EFFECTS OF CAVITATION IN A NOZZLE ON LIQUID JET ATOMIZATION

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ABSTRACT Cavitation in two-dimensional (2D) nozzles and liquid jet were visualized using high-speed cameras to investigate the effects of cavitation on liquid jet under various conditions of the cavitation and Reynolds numbers $\sigma$ and $Re$. Liquid velocity in a 2D nozzle was measured using a Laser Doppler Velocimetry to examine the effects of cavitation on the flow in the nozzle and liquid jet. As a result, the following conclusions were obtained: (1) the cavitation in the 2D nozzles and the liquid jet can be classified into the four regimes: (cavitation regime, liquid jet regime) = (no cavitation, wavy jet), (developing cavitation, spray) and (hydraulic flip, flipping jet), (2) liquid jet behavior depends on cavitation regime, (3) cavitation and liquid jet near the nozzle exit are not strongly affected by $Re$ but by $\sigma$, and (4) ligament formation at liquid jet interface is induced by the collapse of cavitation cloud near the exit.

Keywords: Cavitation, Liquid Jet, Visualization, Cavitation Number, Reynolds Number, Nozzle, Ligament, Turbulence, LDV

1. BACKGROUND

It has been pointed out through a number of experimental studies [1-5] that cavitation takes place in the nozzle of fuel injectors for Diesel engines and affects the characteristics of a discharged liquid jet. Hiroyasu et al. [1] showed that liquid jet atomization was promoted when cavitation extended from the inlet to the exit of a nozzle. Since the shapes of the nozzles used in most of the previous studies have been cylindrical [1-5], it has been difficult to measure liquid velocity, turbulence intensity and radial distribution of cavitation bubbles in nozzles. Hence, several studies have been carried out using two-dimensional (2D) nozzles for visualization of detailed cavitation behavior [6-8]. Recently some attempts have been made to measure the velocity in the nozzle, which might play an important role in liquid jet atomization [9-12]. However the mechanism of atomization enhancement by cavitation has not been clarified yet.

In the present study, cavitation in 2D nozzles and liquid jet were visualized using a digital camera and high-speed video cameras under various conditions of Reynolds and cavitation numbers to examine the effects of the two dimensionless numbers on cavitation and liquid jet and to investigate the atomization enhancement mechanism by cavitation. Liquid velocity in a 2D nozzle was measured by using a Laser Doppler Velocimetry (LDV) to investigate the effects of cavitating internal flow on liquid jet atomization.

2. EXPERIMENTAL SETUP

2.1 Liquid Injection System

Schematic of experimental setup is shown in Fig. 1 [13-18]. Filtered tap water or light oil was discharged from 2D nozzles into ambient air by the plunger pump through the cylindrical air separation tank of 90 mm in inner diameter and 800 mm in height. As shown in Fig. 2, the 2D nozzle consists of two acrylic flat plates and two stainless steel thin flat plates, by which sharp-edges were formed at the inlet of the nozzle. To examine the effect of nozzle size on the cavitation and liquid jet characteristics, two nozzles of different sizes were used. The width $W_N$, length $L_N$ and thickness $D_N$ of a nozzle were 4, 16 and 1 mm, and those of the half scale nozzle were 2, 8 and 0.5 mm, respectively ($L_N / W_N = 4$). This nozzle shape enabled us to measure not only streamwise but also lateral component of the liquid velocity by LDV.
Table 1  Experimental conditions \((T_L=292\text{K}, W_N=4\text{mm})\)

<table>
<thead>
<tr>
<th>Mean velocity, (V_N) [m/s]</th>
<th>Reynolds number, (Re)</th>
<th>Cavitation number, (\sigma)</th>
<th>Cavitation in nozzle</th>
<th>Liquid jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.25</td>
<td>45000</td>
<td>1.57</td>
<td>No cavitation</td>
<td>Wavy jet</td>
</tr>
<tr>
<td>12.5</td>
<td>50000</td>
<td>1.27</td>
<td>Developing cavitation</td>
<td>Spray</td>
</tr>
<tr>
<td>14.5</td>
<td>58000</td>
<td>0.94</td>
<td>Super cavitation</td>
<td>Hydraulic flip</td>
</tr>
<tr>
<td>16.0</td>
<td>64000</td>
<td>0.78</td>
<td></td>
<td>Flipping jet</td>
</tr>
<tr>
<td>17.0</td>
<td>68000</td>
<td>0.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td>70000</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.0</td>
<td>76000</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.5</td>
<td>78000</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where \(P_a\) is the atmospheric pressure, \(P_v\) the vapor saturation pressure, \(\rho_l\) the liquid density, \(V_N\) the mean liquid velocity in the nozzle, \(\nu_L\) the liquid kinetic viscosity. These parameters were controlled by the changing liquid flow rate, fluid properties and nozzle size. Typical experimental conditions are listed in Table 1 (water, \(T_L=292\text{K}, W_N=4\text{mm}\)). The concentration of dissolved oxygen \((DO)\) in water was 9.0 mg/l when the water temperature \(T_L\) was 291K.

