

Liquid Jet Deformation Induced by Cavitation in Nozzles of Various Shapes

Akira Sou
Kobe University

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ABSTRACT

Cavitation in the nozzles of various shapes and liquid jets discharged from the nozzles are visualized using a high-speed camera to investigate the effects of cavitation on liquid jet deformation. Cylindrical nozzles and two-dimensional (2D) nozzles of various upstream diameters and length-to-diameter ratios (L/D) are used. For simultaneous high-speed visualizations of cavitation and a jet, a tilted acrylic plate is placed in front of the jets injected through the 2D nozzles, while three mirrors are used to capture both the front view of the jet injected through a cylindrical nozzle and the side view of cavitation. The visualizations confirm that the collapse of a cavitation cloud near the exit induces a ligament formation in 2D and cylindrical nozzles of various L/D s. Although no vapor film is formed in short nozzles, cavitation clouds are shed near the exit and induce ligaments. It is also confirmed that the modified cavitation number, which takes into account the effects of flow contraction and frictional pressure drop, can be used to predict the development of cavitation in nozzles of various shapes.

INTRODUCTION

In various industrial fields efforts have been made to develop atomizers which produce fine droplets. In 1959, Bergwerk [1] pointed out that cavitation occurs in a nozzle of pressure atomizers and affects liquid jet behavior. Hiroyasu *et al.* [2] showed that atomization of a liquid jet is promoted when cavitation is fully developed in a nozzle (super cavitation [3]). Following these studies, a number of experiments have been carried out to observe cavitation in various nozzles [3-5]. Attempts have been also made to control and utilize cavitation to produce fine droplets [6].

The mechanism how cavitation enhances atomization has also been investigated. Wu *et al.* [7] reported that vorticity in the boundary layer of a nozzle plays an important role in ligament formation at the liquid jet interface. He and Ruiz [8] measured liquid velocity inside a two-dimensional (2D) nozzle using a laser Doppler velocimetry (LDV). Oda and Yasuda [9] applied a particle tracking velocimetry (PTV) to a cavitation flow in a 2D nozzle. These measurements showed that a strong turbulence is produced near the cavitation zone, which may contribute to atomization. These experiments were, however, not conducted in super cavitation regime.

Recently the authors [10] measured liquid velocity in a 2D nozzle in super cavitation regime using LDV, and found that a strong turbulence is produced near the exit of the nozzle. Then, A simultaneous visualization of cavitation in the nozzle, whose length-to-width ratio (L/D) is 4, and a liquid jet were conducted using a high-speed camera [11] to confirm that in the super cavitation regime cavitation bubble clouds are shed and collapse near the nozzle exit and a strong turbulence is induced at the trace of the cavitation cloud. When the strong turbulence comes out of the nozzle, a ligament, which initiates atomization, is formed. The result will be briefly shown later. The case of cylindrical nozzles, however, remains unknown. Hence, cavitation in a cylindrical nozzle and a liquid jet are simultaneously visualized to investigate cavitation in a cylindrical nozzle and its effects on atomization [12].

A number of experiments [1-25] have been carried out using various nozzles of different shapes and sizes. The effects of L/D on discharge coefficient [14], spray tip penetration and spray angle [15], droplet size [16], condition of the transition to fully developed cavitation [1] have also been examined and cavitation in nozzles of $L/D \geq 3$ has been reported [3,17-20]. The mechanism of atomization

enhancement by cavitation in a short ($L/D = 2$) and a long ($L/D = 8$) nozzle has not been clarified yet, which is investigated in this study.

Various cavitation numbers σ , σ_2 , σ_3 and σ_c of different definitions, whose definitions will be presented later in this paper, have been proposed and used. The fact 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. We confirmed that the modified cavitation number σ_c , which takes into account the effects of flow contraction and frictional pressure drop in a nozzle, can be used to predict the formation of super cavitation in nozzles with various upstream sizes [13]. In the present study, the applicability of σ_c to nozzles with various L/D s is examined.

EXPARIMENTAL SETUP

Schematic of the experimental setup is shown in Fig. 1. Filtered tap water was supplied from the plunger pump and discharged from a two-dimensional (2D) or a cylindrical nozzle 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 jets were taken using a high-speed camera (Redlake, MotionPro HS-1) or a digital camera (Nikon, D70, 2000 x 3008 pixels) and a flash lamp (Nissin Electronic, MS-1000 and LH-15M, duration = 4 μ s). The concentration of oxygen dissolved in the water was measured using a dissolved oxygen probe (Hach company, HQ30d) and was about 9 mg/L.

