Effects of ambient pressure on cavitation in the nozzle and the discharged liquid jet

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Abstract
Cavitation in the nozzle plays an important role in the atomization of the discharged liquid jet. Because of this, understanding in-nozzle cavitation is very important for the control of spray characteristics. However, in-nozzle cavitation is not fully understood at present, in part because it is affected by various factors, such as fluid properties, injector geometries, and ambient pressure. Although it is obvious that ambient pressure hinders cavitation development in the nozzle, the extent of the effect has not been quantitatively predicted yet. In the present study, visualization of cavitation in an enlarged two-dimensional (2D) transparent nozzle and the discharged liquid jet is carried out under various ambient pressure $P_a$ ($P_a = 0.1, 0.2, 0.3, 0.4$, and $0.5 \text{ MPa}$). From the flow visualization result, an image analysis is carried out to obtain the experimental data on the effects of ambient pressure on cavitation length $L_c$, cavitation width $W_c$, and liquid jet angle $\theta$. Finally, a set of correlations on $L_c$, modified cavitation number $\sigma_c$, jet angle $\theta$, and the Weber number $We$ at various ambient pressures are proposed, based on the image analysis results.

Keywords : Internal flow, Cavitation, Modified cavitation number, 2D nozzle, Ambient pressure, Liquid jet, Atomization

1. Introduction

A number of studies on fuel injector have revealed that cavitation in the nozzle plays a large role in the atomization of the discharged liquid jet. This fact was first pointed out by Bergwerk (1959), who visualized the internal flow and the discharged liquid jet from single-hole diesel nozzles under cavitating and non-cavitating conditions. Although Bergwerk’s study did not give a detailed analysis on the mechanism of how cavitation affects discharged liquid jet, it was the first to underscore the importance of internal cavitating flow for the control of fuel spray characteristics. Since then, various studies have been carried out to investigate in-nozzle cavitation and how it affects liquid jet break-up. These studies were carried out with various injector configurations. For example, Soteriou et al. (1995) and Chaves et al. (1995) compared cavitation occurrences in enlarged and small injectors with realistic geometry, while Sou et al. (2007, 2008a, 2008b) experimentally clarified the mechanism of atomization enhancement by cavitation using enlarged single-hole nozzles. Even so, cavitation in the nozzle is still not fully understood at the present. One of the reasons is because cavitation is very sensitive to various factors, such as fluid properties, injector geometries, and ambient pressure. Furthermore, these factors are interconnected with each other, which made it hard to quantify the effect of a single factor on in-nozzle cavitation. For example, although it is obvious that ambient pressure affects cavitation, a quantitative evaluation of its effect on in-nozzle cavitation is still not available.

In this study, flow visualization of internal cavitating flow and the discharged liquid jet from a transparent, enlarged two-dimensional (2D) nozzle (Sou et al., 2006) is carried out under various ambient pressures $P_a$ ($P_a = 0.1, 0.2, 0.3, 0.4$, and $0.5 \text{ MPa}$), in order to clarify the effects of $P_a$ on cavitation development and the discharged liquid jet characteristics. Then, the applicability of various non-dimensional cavitation numbers (Bergwerk, 1959; Nurick, 1976; Payri et al., 2004;
Soteriou et al., 1995; Sou et al., 2008a) to quantitatively predict cavitation at various ambient pressures is examined. Finally, a correlation on the liquid jet angle $\theta$ for various $P_a$ and $\sigma_c$ is proposed.

2. Nomenclature

- $C_c$: Contraction coefficient at vena contracta [-]
- $D_H$: Hydraulic diameter of the nozzle [m]
- $V$: Mean flow velocity in the nozzle [m/s]
- $V_c$: Mean flow velocity at vena contracta [m/s]
- $L$: Nozzle length [mm]
- $L_c$: Cavitation length [mm]
- $P_a$: Ambient pressure in the test chamber [MPa]
- $P_c$: Pressure at vena contracta [MPa]
- $P_u$: Pressure upstream of the nozzle [MPa]
- $P_r$: Recovery pressure [MPa]
- $P_v$: Vapour saturation pressure [MPa]
- $R$: Curvature radius of the nozzle inlet [μm]
- $Re$: Reynolds number [-]
- $W$: Nozzle width [mm]
- $W_c$: Cavitation width [mm]
- $We$: Weber number [-]
- $\Delta P_a$: $P_u - P_a$ [MPa]
- $\gamma$: Surface tension [N/m]
- $\theta$: Liquid jet angle [degree]
- $\theta_{max}$: Maximum liquid jet angle [degree]
- $\lambda$: Friction coefficient [-]
- $\nu$: Kinematic viscosity [m$^2$/s]
- $\rho$: Liquid density [kg/m$^3$]
- $\rho_a$: Ambient gas density [kg/m$^3$]
- $\sigma_1$: Cavitation number 1 [-]
- $\sigma_2$: Cavitation number 2 [-]
- $\sigma_3$: Cavitation number 3 [-]
- $\sigma_c$: Modified cavitation number [-]
- $\sigma_H$: Hiroyasu cavitation number [-]

