# Spray Characteristics of Slit Nozzle for DI Gasoline Engines*

Kiyomi KAWAMURA**, Akinori SAITO**, Mutsumi KANDA***, Toshimi KASHIWAGURA*** and Yasuhiro YAMAMOTO****

Direct injection gasoline engines have been developed for the improvement of fuel economy and exhaust emissions. Recently, a new concept of stratified charge combustion has been proposed. A slit nozzle was adopted to realize the new concept. The nozzle has a rectangular orifice and forms a thin fan-shaped spray. This paper describes the spray characteristics of the slit nozzle. The following results were obtained. ( 1 ) The spray penetration increases with increasing the slit thickness. ( 2 ) The effect of the slit thickness on spray drop size is small. ( 3 ) The features of the slit nozzle are high spray penetration, widely diffuse spray and fine atomization compared with the swirl nozzle.

***Key Words***: Spray Characteristics, Direct Injection Gasoline Engine, Fuel Injection

## 1.Introduction

Direct injection gasoline engines have been developed for the improvement of fuel economy and exhaust emissions in several manufacturers. These direct injection gasoline engines utilize air motions such as swirling or tumbling to lead the mixture to the spark plug. However, the suction port generating the swirling or tumbling sometimes has a lower volumetric efficiency compared with the straight port. Therefore, a new combustion concept which does not depend on air charge motion was proposed. Figure 1 shows the fuel spray and piston cavity configuration of the new direct injection gasoline engine (New concept D-4) compared with an example of the conventional direct injection gasoline engine (Conventional D-4)[(1),(2)]. For the conventional system, swirl nozzles are used. The injected spray is led to the spark plug by the swirling flow of air generated by a helical suction port and the optimized piston cavity shape, in order to achieve a suitable dispersion of spray in the piston cavity and ensure a good combustible mixture in the vicinity of the spark plug. However, the new combustion concept adopting the straight suction port for higher output performance requires a new mixture formation. The required mixture formation is (1) moderate spray penetration which enables the spray to be lead to the spark plug without the help of air motion in the cylinder, (2) thin fan-shaped wide dispersion spray which can prevent too rich mixture and achieve homogenization inside the mixture, and (3) fine atomization which is able to promote the mixture preparation. For realization of this mixture formation, thin fan-shaped spray was suitable, and therefore a slit nozzle with a rectangular orifice was adopted. The characteristics of the fan spray were analyzed theoretically and experimentally in the 1960s by Dombrowski and Hooper [(3)]. However, the injection pressure in their experiments was considerably lower than that of direct injection

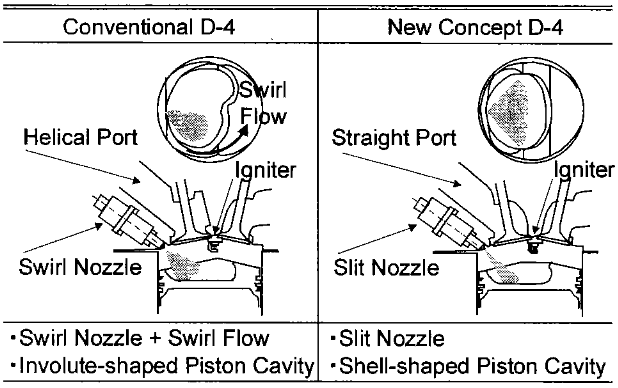


Fig.1 Configuration of combustion systems.

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** Special Research Lab. 3, Toyota Central R & D Labs., Nagakute-cho, Aichi 480-1192, Japan. E-mail: e0410@mosk.tytlabs.co.jp
*** Power Train Engineering Div. 2, Toyota Motor Corporation, 1200 Mishuku, Susono, Shizuoka 410-1193, Japan
**** Product Engineering Div., Toyota Motor Manufacturing North America Inc., 25 Atlantic Avenue Erlanger, Kentucky 41018, USA

gasoline engines. Moreover, there is no knowledge about spray penetration because a steady flow jet from the nozzle was evaluated. In this study, the spray characteristics of the slit nozzle developed for direct injection gasoline engines are evaluated and compared with those of a swirl nozzle.

