Cavitation in a Two-Dimensional Nozzle and Liquid Jet Atomization

(LDV Measurement of Liquid Velocity in a Nozzle)

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Cavitation in nozzles of liquid injectors is known to affect the atomization of a discharged liquid jet. To understand how cavitating flow in a nozzle enhances the liquid jet atomization, liquid velocity distribution of cavitating flow in a two-dimensional transparent nozzle was measured using a Laser Doppler Velocimetry (LDV) system. As a result, the following conclusions were obtained: (1) The inception of cavitation occurs near the outer edge of separated boundary layer (SBL), where the time-averaged local velocity takes the highest value and the time-averaged pressure is almost equal to the vapor saturation pressure. (2) When the cavitation number \( \sigma \) is greater than 0.78 (in no cavitation and developing cavitation regimes), the reattachment of SBL occurs in the middle of the nozzle. A large velocity fluctuation, which appears just downstream of SBL, decreases near the nozzle exit. Hence the wavy jet is formed in these regimes. (3) For \( \sigma \leq 0.65 \) (in super cavitation regime), the lateral flow directing from the core region toward the side walls just upstream of the nozzle exit is a major cause of the increase in the spray angle and drastic enhancement of liquid jet atomization. The strong turbulence just upstream of the exit must play an important role in the formation of ligaments on liquid jet interface.

Key Words: Atomization, Injector, Nozzle, Cavitation, LDV, Internal Flow, Liquid Jet

1. Introduction

Cavitation is known to occur in nozzles of fuel injectors for Diesel engines and enhance atomization of a discharged liquid jet\(^1\)–\(^3\). Several studies\(^4\)–\(^6\) have been carried out using two-dimensional (2D) nozzles to visualize cavitation in nozzles. Since the deformation of liquid element (atomization) is not directly caused by cavitation bubbles but by the change of liquid velocity in space and time, the knowledge on liquid velocity distribution in nozzles is of use to understand the mechanism of atomization enhancement. Walther et al.\(^7\) measured liquid velocity distribution upstream of a nozzle using Particle Image Velocimetry (PIV). Gnirss et al.\(^8\) obtained streamwise velocity and its fluctuation near the exit of a 2D nozzle using Laser Doppler Velocimetry (LDV) when cavitation did not take place. He and Ruiz\(^9\) succeeded in measuring liquid velocity in a 2D long orifice by LDV when cavitation appeared only near the nozzle inlet. Oda and Yasuda\(^10\) carried out Particle Tracking Velocimetry (PTV) measurement in a 2D nozzle when cavitation occurred near the nozzle inlet. However the distributions of liquid velocity and its fluctuation in a nozzle at various regimes\(^6\) such as incipient cavitation, developing cavitation (in which cavitation appears only near the nozzle inlet) and super cavitation (in which cavitation develops from the nozzle inlet to the exit and liquid jet atomization is enhanced) have not been measured yet. In the present study, liquid velocity in a 2D nozzle was, therefore, measured using LDV in these various cavitation regimes.

2. Experimental Setup and Conditions

Tap water of 291 K in temperature was discharged through a 2D transparent nozzle into ambient air. The
width $W_N$, length $L_N$ and thickness $D_N$ of the nozzle were 4, 16 and 1 mm, respectively. The details of the experimental setup are described in Ref. (6). Liquid velocity in the nozzle was measured using an LDV system, which consisted of an Ar-ion laser, an LDV optics (DANTEC, 60 × 83) and a signal processor (DANTEC, 58 N10). As shown in Fig. 1, forward-scattered light was detected by the receiving optics to avoid receiving the scattered light on the nozzle wall. The nozzle geometry and coordinate system are shown in Fig. 2, where $x$ is the horizontal distance from the nozzle center, $y$ the streamwise distance from the nozzle inlet, $u$ and $v$ the streamwise and horizontal components of local instantaneous liquid velocity. LDV measurements were carried out on the center plane ($x$–$y$ plane) in the nozzle. A 3D traverse system with the minimum scale of 10 $\mu$m was used to move the LDV measurement volume. The time-averaged velocity ($U$, $V$) and the R.M.S. of fluctuation velocity (turbulence intensity) ($u'$, $v'$) were calculated from 50,000 data of the local instantaneous liquid velocities measured at each point.