3. Experimental Setup

The schematic of the experimental setup is shown in Fig. 1. Filtered tap water at 303 K temperature was discharged under steady-state injection condition using a plunger-type pump (Kyowa KY-300-6) through an enlarged 2D nozzle into a pressurized test chamber. The width $W$, length $L$, and inlet curvature radius $R$ of the nozzle are 4.0 mm, 16.0 mm, and 22.6 μm, respectively. To investigate the effect of ambient pressure, the pressure inside the chamber $P_a$ was adjusted using a compressor (Anest Iwata TFD55-10, $P_a = 0.1, 0.2, 0.3, 0.4, 0.5$ MPa). The flow rate, which was used to derive the mean flow velocity $V$ in the nozzle, was measured using a digital Coriolis flowmeter (Keyence FD-SS20A). The pressure upstream of the nozzle $P_u$ and $P_a$ were measured using piezoelectric pressure transducers (Kyowa PGL-A-50MP-A and PGMC-A-1MP). Still images of cavitation in the nozzle and the discharged liquid jet were taken using a digital camera (Canon D800, Nikon 200mm f/4 AF-D lens) and a strobe backlight (Nissin Electronics, MS-1000 / LH-15M) with a flash duration of 2-4 μs. The still images were analyzed to quantify cavitation length $L_c$, cavitation width $W_c$, and liquid jet angle $\theta$. Jet angle $\theta$ was measured at the distance of $1L$ from the nozzle exit. The definitions of $L$, $L_c$, $W$, $W_c$, and $\theta$ are illustrated in Fig. 1.
Fig. 1 Experimental setup and the definitions of \( L, L_c, W, W_c, \) and \( \theta \)

4. Results and Discussion

4.1 Images of cavitation and liquid jet

The increase in the liquid jet angle by cavitation is induced by the lateral velocity component at the nozzle exit, as well as the vortex flow structure shed from the tail of the cavitation. This is especially noticeable when the cavitation tail is located close to the nozzle exit, i.e. at super cavitation regime. In contrast, when hydraulic flip (Soteriou et al., 1995) occurs, the surrounding gas enters the nozzle and there is no flow reattachment in the nozzle. As a result, the liquid jet turns into a smooth jet at the hydraulic flip regime. The mechanism of in-nozzle cavitation effects to liquid jet break-up is well-documented in various studies (Chaves et al. 1995; Soteriou et al., 1995; Sou et al., 2007, 2010). The result of the current study also shows the evidence of a similar mechanism. Typical images of cavitation in the nozzle and the discharged liquid jet at various ambient pressures are shown in Fig. 2. Under all \( P_a \) conditions, liquid jet break-up is enhanced significantly at super cavitation and decreases at hydraulic flip. It should be noted that as \( P_a \) increases, mean flow velocities \( V \) and upstream pressure \( P_u \) needed to achieve similar \( L_c \) increases. Furthermore, the increase in \( P_a \) not only decreases \( L_c \) but also induces the formation of the complex interface structure of the liquid jet. Measured \( L_c \) normalized by \( L \) is summarized in Fig. 3. The result confirms that at higher \( P_a \), higher \( V \) and \( P_u \) is needed to reach the same length of \( L_c \) at lower \( P_a \). It can also be seen that at higher \( P_a \), the range of \( V \) and \( P_u \) at which super cavitation occurs \((0.7 \leq L_c/L < 1)\) becomes wider. These changes are caused by the changes in static pressure distribution in the nozzle. This will be explained in more detail in the next section.
Fig. 2 Typical images of in-nozzle cavitation and the discharged liquid jet at various $P_a$

Fig. 3 Measured $L_c/L$ against $V$ and $\Delta P_u$ at various $P_a$
4.2 Pressure distribution in the nozzle