### Nomenclatures

$y$: Spray tip penetration
$c$: Coefficient of discharge
$\rho_a$: Surrounding gas density
$\rho_f$: Fuel density
$\rho_0$: Air density under standard atmospheric conditions
$\Delta P$: Injection pressure
$P_a$: Surrounding air pressure
$t$: Time
$Ae$: Inlet area of slit orifice
$\theta$: Half spray angle observed from the side
$\phi$: Spray angle observed from the front
$H$: Slit thickness

## 2.Experimental Setup

Figure 2 shows an experimental setup. Spray is injected into an injection vessel which is adjusted to the appointed pressure. The images of the spray are obtained with shadow photography which uses a He-Ne laser as light source and a TV camera with an electronic shutter function. The spray concentration is measured by a laser light computed tomography method [4]. The optical arrangement is the same as that of the above-mentioned photography. The nozzle is rotated around the nozzle axis in order to obtain spray images at every 3 degrees. The images are input into an image processor and the three-dimensional image of the spray concentration is calculated by CT algorithm. The calculated spray concentration is the total surface area of droplets in a unit volume. Droplet size is measured by a laser diffraction method, and the laser beam is passed through from the front of the spray at a point 60 mm downstream from the nozzle tip. In all experiments, n-heptane was used, and the surrounding air temperature was about 20 ℃.

## 3.Fundamental Spray Characteristics of Slit Nozzle

Figure 3 shows the configuration of the slit nozzle that was used to evaluate the fundamental spray characteristics. The nozzle is actuated electro-magnetically. A thin slit is formed on the sac wall of the nozzle tip by wire electric discharge processing. The slit thicknesses of the tested nozzles are 0.13 mm, 0.2 mm and 0.26 mm, and the injection rates at the injection pressure of 12 MPa are 11 mm$^3$/ms, 17 mm$^3$/ms and 23 mm$^3$/ms, respectively. The slit depth of these nozzles is the same, so that these nozzles form the same spray angle as observed from the front, as shown in figure 4. Figure 4 also shows the effect of slit thickness on the spray pattern. The spray angle observed from the side increases with increasing slit thickness.

### 3.1 Spray tip penetration

Figure 5 shows the effect of slit thickness on the

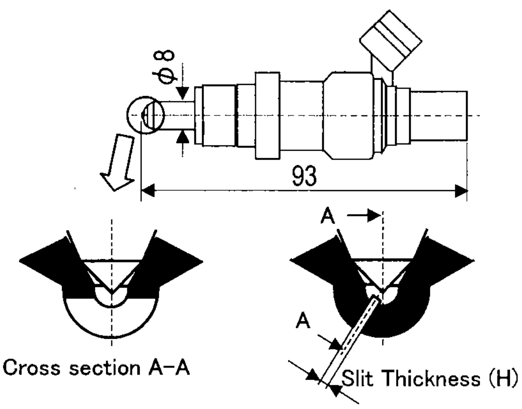
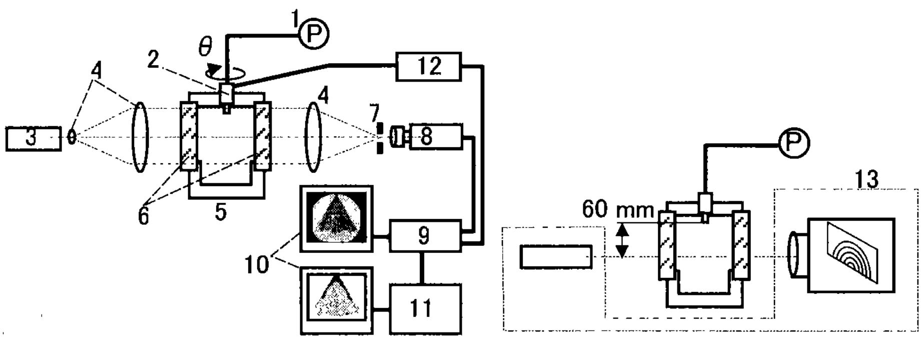



Fig.3 Configuration of nozzle tip (Wire cut type).




