Dimensionless Numbers on Cavitation in a Nozzle of a Plain Orifice Atomizer

A. Sou*, S. Hosokawa and A. Tomiyama
Graduate School of Maritime Sciences
Kobe University
Kobe, 658-0022 Japan

Abstract

Although it is known that the development of cavitation (super cavitation) in a nozzle of pressure atomizers promotes liquid jet atomization, our knowledge on various dimensionless numbers, such as the cavitation number σ and the Reynolds number *Re*, on cavitation and jets is still rudimentary. We do not know which dimensionless number can be used to quantitatively predict the formation of super cavitation in various nozzles. In this study, effects of various dimensionless numbers on cavitation in plain orifice atomizers and liquid jets are investigated. To examine the effects of σ and *Re* on cavitation and jets, water temperature and flow rates are varied to adjust σ and *Re* to desired values. Nozzles of different upstream widths and length-to-diameter ratios L/D are used to examine the effects of flow contraction on cavitation and whether or not various dimensionless numbers can be used to predict the formation of super cavitation. As a result, we confirm that (1) cavitation length L_{cav}/L and associated jet are not strongly affected by *Re* but by σ, (2) the thickness of the cavitation zone increases with the ratio C_u of the cross-sectional area upstream of the nozzle to that of the nozzle due to the decrease in contraction coefficient C_c, (3) the formation of super cavitation in nozzles with different C_u and L/D is predicted not by the conventional cavitation numbers, such as σ, σ_2 and σ_3, but by the modified cavitation number σ_c ($= C_c^2[2(P_b - P_v)/\rho V^2 + \lambda L/D_H + 1]$) in which effects of the flow contraction and the frictional pressure drop in a nozzle are taken into account.

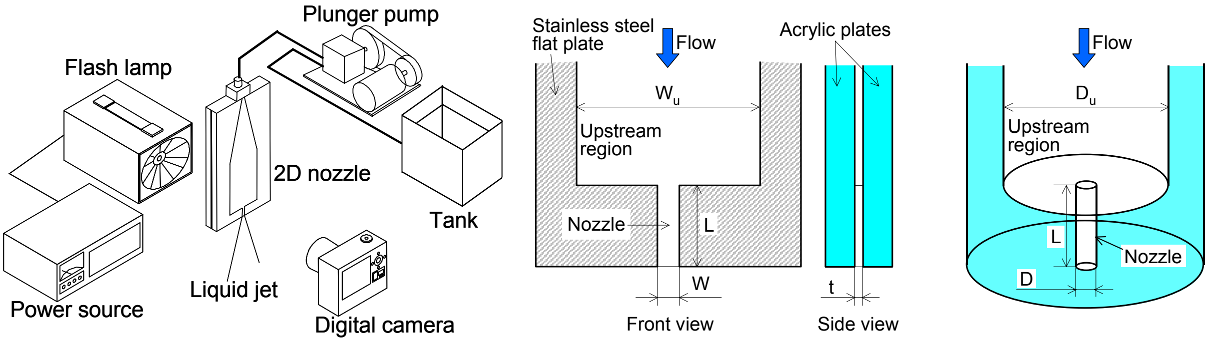
Introduction

It is known through a number of experiments [1-11] that cavitation takes place in the nozzle of pressure atomizers, and it affects the atomization of discharged liquid jets. Visualizations of cavitation in nozzles [2-6] confirm that liquid jet atomization is enhanced when cavitation is fully developed in a nozzle, *i.e.*, in super cavitation regime [3, 6]. An indicator which can be used to predict the formation of super cavitation is, therefore, useful for the design of pressure atomizers. Various dimensionless numbers, such as the cavitation numbers and the Reynolds number *Re*, have been used as parameters on cavitation in nozzles [1, 2, 4-10]. Various cavitation numbers σ, σ_2, σ_3 and σ_c of different definitions have been proposed and used, which implies that we do not know which one can be utilized to quantitatively predict the development of cavitation in nozzles with different sizes and shapes. In this study cavitating flows of various fluid properties flowing through nozzles of plain orifice atomizers with various sizes and different upstream widths or length-to-diameter ratios L/D are visualized to investigate the effect of the cavitation and Reynolds numbers on cavitation and jets. Whether or not the dimensionless numbers can be used to predict the formation of super cavitation is also examined.

