Improvement of Spray and Flow Characteristics of Injection Nozzle for Direct Injection Diesel Engine

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Abstract

The purpose of this study is to develop of a direct injection Diesel nozzle, which is obtained high-dispersion spray inside a combustion chamber by strong disturbance of liquid flow due to cavitation phenomena. Diesel injector is necessary to jet of fuel high-injection pressure over about 200 MPa. In spite of high-injection pressure, at best spray angle may take about from 10 to 20 degrees and droplet diameter; Sauter mean diameter may take about 10 microns. Moreover, since conventional Diesel injector cuts away an edge of inlet of nozzle holes in order to increase discharge coefficient and to improve flow characteristics, high-injection pressure is demanded to obtain spray suitable for combustion. The nozzle, which was designed and invented in this study, was obtained with considerably large spray angle of over 70 degrees, short breakup length; liquid core length of about 2 mm for hole diameter of 0.3 mm, Sauter mean diameter of 10 microns order; about 15 microns and homogeneous droplets of spray toward radial direction of spray at injection pressure of 8 MPa. Moreover, volumetric flow rate of nozzle with round cutting at inlet of the nozzle hole was obtained about two times one compared with sharp inlet shape nozzle at all injection pressure region. Both spray and flow characteristics were improved significantly.

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Introduction

Diesel engine is lifted in terms of the highest thermal efficiency, excels in fuel consumption rate and it will lead to reduce carbon dioxide, which is caused by global warming. It is a matter of great urgency to reduce carbon dioxide, and it is important to obtain excellent spray characteristics and combustion characteristics in order to reduce fuel consumption rate and carbon dioxide for control of global warming.

In previous studies including in this author, it was clarified that disturbance of liquid flow in the nozzle hole due to occurrence of cavitation has a dominant effect on atomization of liquid jet [1]-[11].

Moreover, it was developed the high-efficiency and high-dispersion pressure atomized type injection nozzle, which excellent spray characteristics with considerably large spray angle, short breakup length, that is, short liquid core length and small and uniformity droplets by small energy.

Even though excellent spray characteristics was obtained at low-injection pressure, when cavitation occurred in the nozzle hole, volumetric flow rate tends to decrease due to generation of cavitation bubbles.

Therefore, it was assignment in order to improve flow characteristics, that is, increase discharge coefficient of the developed nozzle.

In general, it is well known that the nozzle, which was round cut away an edge of inlet of the nozzle hole, although discharge coefficient is over about from 0.8 to 0.9, spray characteristics become wrong and considerably high-injection pressure is needed to obtain excellent spray characteristics.

The purpose of this study is to develop of a direct injection Diesel nozzle, which is obtained high-dispersion spray inside combustion chamber by strong disturbance of liquid flow due to cavitation phenomena inside the nozzle hole. Authors have high-expectation of this developed injection nozzle with suitable for lean burn combustion.

The final objects of this study are improvement of combustion characteristics of a direct injection Diesel engine, reduction of soot emission, progress of thermal efficiency and fuel consumption rate by improvement over the injection nozzle and spray characteristics.

In this paper, it was described that effects of geometric shapes of inlet and outlet of four nozzle holes, which was divided one nozzle hole, on improvement of spray characteristics, and effect of the nozzle, which was inclined angle of 45 degrees at nozzle holes toward injection direction, on spread of spray and improvement of spray characteristics.

Experimental Apparatus

Schematic of experimental apparatus is shown in Fig. 1. Equipment consists of the high-pressure pump, which is worked by the air compressor, two spark light sources for taking photographs of spray and apparatus for measurement of droplet size and its distributions LDSA particle analyzer. A narrow angle forward scattering type LDSA particle analyzer at 120 mm downstream from nozzle exit measured droplets size and its distributions. It gives Sauter mean diameter that is spatially averaged along a line through spray. Estimation of measure of atomization of spray was used breakup length; liquid core length, spray angle, Sauter mean diameter and droplet size distributions.

