Effects of Inlet Edge Roundness on Cavitation in Injector Nozzles and Liquid Jet

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ABSTRACT: Innovation of fuel injection technology are necessary for lower emission and higher thermal efficiency of diesel engines. The effects of the geometry of injector nozzles on cavitation flows in the nozzles and discharged liquid jets have to be understood well, since the liquid jet and spray characteristics affect diesel combustion largely. In this study the effects of the inlet edge radius of injector nozzles on cavitation and liquid jet are quantitatively investigated by the visualization of two-dimensional nozzles with various inlet radii. As a result, we found that round inlet edge nozzles results in a thin cavitations,small cavitation clouds shed with a high frequency,and small liquid jet angle.

KEY WORDS: heat engine, compression ignition engine, fuel injection/fuel spray, injector/ nozzle,cavitation [A1]

1. Introduction

Fuel injection is a key technology to improve exhaust gas emissions and thermal efficiency of the diesel engine. Fuel Spray characteristics are influenced by cavitation in fuel injector nozzles1). Therefore a number of visualization experiments have been carried out 2)-(8). In the manufacturing process of fuel injector nozzles, in order to achieve the target of fuel flow rate at the prescribed injection pressure, fluid polishing is performed to round the hole inlet edges. Its radius R of the curvature have a significant impact on cavitation flow in the nozzle, fuel spray and combustion characteristics. However, the effects of R on cavitation and jet have still not been clear. In this study, cavitation and liquid jet in two-dimensional (2D) nozzles with various inlet radii were visualized, and the effects of R was examined quantitatively through image analysis.

2. EXPERIMENTAL METHODOLOGY

2.1. Laboratory Equipment and Method

Figure 1 shows an overall view of the experimental setup. Water of 30 ± 0.5°C was injected from the transparent 2D nozzle into the air at room temperature. The nozzles were prepared with different nozzle inlet radii. The images of discharged liquid jets and cavitations were taken with a transmitted light at various mean flow velocities V in the nozzle. For still image shooting, a digital camera and a strobe light (Nissin Electronics Kogyo Co., Ltd Micro Flash Stroboscope, MS-1000/LH-15M, flash time is 2 to 4μs) were used. For movie shooting, a high-speed camera (Nobby Tech. Ltd., Phantom v1610) and a metal halide lamp (Kyowa Co., Ltd., MID-25FC) were used.

2.2. Test Nozzle

Symmetrical structured 2D nozzles of hole length L = 16.0mm, hole width W = 4.0 mm (L/W= 4), and thickness 1.0 mm were used. The inlet edges of the holes were ground with hand finishing. Figure 2(a) and (b) show microscope photos of the nozzle inlet edges whose radii R are 40μm and 260μm, respectively. Eight nozzles with R=3, 12, 30, 40, 180, 260, 500, 800μm (R/W = 0.08, 0.3, 0.75, 1.0, 4.5, 6.5, 13, 20%) were prepared.
Definitions of cavitation length $L_C$ and cavitation width $W_C$ are shown in Figure 3. Definition of jet angle $\theta$ is illustrated in Figure 4, which was measured at 24 mm (=1.5L) downstream from the nozzle exit. At each mean velocity $V$, ten images (still picture) were taken to calculate the average values of $L_C$, $W_C$ and $\theta$.

As the dimensionless number for cavitation in a nozzle, the modified cavitation number $\sigma_c$ based on the static pressure at contracted flow section was used:

$$\sigma_c = \frac{P_b - P_v}{\frac{1}{2} \rho \nu^2} + \frac{2L}{W} + 1$$  

(1)

where $C_c$ is the contraction coefficient, $P_b$ the back pressure (ambient pressure), $P_v$ the vapor saturation pressure, $\rho$ the liquid density, and $\lambda$ the friction factor, respectively.

3. Results and Discussion

3.1. Still image shooting

Figures 5(a)-(f) show cavitation in nozzles with various inlet edge radii and liquid jets discharged from them. Regardless of the inlet edge radius, the processes of cavitation development such as cavitation inception, cavitation development, super cavitation and hydraulic flip are observed as $V$ is increased. When the inlet edge radius of the nozzle becomes larger, the process of cavitation development in the nozzle is observed at the higher mean velocity.
To examine the effect of the mean velocity \( V \) on cavitation development, mean cavitation lengths \( L_c \) were measured based on still images. To clarify the reason of the difference of \( V \) at the same cavitation length \( L_c \) for various inlet edge radii, cavitation profiles around inlet edges at super cavitation, which are steady, were measured based on still images.