Experimental Setup

A schematic of the experimental setup is shown in Fig. 1(a). Filtered tap water was supplied from the plunger pump and discharged from a two-dimensional (2D) or a cylindrical nozzle of a plain orifice atomizer into ambient air at atmospheric pressure P_b. The liquid flow rate was measured using flowmeters. The uncertainty in measured flow rate was less than 3.7 %. The injection pressure P_u was measured at 100 mm upstream the nozzle using Bourdon pressure gauges. Images of cavitation and jet were taken using a digital camera (Nikon, D70, 2000 x 3008 pixels), various lenses and a flash lamp (Nissin Electronic, MS-1000 and LH-15M, duration = 4 μs). The concentration of oxygen dissolved in the water was measured using a dissolved oxygen probe (Hach company, HQ30d) and was about 9 mg/L. As shown in Fig. 1(b), a 2D nozzle consists of two acrylic flat plates and two stainless steel thin flat plates, by which sharp-edges are formed at the nozzle inlet. The width W (For simplicity it is sometimes written as D.), length L and thickness t of the 2D nozzles and the width W_u of the upstream regions are varied. The diameter D_u of the upstream region and the nozzle length L are varied for cylindrical nozzles (Fig. 1(c)).

*Corresponding author, sou@maritime.kobe-u.ac.jp



(a) Experimental setup (b) Two-dimensional (2D) nozzle (c) Cylindrical nozzle

Figure 1. Experimental setup and nozzles

Which is Dominant Reynolds Number or Cavitation Number?

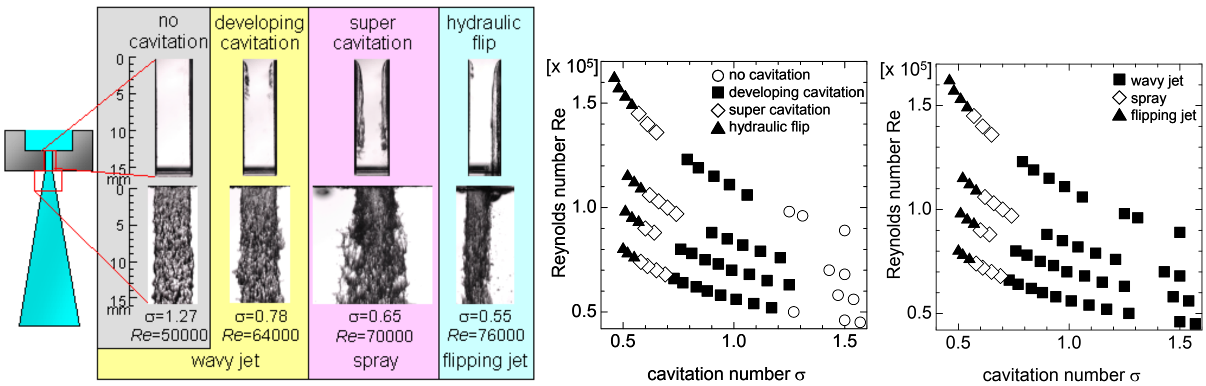
Since cavitating flow is affected by the sharpness of the nozzle edge, a single 2D nozzle of $W = 4$ mm, $L = 16$ mm and $t = 1$ mm is used ($L/W = 4$). The Re increases with water temperature T_L since kinematic viscosity ν of water decreases with increasing T_L, while σ does not change a lot by varying T_L. To examine the influences of σ and Re on cavitation and jet, observations are carried out under various T_L ($293 \leq T_L \leq 333$ K) and the liquid flow rates [6]. The σ and Re are defined by

$$\sigma = \frac{P_b - P_v}{0.5\rho V^2}, \qquad Re = \frac{VW}{\nu} \tag{1, 2}$$

where P_b is the back pressure, P_v the vapor saturation pressure, ρ the liquid density, V the mean liquid velocity in the nozzle, ν the liquid kinematic viscosity, respectively. In the experiment Re is varied from 40000 to 162000, while σ is changed from 0.46 to 1.6.

