ICLASS 2009, 11th Triennial International Annual Conference on Liquid Atomization and Spray Systems, Vail, Colorado USA, July 2009

Effect of Cavitation inside Nozzle on Liquid Jet

M. Daikoku* and S. Ogasawara
Department of Mechanical Engineering, Hachinohe Institute of Technology
Hachinohe, Aomori 031-8501 JAPAN
T. Inamura
Department of Intelligent Machines and System Engineering, Hirosaki University
Hirosaki, Aomori 036-8561 JAPAN
M. Noro
Towada Technical High School
Towada, Aomori 034-0001 JAPAN

Abstract

The purpose of this study is to investigate how the generation and extinction of cavitation inside a nozzle affects breakup of the liquid from the nozzle. A cylindrical nozzle, whose ratio of nozzle length L to inner diameter D is L/D = 12, was used with an injection pressure P_{inj} of 0.3 to 1.0 MPa (gauge) and a fluid flow rate Q from 7.25 to 12.0 L/min in order to investigate the generation of cavitation inside the nozzle that affects liquid jet turbulence. When the injection pressure P_{inj} ranged from 0.3 to 0.5 MPa, we found that a cavitation region was formed and disappeared near the nozzle exit, large pressure fluctuations occurred, and the liquid flow inside the nozzle was disturbed. After determining the power spectrum density of pressure fluctuations inside the nozzle, we confirmed that the power spectrum density peaked in the lower frequency, which indicates fluctuations in the cavitation region. We also confirmed that liquid droplets were generated from the outer edge of the liquid jet due to large pressure fluctuations near the nozzle exit. In contrast, when the injection pressure P_{inj} was 1.0 MPa, it was confirmed that the cavitation region did not disappear completely inside the nozzle. In this case, few liquid droplets were generated even though the flow rate was larger and the air-liquid relative velocity was higher than when injection pressure is low. It is found that the large pressure fluctuations did not occur inside the nozzle due to extinction of the cavitation. The extinction of the cavitation region near the nozzle exit resulted in disturbed liquid flow inside the nozzle, and increased turbulence in the liquid jet, generation of liquid droplets from the outer edge, and spread of the liquid jet.

Introduction

In recent years, many attempts have been made to use cavitation inside a nozzle which is related to a high-speed liquid jet, so that atomization can be promoted, even under low pressure. It is well known that generation of cavitation is varied with the conditions [1]. Focusing on promotion of atomization by cavitation, the authors used a cylindrical nozzle to investigate how the generation and extinction of cavitation under relatively low pressure affects the liquid breakup from the nozzle, and clarified the simple nozzle that promotes atomization [2]. In order to clarify the mechanism of such liquid breakup, the authors also used a 2D nozzle to observe the liquid flow inside the nozzle [3]. Furthermore, the authors also investigated how the pressure fluctuation and pressure distribution affect the generation and extinction of cavitation [4], [5]. On the other hand, the authors also made a comparison between the cylindrical and 2D nozzles, and showed the similarity between the fluid flow turbulence inside the nozzle and the fluid breakup that occurred in both nozzles [6]. Because Sou et al. [7] have analyzed the correlation between cavitation occurring inside the 2D nozzle and the breakup of a liquid jet, the effects of the generation and extinction of cavitation inside the nozzle on the promotion of atomization are being clarified. On this account, this study aims to investigate the relationship between the cavitation inside a nozzle and the liquid jet after it is ejected from the nozzle.

Experimental Procedures

1. Experimental Setup and Nozzle

Figure 1 shows a schematic of the experimental setup. Tap water was used and it is pressurized by the plunger pump, following which the liquid is issued from the nozzle. The digital camera was used to observe the generation

*Corresponding author

of cavitation inside the nozzle, the flow pattern of the internal liquid and its breakup pattern. A signal sent from the pressure sensor of strain gauge type was obtained and analyzed by the data logger and PC. The breakup of liquid jet was analyzed by measuring the intensity of the light transmitted from the light (4-element LED). The cylindrical nozzle, which is made of transparent PMMA, is shown in Fig. 2. In the present paper, the experimental results for a nozzle having such ratio of nozzle length L to inner diameter D as L/D =12 (L =36 mm) were mainly discussed.

