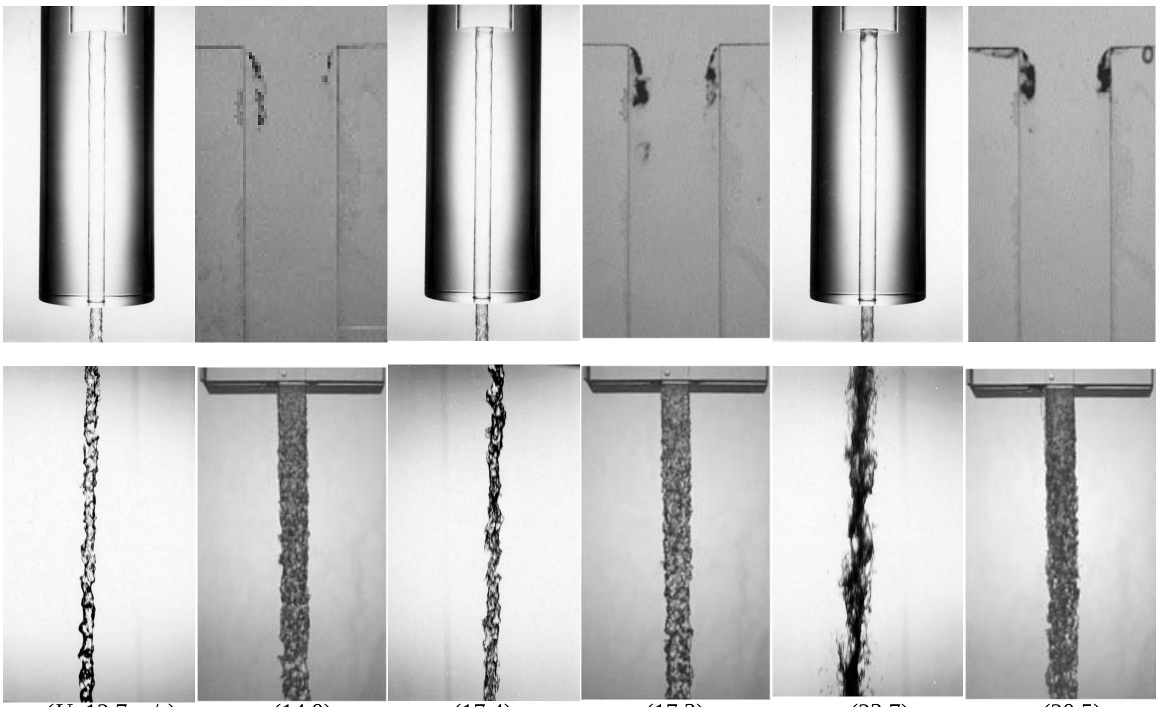


Fig.1 2D nozzle



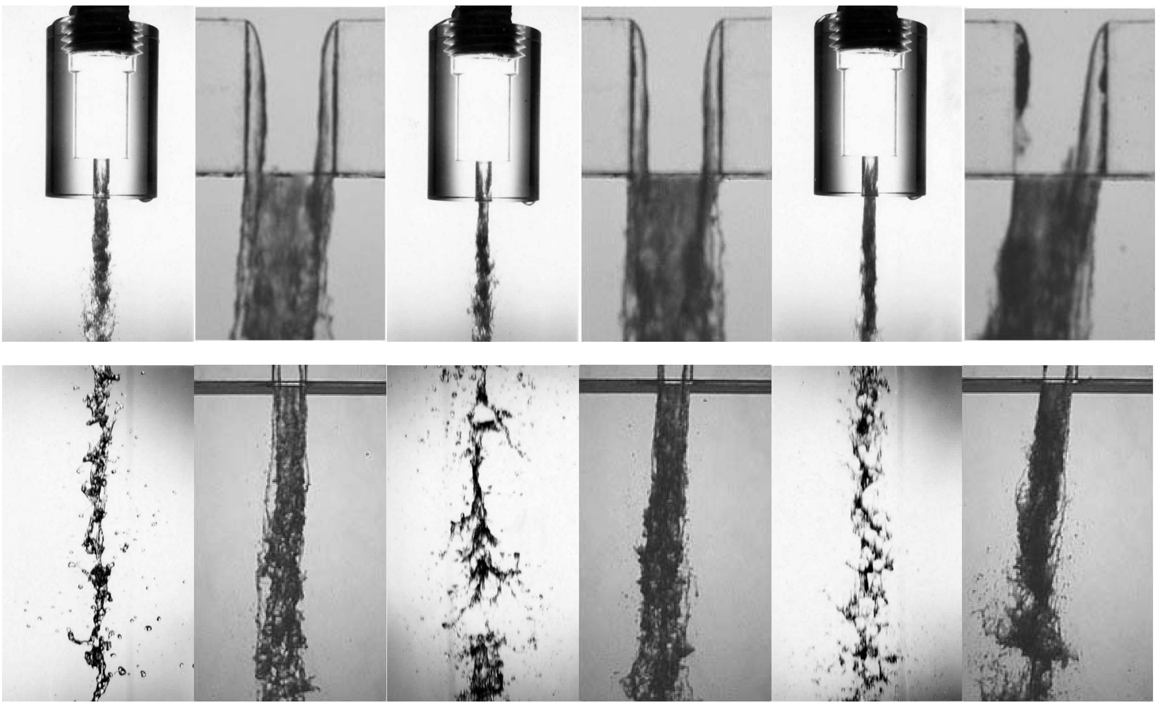
(U=12.7 m/s) (14.0) (17.4) (17.3) (23.7) (20.5)

(a) p =0.4 MPa (b)0.6 (c)0.8

Fig.2 Internal flow and breakup phenomena for L/D_e=20

(L/D=20 for Cylindrical nozzle (left), L/W=10 for 2D nozzle (right))

(In Figs.2 and 3, the center of the picture was 50 mm below the 2D nozzle outlet.)



(U=12.4m/s) (13.4) (16.5) (17.0) (21.8) (20.3)

(a) p =0.4 MPa (b)0.6 (c)0.8

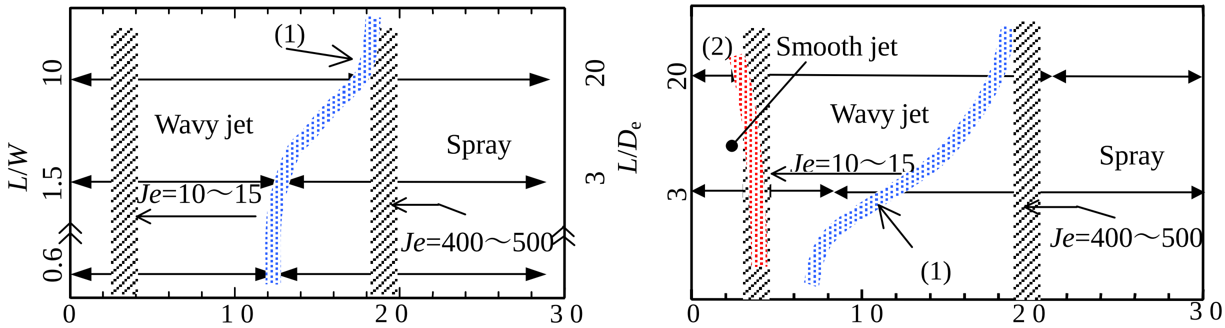
Fig.3 Internal flow and breakup phenomena for L/D_e=3

(L/D=3 for Cylindrical nozzle (left), L/W=1.5 for 2D nozzle (right))

issued as a planar liquid film equal in width to the nozzle width despite the generation of a contraction flow. It means that when a contraction flow arises, liquid also exists in the vicinity of the right and left walls of the nozzle.
For L/D_e=3, the liquid after being issued from the nozzle is significantly disturbed, which indicates the promotion of atomization. Since the thickness (t=2 mm) is small relative to the nozzle width (W=6 mm), the liquid film that flows through such a thin layer may be considered stable. However, when L/D_e=3, the liquid film exiting from the center of the nozzle is also significantly disturbed. This may be attributable to the fact that the turbulence due to the cavitation has reached the center of the liquid flow in the nozzle. As the injection pressure exceeds 0.6 MPa (Fig. 3 (b), (c)), the exiting liquid transitions almost entirely to spray. It means that the atomization is promoted.

