Mechanism of cavitation-induced atomization in two-dimensional nozzles

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Abstract. It has been pointed out that cavitation, i.e., super cavitation regime may occur in a nozzle of pressure atomizers, and may influence atomization of a liquid jet discharged from the 2D nozzle. Once we clarify the mechanism of atomization induced by the supercavitation, we will be able to develop new atomizers in which the atomization mechanism is utilized more efficiently. Hence, this study has been conducted to clarify the mechanism in the 2D nozzle. As a result, the following conclusions are obtained: (1) The frequency of the shedding and collapse of cavitation clouds in the supercavitation regime agrees with that of strong turbulence near the exit; (2) When the trace of a cavitation cloud comes out of the 2D nozzle, a ligament is formed at the liquid jet interface; (3) Strong turbulence is produced by the collapse of cavitation clouds near the exit of the 2D nozzle.and induces ligament formation, which, in turn, causes liquid jet atomization.

Keywords: cavitation, nozzle, liquid jet, ligament

Introduction

Cavitation is known to occur in nozzles of fuel injectors for Diesel engines and enhance atomization of a discharged liquid jet. In the previous study (1) we have confirmed that liquid jet atomization is enhanced when super cavitation regime is developed in a 2D nozzle. Our understanding on the mechanism of atomization by super cavitation is, however, rudimentary.

A number of studies (2-5) have been conducted to clarify the mechanism. Wu *et al.* (2) have shown that vorticity in the boundary layer in a nozzle plays an important role in ligament formation at the liquid jet interface. He and Ruiz (3) measured liquid velocity inside a two-dimensional (2D) nozzle using a laser Doppler velocimetry (LDV). Oda and Yasuda (4) applied a particle tracking velocimetry (PTV) to a cavitation flow in a 2D nozzle. Both experiments showed that strong turbulence is produced near the cavitation zone, which might contribute to atomization.

The relation among cavitation, turbulence and atomization, however, remains unclear. Hence, high-speed simultaneous visualizations of cavitation in a nozzle and liquid jet interfaces are carried out. 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 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 (1):

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

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

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. Liquid velocity in the 2D nozzle is measured using LDV to investigate the effects of cavitation on turbulence.

Materials and 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). Filtered tap water at room temperature was injected from the 2D nozzle into ambient air.

In order to examine the relation between cavitation and the deformation of liquid jet interfaces in the supercavitation regime, A high-speed digital video camera (Redlake, MotionPro, HS-1, 32 x 1280 pixels, frame rate = 20000 fps) was used to visualize evolution of cavitation in the nozzle and liquid jet deformation near the nozzle exit. Since the refractive index of the acrylic plate of the nozzle is higher than that of air, an acrylic plate was placed between the liquid jet and the camera to match the optical distance from the camera to the cavitation and the distance from the camera to the liquid jet. In the high frame rate imaging, the image size was limited to 32 x 1280 pixels. Hence, the acrylic plate was tilted to capture both cavitation and jet interfaces within the narrow visualized region.