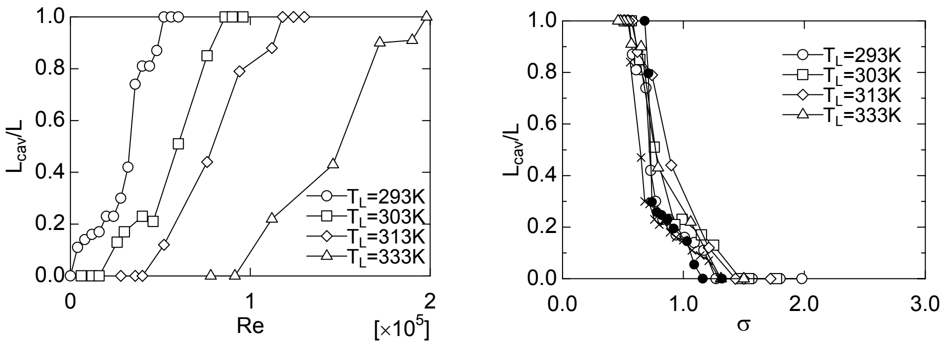
Regimes of cavitating flow and jet near the nozzle are summarized in Fig. 2(a) ($T_L = 293$ K, $W = 4$ mm, $L/W = 4$). At $\sigma > 1.2$ cavitation is not observed and the jet is wavy jet. For $0.75 \leq \sigma \leq 1.2$ cavitation bubble clouds appear in the separated boundary layer at the upper half of the nozzle (developing cavitation) and a jet remains wavy jet. For $0.55 < \sigma < 0.75$ cavitation zone extends from the inlet to just above the nozzle exit (normalized cavitation length $L_{cav}/L = 0.7$-1, super cavitation) and atomization is promoted, i.e., ligaments and droplets appear and the spray angle increases (spray). In the nozzles of $L/W = 4$, long cavitation films attached to the side wall are formed, and cavitation clouds are intermittently shed to induce ligament formation. At $\sigma < 0.55$ hydraulic flip is formed [6].

Cavitation and jet regimes are shown in Figs. 2(b) and (c), respectively. The spray region on the jet regime map corresponds to the super cavitation region on the cavitation regime map, which indicates that the formation of super cavitation enhances atomization. Since the transition from developing to super cavitation does not strongly depend on Re but on σ, the transition from wavy jet to spray also depend on σ.



(a) Images of cavitation and jets (L/W=4) (b) Cavitation regime (c) Liquid jet regime

Figure 2. Cavitation in a 2D nozzle and jet ($W = 4$ mm, $L/W = 4$, $C_u = 8$)



(a) L_{cav}/L vs. Re (b) L_{cav}/L vs. σ

Figure 3. Relation of L_c/L and Re and that of L_c/L and σ (W = 4 mm, L/W = 4)

The effects of Re and σ on the normalized cavitation lengths L_{cav}/L are shown in Figs. 3 (a) and (b), respectively. The results indicates that Re does not affect L_{cav}/L, and L_{cav}/L for different T can be predicted quantitatively using the cavitation number σ in the case of a 2D nozzle of L/W = 4.

Cavitation Numbers

Pressure distribution along the axis of a nozzle is illustrated in Fig. 4. It should be pointed out that cavitation appears in the vena contracta. In addition to σ defined by Eq. (1), various cavitation numbers have been proposed and used. Bergwerk [1], Soteriou et al. [4] and many other researchers [7-9] used σ_2, Nurick [10] and Payri et al. [11] used σ_3, and Hiroyasu et al. [2] proposed σ_H. They are defined as

$$\sigma_2 = \frac{P_u - P_b}{P_b - P_v}, \qquad \sigma_3 = \frac{P_u - P_v}{P_u - P_b}, \qquad \sigma_H = \frac{P_c - P_v}{\rho V_c^2 / 2} \tag{3, 4, 5}$$

where V_c is the contraction velocity. Hiroyasu et al. used the Bernoulli's equation and derived the following form of σ_H. By not ignoring the friction loss and following the definition of σ, we define the modified cavitation number σ_c:

$$\sigma_H = C_c^2\left[\frac{P_b - P_v}{0.5\rho V^2} + \frac{\lambda(L - L_{cav})}{D_H} + 1\right] - 1 \cong 0.36\left[\frac{P_b - P_v}{0.5\rho V^2} + 1\right] - 1, \qquad \sigma_c = C_c^2\left[\frac{P_b - P_v}{0.5\rho V^2} + \frac{\lambda L}{D_H} + 1\right] \tag{6, 7}$$

where λ is the friction factor, D_H the hydraulic equivalent diameter of a nozzle, and C_c (= V / V_c) the contraction coefficient. It is noted that the effects of flow contraction on cavitation is taken into account only in σ_H and σ_c.

Whether or not the cavitation numbers can quantitatively predict the formation of super cavitation in nozzles with different shapes, however, has not been verified yet.

Effects of Flow Contraction

Since C_c of a nozzle is expressed as a function of the ratio C_u between the cross-sectional area upstream of the nozzle to that of the nozzle, C_u may affect cavitation. Cavitation in nozzles with different C_u (C_u = 1.5-8.1 for 2D nozzles, C_u = 4-100 for cylindrical nozzles) are visualized in Ref. [12]. As a result, it is found that cavitation in nozzles with different C_u exhibit almost the same regime transition, while the inception and the transition to super cavitation in a nozzle of smaller C_u occur at smaller σ. At C_u = 1.5 hydraulic flip does not appear even at very large flow rates. Images of cavitation near the inlet edge of 2D nozzles with different C_u are shown in Fig. 5. The thickness W_{cav} of the cavitation zone increases with C_u. When W_{cav} is large, V_c at vena contracta is large and the pressure P_c at vena contracta is low. This is the reason why super cavitation is formed at smaller σ in the case of smaller C_u. The result clearly shows that flow contraction plays an important role in cavitation.

In the following, the Blasius equation is used to evaluate λ, while the factor of 1.15 is multiplied in the case of 2D nozzle of W/t = 4. The values of C_c for 2D nozzles are calculated using measured W_{cav}, while those for cylindrical nozzles are given as a function of C_u (C_c = 0.61 for $C_u \geq$ 10, and C_c = 0.625 for C_u = 4).

Figure 6 shows the relation between L_{cav}/L and the cavitation numbers. The result confirms that only σ_c has a potential to qualitatively predict the formation of super cavitation (0.7 < L_{cav}/L < 1 at σ_c = 0.8).

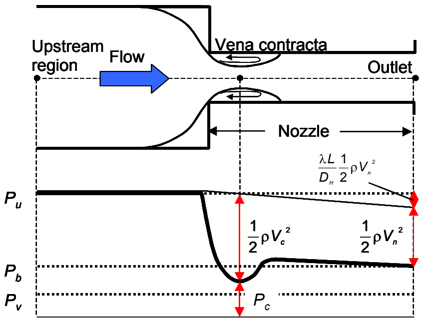
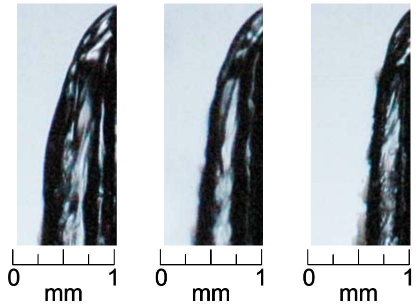
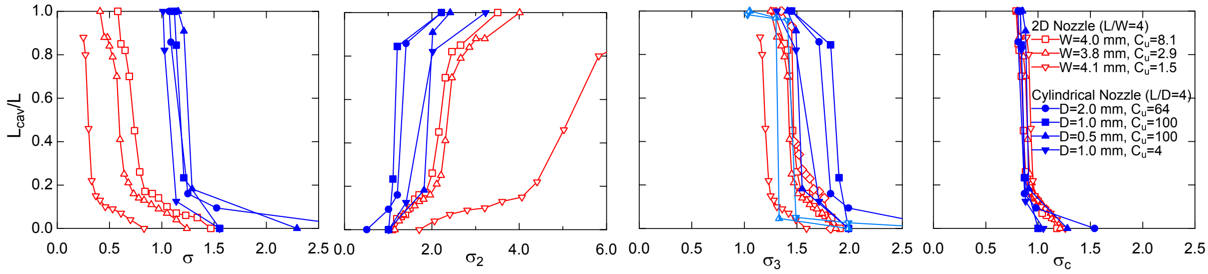