3.2 Comparison between the 2D nozzle and the cylindrical nozzle in terms of liquid breakup
For L/D_e=20, comparison of the cylindrical nozzle (Fig. 2, left, L/D=20) and the 2D nozzle (Fig. 2, right, L/W=10) in terms of liquid breakup patterns indicates that, with the exception of the cylindrical nozzle with a injection pressure of 0.4 MPa, the two nozzles are similar with respect to the behavior in which cavitations arise and immediately disappear, and with respect to the manner in which the liquid column and the liquid film surface are disturbed after being issued from the nozzle.
For L/D_e=3, a comparison of the cylindrical nozzle (Fig. 3, left, L/D=3) and the 2D nozzle (Fig. 3, right, L/W=1.5) in terms of liquid breakup reveals similar behavior in terms of liquid flow inside the nozzle and the liquid breakup, despite differences in the state of the issued liquid: liquid column vs. liquid film, respectively. In terms of liquid breakup, the cylindrical nozzle is subject to a greater degree of disturbance, apparently due to the fact that the liquid is more stable in the 2D nozzle.
If the 2D nozzles have similar Reynolds numbers (e.g., for a 0.4 MPa injection pressure, Re=4.02×10^4-4.2×10^4), at L/W=10, any cavitation disappears immediately, such that no disturbance in liquid flow can be confirmed downstream of the nozzle. On the other hand, for L/W=1.5, liquid flow is issued directly from the nozzle outlet without re-attaching to the nozzle wall. Comparison between a 0.6 MPa injection pressure cylindrical nozzle (Re=4.94×10^4-5.23×10^4) and a 0.4 MPa injection pressure 2D nozzle having similar Reynolds numbers indicates that for L/D_e=20 (cylindrical nozzle: L/D=20; 2D nozzle: L/W=10), any cavitation disappears immediately, and, downstream, the disturbance diminishes. Thus, the cylindrical and 2D nozzles exhibit similar behavior. For L/D_e=3 (L/D=3, L/W=1.5), a similar trend is confirmed in that cavitation generates in the entire nozzle in both nozzles, and the disturbance extends to the entire nozzle.

3.3 Transition in 2D nozzle liquid breakup phenomena
Fig. 4 (a) shows liquid breakup patterns (wavy jet, spray) classified in terms of flow velocities and L/W ratios. For comparison, Fig. 4 (b) shows liquid breakup patterns for cylindrical nozzles. Although there exists no clear definition of the jet flow produced from a 2D nozzle, we provide the following definitions: smooth jet refers to a condition in which the liquid film surface is continuously and smoothly issued; wavy jet refers to a condition in which the liquid film becomes unstable [4],[5], and spray refers to a condition the liquid film has broken apart into liquid columns and finally into droplets. The transition from a wavy jet to a spray in a 2D nozzle (curve (1) in Fig. 4 (a)) and the transition from a smooth jet to a wavy jet and then from a wavy jet to a spray (curves (2) and (1) in Fig. 4 (b)) in a cylindrical nozzle have been determined based on several photographic images and on visual inspection. The breakup of the liquid jet from a nozzle is often correlated using the jet number Je;



Liquid velocity U (m/s)

(a) 2D nozzle

Liquid velocity U (m/s)

(b) Cylindrical nozzle

Fig.4 Transition of breakup phenomena

(1)Transition from wavy jet to spray (2) Transition from smooth jet to wavy jet

$$Je = \frac{\rho_l U^2 D_e}{\sigma}\left(\frac{\rho_a}{\rho_l}\right)^{0.55} \tag{3}$$