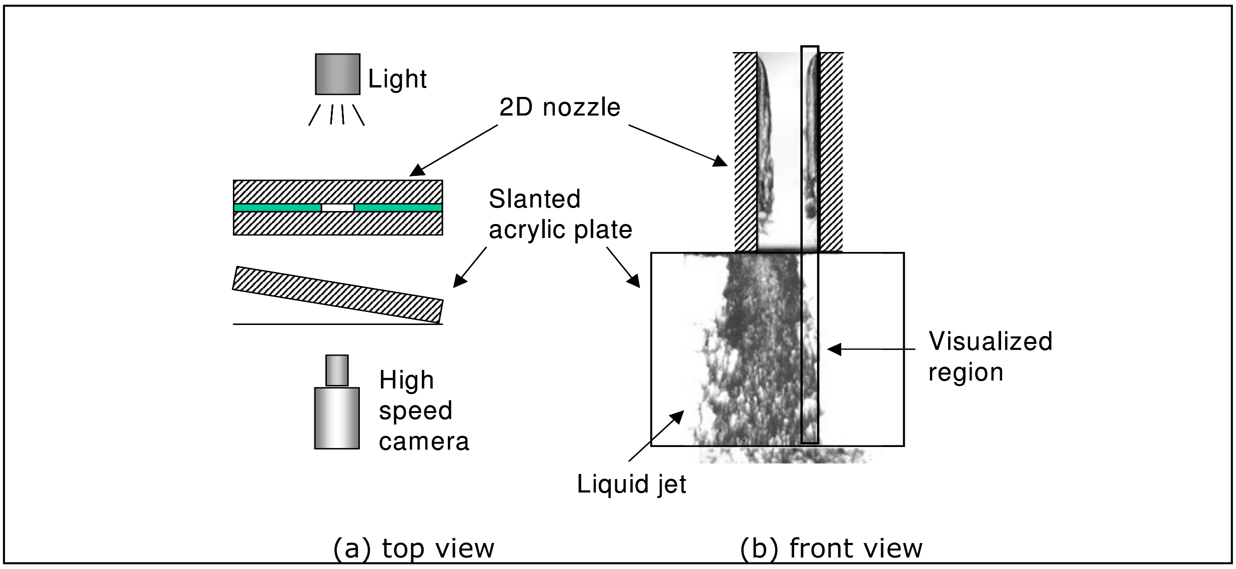


Figure 1. Experimental setup for simultaneous visualizations of cavitation and liquid jet (2D nozzle).

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.

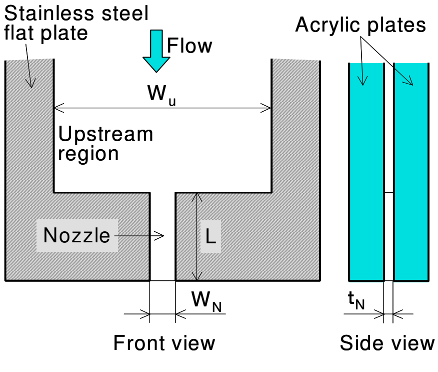
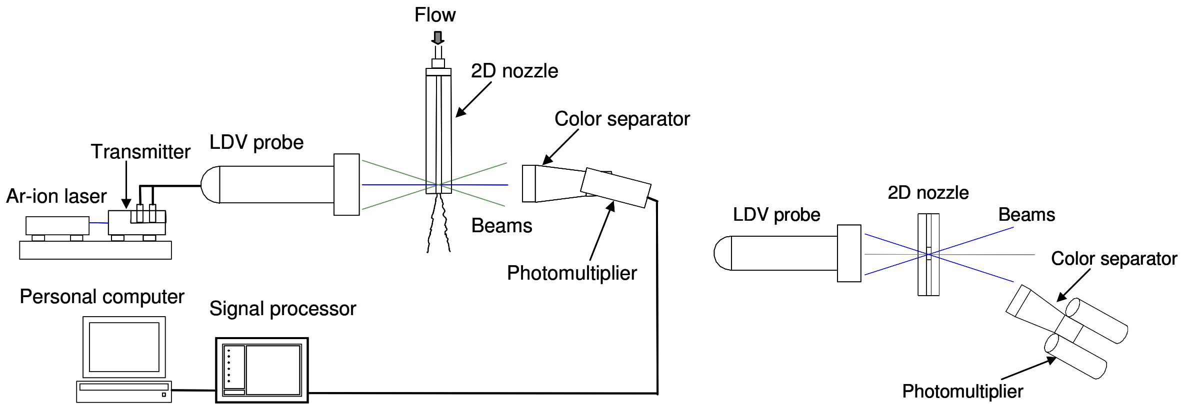


Figure 2. Schematics of 2D and cylindrical nozzles.