(a) Measurement of spray shape and spray concentration.

(b) Drop size measurement.

1:Injection Pump
2:Injector
3:He-Ne Laser
4:Lenses
5:Injection Vessel
6:Quartz Windows
7:Pin Hole
8:High-Speed-Shutter TV Camera
9:Laser Video Disk
10:Monitor
11:Image Processor
12:Injection Control Unit
13: Drop Size Analyzer (Laser Diffraction Method)

Fig.2 Optical arrangement.

spray tip penetration. At the beginning of injection, the effect of slit thickness on the spray tip penetration is not apparent. However, in the middle stage of injection, the spray tip penetration increases with increasing slit thickness. The spray penetration is at first proportional to time, and after that, it is proportional to the root of the time from the beginning of the injection. These trends are similar to those in the case of the hole nozzle. These data lead to the following equations.

For the first stage of penetration: t < tc

$$y = c_s \cdot \sqrt{2 \cdot \frac{\Delta P}{\rho_f}} \cdot t \qquad (1)$$

$$c_s = c \cdot \left( \frac{\rho_a}{\rho_0} \right)^{-0.25} \qquad (2)$$

For the second stage of penetration: t > tc

$$y = \left( \frac{4 \cdot c \cdot Ae \cdot \Delta P}{\rho_a \cdot \tan\theta \cdot \psi} \right)^{0.25} \cdot t^{0.5} \qquad (3)$$

$$t_c = \sqrt{\frac{c \cdot Ae}{\rho_a \cdot \tan\theta \cdot \psi \cdot \Delta P} \cdot \frac{\rho_f}{c_s^2}} \qquad (4)$$

For the first stage of injection, the spray tip penetration is expressed by equation (1), which is the same as Arai et al.'s equation for the hole nozzle at the initiation of injection [5]. A constant value of 0.39 was proposed as the coefficient $c_s$ for diesel spray, which was obtained from experiments at higher surrounding gas densities. However, in the case of direct injection gasoline engines, the surrounding gas density at injection timing is usually lower than that in the case of diesel engines. For example, when the fuel is injected at the suction stroke, the air pressure in the cylinder is almost atmospheric. Therefore, the relation between the coefficient $c_s$ and the surrounding gas density was evaluated in the present study. It is found from the evaluation that the coefficient $c_s$ decreases with increasing the surrounding gas density as shown in figure 6 and the relation is expressed by equation (2). On the other hand, the spray tip penetration after the first stage is expressed by equation (3) based on Waguri et al.'s spray momentum theory [6]. The point of intersection of equations (1) and (3) is expressed by equation (4).

Figure 7 shows the comparison between the calculated and measured spray tip penetration. It is found that the above-mentioned equations are suitable to predict the spray tip penetration.

### 3.2 Drop size

Figure 8 shows the effect of injection pressure on the Sauter mean diameter. The injection pressure was adjusted from 0.2 MPa to 0.4 MPa and 6 MPa to 12 MPa. The former corresponds to the injection pressure range for port injection, and the latter corresponds to