3. RESULTS AND DISCUSSION

3.1 Flow Regimes

Flow regimes in the nozzle and liquid jet near the nozzle exit are summarized in Fig. 3 and Table 1 (water, \(T_L=292\text{K}, W_N=4\text{mm}\)) [14,17]. When \(\sigma>1.2\), cavitation bubbles were not observed and liquid jet took the form of "wavy jet". For \(0.75<\sigma<1.2\), cavitation bubble clouds appeared in the upper half of the nozzle. We defined this type of the cavitation as "developing cavitation". In developing cavitation, liquid jet near the exit was wavy jet. For \(0.55<\sigma<0.75\), cavitation zone extended from the inlet to just above the nozzle exit. We named this regime "super cavitation". In super cavitation, liquid jet atomization was enhanced, i.e., ligaments and droplets appeared ("spray") and the spray angle increased. Further decrease in \(\sigma\) \((\sigma<0.55)\) resulted in the formation of "hydraulic flip", in which liquid flow separated at one inlet edge and did not reattach to the side wall.

Figure 4 shows the distribution of mean liquid velocity in a nozzle of 4mm in width [15-17]. We confirmed that cavitation appeared within the separated boundary layer (SBL). The distribution of mean velocity was not uniform just below the cavitation zone, i.e. the reattachment point of SBL, however it became almost uniform near the nozzle exit in no cavitation or developing cavitation regimes.

Fig. 3  Images of cavitation in 2D nozzle and liquid jet (water, \(T_L=292\text{K}, W_N=4\text{mm}, t_{EX}=12\mu s\))
3.2 Effects of $\sigma$ and Re on Cavitation and Liquid Jet

The Reynolds number $Re$ increases with $T_i$, since $v_i$ of water decreases with increasing $T_i$, while $\sigma$ does not change a lot by varying $T_i$. To examine the influences of $\sigma$ and $Re$ on cavitation and liquid jet, observations were conducted under various $T_i$ conditions [18]. Regimes of cavitation and liquid jet are shown in Figs. 5(a) and (b), respectively. The spray regime region on the liquid jet regime map corresponds to the super cavitation region on the cavitation regime map, which means that the formation of super cavitation enhances liquid jet atomization. Since the transition from developing to super cavitation does not strongly depend on $Re$ but on $\sigma$, the transition from wavy jet to spray also depend on $\sigma$.

The effects of $Re$ and $\sigma$ on normalized cavitation length $L_{cav}^*$ (streamwise length of cavitation zone $L_{cav}$ / nozzle length $L_N$) are shown in Figs. 6(a) and (b), respectively. The values of $L_{cav}^*$ in the cases of the nozzle of 4mm in width, the half scale nozzle ($W_N=2mm$) and light oil are plotted in the figure. Regime transition in the cases of the half scale nozzle and light oil showed the same trends as that in the 4mm nozzle, and $L_{cav}^*$ did not depend on $Re$ but on $\sigma$, though the effects of dissolved gases, turbulence and sharpness of the nozzle inlet edge were not taken into account in the definition of $\sigma$. 

![Fig. 4 Mean liquid velocity distributions in a 2D nozzle ($W_N=4mm$, $T_i=291K$)](image)

![Fig. 5 Effects of $\sigma$ and $Re$ on cavitation and jet ($W_N=4mm$)](image)

![Fig. 6 Effects of $Re$ and $\sigma$ on cavitation length $L_{cav}^*$](image)
Spray angles were measured from the recorded images as shown in Fig. 7, and plotted against \( L_{\text{cav}}^* \) in Fig. 8. When the value of \( L_{\text{cav}}^* \) is about 0.8-0.9, i.e. in super cavitation, spray angle increases as shown in Fig. 8.