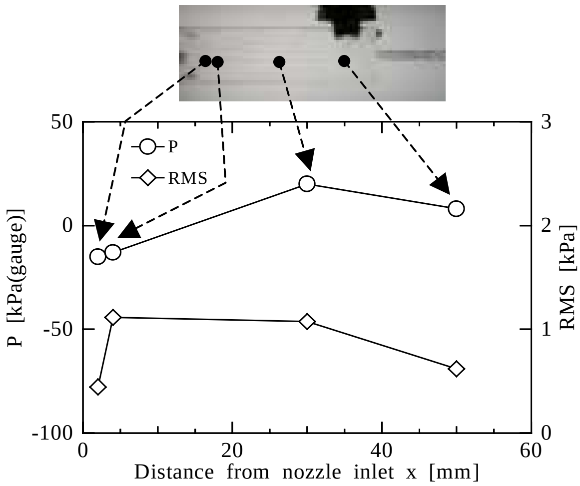
In 2D nozzles, as L/W decreases, the transition flow velocity from the wavy jet to the spray decreases. As shown in Figs. 2 and 3, this phenomenon corresponds to the promotion of atomization due to the generation of cavitation bubbles. This pattern is similar to that of the cylindrical nozzle (Fig. 4 (b)), which confirms the significant influence of the increase and collapse of cavitation bubbles on the breakup of the liquid, irrespective of the cross-sectional profile of the nozzle. When the L/D_e ratio is small, the transition flow velocity from wavy jet to spray for a cylindrical nozzle (curve (1) in Fig. 4 (b)) is lower than that for a 2D nozzle (curve (1) in Fig. 4 (a)). This phenomenon may be attributable to the fact that, in cylindrical nozzles, cavitation generates in the entire nozzle, which promotes extensively the disturbance of the liquid flow.

With regard to liquid jet flow from a single-hole nozzle, it is reported that the smooth jet transitions into a wavy jet at Je=10-15 and from the wavy jet to a spray at Je=400-500 [6]. In 2D nozzles (D_e=3 mm), the flow velocity at which a transition from smooth jet to wavy jet occurs (the band-like straight line on the left sides of Figs. 4 (a) and (b)) is calculated to be 3.8 m/s for D_e=3 mm, assuming Je=15. A comparison of this data with the transition flow velocity for the liquid breakup in a 2D nozzle (Fig. 4 (a)) indicates that despite the differences in cross-sectional shape, rectangular vs. circular, at any L/W value, a transition velocity from smooth jet to wavy jet is lower than the calculated one. The flow velocity at which a transition occurs from a wavy jet to a spray (the band-like straight line on the right side of Figs. 4 (a) and (b)) is calculated to be 19.5 m/s for the D_e=3 mm, assuming Je=400, which is consistent with the experimental result L/W=10 (L/D_e=20).

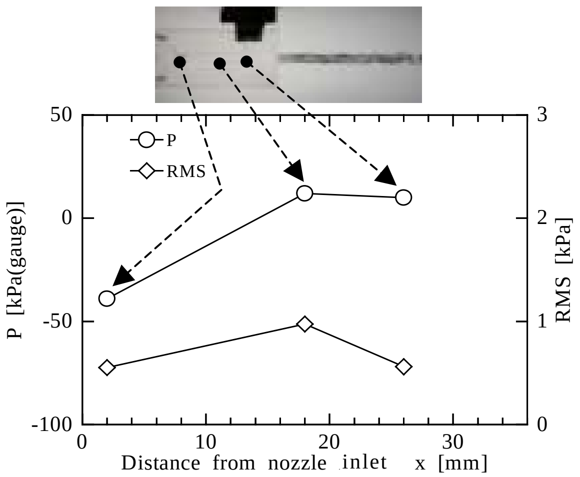
4. In-Nozzle Pressure Distribution and Variation

4.1 Pressure distribution within a nozzle

Figure 5 shows the average pressure (gauge pressure) and its variation (RMS value) on the wall surface inside the nozzle for ratios L/W=10, 6, for an injection pressure p_{inj} =0.3 MPa. When L/W=10 (Fig. 5 (1)), the pressure becomes negative at the nozzle contracted section. The pressure increases at the middle section and decreases again as the flow approaches the outlet, finally approaching the surrounding pressure. Such a pattern of pressure changes is also seen in the L/W=6 configuration (Fig. 5 (2)). The liquid flow inside the nozzle is susceptible to the influence of the atmosphere, with the result that any increase in pressure is suppressed. In the