Figures 6 and 7 show the effects of the inlet radius on cavitation length \( L_c \) and cavitation thickness \( W_c \), respectively. When \( R/W \) is less than 1% (\( R/W < 1\% \)), the effects of \( R/W \) on \( W_c \) are negligible and the difference of \( V \) for the same \( L_c \) is within 2m/s which can be regarded as a sharp inlet edge. On the other hand, when \( R/W \) is more than 5% (\( R/W > 5\% \)), \( W_c \) decreases with increasing inlet edge radius. This indicates that at vena contracta the core velocity \( V_{core} \) decreases and the static pressure increases with increasing inlet edge radius. Therefore, cavitation inception and development for a larger inlet edge radius (large \( R/W \)) are observed at higher mean velocities \( V \). It can be also seen that for the nozzles with a larger inlet edge radius (large \( R/W \)), super cavitation (0.7<\( L_c <1 \)) was observed in a wider range of the mean velocity \( V \), which is suitable for a fuel injector, because super cavitation enhances spray atomization.

In Figure 8 the relationship between \( R/W \) and contraction coefficient \( C_c \) for various radii of inlet edge is presented. When \( R/W \) is larger than 5%, contraction coefficient \( C_c \) increases with \( R/W \) because of smaller \( W_c \) which represents thinner cavitation.

The modified cavitation number \( \sigma_c \) can be calculated using the value of \( C_c \). Figure 9 shows the relationship between the modified cavitation number \( \sigma_c \) and cavitation length \( L_c \), which represents the index of cavitation inception and development. As shown in Figure 6, \( L_c \) takes different values at a mean velocity \( V \) for different \( R/W \). On the other hand, Figure 9 shows that \( \sigma_c \) can be used to quantitatively predict cavitation length \( L_c \).

Figure 10 shows the effects of inlet edge radius \( R \) on liquid jet angle \( \theta \). At super cavitation (0.7<\( L_c <1 \)) liquid jet angle \( \theta \) becomes large. The nozzles with a sharp inlet edge forms a large maximal liquid jet angle. It was reported that a thick cavitation is formed in a nozzle with an asymmetric inflow, which results in a large deformation of a liquid jet\(^{(8)}\). In the nozzles with a sharp inlet edge (small \( R/W \)), the thick cavitation can be related to the large liquid jet angle \( \theta \).
3.2 High-speed camera shooting

In order to investigate the effects of cavitation on liquid jet, high-speed camera shooting for two nozzles with $R/W = 0.75\%$ ($R = 30\mu m$) and $6.5\%$ ($R = 260\mu m$) was carried out. Figure 11 shows the region of the moving image (7.0 mm x 18.0 mm, 89171 fps, 29 μm/pixel). To examine the effects of inlet radius $R$ on transient motion of cavitation and jet, super cavitation in the nozzle with $R/W = 0.75\%$ ($R = 30\mu m$) at $V = 16.7\, m/s$ ($V_{\text{CORE}} = 27.8\, \text{m/s}$) was observed as a sharp edge case and that in the nozzle with $R/W = 6.5\%$ ($R = 260\mu m$) at $V = 19.4\, m/s$ and $V_{\text{CORE}} = 29.5\, m/s$ was observed as a round edge case, whose $V_{\text{CORE}}$ and $L_C$ are almost matched for the two nozzles.

Figure 12(a) shows the images of cavitation for the sharp edge nozzle ($R/W = 0.75\%$) and the discharged liquids. A large deformation of the discharged liquid expanded to the right direction is observed when the trace of the cavitation cloud flows out of the nozzle. On the other hand, as shown in Figure 12(b), the deformation of the discharged liquid is smaller and only the fine ligaments are formed for the round edged nozzle ($R/W = 6.5\%$).
3.3. Moving Image Analysis

To examine the scale and frequency of cavitation cloud shedding in the vicinity of the nozzle exit as well as the delay and frequency of liquid jet deformation, image analysis was carried out. Figure 13 shows the image analysis zones of the cavitation cloud (14 mm from the nozzle inlet) and the liquid jet (4 mm below the nozzle exit). The width and height of the cavitation cloud zone are 1.0 x 0.8 mm, and those of the liquid jet zone are 2.5 x 0.8 mm, respectively.

![Image of a moving image analysis zone](image)

**Fig. 13 Zones for moving image analysis**

Figure 14 shows the original and binary images of the cavitation cloud zone of the nozzle with the sharp edge (R/W=0.75%), while Figure 15 shows those of the liquid jet zone. As shown in Figure 14, a cavitation cloud is shedding from the trailing edge of the sheet cavitation to downstream intermittently and then occupies most of the zone of 1.0 x 0.8 mm. For example, a small cavitation cloud occupied the zone at t = 45 µs and a large cavitation cloud occupied the zone at t = 180 µs. As shown in Figure 15, the deformed liquid jet occupied the most of the zones when a liquid jet spread to the right at T=438 – 607 µs. It should be noted that a droplet from the ligament of the liquid jet is observed at t = 663 µs as an early stage of atomization. The mean liquid velocity V is 16.7 m/s and the vertical distance ∆y between the cavitation cloud zone and the liquid jet zone is 6.0 mm. Hence, the estimated delay τ (= ∆y / V) is about 360 µs for liquid jet deformation caused by the cavitation cloud. It means that the start of a liquid jet deformation is observed in the liquid jet zone about 360 µs after the cavitation cloud flows through the cavitation cloud zone. As can be seen in Figure 15, the liquid jet deformation starts around t = 382 µs after the small cavitation cloud occupied the zone at t = 45 µs with the delay of about 337 µs (=382 µs – 45 µs) which is almost the same as the estimated delay τ=360 µs.