Experimental conditions are listed in Table 1. The cavitation number $\sigma$ and the liquid Reynolds number $Re$ defined by the following equations were used as dimensionless parameters.

\[
\sigma = \frac{P_a - P_v}{0.5 \rho_L V_N^2} \quad (1)
\]

\[
Re = \frac{V_N W_N}{\nu_L} \quad (2)
\]

where $P_a$ denotes the atmospheric pressure, $P_v$ the vapor saturation pressure, $\rho_L$ the liquid density, $V_N$ the area-averaged liquid velocity in the nozzle, and $\nu_L$ the liquid kinematic viscosity.

Silicone carbide (SiC) particles of 1.69 in specific weight and 3 $\mu$m in mean diameter were added in water (2.5 g/m$^3$) as seeding particles for the LDV measurement. Since cavitation inception might take place on the surface of solid particles, the seeding particles might affect the cavitation behavior in a nozzle. To evaluate the effects of seeding particles on cavitation, visualization of cavitating flows with and without the particles was carried out. Figure 3 shows the images of flows with the seeding particles. The duration of the flush lamp used for imaging was 12 $\mu$s. For $\sigma \geq 1.27$, cavitation bubbles were not observed (no cavitation). When $\sigma = 0.95$ and 0.78, cavitation appeared and collapsed in the upper half of the nozzle (developing cavitation). For $\sigma = 0.65$, cavitation zone extended from the nozzle inlet to just above the exit (super cavitation). Atomization of a liquid jet near the exit was enhanced only in the super cavitation regime. These results qualitatively agreed with those in the case with no seeding particles (6).

The dimensionless cavitation length $L_{cav}^*$, which is defined as the ratio of the mean streamwise length of cavitation zone $L_{cav}$ to the nozzle length $L_N$, is shown in

<table>
<thead>
<tr>
<th>Cavitation number, $\sigma$</th>
<th>Reynolds number, $Re$</th>
<th>Cavitation regime</th>
<th>Liquid jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.27</td>
<td>45000</td>
<td>no cavitation</td>
<td>wavy jet</td>
</tr>
<tr>
<td>1.27</td>
<td>50000</td>
<td>developing cavitation</td>
<td>wavy jet</td>
</tr>
<tr>
<td>0.95</td>
<td>58000</td>
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<td>wavy jet</td>
</tr>
<tr>
<td>0.78</td>
<td>64000</td>
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<td>wavy jet</td>
</tr>
<tr>
<td>0.65</td>
<td>70000</td>
<td>super cavitation</td>
<td>spray</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic of LDV system (top view)

Fig. 2 Nozzle geometry and coordinates

Fig. 3 Images of flows with seeding particles
Fig. 4. Solid squares in the figure show measured cavitation lengths $L_{cav}^*$ without particles, and open triangles those with particles. Since the cavitation length $L_{cav}$ varies with time, the mean cavitation length $L_{cav}$ was obtained by arithmetically averaging ten data of $L_{cav}$. Under the constant injection pressure difference $\Delta P_{inj}$, $L_{cav}^*$ with particles was slightly larger than that without particles, which implies the particles slightly enhance cavitation. However the increase in $L_{cav}^*$ due to the particles was less than 8%. Hence the effects of the seeding particles in the present condition were small.

3. Results and Discussion

3.1 Mean velocity distributions

Velocity measurements were carried out near the inlet ($y = 0.5$ mm), downstream of cavitation zone, and just above the exit ($y = 13, 15$ mm). It should be noted that velocity was not measured in cavitation zone. The distributions of time-averaged velocity are shown in Fig. 5. The presence of recirculating flows with upward flows along the side walls (which will be more clearly shown in Fig. 6 (a)) were measured in the no cavitation regime (Fig. 5 (a), $\sigma = 1.27$). This in turn means the formation of a separated boundary layer (SBL). No upward flow is formed just below the cavitation zone ($y = 4.05$ mm in Fig. 5 (b), $y = 8.83$ mm in Fig. 5 (c) and $y = 15$ mm in Fig. 5 (d)), which implies the reattachment of SBL just above the tail of the cavitation zone. As shown in

![Image](image_url)
Fig. 6 Streamwise velocity near the nozzle inlet (y = 0.5 mm)