A laser Doppler velocimetry (LDV) was used to measure liquid velocity in the nozzle. Figure 3 illustrates the measurement system. The system consisted of the Ar-ion laser, the LDV probe, the receiver and the signal processing system. Streamwise and lateral velocity components were measured.



(a) side view

(b) top view

Fig. 3 Experimental setup for LDV measurement.

The measurement locations and coordinate system are shown in Fig.4, where *x* is the lateral distance from the nozzle center, *y* the streamwise distance from the nozzle inlet, *u* and *v* the streamwise and lateral components of the local instantaneous liquid velocity. A 3D traverse system with the minimum scale of 10 □m was used to move the measurement volume. The mean velocities and RMS of the fluctuation components (turbulence intensities) *u*' and *v*' were obtained from 50000 data of the local instantaneous liquid velocities *u* and *v* measured at each point.

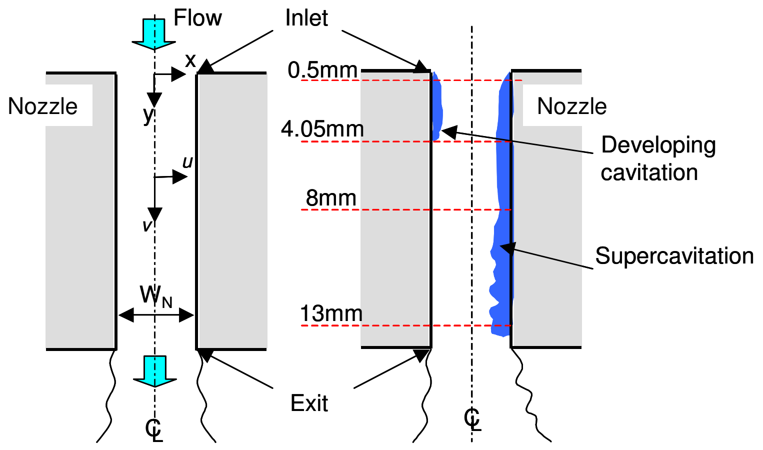


Figure 4 Locations of LDV measurements.

Mechanism of Cavitation-induced Atomization

Time-series images of cavitation in the 2D nozzle and the liquid jet are shown in Fig. 5. A cavitation cloud is shed at time *t* = 0.4 ms and collapses near the exit at *t* = 0.75 ms. A ligament is formed when the trace of the cavitation cloud comes out of the nozzle at *t* = 0.95 ms. The arrows in the figure represent the paths moving at the mean liquid velocity

V_N. By observing 10000 images it is found that the frequencies of the shedding and collapse of cavitation clouds are about 1 to 4 kHz. Figure 6 illustrates the ligament formation induced by the collapse of a cavitation cloud in the 2D nozzle.