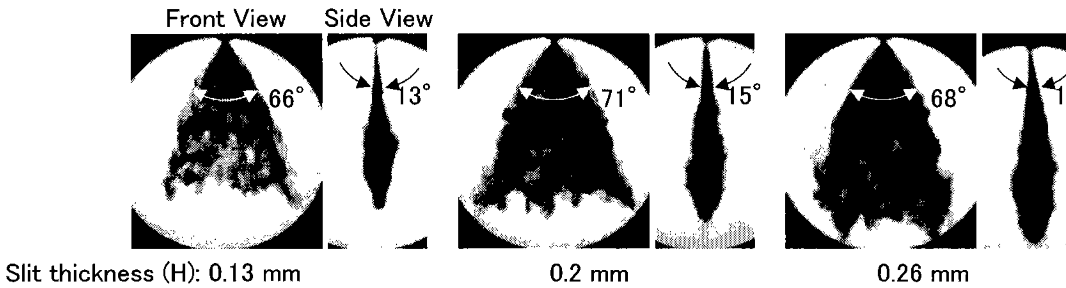



Fig.4 Spray pattern ( Δ P=20 MPa, Pa=0.1 MPa).

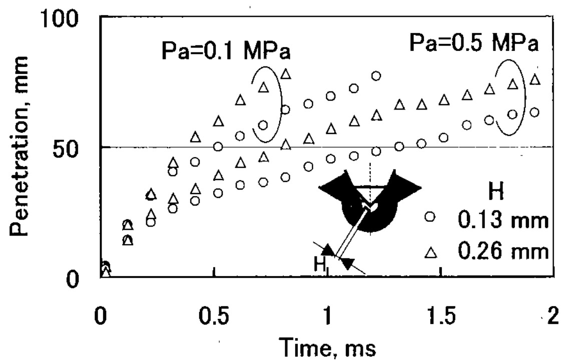



Fig.5 Effect of slit thickness on spray tip penetration. ( Δ P=20 MPa)

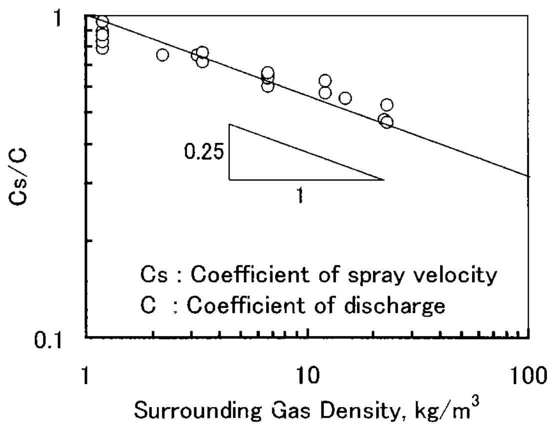



Fig.6 Coefficient of spray velocity.

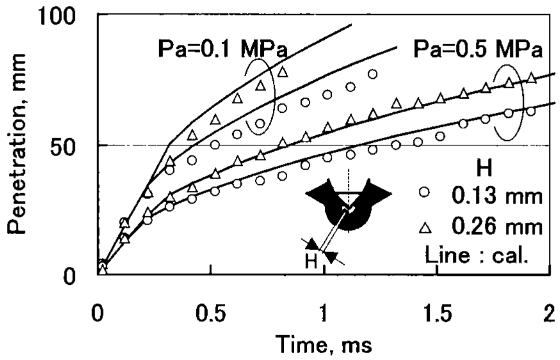



Fig.7 Comparison of measured and calculated spray tip penetrations.( Δ P=20 MPa)

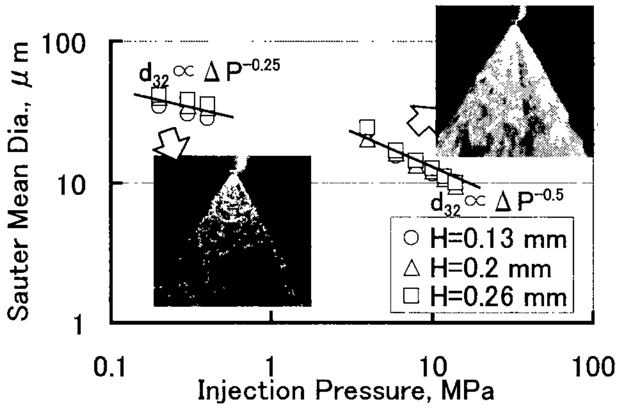



Fig.8 Effect of injection pressure on Sauter mean diameter.