Figure 4. Pressure distribution



(a) $C_u = 8.1$ (b) $C_u = 2.9$ (c) $C_u = 1.5$

Figure 5. Images of cavitation near the inlet edge



(a) L_{cav}/L vs. σ (b) L_{cav}/L vs. σ_2 (c) L_{cav}/L vs. σ_3 (d) L_{cav}/L vs. σ_c

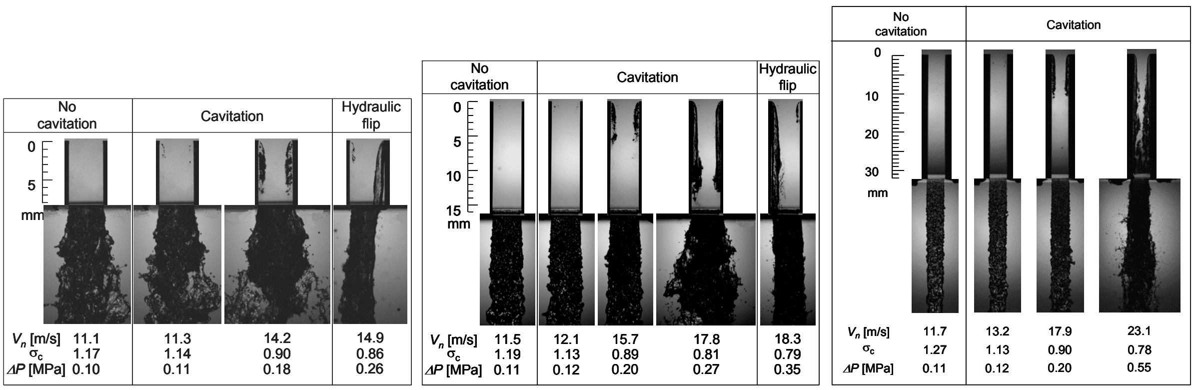
Figure 6. Relation between cavitation length L_{cav}/L and various cavitation numbers

Effects of Length-To-Diameter Ratio

The effects of the length-to diameter ratio L/D (L/W in the case of 2D nozzles) on the discharge coefficient [13], spray-tip penetration and spray angle [14], droplet size of a spray [15], critical cavitation number σ_2 at which cavitation is fully developed [1] have been examined, and cavitation in nozzles with various L/D has been reported [3, 5, 12, 16, 17]. Cavitation in short nozzles ($L/D < 3$) and 2D nozzles, and the mechanism of how cavitation induces ligament formation have not been clarified yet. In this study, cavitation in 2D and cylindrical nozzles with various L/D ($L/D = 2, 4, 8$) are visualized and a simultaneous and high-speed visualization of cavitation and jet is conducted.

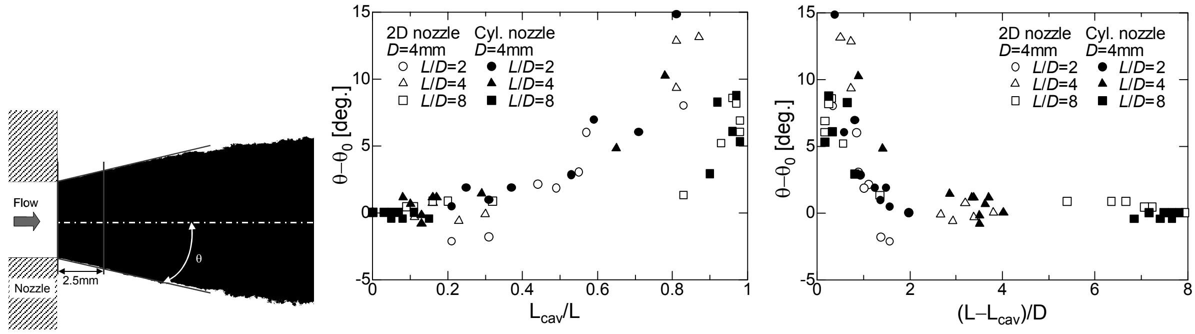
Images of cavitation and jets are shown in Fig. 7. As shown in Fig. 7 (a), spray angle is larger and no cavitation film is formed at super cavitation conditions in the short nozzle ($L/W = 2$). In the 2D and cylindrical nozzles with $L/D \geq 8$, no hydraulic flip is formed. By the simultaneous and high-speed visualization of cavitation and the associated jet, we found that ligament formation is induced by the collapse of cavitation clouds near the exit not only for $L/W = 4$ [6] and $L/D = 4$ (a cylindrical nozzle) [18] but also for the short and the long nozzles ($L/W = 2$ and 8).