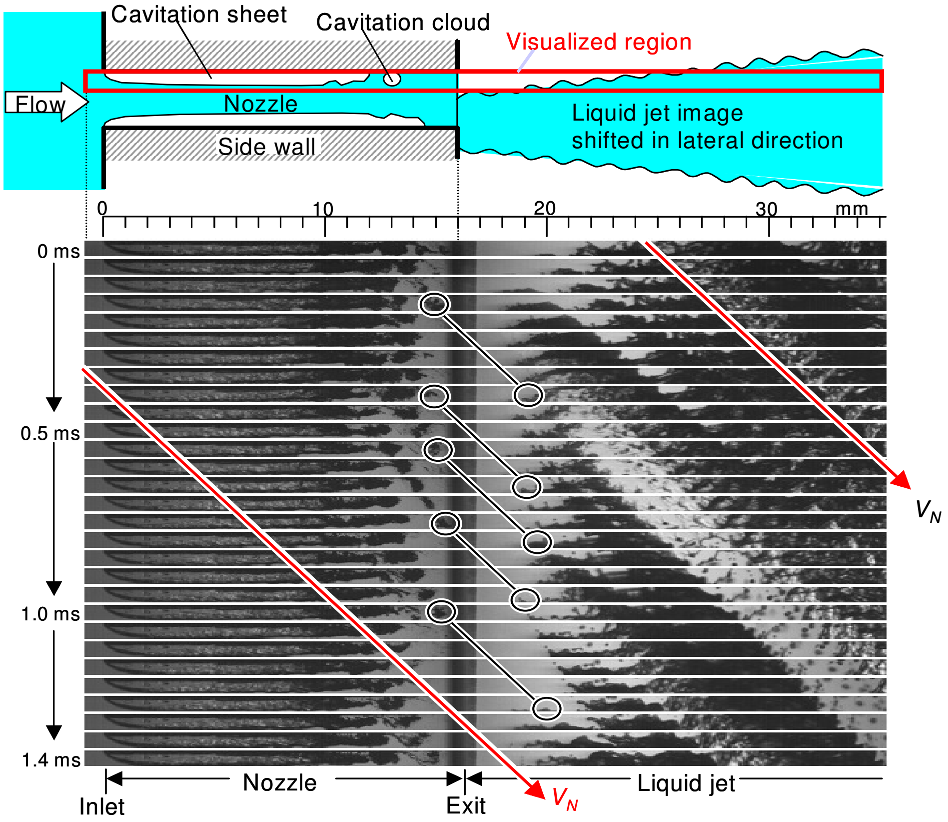


Figure 5 Simultaneous visualization of cavitation and liquid jet interface (2D nozzle, ☐ = 0,69; 20000 fps).

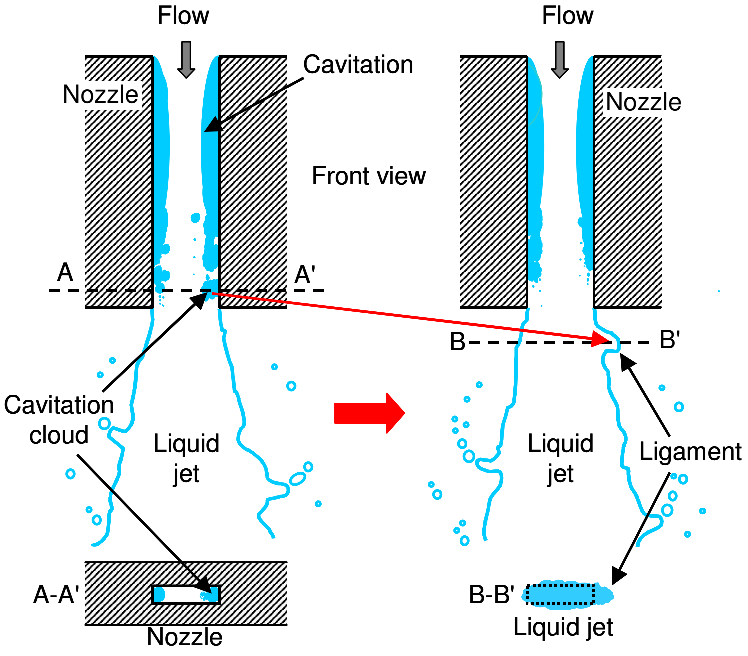


Figure 6. Ligament formation induced by cavitation in the two-dimensional nozzle. (a) before the collapse of a cavitation cloud (b) after the collapse of the cavitation cloud

Fig. 7 shows the power spectrum of the area-averaged intensity in the region (32 x 40 pixels) of the high-speed images where cavitation clouds pass through (y = 12 mm). The intensity of the spectrum does not decrease in the range of about 1 to 4 kHz, which corresponds to the frequency of the cloud shedding.