![Fig. 4 Pressure distribution in a cavitating nozzle](image)

The distribution of static pressure in a cavitating nozzle is illustrated in Fig. 4 (Sou et al., 2008a). The streamwise distance from the nozzle inlet is defined as \(y\). At the vena contracta area, the static pressure in the recirculation flow decreases to the value of \(P_c\). The static pressure recovers to the value of \(P_r\) downstream of the vena contracta area before it becomes as high as the ambient pressure \(P_a\) at the nozzle exit. When the \(P_u\) at the upstream of the nozzle increases, pressure \(P_c\) at vena contracta decreases due to the increase in dynamic pressure in the nozzle. The onset of cavitation takes place when \(P_c\) becomes lower than the vapor saturation pressure \(P_v\). Further increase in \(P_u\) results in lower \(P_c\) and extends the low-pressure region in the nozzle. These static pressures at various points in the nozzle can be approximated using the Bernoulli equation, which is given by:

\[
P_c + \frac{1}{2} \rho V_c^2 = P_a + \frac{1}{2} \rho V^2 + \frac{\lambda L_c}{D_H} \frac{1}{2} \rho V^2
\]  

where \(V_c\) is the flow velocity at the vena contracta, \(D_H\) the equivalent hydraulic diameter of the nozzle, \(\lambda\) the friction coefficient of the nozzle wall, and \(\rho\) the liquid density. \(\lambda\) is given by the modified Blasius equation (Sou et al., 2008a):

\[
\lambda = \beta \left( \frac{0.3164}{Re^{0.25}} \right)
\]

where \(\beta\) is the aspect ratio, which is taken as 1.15 for rectangular plain-orifice nozzles (JSME, 1979) and \(Re\) is the Reynolds number, given by:

\[
Re = \frac{V D_H}{\nu}
\]

where \(\nu\) is the kinematic viscosity of the liquid, which is taken as \(8.01 \times 10^{-7}\) in this study. Note that the amount of frictional pressure drop in nozzle with \(L/W = 4\), as used in the current study, is not so large. The effect of frictional pressure drop should be more apparent for nozzles with higher ratio of \(L/W\). Based on Eq. (1), the pressure \(P_c\) at vena contracta can be calculated by:

\[
P_c = P_a + \frac{1}{2} \rho V^2 + \frac{\lambda L_c}{D_H} \frac{1}{2} \rho V^2 - \frac{1}{2} \rho V_c^2
\]

with the velocity \(V_c\) at vena contracta is given using mean flow velocity \(V\) and contraction coefficient \(C_c\), based on the mass conservation equation:

\[
V_c = \frac{V}{C_c}
\]
where $C_c$ for the 2D nozzle is calculated from the measured cavitation thickness $W_c$:

$$C_c = 1 - \frac{2W_c}{W}$$

the recovery pressure $P_r$ is calculated from Eq. (7):

$$P_r = P_a + \frac{\lambda(L+L_c)}{D}\frac{1}{2} \rho V^2$$

these simple models can be used to quantitatively estimate $V_c$, $P_c$, and $P_r$ if the value of contraction coefficient $C_c$ is known.

Normalized cavitation thicknesses $W_c/W$ for various $P_a$ are plotted in Fig. 5. The cavitation profiles confirm that $P_a$ has little effect on the cavitation profile. Hence, an averaged value of measured $W_c$ from all experimental conditions is used to calculate $C_c$, using Eq. (6). $W_c$ for $C_c$ calculation is measured at $0.5W$ from the nozzle inlet, where mean flow velocity $V$ reaches the maximum value for nozzles where the cross-sectional area of the sac $\gg$ cross-sectional area of the nozzle and $L/W \geq 4$ (Sou et al., 2008a). $W_c = 0.189$ mm in the current study. The static pressure distribution for all $P_a$ conditions is calculated based on the value of $C_c = 0.622$.