Fig. 7 Critical velocity $V_{\text{cav}}$ predicted by the Bernoulli’s principle vs. measured velocity $V_{\text{max}}$

$$V_{\text{max}} = \sqrt{U'^2 + V^2}$$

The $V_{\text{cav}}$ was calculated using the Bernoulli’s equation as follows:

$$V_{\text{cav}} = \sqrt{\frac{V_{\text{N}}^2 + 2(P_s - P_v)}{\rho_l}}$$

which was based on the following assumptions: (1) the pressure outside the nozzle is the atmospheric pressure $P_s$, (2) liquid velocity at the exit is equal to $V_N$, since time-averaged velocity near the exit was almost uniform, and (3) gravity, turbulence, pressure drop in the nozzle, and the effects of dissolved gases are neglected. Comparisons between $V_{\text{max}}$ and $V_{\text{cav}}$ at various conditions are shown in Fig. 7. When there is no cavitation ($\sigma \geq 1.27$), $V_{\text{max}}$ is smaller than $V_{\text{cav}}$, in other words, the time-averaged local pressure is higher than $P_s$. For $\sigma = 0.95$, cavitation appears near the inlet as shown in Fig. 3. In this case, $V_{\text{max}}$ is nearly equal to $V_{\text{cav}}$, which implies that cavitation inception takes place when the time-averaged local pressure is almost equal to $P_s$. The slight difference between $V_{\text{max}}$ and $V_{\text{cav}}$ might be caused by the pressure reduction due to turbulent eddies.

3.2 Inception of cavitation

In the previous paper, we reported that cavitation bubbles appear near the nozzle inlet (about 0.5 mm downstream of the inlet) at the location apart from the side wall, and move along the outer edge of SBL in the case of incipient cavitation. Measures $U'$ and $u'$ near the inlet ($y = 0.5$ mm) are shown in Fig. 6(a) and (b), respectively. Measured data only in the right half of the nozzle ($x \geq 0$ mm) will be shown in the following, since they are almost symmetric. As shown in Fig. 6(a), the reverse flow presents near the wall ($x = 1.90$ mm) in the no cavitation regime ($\sigma = 1.27$), which clearly shows the existence of SBL ($x \geq 1.7$ mm). The flow outside SBL, i.e., the core flow, is similar to a potential flow through a sharp-edged corner, i.e., the largest velocity appears in the vicinity of a sharp-edged corner. As shown in Fig. 6(b), the turbulence intensity $u'$ is almost uniform in the core region, and $u'$ shows a large value in SBL.

Since cavitation bubbles do not exist steadily at a position in the cases of cavitation inception and developing cavitation, turbulent eddies and bubble nuclei might play an important role in cavitation inception. However it is of use to estimate time-averaged pressure at the position of cavitation inception and to compare it with the vapor saturation pressure $P_v$. Hence the time-averaged local velocity $V_{\text{max}}$ at the inception position (at the outer edge of SBL and $y = 0.5$ mm) was compared with the critical velocity $V_{\text{cav}}$ at which the local pressure was equal to $P_v$. The $V_{\text{max}}$ at the inception position was given by
Fig. 8  Velocity at $\sigma = 1.27$ (no cavitation)

Fig. 9  Turbulence intensity at $\sigma = 0.95$ (developing cavitation)

Fig. 10  Turbulence intensity at $\sigma = 0.78$ (developing cavitation)

Fig. 11  Velocity at $\sigma = 0.65$ (super cavitation)

Fig. 12  Velocity and turbulence intensity near the exit ($y = 15$ mm)

Fig. 13  Effects of cavitation regime and the Reynolds number

4. Conclusion

To understand how a cavitating flow in a nozzle enhances the liquid jet atomization, liquid velocity distributions of cavitating flows in a two-dimensional nozzle were measured using a Laser Doppler Velocimetry (LDV) sys-
tem. As a result, the following conclusions were obtained:

(1) The inception of cavitation occurs near the outer edge of separated boundary layer (SBL), where the time-averaged local velocity takes the highest value and the time-averaged pressure is almost equal to the vapor saturation pressure.

(2) When the cavitation number $\sigma$ is greater than 0.78 (in no cavitation and developing cavitation regimes), the reattachment of SBL occurs in the middle of the nozzle. A large velocity fluctuation, which appears just downstream of SBL, decreases near the nozzle exit. Hence the wavy jet is formed in these regimes.

(3) For $\sigma \leq 0.65$ (in super cavitation regime), the lateral flow directing from the core region toward the side walls just upstream of the nozzle exit is a major cause of the increase in the spray angle and drastic enhancement of liquid jet atomization. The strong turbulence just upstream of the exit must play an important role in the formation of ligaments at liquid jet interface.

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