Water at room temperature, which was pressurized by the high-pressure pump, was continuously injected under atmospheric pressure condition. Maximum injection pressure is \(P_i=8\) MPa for total sectional area of the multi-hole nozzle which is corresponded to sectional area of one nozzle hole of 0.6 mm. Moreover, experimental data is discussed at spray region over about \(P_i=5\) MPa [12]. At these injection pressure region, even though injection pressure is increased, breakup length and spray angle are almost constant [12].

Disintegration behavior of spray was photographed by scattered light illumination method, using two stroboscopes. Breakup length of a liquid core, which is defined as distance from the nozzle exit to breakup point of liquid core, was measured by electrical resistance method [1] in which the screen detector was used. Breakup length was defined as liquid core length, which was injected from four nozzle holes [13].

Test Nozzles

Configurations of schematic of structure of atomization enhancement nozzle and by three-dimensional image of it are shown in Figs. 2 and 3, respectively. Structure of the atomization enhancement nozzle invented in previous studies [12]-[17] is that the bypass,
which is connected between the upstream chamber corresponding to sac chamber of actual Diesel injector and the gap, which was made at middle of the nozzle hole. It is observed that swirling flow occurs inside the gap by incoming from the bypass.

Configuration of structure of test nozzles by three dimensional images and schematic of test nozzles are shown in Figs. 4 and 5, respectively. Test nozzles are the multi-hole nozzle, which is separated four nozzle holes to one nozzle hole. Figure 4 (a) is the nozzle with sharp inlet shaped nozzle (called Nozzle-S, S). Figures 4 (b), (c) and (d) are nozzles which the bypass was inclined of 45 degrees toward injection direction. Figure 4 (b) is the nozzle with sharp inlet shaped nozzle (called Nozzle-Si, S). Figures 4 (c) and (d) are nozzles, which was dressed with round cutting at inlet or outlet of the multi-hole nozzle (called Nozzle-Si, Rdi, Nozzle-Si, Rdo, respectively).

Total sectional area of nozzle holes at outlet of the nozzle hole is same values independent of geometric shapes of inlet and outlet of the nozzle hole. Sectional area of the nozzle hole upstream from the gap equals total sectional areas of nozzle holes downstream from the gap \( A_1 \text{ mm}^2 \) \( A_2 = A_2 \text{ mm}^2 \).

**Figure 2.** Schematic of structure of atomization enhancement nozzle.

**Figure 3.** Configuration of atomization enhancement nozzle by three dimensional image (Reproduced from Fig.2).

**Figure 4.** Configuration of structure of test nozzles by three dimensional images.

**Figure 5.** Schematic of structure of test nozzles.
Results and Discussion

Effect of Pitch Circle Diameter of Bypass on Atomization Characteristics

Effect of pitch circle diameter of the bypass $D_{bp}$ on spray angle is shown in Fig. 6. Spray angle becomes large with a decreasing in pitch circle diameter of the bypass, and spray angle of the nozzle with the smallest one of $D_{bp}=1.2$ mm is the largest. Spray angle of $D_{bp}=1.2$ mm is large about two times compared with one of the largest pitch circle diameter of $D_{bp}=3.0$ mm.

It can be seen that when pitch circle diameter of the bypass is small, dispersion of spray is enhanced.

Effect of Pitch Circle Diameter of Nozzle Hole Downstream from Gap on Spray Characteristics

Effect of pitch circle diameter of the nozzle hole downstream from the gap $D_p$ on breakup length and spray angle are shown in Figs. 7 and 8, respectively.

As shown in Figs. 7 and 8, with an increasing in injection pressure, decreasing in breakup length and increasing in spray angle independent of pitch circle diameter of the nozzle hole downstream from the gap $D_p$. Breakup length of the nozzle with larger pitch circle diameter of the nozzle hole downstream from the gap $D_p$ becomes short and spray angle of one becomes large about two times compared with the smallest one of $D_p=1.2$ mm at almost all injection pressure region.