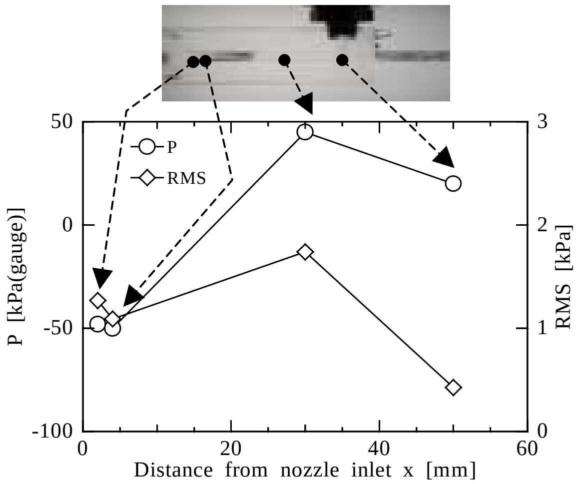
(1) *L*/*W*=10



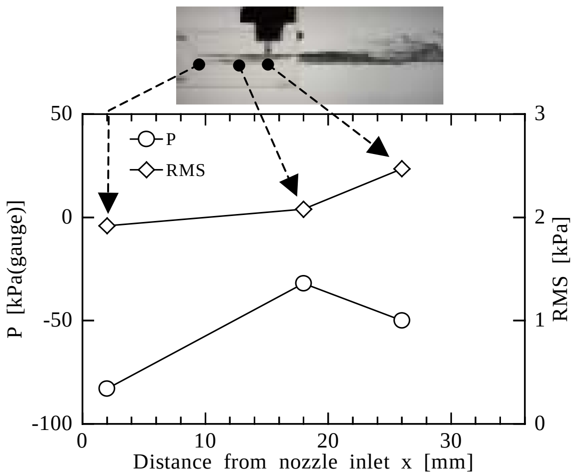
(2)*L*/*W*=6

Fig.5 Pressure distribution

(P_{inj}=0.3 MPa)



(1) *L*/*W*=10



(2)*L*/*W*=6

Fig 6 Pressure distribution

(P_{inj}=0.7 MPa)

photograph, cavitation bubbles are generated in the sharp corner section and disappear immediately, with this trend being more pronounced when *L*/*W*=6 than when *L*/*W*=10. Probably due to a relatively low injection pressure and the small scale of cavitation, the RMS value inside the flow path is small, which seems to inhibit a disturbance that would be large enough to promote the atomization.

Figure 6 shows similar measurement results when injection pressure p_{inj}=0.7 MPa. For *L*/*W*=10 (Fig. 6 (1)), as for 0.3 MPa, the pressure becomes negative at the inlet and increases significantly at the middle section. In such cases, any cavitation bubbles disappear before they reach the middle section as shown in the photograph. The disturbance inside nozzle that originates from the generation and disappearance of cavitation bubbles seems to decrease near the nozzle outlet, especially when the *L*/*W* value is large. In fact, the RMS value is smaller for *L*/*W*=10 (*x*=50 mm) than for *L*/*W*=6 (*x*=26 mm). Although for *L*/*W*=6 (Fig. 6 (2)), the pressure increases around the middle section of the nozzle, negative pressure holds even in the vicinity of the outlet, which suggests that the disturbance due to cavitation does not diminish even at the outlet.