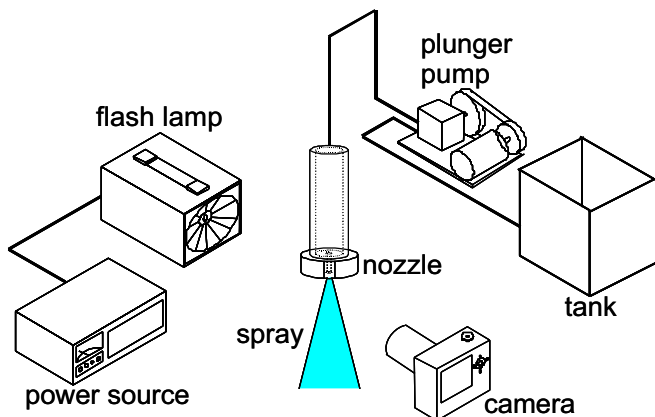
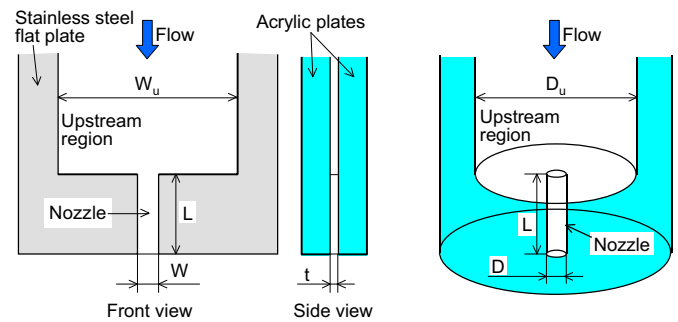


Figure 1. Experimental setup

As shown in Fig. 2 (a), a 2D nozzle consists of two acrylic flat plates and two stainless steel thin flat plates, by which sharp-edges are formed at the inlet. The width W (For simplicity it is sometimes written as D .), length L and thickness t of the 2D nozzle and the width W_u of the upstream region were varied. The diameter D_u of the upstream region, nozzle diameter D and nozzle length L were varied for acrylic cylindrical nozzles (Fig. 2 (b)).



(a) Two-dimensional (2D) nozzle (b) Cylindrical nozzle

Figure 2. Geometry of 2D and cylindrical nozzles

CAVITATION IN 2D NOZZLE

Figure 3 shows the typical images of cavitation in a 2D nozzle of $W = 4$ mm, $L/W = 4$, and $t = 1$ mm (water temperature $T = 293$ K). In super cavitation regime [3,11], ligaments are formed even at the vicinity of the nozzle and liquid jet atomization is promoted. The σ and Re presented in the figure are the cavitation and Reynolds numbers, respectively. They are defined by

$$\sigma = \frac{P_b - P_v}{0.5\rho V^2} \quad (1)$$

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

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.

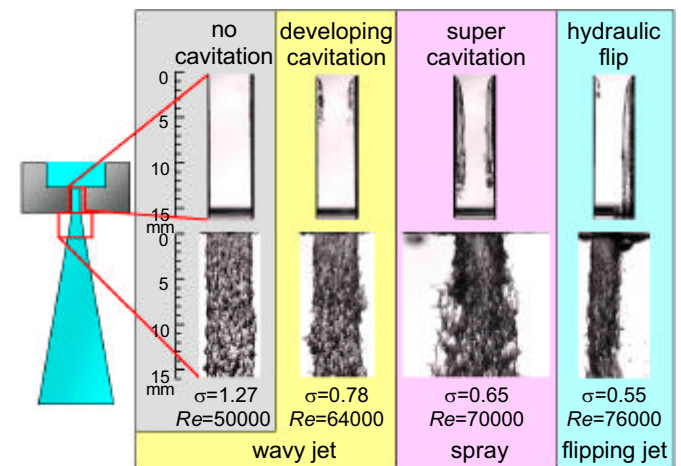


Figure 3. Cavitation in a 2D nozzle and jet ($W = 4$ mm)

To examine the causal relationship between cavitation and a jet deformation in super cavitation regime, cavitation and a liquid jet interface were visualized simultaneously with a high frame rate (20000 fps) [11]. Since the refractive index of the acrylic plate of the nozzle is higher than that of air, an acrylic plate was placed between the jet and the camera to match the

optical distances. In the high frame rate imaging, the image size was limited to 32 x 1280 pixels. Hence, as shown in Fig. 4, the acrylic plate was tilted to capture both cavitation and the jet interface within the narrow region.

Time series images of cavitation and the jet are shown in Fig. 5 ($W = 4$ mm, $L/W = 4$, $\sigma=0.65$, 32 x 1280 pixels, 20000 fps). The arrows in the figure represent the paths moving with mean liquid velocity V in the nozzle. A ligament is formed when a trace of a cavitation cloud flows out of the nozzle, which is the mechanism of atomization enhancement by cavitation in a nozzle of $L/W = 4$.