As shown in Fig. 8, The relation between measured spray angle θ and cavitation length L_{cav} clarifies that the increase in θ not occurs at $0.7 < L_{cav}/L < 1$ but at $(L-L_{cav})/D < 1$.



(a) $L/W = 2$ (b) $L/W = 4$ (c) $L/W = 8$

Figure 7. Cavitation in 2D nozzles with different L/W (L/W = 2, 4, 8)

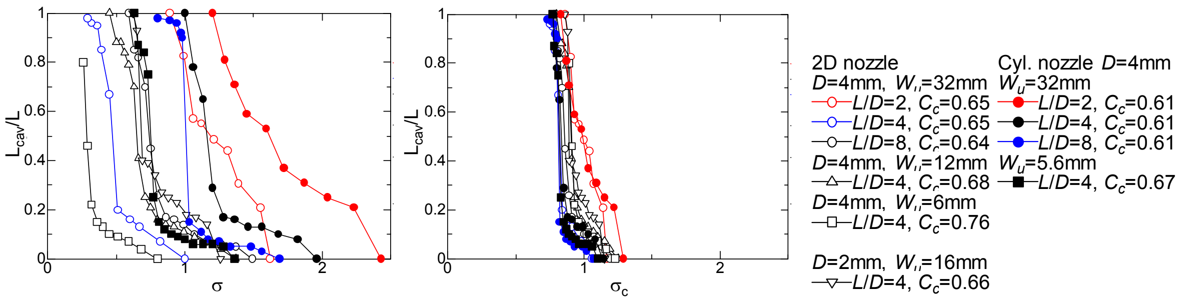


(a) Spray angle θ (b) $(\theta-\theta_0)$ vs. L_{cav}/L (c) $(\theta-\theta_0)$ vs. $(L-L_{cav})/D$

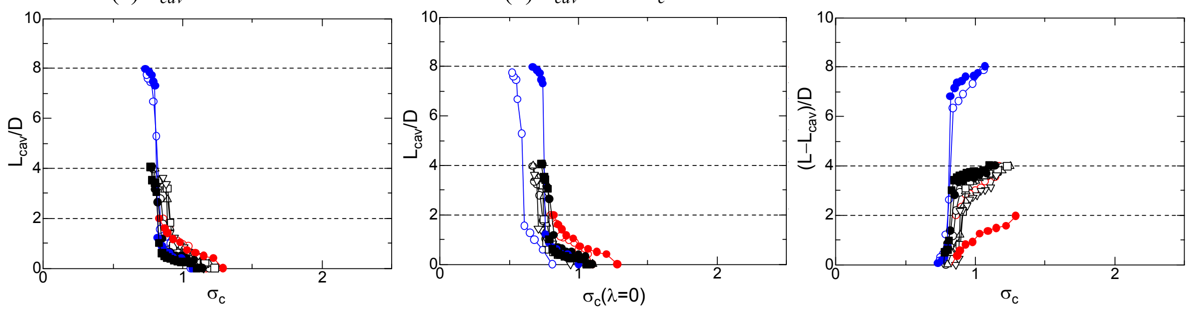
Figure 8. Relation between cavitation length L_{cav} and spray angle θ

Potential of the Modified Cavitation Number

To examine whether or not the modified cavitation number σ_c can be applied to short and long nozzles, the relation between L_{cav}/L and σ and that between L_{cav}/L and σ_c are shown in Figs. 9(a) and (b), respectively. The result confirms that σ_c can be applied to short and long nozzles since it takes into account the frictional pressure drop in nozzles. As shown in Figs. 9(c) and (d), σ_c gives better prediction for cavitation length L_{cav}/D than that without taking into account the friction term in Eq. (7). Figure 9(e) clearly indicates that $(L-L_{cav})/D$ lies between 0 and 1 at σ_c = 0.8, at which spray angle θ increases (as shown in Fig. 8(c)).