The mean lateral velocity \( V \) and the RMS of lateral fluctuating velocity \( v' \) (turbulence velocity) near the exit (distance from the inlet \( y=15\text{mm} \)) are shown in Fig. 9 to examine the effects of cavitation on turbulence velocity and liquid jet. In developing cavitation (\( \sigma=0.78 \)) the value of \( V \) near the exit was close to zero and \( v' \) was small. On the other hand, \( v' \) in super cavitation (\( \sigma=0.65 \)) was large and the value of \( V \) at \( x>1.5\text{mm} \) was positive, i.e., the mean flow directed toward the side wall. The lateral flow and strong turbulence in super cavitation could be the dominant mechanisms to increase the spray angle and initiate atomization.

### 3.3 Effects of Super Cavitation on Ligament Formation

Cavitation behavior near the nozzle exit in super cavitation regime was visualized using an ultra-high speed camera (\( t_{\text{EX}}=5\text{ns}, 100,000\text{fps} \)). Images of the collapse of cavitation clouds are shown in Fig. 10 (\( \sigma=0.69 \)). The collapse of cavitation clouds took place intermittently. The collapse might cause a high turbulence velocity near the exit, and therefore affects the ligament formation.

To examine the relation between the collapse of cavitation cloud and ligament formation in super cavitation regime, cavitation and liquid jet interface were visualized simultaneously with a high frame rate (20,000 fps). 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 distances. 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 interface within a narrow region shown in Fig. 11.
Fig. 12  Simultaneous visualization of cavitation and liquid jet interface ($\sigma$=0.61, 32 x 1280 pixels, 20,000 fps)

Fig. 13  RMS of streamwise fluctuating velocity
Time series images of cavitation and liquid jet are shown in Fig. 12 (σ=0.61, 32 x 1280 pixels, 20,000 fps). The arrows in the figure represent the paths moving with mean liquid velocity in the nozzle $V_N$. A ligament was formed when a trace of cavitation collapse came out with the velocity $V_N$ from the nozzle.

The RMS of streamwise fluctuating velocity is plotted in Fig. 13. As shown in the figure, strong turbulence appeared just below the cavitation collapse point ($y=4.05\text{mm}$ for $\sigma=0.95$, $y=8.83\text{mm}$ for $\sigma=0.78$, $y=15\text{mm}$ for $\sigma=0.65$), and the turbulence decreased as $y$ increased. This indicates that turbulence velocity increases just below the collapse point, and the strong turbulence reaches the nozzle exit only in the case of super cavitation. Hence we could confirm that a ligament is formed when liquid with strong turbulence induced by the collapse of cavitation cloud near the exit flows out from a nozzle in super cavitation regime.

4. CONCLUSIONS

Cavitation in two-dimensional (2D) transparent nozzles and liquid jets were visualized using a digital camera, an ultra high-speed video camera and a high-speed video camera. Liquid velocity in the 2D nozzle was measured using a LDV system. The effects of the cavitation number $\sigma$ and the Reynolds number $Re$ on cavitation in the nozzle and liquid jet were examined by varying the liquid flow rate, fluid properties and nozzle size. Cavitation in the nozzle and ligament formation at liquid jet interface were simultaneously visualized using a high-speed camera to examine the mechanism of atomization enhancement by cavitation. As a result, the following conclusions were obtained:

1. Cavitation in 2D nozzles and liquid jet are classified into the following regimes: (1: no cavitation, wavy jet), (2: developing cavitation, wavy jet), (3: super cavitation, spray) and (4: hydraulic flip, flipping jet).
2. Liquid jet atomization depends on cavitation regime, i.e., ligament formation and spray angle depend on cavitation length $L_{cav}^*$.
3. Cavitation and a liquid jet near the nozzle exit are not strongly affected by $Re$ but by $\sigma$.
4. Ligament formation is induced by the collapse of cavitation cloud near the nozzle exit.

NOMENCLATURE

- $L_{cav}^*$: dimensionless cavitation length ($=L_{cav} / L_N$)
- $L_N$: length of 2D nozzle [m]
- $Re$: the Reynolds number
- $T_L$: liquid temperature [K]
- $V_N$: mean liquid velocity in a nozzle [m/s]
- $W_N$: width of 2D nozzle [m]

Greek Symbols

- $\theta$: spray angle [deg.]
- $\sigma$: the cavitation number

ACKNOWLEDGEMENT

The authors would like to express their thanks to Mr. Shinji Nigorikawa and Mr. Tatsutoshi Maeda. This study was supported by a Grant-in-Aid for Scientific Research (#18560170) of the Japan Society for the Promotion Science (JSPS).

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