Effect of cavitation in cylindrical and two-dimensional nozzles on liquid jet formation

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Abstract. Cavitation in various nozzles of different geometries and dimensions, i.e., two-dimensional (2D) and cylindrical nozzles, and liquid jets discharged from the nozzles are visualized using a digital camera, and the index for estimating cavitation in a nozzle is discussed. Simultaneous high-speed visualization of cavitation in the cylindrical nozzle and a liquid jet are also carried out to investigate the relation between cavitation and ligament formation. As a result, the following conclusions are obtained: (1) Flow pattern transition in cavitating flows induces the transition in liquid jet patterns. As the liquid flow rate increases, flow patterns of cavitating flows and liquid jets transit from (no cavitation and wavy jet), (developing cavitation and wavy jet), (supercavitation and spray), to (hydraulic flip and flipping jet); (2) When the trace of a cavitation cloud comes out of the nozzle, a ligament is formed at the liquid jet interface. (3) The collapse of cavitation clouds near the exit and induces ligament formation, which, in turn, causes liquid jet atomization; (4) The causal relationship between cavitation cloud and ligament formation holds not only in the two-dimensional nozzle but also in the cylindrical nozzle.

Key words: cavitation, nozzle, liquid jet, ligament

Introduction

It has been pointed out that cavitation may occur in a nozzle of pressure atomizers, and may influence atomization of a liquid jet discharged from the nozzle (Bergwerk, 1959). Hence, efforts have been made to visualize cavitation in nozzles (Hiroyasu et. al, 1991; Ilham Maulana, 2008; Miranda et. al, 2003; Payri et. al, 2004; Sou et. al 2006). The observation of cavitation in the nozzle and the liquid jets confirmed that liquid jet atomization is enhanced when cavitation is developed in a nozzle, i.e., in super cavitation regime.

Large efforts have been devoted to optimize the geometries of the nozzles, since it is difficult to predict the development of cavitation in the nozzles. An indicator which can be utilized to predict the formation of super cavitation is, therefore, of great use in designing pressure atomizers. The relation among cavitation, turbulence and atomization, however, remains unclear.

To observed cavitation in 2D and cylindrical nozzles and liquid jet, we used a digital camera under various conditions of Reynolds and cavitation numbers. The cavitation number σ and the Reynolds number *Re* as indicators of cavitation in a nozzle are defined by (So et al., 2006):

$$\sigma = \frac{P_b - P_v}{\frac{1}{2}\rho_L V_N^2}$$

$$Re = \frac{V_N W_N}{\nu_L}$$

where P_b is the back pressure (pressure at the exit of nozzle), P_v the vapor saturation pressure, ρ_L the liquid density, V_N the mean liquid velocity in the nozzle, W_N the nozzle width and ν_L the liquid kinematic viscosity.

In the present study images of cavitation and a liquid jet in a cylindrical nozzle are obtained to find better information about cavitation in various nozzle geometries. Simultaneous visualization of a cavitation cloud in a cylindrical nozzle and a liquid jet interface using a high-speed camera is also carried out to examine the relation between cavitation and ligament formation in a 2D and cylindrical nozzles. First we conduct high-speed visualization using a 2D nozzle, which enables us to observe the structure of cavitation and to measure liquid velocity in the nozzle. In practical applications, nozzles are often cylindrical. Hence, in the next step we observe cavitation and liquid jet using a cylindrical nozzle.

Experimental Methods

Schematic of the experimental setup is shown in Fig. 1. Filtered tap water of 293K in temperature was injected through various nozzles of different geometries and dimensions into ambient air of 0.1 MPa in pressure. Water flow rate was measured using a flowmeter (Nippon flow cell, D10A3225).