Effect of pitch circle diameter of the nozzle hole downstream from the gap $D_p$ on Sauter mean diameter

![Figure 6](image)

**Figure 6.** Effect of pitch circle diameter of bypass on spray angle

![Figure 7](image)

**Figure 7.** Effect of pitch circle diameter of nozzle hole downstream from gap on breakup length.

![Figure 8](image)

**Figure 8.** Effect of pitch circle diameter of nozzle hole downstream from gap on spray angle.
is shown in Fig. 9. In case pitch circle diameter of the nozzle hole downstream from the gap \( D_p \) is the smallest of \( D_p=1.2 \) mm, with an increasing in injection pressure, Sauter mean diameter becomes small monotonically. Sauter mean diameter of it (\( D_p=1.2 \) mm) are larger than ones of relatively large \( D_p \) of \( D_p=2.4 \) mm and \( 3.0 \) mm at all injection pressure region.

In case \( D_p \) is relatively large of \( D_p=2.4 \) mm and \( 3.0 \) mm, with an increasing in injection pressure, Sauter mean diameter becomes small. Moreover, when injection pressure excesses over about \( P_i=5 \) MPa, Sauter mean diameter are almost same large and small compared with one of \( D_p=1.2 \) mm.

**Effect of Existence of Inclination of Bypass on Spray and Flow Characteristics**

Structure of the atomization enhancement nozzle invented in previous studies [12]-[17] is that holes of the bypass are installed toward injection direction as shown in Fig. 3. It was clarified in this study that liquid flow from the bypass generates swirling flow inside the gap. Therefore, when the bypass was inclined toward injection direction, it is guessed that more strong swirling flow is generated inside the gap, atomization of spray is enhanced significantly.

Effect of existence of inclination angle of the bypass on disintegration behavior of spray and dispersion of spray, and variations of spray angle as a function of injection pressure and effect of existence of inclination angle of bypass on spray angle are shown in Figs. 10 and 11, respectively.

As shown in Fig. 10, spread of spray of the nozzle with inclination angle of the bypass (Nozzle-Si, S) becomes wide compared with one of the nozzle without inclination angle of the bypass (Nozzle-S, S), and in case of Nozzle-Si, S, it is observed that small spray droplets are generated overall this spray.

As shown in Fig. 11, spray angle becomes large monotonically with an increase in injection pressure. Spray angle of Nozzle-Si, S are larger than one of Nozzle-S, S from about 20 to 30 percent.

**Effects of Inlet and Outlet Shapes of Nozzle Hole Downstream from Gap on Spray and Flow Characteristics**

It is well known that inlet and outlet shapes of the nozzle hole are affected to spray and flow characteristics [5], [6], [14]. Effects of geometric shapes of the nozzle hole, that is, inlet and outlet shapes of the nozzle hole downstream from the gap on disintegration behavior of spray and dispersion of spray is shown in Fig. 12.

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**Figure 9.** Effect of pitch circle diameter of nozzle hole downstream from gap on Sauter mean diameter.

**Figure 10.** Effect of existence of inclination angle of bypass on disintegration behavior of spray and dispersion of spray.

**Figure 11.** Variations of spray angle as a function of injection pressure and effect of existence of inclination angle of bypass on spray angle.
Spread of spray becomes wide, and homogeneity of spray is obtained by judgement from spray images independent of geometric shapes of inlet and outlet of nozzle holes downstream from the gap. Especially, spread of spray of Nozzle-Si, R_\text{di}, that is, the nozzle, which is dressed with round inlet cutting at inlet of the multi-hole nozzle, becomes largest compared with ones of Nozzle-Si, S and Nozzle-Si, R_\text{do}.

Effect of geometric shapes of the nozzle hole downstream from the gap on atomization characteristics is shown in Fig. 13. Breakup length of Nozzle-Si, R_\text{di} is the shortest of about 2 mm for hole diameter of D_2=0.3 mm, and spray angle of it is the largest over 70 degrees at maximum injection pressure of P_\text{i, max}=8 MPa. Every nozzle is obtained spray angle over 50 degrees, spray angle becomes large significantly as a pressure atomized type injection nozzle.