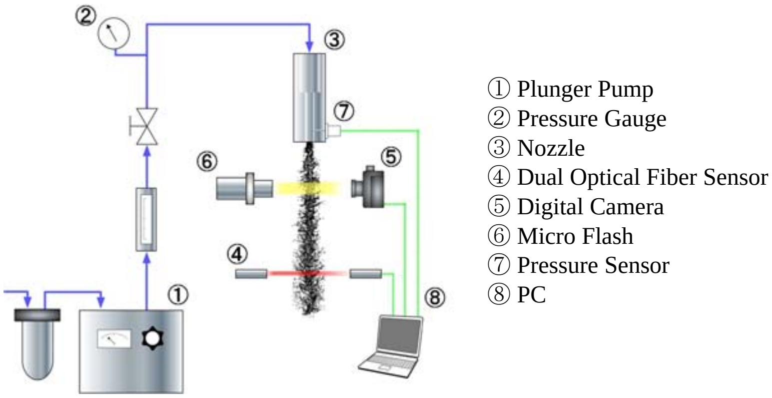


Figure 1 Schematic of the experimental setup

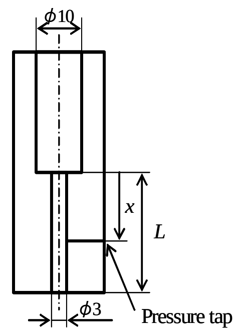


Figure 2 Cylindrical nozzle

2. Experimental Conditions

In this study, to focus on the comprehension of basic phenomena, such as the generation and extinction of cavitation, the injection pressure P_{inj} was set to a lower level, which ranges from 0.3 to 1.0 MPa (gauge). The liquid was injected into the atmosphere steadily, with its flow rate Q ranging from 7.25 to 12.0 L/min. With the nozzle's contraction section as x=0 mm, the pressure inside the nozzle was measured at three points shown in Fig. 2; the upstream (x=9 mm), the intermediate (x=18 mm) and the downstream (x=26 mm).

3. Dual Optical Fiber Sensor

Figure 3 shows the measuring locations of the dual optical fiber sensor used to analyze the liquid jet breakup. With the nozzle exit used as the origin (z=0 mm), each measurement was made on three horizontal planes at z=5, 40 and 60 mm, at intervals of 1 mm in the radial direction r from the nozzle center. Figure 4 shows the characteristics of the optical fiber sensor. As a preliminary experiment, the variation of the transmitted light intensity with the liquid film thickness was obtained. It is clear that the intensity of transmitted light decreases as the film thickness increases, the relation between the intensity of incident light (I_0 = 3.01) and that of transmitted light intensity I can be expressed by I = 3.01exp (-0.0263t). This equation indicates that the Lambert-Beer's law is applied to the measurement system. Also, as the response time of the sensor is about 1 ms, the sensor can also be used when the film thickness varies with time.