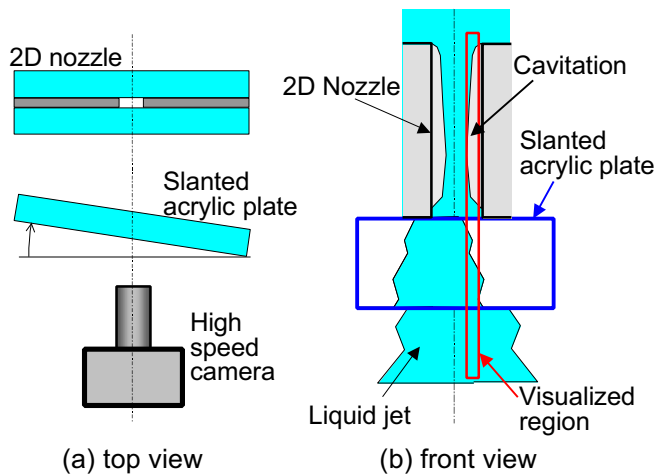


Figure 4. Experimental setup for the simultaneous visualization of cavitation in a 2D nozzle and jet

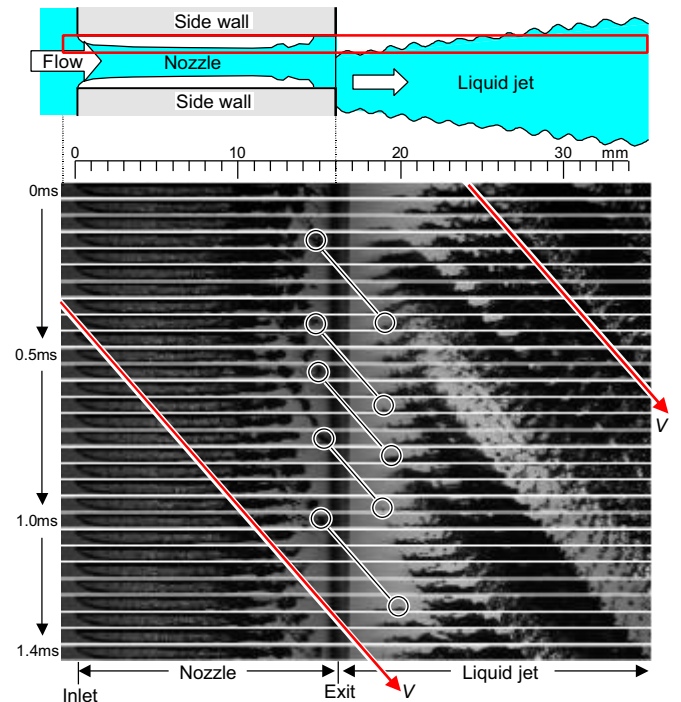


Figure 5. Cavitation cloud in a 2D nozzle and ligament formation ($L/W = 4$, $W = 4$ mm)

CAVITATION IN CYLINDRICAL NOZZLE

Based on the fact that cavitation clouds collapsing near the exit of a 2D nozzle induce ligament formation, we propose the following hypothesis for cylindrical nozzles. As shown in Fig. 6 (a), we assume that clouds of cavitation bubbles are formed at the skirt of the annular cavitation sheet, and a ligament is ejected at the trace of the cavitation cloud as illustrated in Fig. 6 (b).

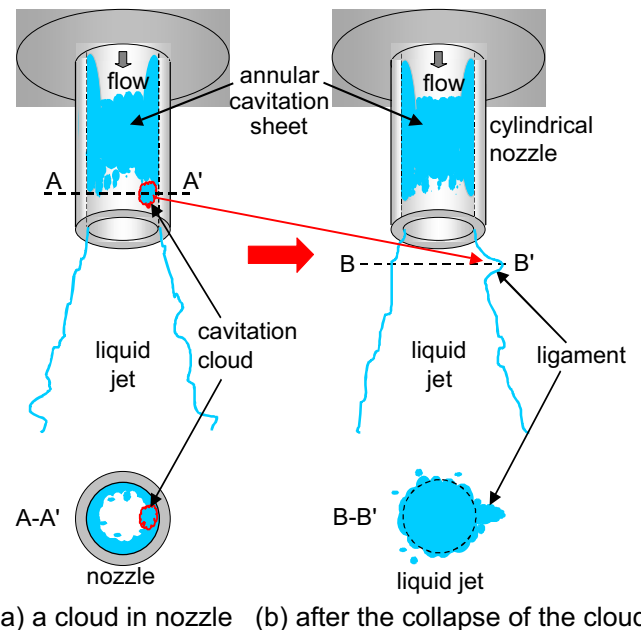


Figure 6. Hypothesis: ligament formation induced by cavitation clouds in a cylindrical nozzle