Figure 6 shows the images of cavitation at various $V$ at $P_a = 0.1$ MPa, while Fig. 7 shows the measured $P_a$ and $P_u$ as well as calculated $P_c$ and $P_r$ based on Eqs. (4) and (7), respectively. The result agrees well with the previous explanation about static pressure distribution in a nozzle. Cavitation occurs when $P_c \leq P_v$. When $V$ increases, the value of $P_c$ drops further. Pressure below 0 MPa shows the extent of pressure drop at the vena contracta area at higher $V$. This pressure drop is also followed by the expansion of low-pressure region in the streamwise direction, which cause cavitation to grow longer as $V$ increases. It should be noted that after cavitation occurs, pressure quickly recovers to the value of recovery pressure $P_r$, as defined in Eq. (7).
Figure 8 shows the images of super cavitation ($0.7 \leq L_c/L < 1$) at various $P_a$, while Fig. 9 shows the $P_u$, $P_e$, $P_r$, and $P_a$. The nozzle pressure distributions at super cavitation at various $P_a$ values qualitatively agree with those at $P_a = 0.1$ MPa. Furthermore, Fig. 9 indicates that the increase in ambient pressure $P_a$ causes the static pressure at all positions in the nozzle to increase. As a result, a higher pressure drop in the nozzle is needed to achieve critical cavitation pressure. Consequently, the $P_a$ at the onset of cavitation increases as $P_a$ increases.
4.3 Applicability of various cavitation numbers for cavitation length prediction

From the calculation of the pressure distribution in the nozzle, the sensitivity of cavitation to $P_a$ has been proven. In this section, a comparison of several cavitation numbers is carried out to examine their applicability in predicting cavitation length under various ambient pressures. In most studies, cavitation numbers based on the pressure difference between $P_u$, $P_a$, and/or $P_r$ have been used to predict the onset of cavitation in the nozzle. The examples of such cavitation numbers are given in Eqs. (8)-(11) below, such as the conventional cavitation number $\sigma_1$ (Brennen, 1995):

$$\sigma_1 = \frac{P_a - P_r}{\rho V^2}$$  \hspace{1cm} (8)

where $\rho$ is the liquid density; $\sigma_2$ used by Bergwerk (1959) and Soteriou (1995):

$$\sigma_2 = \frac{P_a - P_r}{P_u - P_r}$$  \hspace{1cm} (9)

and $\sigma_3$ used by Nurick (1976) and Payri et al. (2004):

$$\sigma_3 = \frac{P_a - P_r}{P_u - P_r}$$  \hspace{1cm} (10)

The pressure distributions shown in Figs. 7 and 9 indicate the importance of flow contraction at vena contracta to
determine the pressure drop and cavitation onset in the nozzle. However, it can be seen from Eqs. (8), (9), and (10) that \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) do not take flow contraction into account.

Hiroyasu et al. (1991) proposed the cavitation number \( \sigma_H \) based on the pressure at vena contracta, which is defined by:

\[
\sigma_H = \frac{P_c - P_a}{\frac{1}{2} \rho V_c^2}
\]

where \( P_c \) and \( V_c \) is the pressure and flow velocity at vena contracta, respectively. However, Hiroyasu et al. failed in quantitatively predicting the cavitation growth with this cavitation number. A study by Sou et al. (2008a) found that the reason Hiroyasu et al. failed in predicting cavitation growth with \( \sigma_H \) was that they assumed that frictional pressure drop was negligible. Additionally, Hiroyasu et al. did not use an exact value of the flow contraction for each case, which should vary with injector geometry or needle lift. Sou et al. then proposed an improvement upon \( \sigma_H \), by taking measured contraction coefficient \( C_c \) and frictional pressure drop into account. The resulting cavitation number is called modified cavitation number \( \sigma_c \), which is given by:

\[
\sigma_c = C_c^2 \left[ \frac{P_c - P_a}{\frac{1}{2} \rho V_c^2} + \frac{\lambda L}{D_H} + 1 \right]
\]

where \( \lambda \) is the friction coefficient and \( D_H \) is the equivalent hydraulic diameter of the nozzle. In the following section, the applicabilities of \( \sigma_1, \sigma_2, \sigma_3, \) and \( \sigma_c \) for quantitative prediction of cavitation length \( L_c \) are tested. The relationship between cavitation lengths \( L_c/L \) and the cavitation numbers \( \sigma_1, \sigma_2, \sigma_3, \) and \( \sigma_c \) are shown in Fig. 10.

![Fig. 10 Comparison of \( L_c/L \) and various non-dimensional cavitation numbers](image-url)
As evident from Fig. 10, by taking frictional pressure drop and flow contraction in the nozzle into account, the modified cavitation number $\sigma_c$ can accurately predict the inception of in-nozzle cavitation and its subsequent development under various $P_a$ conditions, with greater accuracy compared to $\sigma_1$, $\sigma_2$, and $\sigma_3$.