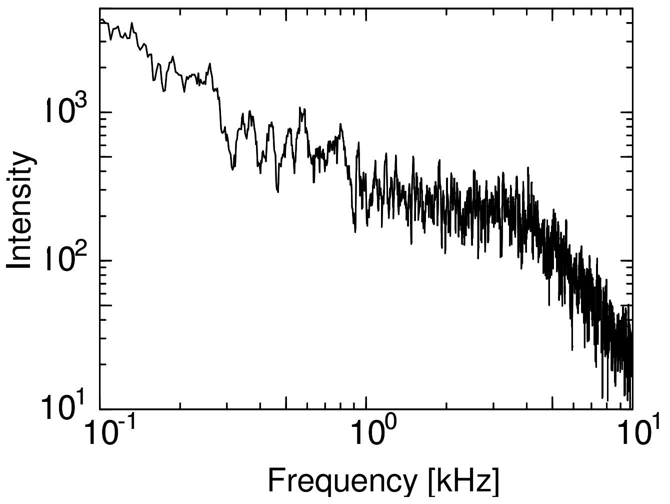
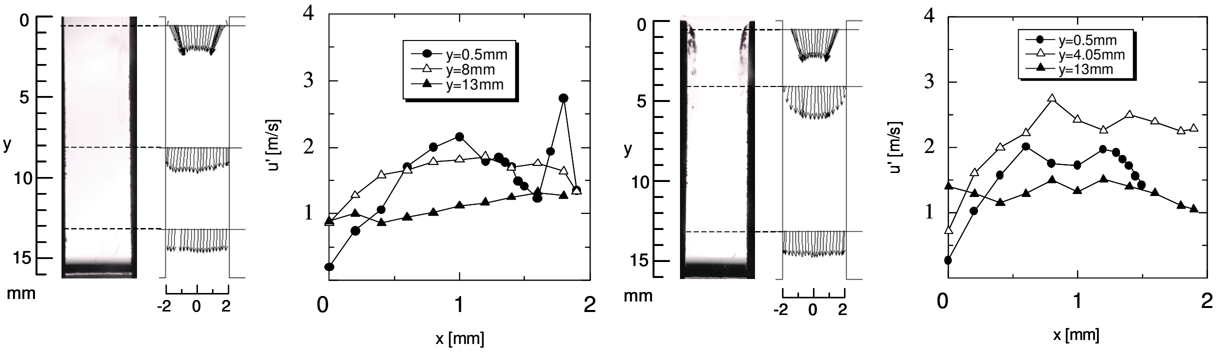
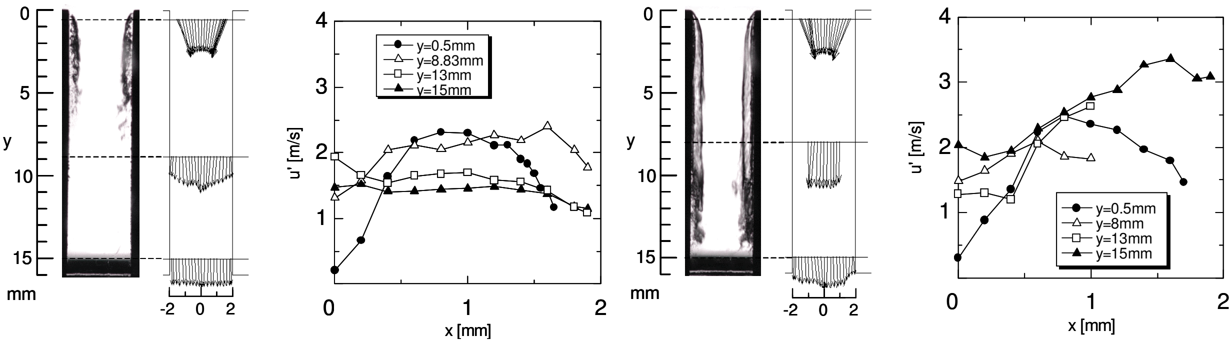


Figure 7. Power spectrum of image data

The mean velocity vectors and RMS of the lateral component of velocity fluctuation u' are plotted in Fig. 8. Strong turbulence appears just downstream of the cavitation region (y = 4.05 mm at $\square_c'$ = 1.06, y = 8.83 mm for $\square_c'$ = 0.98, y = 15 mm for $\square_c'$ = 0.91), and the turbulence intensity u' decreases as y increases. This result indicates that the turbulence intensity increases just below the cavitation zone, and strong turbulence can reach the nozzle exit only in the supercavitation regime.