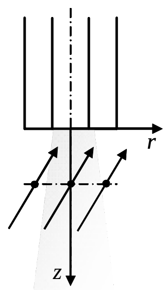


Figure 3 Measuring locations of dual optical fiber sensor

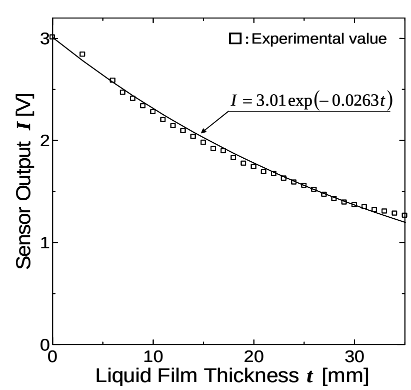


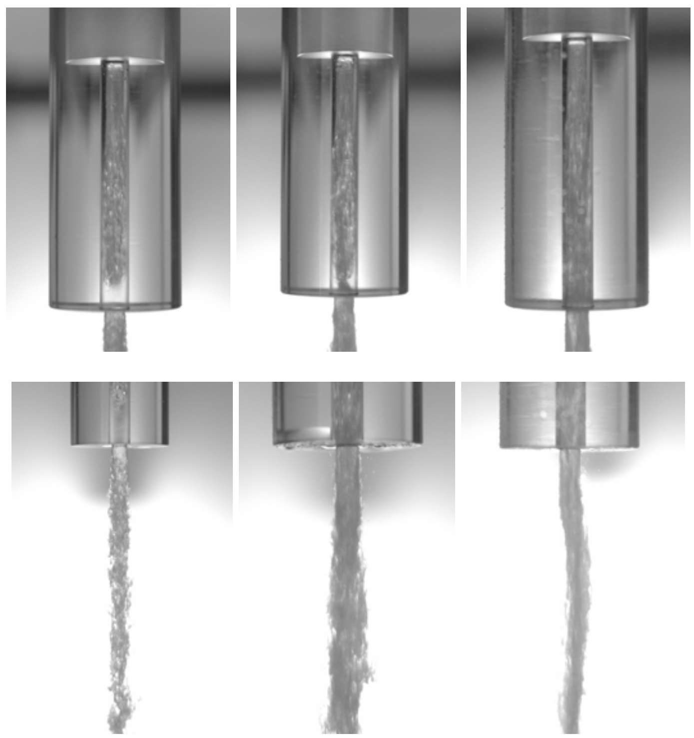
Figure 4 Characteristics of the optical fiber sensor

Results and Discussion

1. Observation of the Liquid Jet

Figure 5 shows the behaviors of the liquid flow inside the nozzle and that issued from the nozzle. When the injection pressure P_{inj} was 0.3 MPa (Fig. 5 (a)), it was found that cavitation occurred from the contraction section and disappeared inside the nozzle and that coarse liquid droplets were generated from the outer edge of the liquid jet. While the breakup of droplets from the surface of liquid jet generally resulted from an increase in the air-liquid relative velocity, it is considered here to be also attributable to the significant pressure fluctuation due to the extinction of cavitation inside the nozzle. Moreover, it was confirmed that the breakup length was approximately 90 mm.

When the injection pressure P_{inj} was to 0.5 MPa (Fig. 5 (b)), the cavitation region almost disappeared near the nozzle exit, and, as is the case with P_{inj}=0.3 MPa, liquid droplets were generated from the outer edge of the liquid jet. It was also found that the droplet diameter was smaller than that in cases where P_{inj}=0.3 MPa, and the liquid jet was expanded a little in the radial direction.



(a) P_{inj}=0.3 MPa (b) P_{inj}=0.5 MPa (c) P_{inj}=1.0 MPa

Figure 5 Behaviors of the liquid flow inside the nozzle and the liquid jet

This result agrees with the experimental result of Sou et al. [7] in that a liquid jet expands if the cavitation region becomes almost equivalent to the nozzle length. It was also confirmed that the breakup length jet was shorter than that in cases where P_{inj}=0.3 MPa, which was found to be approximately 60 mm. This is likely to be attributable to the fact that significant pressure fluctuation occurred near the nozzle exit due to the extinction of cavitation, which disturbed the fluid flow inside the nozzle.

By contrast, when the injection pressure P_{inj} was 1.0 MPa (Fig. 5 (c)), the liquid jet issued without the complete extinction of the cavitation region inside the nozzle. In this case, as compared with that where P_{inj}=0.3 or 0.5 MPa, despite the larger flow rate and the higher air-liquid relative velocity, there was little generation of droplets at the outer edge of the liquid jet. This means that no extinction of cavitation inside the nozzle causes the significant pressure fluctuation. Also, in the case of low pressure, under which the cavitation region disappeared inside the nozzle, the liquid jet turbulence generated liquid droplets on the surface of liquid jet. When the pressure was high, however, the cavitation region elongates to the entire nozzle and the liquid flow inside the nozzle remained issued as the disturbed liquid, while the liquid jet's injection direction was vibrated.