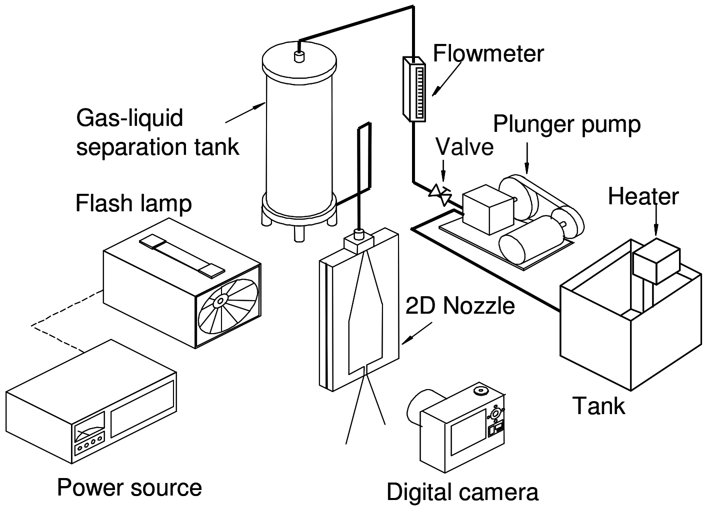
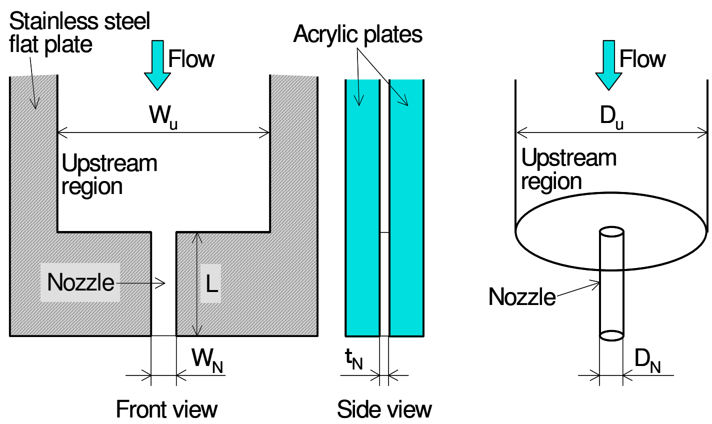


Figure 1. Experimental setup.

Schematics of 2D and cylindrical nozzles are shown in Figs. 2 (a) and (b), respectively. A schematic diagram of a photographic system to observe cavitation and a liquid jet is shown in Fig. 3. The nozzle was placed between the light source (Nissin Electronic, MS-100 & LH-15M, duration 12 μs) and the digital camera (Nikon D70, 3008x2000 pixels). Images of cavitation and the liquid jet were taken by using the digital camera.



(a) two-dimensional (2D) nozzle (b) cylindrical nozzle

Figure 2. Schematics of 2D and cylindrical nozzles

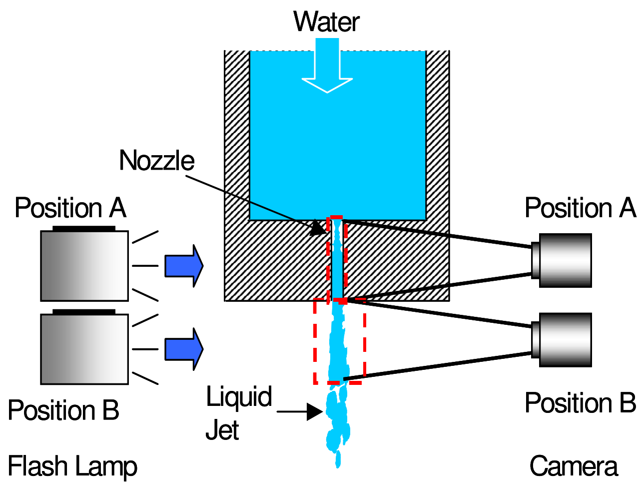


Figure 3. Schematic diagram of the photographic system

Cavitation in a Nozzle

Cavitation and liquid jet regimes for a 2D nozzle of 4 mm in width W_N shows in figures 5. When σ is large, cavitation bubbles are not formed and a liquid jet is wavy. As σ decreases, cavitation bubbles appear in the upper part of the nozzle (developing cavitation). In the developing cavitation regime, a liquid jet remains wavy. When σ is smaller, cavitation zone extends to just above the nozzle exit (super cavitation). In the super cavitation regime, liquid jet atomization is enhanced, i.e., ligaments and droplets appear and the spray angle increases. Further decrease in σ results in the formation of hydraulic flip. Hence, a cavitation index, which enables us to estimate the flow condition corresponding to the super cavitation regime, would be of use in practical design of injectors.