(a) σ=1.23 (no cavitation)   σ =1.0 (developing cavitation)



(b) σ =0.82 (developing cavitation)   (c) σ =0.69 (supercavitation)

Figure 8. Turbulence intensity in the 2D nozzle (continued)

The power spectrum of the lateral component of the velocity near the exit (*y* = 15 mm) is shown in Fig. 8. A high intensity appears in the range of about 1 to 4 kHz in the supercavitation regime ($\square_c'$ = 0.91). The frequency agrees with that of the shedding of the cavitation clouds and that of the ligament formation. Hence, the strong turbulence induced by the collapse of cavitation clouds near the exit induces ligament formation, which, in turn, initiates atomization.

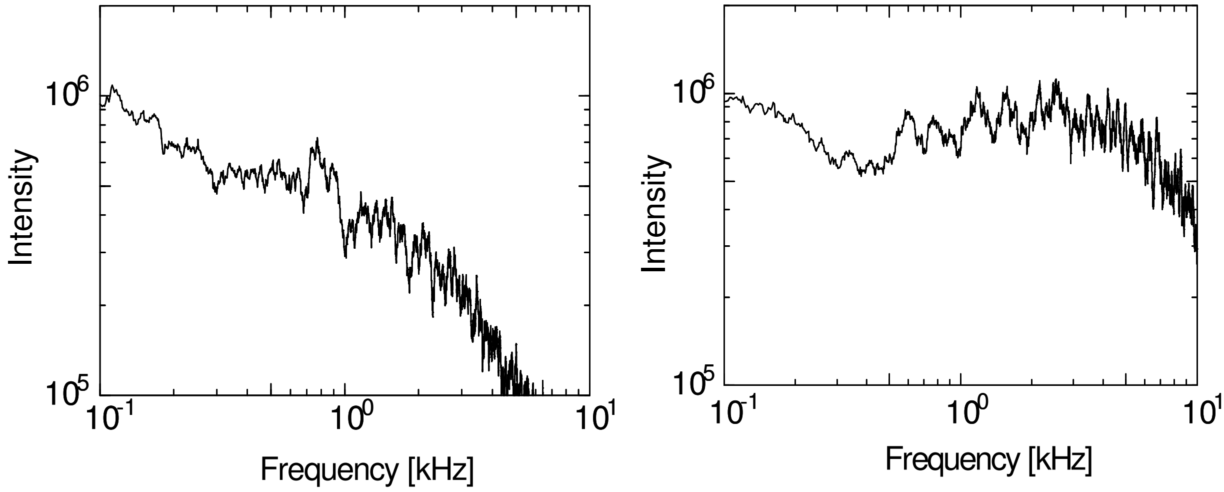


Figure 8 Power spectrum of LDV data near the exit (*y* = 15 mm) (Left: σ = 0.82 (developing cavitation, Right: σ = 0.69 (supercavitation)

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 high-speed camera to investigate the mechanism of cavitation-induced atomization. In the high-speed visualization for the 2D nozzle, an acrylic plate is placed between the liquid jet and the camera to match the optical distances. The plate is slanted to capture cavitation and ligament formation in a narrow frame of the camera. As a result, the following conclusions are obtained: (1) The frequency of the shedding and collapse of cavitation clouds in the supercavitation regime agrees with that of strong turbulence near the exit, (2) When the trace of a cavitation cloud comes out of the nozzle, a ligament is formed at the liquid jet interface, (3) Strong turbulence is produced by the collapse of cavitation clouds near the exit and induces ligament formation, which, in turn, causes liquid jet atomization.

Acknowledgements

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