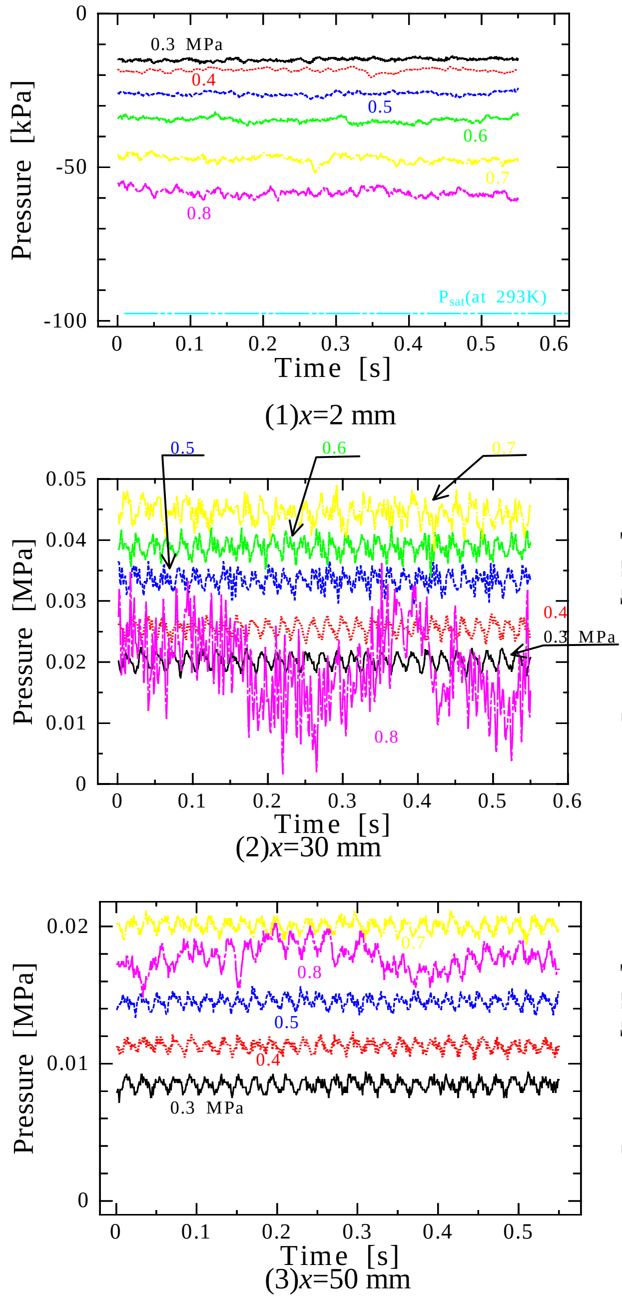


Fig.7 Pressure waveform (*L*/*W*=10)