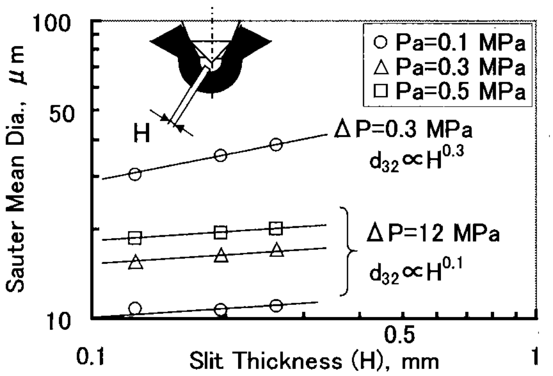



Fig.9 Effect of slit thickness on Sauter mean diameter.

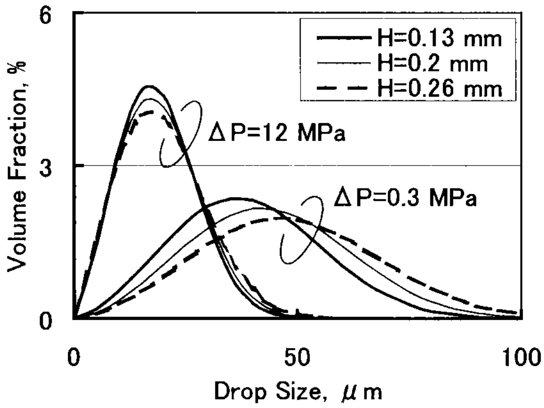



Fig.10 Drop size distribution.

that for direct injection. As shown in the figure, the Sauter mean diameter decreases with increasing the injection pressure. However, at the higher injection pressure, the effect of the injection pressure on the Sauter mean diameter is greater than that at the lower injection pressure. The relation between the injection pressure and the Sauter mean diameter is as follows.

At the lower injection pressure, the Sauter mean diameter is proportional to the $-0.25$ power of injection pressure. At the higher injection pressure, it is proportional to the $-0.5$ power of injection pressure. It is evident from the photograph in figure 8 that at the lower injection pressure, the atomization is mainly dominated by the instability of the liquid film. However, at the higher injection pressure, the atomization is dominated by the interference of liquid and surrounding gas. Consequently, it is considered that the effect of injection pressure is strongly apparent at the higher injection pressure.

Figure 9 shows the relation between the slit thickness and the Sauter mean diameter. In the case of the lower injection pressure, the Sauter mean diameter is proportional to the 0.3 power of the slit thickness, and in the case of a higher injection pressure, it is proportional to the 0.1 power of the slit thickness. The relation between the slit thickness and the droplet size distribution is shown in figure 10. The figure shows that larger droplets are produced from the larger slit.

It is evident from the above-mentioned results that at the higher injection pressure used for direct injection, the effect of the injection pressure on the Sauter mean diameter is dominant and the effect of the slit thickness is weakened in comparison with the case of the lower injection pressure used for port injection.

Figure 11 shows the relation between the surrounding gas pressure and droplet size. The droplet size increases with increasing surrounding gas pressure and the Sauter mean diameter is proportional to the 0.33 power of the surrounding gas pressure (density). The reason for this result has not been confirmed, but the following factors are considered. (1)It was proposed by Dombrowski and Hooper [(3)] and Clark and Dombrowski [(11)] that the breakup length of the liquid film decreases with increasing surrounding air pressure because of the increase of air resistance. The shorter breakup length results in a thicker liquid film at the breakup point as shown in figure 12, so that larger droplets are formed initially. (2)The coalescence of droplets increases with increasing air pressure, since increase of the surrounding air pressure causes the