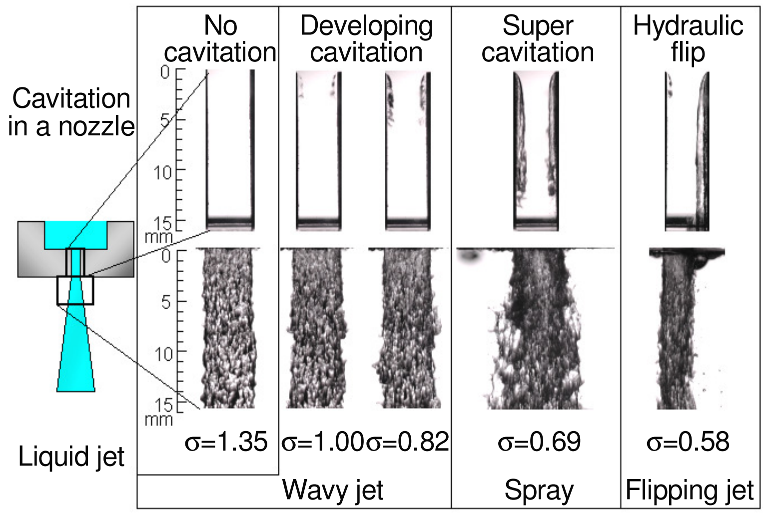


Figure 4. Cavitation in a 2D nozzle and a liquid jet (*WN* = 4.21 mm, *LN* = 16 mm).

Figure 5 shows typical images of cavitation in the cylindrical nozzle of 4.0 mm in diameter and liquid jets. The regime transitions of cavitation and liquid jet for the cylindrical nozzle show the same trend as those for the 2D nozzles (Fig. 4). However, as can be understood from the values of σ in Figs. 4 and 5, the value of σ corresponding to each regime depends on the nozzle geometry.

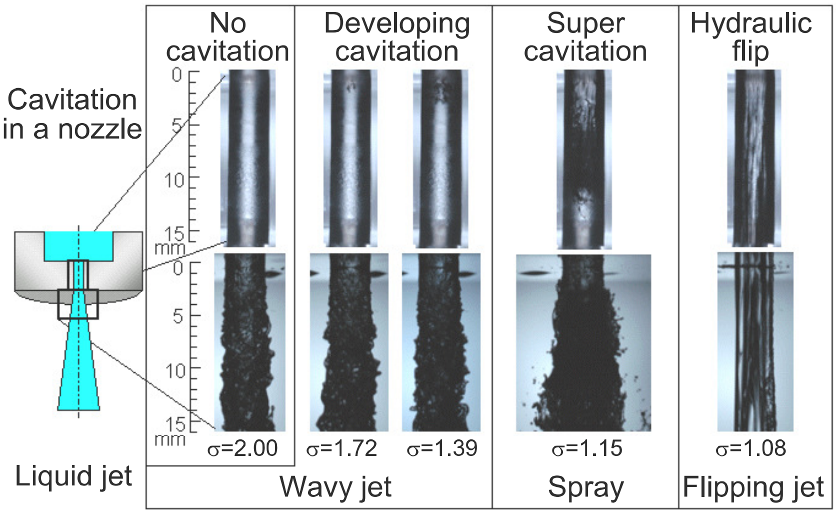
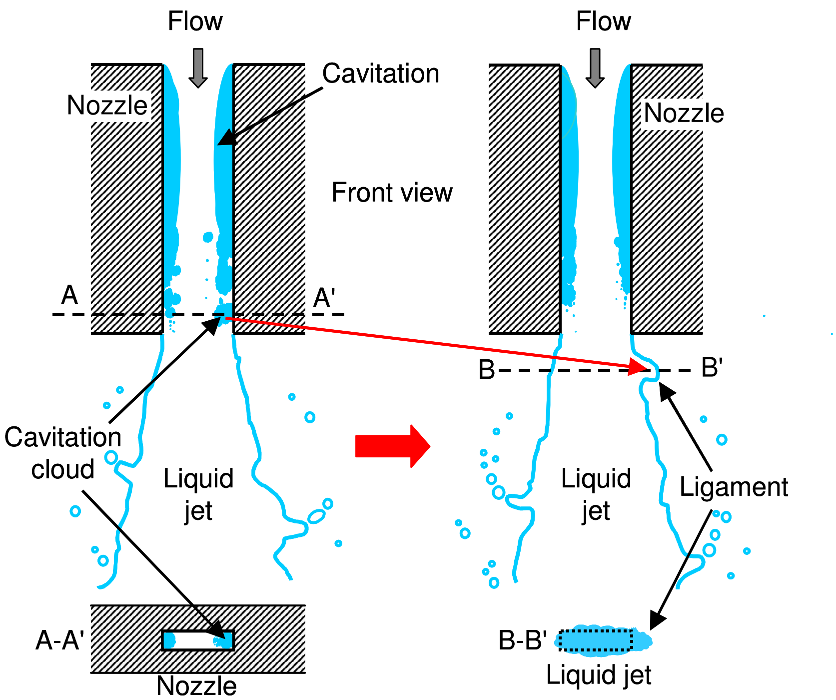