(a) L_{cav}/L vs. σ (b) L_{cav}/L vs. σ_c



(c) L_{cav}/D vs. σ_c (d) L_{cav}/D vs. $\sigma_c(\lambda=0)$ (e) $(L-L_{cav})/D$ vs. σ_c

Figure 9. Relation between cavitation length L_{cav} and cavitation numbers

Conclusions

Cavitating flows of different fluid properties flowing through a two-dimensional (2D) or a cylindrical nozzle with various shapes and lengths are visualized to investigate the effects of various dimensionless numbers on cavitation in nozzles. The effects of the cavitation number σ and the Reynolds number *Re* are examined by varying the flow rates and water temperature *T*. The effects of flow contraction on the development of cavitation are studied using nozzles with different upstream widths W_u. The influences of the length-to-diameter ratio *L*/*D* of a nozzle on cavitation are investigated. As a result, the following conclusions are obtained: (1) *Re* does not affect cavitation length L_{cav}/L, (2) L_{cav}/L for different fluid properties can be predicted quantitatively using σ in the case of a 2D nozzle of a plain orifice atomizer, (3) the thickness of the cavitation zone increases with the ratio C_u of the cross-sectional area upstream of the nozzle to that of the nozzle due to the decrease in contraction coefficient C_c, (4) the conventional cavitation numbers σ, σ_2 and σ_3 cannot predict the cavitation length L_{cav}/L in nozzles with different upstream widths W_u, (5) the modified cavitation number σ_c which takes into account the effects of flow contraction and friction loss can predict qualitatively the formation of super cavitation in nozzles of plain orifice atomizers with different W_u and L/D, (6) ligament formation is induced by the collapse of cavitation clouds near the nozzle exit not only for standard nozzle length of $L/W = 4$ but also for short and long nozzles of $L/W = 2$ and 8.

Nomenclature

C_c contraction coefficient (= V / V_c)
C_u ratio between the cross-sectional area upstream of nozzle and that of nozzle
D diameter (or width in the cases of 2D nozzles)
D_H hydraulic equivalent diameter of nozzle
L streamwise length of nozzle
L_{cav} streamwise length of cavitation zone
P pressure
P_b back pressure
P_c contraction pressure (pressure at vena contracta)
P_u pressure at a upstream region
P_v vapor saturation pressure
Re Reynolds number
t thickness
T_L liquid temperature
V mean liquid velocity in nozzle
V_c contraction velocity (at vena contracta)
W width of nozzle
W_{cav} width (thickness) of cavitation zone from nozzle wall
λ friction factor
ν kinematic viscosity of liquid
θ spray angle (angle of liquid jet near the nozzle exit)
θ_0 spray angle in the condition with no cavitation
ρ density of liquid
σ cavitation number (defined by Eq. (1))
σ_2 cavitation number used by Bergwerk (defined by Eq. (3))
σ_3 cavitation number used by Nurick (defined by Eq. (4))
σ_c modified cavitation number (defined by Eq. (7))
σ_H cavitation number defined by Hiroyasu (defined by Eqs. (5) and (6))

Subscripts
c contraction (vena contracta)
cav cavitation zone
u upstream region

Acknowledgements

The authors would like to express their thanks to Mr. Kenji Isozaki and Mr. Daisuke Goshima of Kobe University for their experimental assistance. This study was supported by a Grant-in-Aid for Scientific Research (# 20560160) of the Japan Society for the Promotion Science (JSPS).

References

1. Bergwerk, W., Flow Pattern in Diesel Nozzle Spray Holes, *Proceedings of the Institute of Mechanical Engineers*, Vol. 173, No. 25, pp. 655-660 (1959).
2. Hiroyasu, H., Arai, M., 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)*, pp. 275-282 (1991).