2. Liquid Jet Turbulence

It was confirmed in the previous section that the injection pressure affected the breakup and fluctuation of the liquid jet. In this section, using the optical fiber sensor, the variations of liquid jet diameter and its turbulence with time were investigated in the vicinity of the nozzle exit.

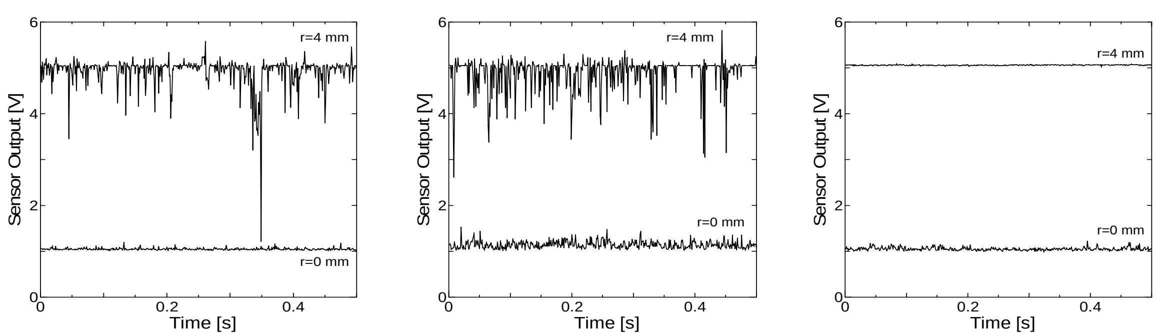
Figure 6 shows the experimental results, which were obtained for horizontal planes (in a radial direction; r=0 or 4 mm) at z=5 mm from the nozzle exit, of light attenuation after the light transmitted through the liquid jet.

Figures 6 (a), (b) and (c) show cases where P_{inj}=0.3 MPa, 0.5 MPa and 1.0 MPa, respectively. In the event of no liquid jet between the light source and sensor, the sensor output is 5 V, whereas the light attenuates and the output decreases if the liquid jet exists. For this reason, the transmitted light intensity decreases significantly at the center of the liquid jet (r=0 mm) without depending on the injection pressure.

In cases where the injection pressure P_{inj} is 0.3 MPa, the transmitted light intensity decreases, and we can find fluctuations, even though they are small. It is because there exists a small turbulence on the surface of liquid jet even immediately after the liquid is issued from the nozzle. On the other hand, when moving away from the center (r=4 mm), the transmitted light intensity will increase and the resultant fluctuations also become large. This means that the liquid jet does not always exist, but droplets are often generated. In particular, this phenomenon corresponds to the formation of liquid droplets having larger diameter when the decrease of the transmitted light intensity is large (see Time=0.35 s).

In cases where the injection pressure P_{inj} is 0.5 MPa, the transmitted light intensity decreases and the fluctuations are larger than those when P_{inj} is 0.3 MPa, in the central area (r=0 mm). Since the extinction of the cavitation region near the nozzle exit causes the larger pressure fluctuation, turbulence is present on the liquid jet surface, even immediately after ejection from the nozzle. On the contrary, when moving away from the center (r=4 mm), it is found that the transmitted light intensity increases with the larger amplitude of variation of the sensor output. This means that more liquid droplets are generated from the outer edge of the liquid jet and that more breakup takes place from the liquid jet surface than the case where P_{inj}=0.3 MPa. Due to the extinction of the cavitation region near the nozzle exit, the liquid flow inside the nozzle is disturbed and the liquid jet is expanded as the pressure fluctuated. These results correspond with those of Sou et al. [7] in that increased turbulence due to the extinction of the cavitation region in the vicinity of the nozzle exit plays a major role in forming liquid threads from the liquid jet surface, provided that the nozzle length is almost equivalent to the cavitation region.