Figure 5. Cavitation in a cylindrical nozzle and a liquid jet (*DN* = 4.0 mm, *LN* = 16 mm).

Mechanism of Cavitation-induced Atomization

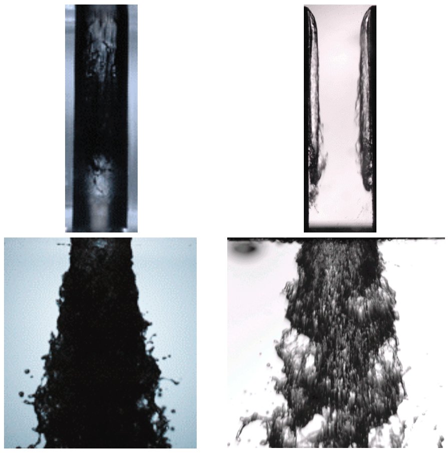
Image of liquid jet and cavitation in a 2D nozzle is shown in Fig. 4 as a reference for the discussion on the effects of cavitation on ligament formation for the cylindrical nozzle. Whenever a trace of a cavitation bubble cloud comes out of the nozzle, a ligament is formed at the liquid jet interface. Figure 5 illustrates the ligament formation induced by the collapse of a cavitation cloud in the 2D nozzle.



(a) before the collapse of a cavitation cloud (b) after the collapse of the cavitation cloud
Figure 6. Ligament formation induced by cavitation in the two-dimensional nozzle

Figure 7 (a) shows the images of cavitation in the cylindrical nozzle of 4 mm in inner diameter and liquid jet in the supercavitation regime. Figure 7 (b) shows the images for the

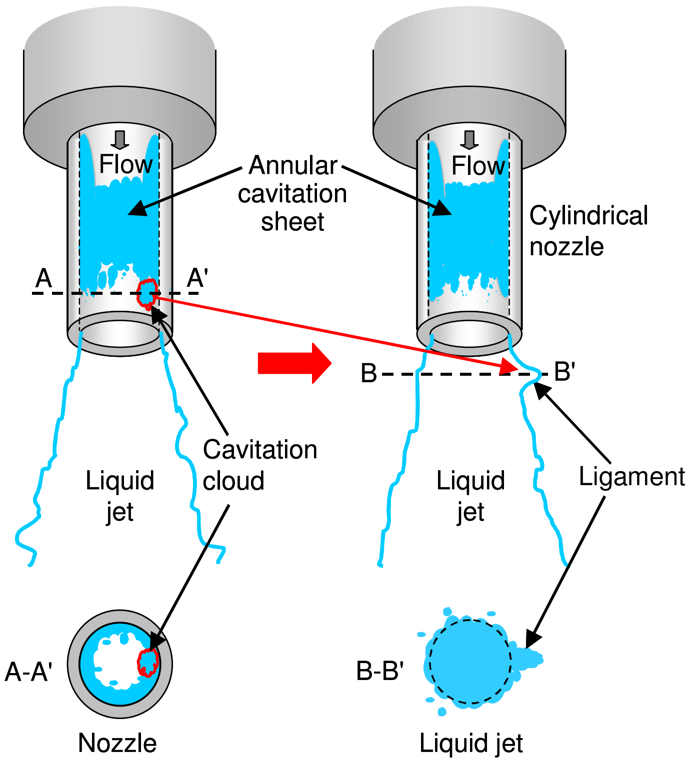
2D nozzles. There is only one circular side wall and one cavitation sheet developed along the wall in the case of cylindrical nozzles, while there are two cavitation sheets and two side walls in the case of 2D nozzles. Hence, the process found in the 2D nozzle, i.e., the collapse of cavitation clouds induces ligament formation, also takes place in cylindrical nozzles.