3. Chaves, H., Knapp, M., Kubitzek, A., Obermeier, F., Schneider, T., Experimental Study of Cavitation in the Nozzle Hole of Diesel Injectors Using Transparent Nozzles, *SAE Paper*, Paper No. 950290, pp. 645-657 (1991).
4. Soteriou, C., Andrews, R., Smith, M., Direct Injection Diesel Sprays and the Effect of Cavitation and Hydraulic Flip on Atomization, *SAE Paper*, Paper No. 950080 (1995).
5. Tamaki, N., Flow in a Nozzle and Mechanism on Atomization of a Liquid Jet (in Japanese), Dr. Thesis, Hiroshima University, (1997). See also Tamaki, N., Shimizu, M., Nishida, K., Hiroyasu, H., Effects of Cavitation and Internal Flow on Atomization of a Liquid Jet, *Atomization and Sprays*, Vol. 8, pp. 179-197 (1998).
6. Sou, A., Hosokawa, S., Tomiyama, A., Effects of Cavitation in a Nozzle on Liquid Jet Atomization, *International Journal of Heat and Mass Transfer*, Vol. 50, Iss. 17-18, pp. 3575-3582 (2007).
7. Iida, H., Matsumura, E., Tanaka, K., Senda, J., Fujimoto, H., Maly, R. R., Effects of Internal Flow in a Simulated Diesel Injection Nozzle on Spray Atomization, *CD-ROM of 8th International Conference on Liquid Atomization and Spray Systems (ICLASS 2000)*, pp. 179-197 (2000).
8. Baz, I., Champoussin, J.-C., Lance, M., Marie, J.-L., Investigation of The Cavitation in High Pressure Diesel Injection Nozzles, *CD-ROM of ASME FEDSM '02* (2002), FEDSM2002-31015.
9. Miranda, R,. Chaves, M., Martin, U., Obermeier, F., Cavitation In a Transparent Real Size VCO Injection Nozzle, *CD-ROM of International Conference on Liquid Atomization and Spray Systems 2003 (ICLASS 2003)*, (2003).
10. Nurick, W. H., Orifice Cavitation and Its Effect on Spray Mixing, *Journal of Fluid Engineering, Transactions of ASME*, pp. 681-687 (1976).
11. 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, pp. 419-431 (2004).
12. Sou, A., Maulana, M. I., Isozaki, K., Hosokawa, S., Tomiyama, A., Effects of Nozzle Geometry on Cavitation in Nozzles of Pressure Atomizers, *Journal of Fluid Science and Technology*, Vol. 3, No. 5, pp. 622-632 (2008).
13. Gelalles, A. G. and March, E. E., Effect of Orifice Length-Diameter Ratio on the Coefficient of Discharge of Fuel-Injection Nozzles, *NACA Report*, No. 369 (1931).
14. Gelalles, A G., Effect of Orifice Length-Diameter Ratio on Fuel Sprays for Compression-Ignition Engines, *NACA Report*, No. 402 (1933).
15. Karasawa, T., Tanaka, M., Abe, K., Shiga, S., Kurabayashi, T., Effect of Nozzle Configuration on the Atomization of a Steady Spray, *Atomization and Sprays*, Vol. 2, pp. 411-426 (1992).
16. Arai, M., Shimizu, M., Hiroyasu, H., Similarity between the Break-up Lengths of a High Speed Liquid Jet in a Atmospheric and Pressurized Conditions, *Proceedings of International Conference on Liquid Atomization and Spray Systems 91 (ICLASS 91)*, pp. 563-570 (1991).
17. Daikoku, M., Furudate, H., H. Noda, T. Inamura, Effect of Cavitation in the Two-dimensional Nozzle on Liquid Breakup Process, *CD-ROM of International Conference on Liquid Atomization and Spray Systems (ICLASS 2003)*, Paper No. 1706 (2003).
18. Sou, A., Maulana, M. I., Hosokawa, S., Tomiyama, A., Ligament Formation Induced by Cavitation in a Cylindrical Nozzle, *Journal of Fluid Science and Technology*, Vol. 3, No. 5, pp. 633-644 (2008).