In order to analyze series images quantitatively, volume fraction of gas α_G in the cavitation cloud zone of the nozzle was calculated by the following expression.

\[
\alpha_G(t) = \frac{A_G}{A_G + A_L}
\]

where \(A_G\) is the area of gas in a binary image, and \(A_L\) is that of liquid in the binary image.

Volume fraction of liquid jet α_J in the liquid jet zone was calculated by the following expression.

\[
\alpha_J(t+\tau) = \frac{A_L}{A_L + A_A}
\]

where \(A_L\) is the area of liquid in a binary image, and \(A_A\) is that of the atomosper in the binary image.

Figure 16 shows the time series data of \(\alpha_G(t)\) and \(\alpha_J(t+\tau)\) for the nozzle with the sharp edge of R/W=0.75%. The delay was set to τ=0.36 ms. When the large cavitation cloud flows through the cavitation cloud zone (t=0.18ms), \(\alpha_G(t)\) becomes about 0.7. \(\alpha_J(t+\tau)\) becomes a large value of about 0.8, which represents the large liquid jet deformation. Within the period of 3 ms in the graph, about four or five sudden increases in \(\alpha_G(t)\) can be seen,
which are related to the cavitation clouds shedding. As showing in Figure 15, the liquid jet keeps expanding to the right direction by a cavitation cloud for about 0.4ms (=775-382µs). Hence after the sudden increase in $\alpha_j$, it dose not decrease sharply. However, the pattern of $\alpha_j(t+\tau)$ shows a very similar pattern to $\alpha_G(t)$. This results confirm that the cavitation clouds shedding induces liquid jet deformation\(^\text{15}\).

Fig. 16 Time histories of $\alpha_G(t)$ and $\alpha_j(t+\tau)$  
(R/W=0.75%, $V=16.7$ m/s, $V_{\text{CORE}}=27.8$ m/s, $\tau=0.36$ ms)

For the nozzle with the rounded edge (R/W=6.5%), the mean flow velocity $V$ is 19.4 m/s, therefore the estimated delay $\tau$ is about 310 µs. Figures 17 and 18 show the original and binary images of the cavitation cloud zone and the liquid jet zone, respectively. Figure 19 shows the time series data of $\alpha_G(t)$ and $\alpha_j(t+\tau)$. In the case of the nozzle with rounded edge, small cavitation clouds shedding from the thin sheet cavitation are observed (Figure 17) and liquid jet deformation is small because of the small cavitation clouds (Figure 18). Hence, $\alpha_G(t)$ and $\alpha_j(t+\tau)$ increase up to 0.5, as shown in Figure 19. In addition, the frequency of the sudden increase in $\alpha_G(t)$ of R/W=6.5% is higher than that of R/W=0.75%. It should be noted that the relationship between $\alpha_G(t)$ and $\alpha_j(t+\tau)$ for R/W=6.5% is unclear because of those small values and high frequencies.

In order to examine the effects of inlet edge roundness on the frequencies of the cavitation cloud shed as well as the liquid jet deformation, time series data of $\alpha_G$ and $\alpha_j$ were analyzed with fast Fourier transform. Figures 20 and 21 show the power spectrum of $\alpha_G$ and $\alpha_j$, respectively. In the case of R/W=0.75%, there are some increases of $\alpha_G$ at approximately 0.7 kHz and some small increases in the higher frequency range of 1-3KHz (Figure 20(a)), which can also be seen in $\alpha_j$ (Figure 21(a)). The clear peak of 0.68kHz represents the large cavitation clouds and the small peaks at 1-3kHz represent the small cavitation clouds. On the other hand, for R/W=6.5%, a small peak of $\alpha_G$ is seen in Figure 20(b) and a small peak of $\alpha_j$ is seen in Figure 21(b). The peaks are not clear because of the small scales. However, the results of our study lead us to conclude that the inlet edge radius decreases cavitation thickness $W_C$, cavitation cloud size, liquid jet deformation and liquid jet angle $\theta$, while it increases the frequencies of cavitation cloud shedding and those of jet deformation.
4. Conclusions

Two-dimensional nozzles with various inlet radii were visualized in order to clarify cavitation cloud and liquid jet behaviors. The visualization and image analysis concluded that:

(1) A small ratio ($R/W<1\%$) between the curvature radius $R$ of the nozzle inlet edge and the nozzle width $W$ does not so much affect cavitation thickness and length.

(2) Cavitation in round inlet edge nozzles is thin and short, which results in a small liquid jet angle.

(3) A thin cavitation in round inlet edge nozzles induces small cavitation clouds shedding with high frequency, which results in liquid deformation with small scale.

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