(a) cylindrical nozzle (b) 2D nozzle

Figure 7. Asymmetric behavior of cavitation in nozzles and liquid jets

The fact that cavitation clouds in the 2D nozzle induce ligament formation leads to the following hypothesis for cylindrical nozzles, i.e., clouds of cavitation bubbles are formed at the skirt of the annular cavitation sheet as shown in Fig. 8 (a), and a ligament is ejected at the trace of the cavitation cloud as illustrated in Fig. 9 (b).



(a) before the collapse of a cavitation cloud (b) after the collapse of the cavitation cloud

Figure 8. A hypothesis: ligament formation induced by cavitation clouds in a cylindrical nozzle

Conclusions

Cavitation in a two-dimensional (2D) nozzle and a cylindrical nozzle and interfaces of liquid jets discharged from the nozzles are simultaneously visualized using a digital camera to investigate the mechanism of cavitation-induced atomization. As a result, the following conclusions are obtained.

(1) Flow pattern transition in cavitating flows induces the transition in liquid jet patterns. As the liquid flow rate increases, flow patterns of cavitating flows and liquid jets transit from (no cavitation and wavy jet), (developing cavitation and wavy jet), (supercavitation and spray), to (hydraulic flip and flipping jet)
(2) When the trace of a cavitation cloud comes out of the nozzle, a ligament is formed at the liquid jet interface.
(3) The collapse of cavitation clouds near the exit and induces ligament formation, which, in turn, causes liquid jet atomization
(4) The causal relationship between cavitation cloud and ligament formation holds not only in the two-dimensional nozzle but also in the cylindrical nozzle.

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References

Bergwerk, W., Flow Pattern in Diesel Nozzle Spray Holes, *Proc. Instn. Mech. Engrs.*, Vol. 173, No. 25 (1959), pp. 655-660.

Hiroyasu, H., Arai, M. and Shimizu, M., Break-up Length of a Liquid Jet and Internal Flow in a Nozzle, *Proceedings of International Conference on Liquid Atomization and Spray Systems 91 (ICLASS 91)* (1991), pp. 275-282.

Knapp, R. T., Daily, J. W. and Hammitt, F. G., *Cavitation*, McGraw-Hill, (1970).

Jalaluddin dan M. Ilham maulana, Pengamatan Eksperimental Terhadap Stuktur Aliran Kavitasi dan Profil Kecepatan di dalam Nosel 2D, Seminar Nasional , Medan, 2010

Miranda, R,. Chaves, M., Martin, U., and Obermeier, F., Cavitation In a Tranparaent Real Size VCO Injection Nozzle, *CD-ROM of International Conference on Liquid Atomization and Spray Systems 2003 (ICLASS 2003)* (2003), CD-ROM.

Nurick, W. H., Orifice Cavitation and Its Effect on Spray Mixing, Journal of Fluid Engineering, Transactions of ASME (1976), pp. 681-687.

Payri, F., Bermudez, V., Payri, R. and Salvador, F.J., The Influence of Cavitation in on the Internal Flow and the Spray Characteristics in Diesel Injection Nozzles, *Fuel*, Vol. 83, (2004), pp. 419-431.

Sou, A., Muhammad Ilham Maulana, Hosokawa, S. & Tomiyama, A., "Effects of Cavitation in a Nozzle on Liquid Jet Atomization", *Proc. ICLASS 2006*, CD-ROM, ICLASS06-043, (2006).

Soteriou, C., Andrews, R., and Smith, R., Direct Injection Diesel Sprays and The Effect Cavitation and Hydraulic Flip on Atomization, *SAE Paper* (1995), Paper No. 950080.