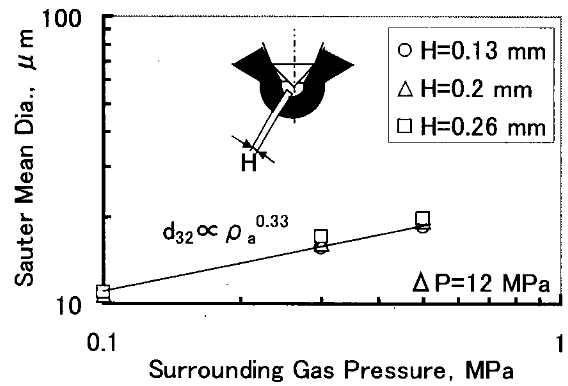



Fig.11 Effect of surrounding gas pressure on Sauter mean diameter.

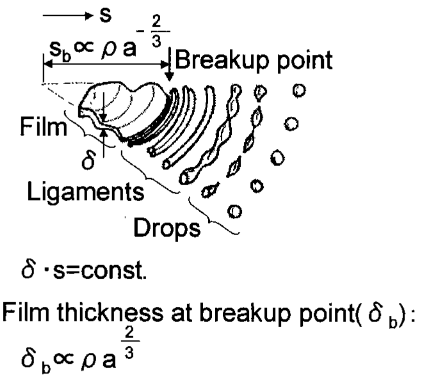



Fig.12 Dombrowski's breakup model.

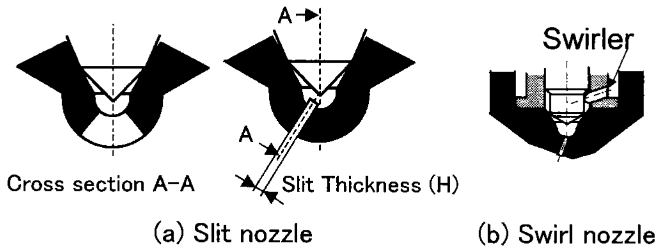



Fig.13 Configuration of slit nozzle (on the market).

increase in the number density.

On the basis of the above-mentioned results, the relation between the Sauter mean diameter and the influence factors is expressed by the following equations.

For lower injection pressure Δ P=0.1 to 0.3 MPa,

$$d_{32} \propto \Delta P^{-0.25} \cdot H^{0.3} \qquad (5)$$

For higher injection pressure Δ P=6 to 12 MPa,

$$d_{32} \propto \Delta P^{-0.5} \cdot H^{0.1} \cdot \rho_a^{0.33} \qquad (6)$$

As the main target of this study is the direct injection gasoline engine, the relation between the droplet size and the surrounding gas density at the lower injection pressure was not evaluated. Therefore, the term for surrounding gas density is not given in equation (5). In the case of the lower injection pressure, the surrounding gas pressure at the time of injection is lower than the injection pressure, and the range of surrounding gas pressure is narrow. Therefore, it is considered that the effect of surrounding gas density on the droplet size is small.

Next, the above-mentioned results are compared with those of Dombrowski and Hooper's study [3]. Dombrowski and Hooper derived the equations for Sauter mean diameter from the theoretical analysis of instability of the liquid film. The relation between the Sauter mean diameter and the influence factors is expressed by the following equations.

For lower injection pressure,

$$d_{32} \propto \Delta P^{-0.33} \cdot H^{0.33} \cdot \rho_a^{-0.17} \qquad (7)$$

For higher injection pressure,

$$d_{32} \propto H^{0.5} \cdot \rho_a^{0.25} \qquad (8)$$

However, the theoretical analysis does not consider the secondary breakup. Under the lower injection pressure, our result is much the same as Dombrowski and Hooper's results. This means that the atomization under the lower injection pressure is dominated by the instability of the liquid film. On the other hand, under the higher injection pressure, Dombrowski's theoretical analysis without considering the secondary breakup shows that the drop size does not depend on the injection pressure as expressed by equation (8). However, our experimental results show that the effect of the injection pressure is considerably large as expressed by equation (6). It is considered on the basis of this result that the atomization under the higher injection pressure is strongly dominated by interference between the liquid and surrounding gas.