In cases where the injection pressure P_{inj} is 1.0 MPa, we can see that the transmitted light intensity decreases, as is the case with P_{inj}=0.3 or 0.5 MPa, and that the fluctuations take place owing to turbulence on the liquid jet surface, although to a lesser extent, in the central area (r=0 mm). In contrast, when moving away from the center (r=4 mm), the transmitted light intensity increases and the output fluctuations are very small. This means that few liquid droplets are generated from the outer edge of the liquid jet because the liquid flows from the nozzle exit without the extinction of the cavitation region inside the nozzle.



(a) P_{inj}=0.3 MPa (b) P_{inj}=0.5 MPa (c) P_{inj}=1.0 MPa

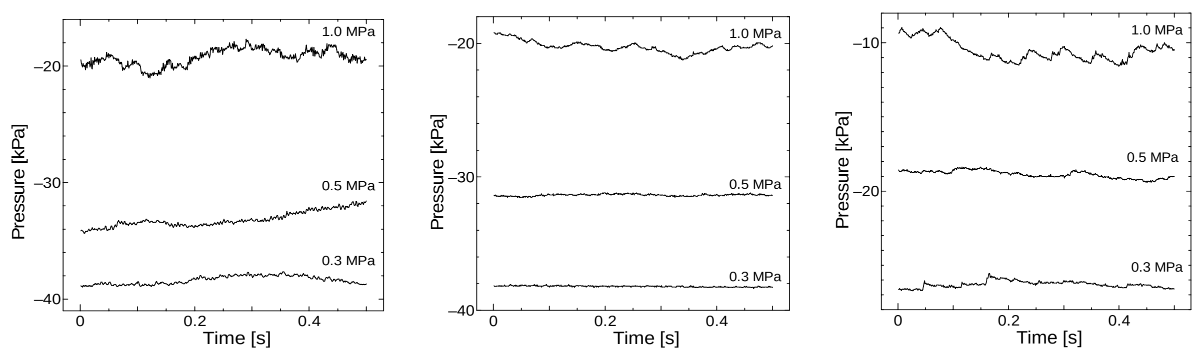
Figure 6 Variations of output voltage with time at z=5 mm

3. Pressure Fluctuations inside the Nozzle

A pressure measurement was made inside the nozzle, because our observation of the liquid jet and our measurement of the liquid jet turbulence showed that the breakup and formation of liquid droplets were caused by the significant pressure fluctuations due to the extinction of the cavitation region.

Figures 7 (a), (b) and (c) show the results of pressure measurements at x=9 mm, 18 mm, and 26 mm, respectively. The pressure inside the nozzle shows negative value without depending on the injection pressure. At the measuring location x=9 mm, the pressure inside the nozzle is negative with relatively small fluctuations. It is found that the pressure fluctuations are small in case P_{inj}=0.3 and 0.5 MPa, and they are large in case P_{inj}=1.0 MPa. This is caused by the turbulence inside the nozzle, which increases as the injection pressure increases (Fig. 5 (c)). Since the measuring location x=18 mm is within the central part of the cavitation region, the pressure fluctuations are rather small for P_{inj}=0.3 and 0.5 MPa. Furthermore, as in the case of x=9 mm, significant pressure fluctuations are observed for P_{inj} =1.0 MPa, also because of the turbulence inside the nozzle.

At the measuring location x=26 mm, we can see that the pressure inside the nozzle increases more than that at x=9 or 18 mm. We can also see that the pressure fluctuations are larger than those when P_{inj}=0.3 or 0.5 MPa at x=18 mm. This is due to the fact that the front edge of cavitation region moves forward/backward along the liquid flow direction. Also, in cases where P_{inj}=1.0 MPa, we can see that more fluctuations will take place as compared with other injection pressures, as in the case where the measuring locations, x=9 or 18 mm.