### 4.4 Effect of ambient pressure on the resulting liquid jet angle

Lastly, the effect of $P_a$ on liquid jet angle $\theta$ is investigated in this section. Measured $\theta$ for various $P_a$ are shown in Fig. 11. As expected, $\theta$ increases with $V$, except when hydraulic flip occurs in the nozzle. It is also evident that the maximum jet angle $\theta_{max}$ at super cavitation increases with $P_a$, due to the increasing density of the ambient gas. This causes the liquid jet to suffer larger drag from the ambient gas and increases the resulting jet angle at all cavitation regimes. The relationship between $L_c/L$ and $\theta$ shown in Fig. 12 clearly indicates the trend.

Recent study (Prasetya et al., 2019) has shown that nozzles with $W < 2$ mm are subject to stronger effect of surface tension on the interface between the liquid jet and the surrounding gas, compared to larger nozzles. As the nozzle used in the current study has a $W$ of 1 mm, the effect of surface tension might play a large role in determining the resulting $\theta$. To investigate the effect of surface tension, $\theta_{max}$ is plotted against the Weber number $We$ for all $P_a$ in Fig. 13. The Weber number is given by:

$$We = \frac{\rho V^2 L}{\sigma}$$
\[ We = \frac{\rho_a V^2 W}{\gamma} \]  

(13)

where \( \gamma \) is the surface tension and \( \rho_a \) is the ambient gas density, which is calculated from the ambient pressure \( P_a \) using the equation of states for an ideal gas. Nozzle width \( W \) is taken as the characteristic length. For cylindrical nozzles, nozzle diameter can be used as the characteristic length. From the plot result, the following correlation between \( \theta_{\text{max}} \) and \( We \) from 2D nozzle experimental data is obtained:

\[ \theta_{\text{max}} = 9.8 We^{0.25} \]  

(14)

Note that the applicability of Eq. (14) to different liquids and nozzles with different geometries has to be examined.

Since the modified cavitation number \( \sigma_c \) can predict the cavitation length \( L_c/L \) in the nozzle, the following correlation equation on \( \theta/\theta_{\text{max}} \) as a simple function of \( \sigma_c \) is proposed to examine the effect of in-nozzle cavitation to liquid jet angle:

\[
\frac{\theta}{\theta_{\text{max}}} = \begin{cases} 
0.2 & ; \sigma_c \leq 0.77 \\
0.2 + 0.43(\sigma_c + 0.19)^{-20} & ; \sigma_c > 0.77 
\end{cases}
\]  

(15)

The relationship between measured \( \theta/\theta_{\text{max}} \) and \( \sigma_c \) for various \( P_a \), as well as the estimation given by Eq. (15), are summarized in Fig. 14. As \( \theta \) scales for different \( P_a \) when the contraction coefficient \( C_c \) is known, Eq. (15) can be used to obtain \( \theta/\theta_{\text{max}} \) at various \( P_a \). As Eq. (15) is derived from \( \sigma_c \), the effect of in-nozzle cavitation is also taken into account in the calculated \( \theta/\theta_{\text{max}} \). The \( \theta_{\text{max}} \) itself can then be approximated from Eq. (14), which takes the effect of surface tension at various \( P_a \) into account. By using the \( \theta/\theta_{\text{max}} \) obtained from Eq. (15) and \( \theta_{\text{max}} \) obtained from Eq. (14), it is possible to predict the liquid jet angle for various \( P_a \).
5. Conclusions

From the visualization result of cavitation in a transparent 2D nozzle and the discharged liquid jet at various ambient pressures $P_a$, it can be concluded that:

1. Increase in ambient pressure $P_a$ hinders cavitation development in the nozzle, as the increase in $P_a$ also increases the overall static pressure in the nozzle. Even so, the modified cavitation number $\sigma_c$ can quantitatively evaluate the onset and development of cavitation at various ambient pressures.

2. The increase in static pressure in the nozzle necessitates a larger flow velocity $V$ and higher upstream pressure $P_u$ in order to obtain similar cavitation length $L_c$ at higher $P_a$.

3. The liquid jet angle $\theta$ increases with $P_a$, as a result of the increasing impact from the ambient gas density $\rho_a$.

4. The liquid jet angle $\theta$ at various $P_a$ can be predicted by using the proposed correlations based on the Weber number $We$ and the modified cavitation number $\sigma_c$.

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