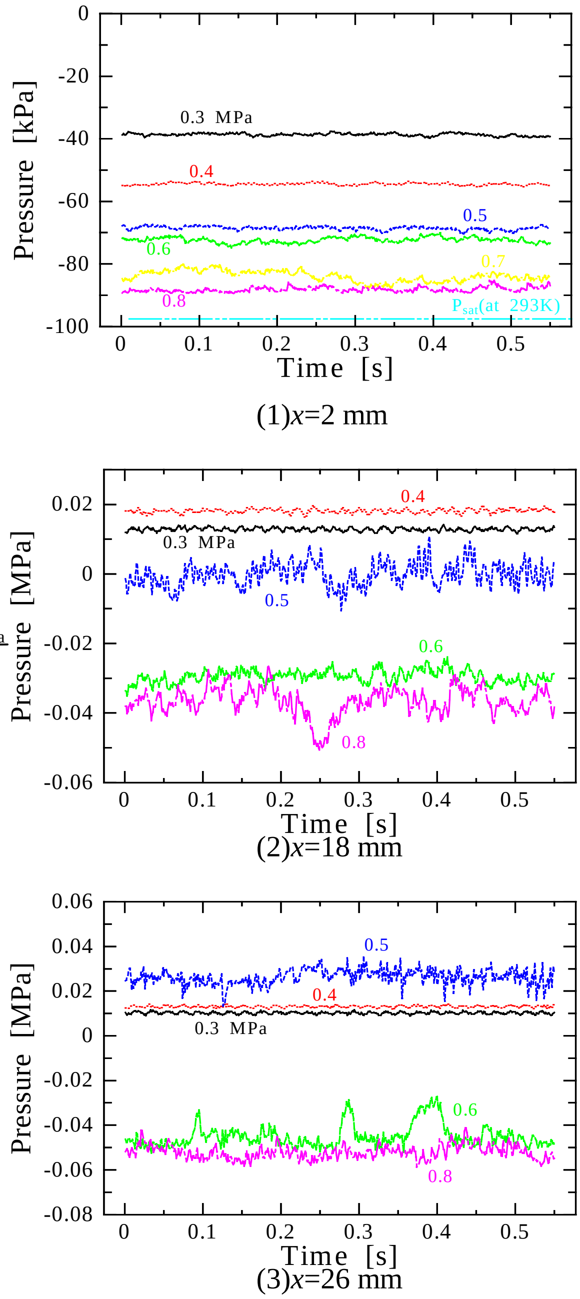


Fig.8 Pressure waveform (*L*/*W*=6)

4.2 Pressure variation in the nozzle

Figure 7 shows the pressure waveform (gauge pressure) on the walls of an $L/W=10$ nozzle ($p_{inj}=0.3$-0.8 MPa). In the vicinity of the nozzle sharp corner (x=2 mm, Fig. 7 (1)), the pressure becomes negative at any injection pressure. In such sites, cavitation generates, but its pressure decreases as the injection pressure increases. By contrast, at x=30 mm (Fig. 7 (2)), the pressure inside the nozzle remains positive, and increases as the injection pressure increases. However, when the injection pressure is 0.8 MPa, the pressure inside the nozzle decreases rapidly and fluctuates extensively. The reason for this is that the front edge of the cavitation region is near the measurement position, which causes the pressure to change greatly in the unsteady state, and the disappearance of bubbles causes wide fluctuations in pressure. Figure 7 (3) shows the results of measurements at x=50 mm, which are similar to the results at x=30 mm.

Figure 8 shows the pressure waveform for an *L*/*W*＝6 nozzle. At *x*=18 mm (Fig.8(2)),the pressure inside the nozzle remains positive until the injection pressure reaches 0.4 MPa and increases as the injection pressure increases. This represents a condition in which the front edge of the cavitation region has not reached the measurement position. At injection pressure of 0.5 MPa, the pressure waveform fluctuates significantly around the atmospheric pressure. This means that the front edge of the cavitation region has reached the measurement position. A significant feature of this region is a large disturbance of the waveform. At *x*=26 mm (Fig.8(3)), which exhibits a trend similar to pressure changes at *x*=18 mm. However, at an injection pressure of 0.5 MPa, the cavitation has not reached the measurement position. Although positive pressure is maintained, pressure fluctuations have increased. This seems to be due to the disturbance of the liquid after the disappearance of cavitation, and this factor may play a significant role in the promotion of the atomization of the liquid jet.

5. Conclusions

With the objective of promoting atomization, in the present study, using 2D nozzles, we examined the influence of injection pressure and nozzle dimensions on the issuing liquid, and compared the results with the experimental results on cylindrical nozzles. The results are summarized below:

(1)In the 2D nozzle having a large *L*/*W* value, cavitation generates and disappears in the sharp corner part in the nozzle, and this phenomenon does not promote the break up of the issuing liquid.

(2) In the 2D nozzles having a small *L*/*W* value, the liquid is ejected as a sufficiently disturbed liquid film, which promotes the atomization.

(3) In the 2D nozzles having a small *L*/*W* value, the atomization process is affected by the generation and disappearance of cavitation, and as a result, the transition flow velocity from wavy jet to spray diminishes.

(4) The transition flow velocity from the wavy jet to the spray is lower in the cylindrical nozzle than in the 2D nozzle.

(5) We confirmed similarities between cylindrical and 2D nozzles in the behavior of liquid flow inside the nozzle and the breakup of the liquid.

(6) When *L*/*W*=10, the pressure, which decreases at the nozzle inlet, increases before the middle section is reached, and any disturbance in the liquid flow inside the nozzle decreases in the vicinity of the outlet.

(7) When *L*/*W*=6, as the injection pressure increases, the pressure that decreased at the nozzle sharp corner part maintains negative pressure until the vicinity of the nozzle outlet. This trend prevents any disturbance due to the generation and disappearance of cavitation from attenuating.

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