Variations of Sauter mean diameter as a function of radial distance from spray center axis x is shown in Fig. 14. Sauter mean diameter from spray center axis to periphery of spray was measured. Width of spray at measurement point of Sauter mean diameter of z=120 mm is about 80 mm, that is, distance from spray center axis to periphery of spray is about 40 mm, independent of geometric shapes of nozzle hole downstream from the gap.

In case of Nozzle-Si, S, when radial distance from spray center axis x is away from spray center axis toward radial direction of spray, Sauter mean diameter becomes large rapidly. Sauter mean diameter of Nozzle-Si, S are large at arbitrary radial distance from spray center axis x.

Moreover, in case of Nozzle-Si, R_\text{do}, Sauter mean diameter are almost same large up to radial distance from spray center axis x=10 mm toward half width of spray of about x=40 mm.

To the contrary, in case of Nozzle-Si, R_\text{di}, Sauter mean diameter are almost same large up to x=20 mm toward half width of spray. Moreover, almost all Sauter mean diameter of Nozzle-Si, R_\text{di} are small at arbitrary radial distance from spray center axis x.

From these results, it can be seen that the nozzle, which was dressed with round cutting at inlet of the multi-hole nozzle; Nozzle-Si, R_\text{di}, spread of spray is the largest, breakup length is the shortest and nearly homogeneity spray is obtained widely toward radial direction of spray.

Effect of geometric shapes of the nozzle hole downstream from the gap on flow characteristics is shown in Fig. 15. Volumetric flow rate increases monotonically with an increasing in injection pressure. Volumetric flow rate of Nozzle-Si, R_\text{di} are largest at all injection pressure regions compared with Nozzle-Si, S and Nozzle-Si, R_\text{do}.

Moreover, volumetric flow rate of Nozzle-Si, R_\text{di} is obtained about two times compared with Nozzle-Si, S at almost all injection pressure region.
Moreover, volumetric flow rate of Nozzle-S, Rdi is obtained about two times compared with Nozzle-Si, S at almost all injection pressure region.

In case of Nozzle-S, Rdi, volumetric flow rate of Nozzle-Si, S at maximum injection pressure of \( P_{\text{max}} \) =8 MPa is obtained by injection pressure of about 30% (\( P_i =3 \) MPa), and flow characteristics is improved significantly.

In general, when the nozzle, which was dressed with round inlet cutting at inlet of the nozzle hole, was used, it is well known that although volumetric flow rate is improved, atomization characteristics are getting worse with an increasing in volumetric flow rate.

However, it was clarified that the nozzle, which was dressed with round inlet cutting at inlet of the nozzle hole downstream from the gap, both spray characteristics and flow one are improved significantly.

It is guessed that in case of Nozzle-S, Rdi, liquid flow with large disturbance due to occurrence of cavitation and strong swirling flow inside the gap are easy to come into the nozzle holes downstream from the gap easily compared with Nozzle-Si, S.

Therefore, it is considered that strong disturbance with swirling flow hardly reduces at there, issuing spray was dispersed toward radial direction of spray.

### Conclusions

The following conclusions were obtained in this study.

1. Pitch circle diameter of the nozzle hole downstream from the gap \( D_p \) is affected to spray characteristics. [When the largest In case pitch circle diameter of the nozzle hole \( D_p \) is the largest of \( D_p=3.0 \) mm, breakup length becomes short, spray angle becomes large about two times compared with the smallest one of \( D_p=1.2 \) mm and Sauter mean diameter becomes small at relatively low-injection pressure compared with one of \( D_p=1.2 \) mm.]

2. It is effective and easy method to enhance atomization of spray by using the nozzle with inclination angle (45 degrees) of the bypass, and spray angle becomes large from about 20 to 30 percent compared with the nozzle without inclination angle of the bypass.