## 4.Comparison with Swirl Nozzle

The spray characteristics of the slit nozzle are compared with those of a swirl nozzle [7]. The slit nozzle has a thin fan-shaped slit orifice as shown in figure 13(a) [8]. On the other hand, the swirl nozzle has a swirler which generates a swirling flow in the sac of the nozzle as shown in figure 13(b). The swirl nozzle is applied in the conventional direct gasoline engine as shown in figure 1. Both nozzles are commercially available.

Figure 14 shows the comparison of the spray patterns. In the case of the slit nozzle, the spray spread observed from the front changes negligibly with the change of surrounding gas pressure, and the spray spread observed from the side at the higher surrounding gas pressure is wider than that at the lower pressure. On the other hand, in the case of the swirl nozzle, the spray spread decreases extremely with increasing surrounding gas pressure [9], [10].

Figure 15 shows the comparison of the spray tip penetrations at the surrounding gas pressures of 0.1 MPa and 0.5 MPa. It is evident from the figure that the slit nozzle forms a higher penetration spray than the swirl nozzle. However, the difference in the spray penetration of the two nozzles at the surrounding gas pressure of 0.5 MPa is smaller than that at 0.1 MPa. This is due to the difference in the change of spray spread with increasing the surrounding gas pressure as shown in figure 14.

Figure 16 shows the comparison of the Sauter mean diameters at the surrounding gas pressures of 0.1 MPa and 0.5 MPa. The Sauter mean diameter of the slit nozzle is slightly smaller than that of the swirl nozzle, and both nozzles exhibit the trend of increasing droplet size with increasing the surrounding gas pressure.

Figure 17 shows the comparison of the spray concentrations at the surrounding gas pressures of 0.1 MPa and 0.5 MPa. Spray concentration in this figure means the total surface area of droplets in a unit volume. At the surrounding gas pressure of 0.1 MPa, the difference between the spray concentrations of the two nozzles is small. On the other hand, at the surrounding gas pressure of 0.5 MPa, the spray concentration of the slit nozzle at the spray tip is lower than that of the swirl nozzle. The difference in the spray concentration at the surrounding gas pressure of 0.5 MPa is due to the difference in the change of spray spread with the change of surrounding gas pressure.

In this study, the spray characteristics were

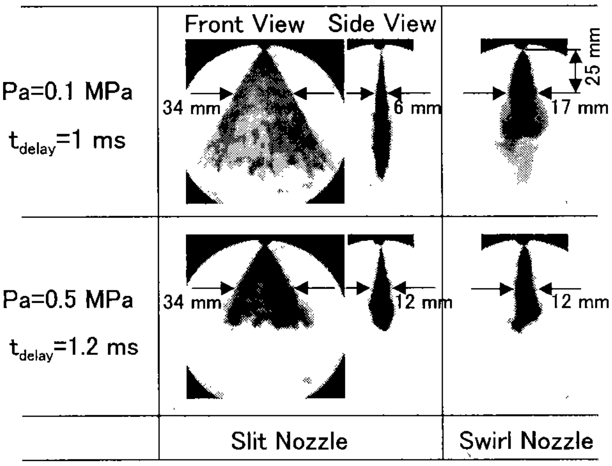
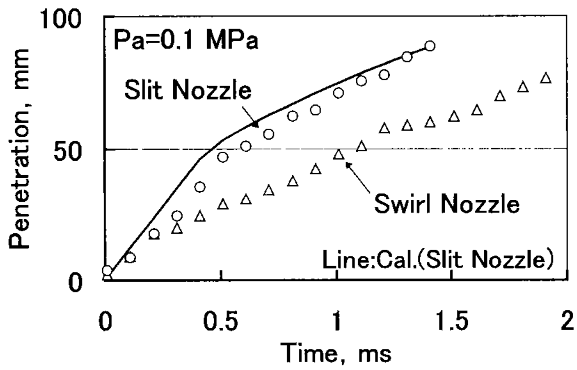
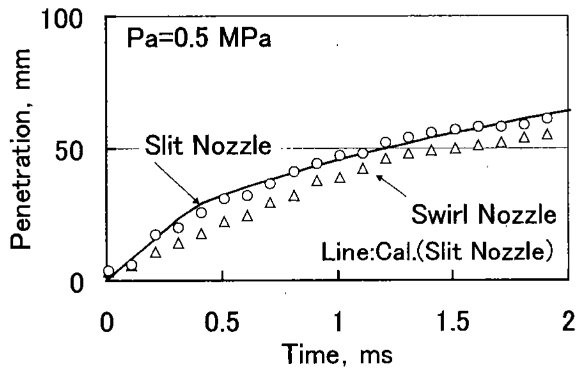