(a) x=9 mm (b) x=18 mm (c) x=26 mm

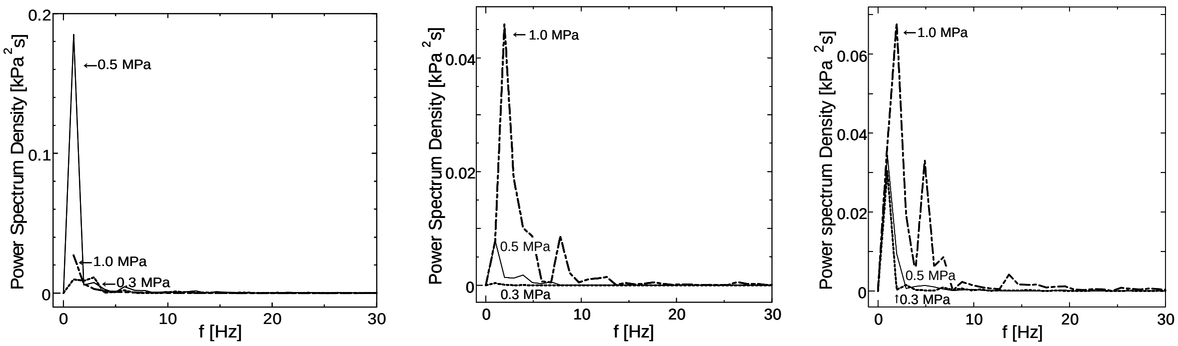
Figure 7 Pressure fluctuations of the liquid flow inside the nozzle

4. Power Spectrum of Pressure Fluctuations inside the Nozzle

Figure 8 shows the results of the power spectrum of the pressure fluctuations inside the nozzle. At the measuring location x=9 mm (Fig. 8 (a)), no peak is found within a specific frequency range when P_{inj}=0.3 MPa, probably because the measuring location is covered with the cavitation region. In contrast, when P_{inj}=0.5 MPa, a significant peak can be verified at lower frequencies. This is considered to be the fluctuations of the cavitation region due to the increase in the injection pressure.

At the measuring location x=18 mm (Fig. 8 (b)), no peak is found in a specific frequency range in P_{inj}=0.3 MPa, it is similar to the result at x=9 mm. In contrast, when P_{inj}=1.0 MPa, a peak can be verified at lower frequencies. The reason why the spectrum density value is small is due to the small turbulence of the liquid flow inside the nozzle.

At the measuring location x=26 mm, additional pressure fluctuations inside the nozzle are found as compared with the case where x=9 or 18 mm. Since the cavitation region disappears near the nozzle exit as the turbulent liquid flow, there is a significant peak at a low frequency in the power spectrum when P_{inj}=0.3 or 0.5 MPa (Fig. 8 (c)). Besides, when P_{inj}=1.0 MPa, we can see there are several peaks over the lower frequency range. These peaks in the lower frequency range, as in the case of the measuring locations (x=9 or 18 mm), are thought to result from the coexistence of increase in the injection pressure, the fluctuations of the cavitation region, and the turbulence due to the generation and extinction of cavitation bubbles from the cavitation region front. Thus, the liquid flow inside the nozzle is significantly disturbed.



(a) *x*=9 mm (b) *x*=18 mm (c) *x*=26 mm

Figure 8 Power spectrum of the pressure fluctuations inside the nozzle

Conclusions

In this study, we investigated the relationships between the fluid flow inside a nozzle and the liquid jet turbulence, with the objective of facilitating the atomization of cavitation inside the nozzle. The results are summarized as follows:

1) Generation of cavitation results in turbulence of fluid flow inside the nozzle and larger liquid jet turbulence after ejection.
2) We confirmed that liquid droplets were formed and the liquid jet expanded if the cavitation region disappeared near the nozzle exit.
3) The pressure inside the nozzle fluctuates under the influence of the cavitation region.
4) The power spectrum density of pressure fluctuations peaked in the lower frequency range, which indicates fluctuations in the cavitation region and the significant turbulence of scale inside the nozzle.
5) We ascertained the fact that atomization was facilitated by extinction of the cavitation region inside the nozzle.

Acknowledgements

This research was supported by the Grants-in-aid for Scientific Research in 2007-2008 for Scientific Research (C) [No.19560181]. We would like to take this opportunity to express our gratitude for the financial assistance.

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