3. In case of the nozzle, which was dressed with round cutting at inlet of the nozzle hole (Nozzle-Si, Rdo), both spray characteristics and flow one are improved significantly.

   [Spread of spray is the largest, breakup length is the shortest and nearly homogeneity spray is obtained widely toward radial direction of spray. Moreover, volumetric flow rate becomes large compared with (Nozzle-Si, S) and (Nozzle-Si, Rdo).]

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### Nomenclature

\[ A_1 \quad \text{Sectional area of nozzle hole upstream from gap} \]
\[ A_2 \quad \text{Total sectional area of nozzle hole downstream from gap} \]
\[ D_1 \quad \text{Hole diameter upstream from gap} \]
\[ D_2 \quad \text{Hole diameter downstream from gap} \]
\[ D_{32} \quad \text{Sauter mean diameter} \]
\[ D_b \quad \text{Bypass diameter} \]
\[ D_{bp} \quad \text{Pitch circle diameter of bypass} \]
\[ D_{bpu} \quad \text{Pitch circle diameter of bypass of nozzle with inclination angle} \]
\[ D_g \quad \text{Gap diameter} \]
\[ D_p \quad \text{Pitch circle diameter of nozzle hole downstream from gap} \]
\[ D_{pd} \quad \text{Pitch circle diameter of outlet of nozzle hole downstream from gap} \]
\[ D_{pu} \quad \text{Pitch circle diameter of inlet of nozzle hole downstream from gap} \]
\[ D_u \quad \text{Upstream chamber diameter} \]
\[ I \quad \text{Inclination} \]
\[ L_1 \quad \text{Hole length upstream from gap} \]
\[ L_2 \quad \text{Hole length downstream from gap} \]
\[ L_b \quad \text{Breakup length which was defined in this study} \]
\[ L_g \quad \text{Gap length} \]
\[ n \quad \text{Bypass number} \]
\[ N \quad \text{Hole number} \]
\[ P_a \quad \text{Ambient pressure} \]
\[ P_i \quad \text{Injection pressure} \]
\( P_{i \text{ max}} \) \hspace{1cm} \text{Maximum injection pressure} \\
\( Q \) \hspace{1cm} \text{Volumetric flow rate} \\
\( R_{di} \) \hspace{1cm} \text{Round inlet shape of nozzle hole downstream from gap} \\
\( R_{do} \) \hspace{1cm} \text{Round outlet shape of nozzle hole downstream from gap} \\
\( S \) \hspace{1cm} \text{Sharp edged nozzle} \\
\( S_A \) \hspace{1cm} \text{Spray angle} \\
\( x \) \hspace{1cm} \text{Radial distance from spray center axis} \\
\( z \) \hspace{1cm} \text{Measurement point of droplet of spray} \\
\( \theta \) \hspace{1cm} \text{Inclination angle of nozzle hole} \\

\textbf{Superscripts} \\
1 \hspace{1cm} \text{Upstream} \\
2 \hspace{1cm} \text{Downstream} \\
32 \hspace{1cm} \text{Volume / Surface Area} \\
a \hspace{1cm} \text{Ambient} \\
A \hspace{1cm} \text{Angle} \\
b \hspace{1cm} \text{Breakup} \\
b \hspace{1cm} \text{Bypass} \\
bp \hspace{1cm} \text{Pitch circle diameter of bypass} \\
bpu \hspace{1cm} \text{Upstream pitch circle diameter of bypass of nozzle with inclination angle} \\
di \hspace{1cm} \text{Nozzle with round cutting at inlet of nozzle hole downstream from gap} \\
do \hspace{1cm} \text{Nozzle with round cutting at outlet of nozzle hole downstream from gap} \\
g \hspace{1cm} \text{Gap} \\
i \hspace{1cm} \text{Injection} \\
i_{\text{max}} \hspace{1cm} \text{Maximum injection pressure} \\
u \hspace{1cm} \text{Upstream} \\

\textbf{References} \\