Fig.14 Comparison of spray pattern.( Δ P=12 MPa)

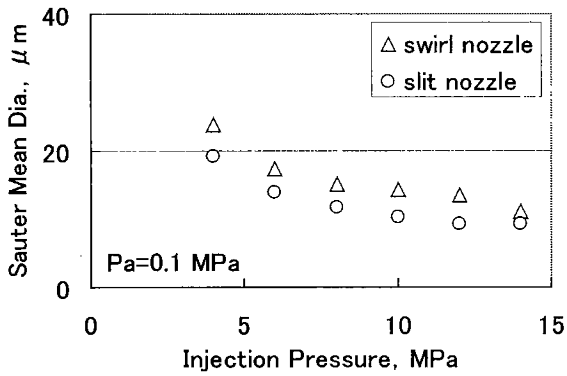



(a) Surrounding air pressure: 0.1 MPa

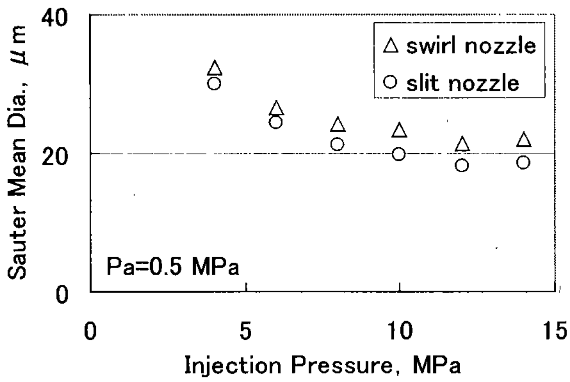



(b) Surrounding air pressure: 0.5 MPa

Fig.15 Comparison between spray tip penetrations of slit nozzle and swirl nozzle.( Δ P=12 MPa)




(a) Surrounding air pressure: 0.1 MPa




(b) Surrounding air pressure: 0.5 MPa

Fig.16 Comparison between Sauter mean diameters of slit nozzle and swirl nozzle.

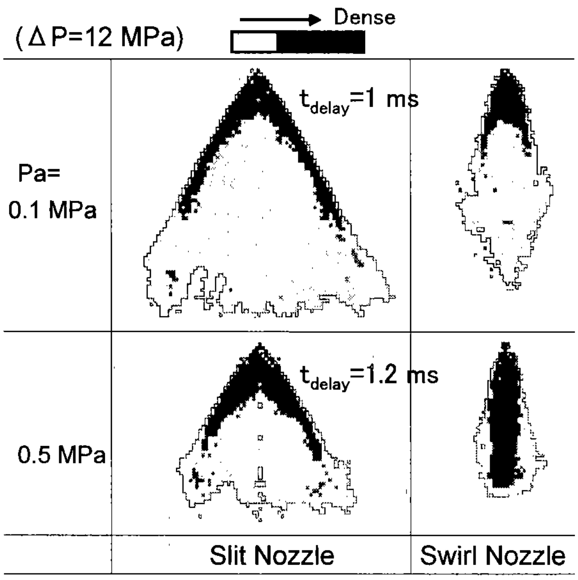



Fig.17 Comparison of spray concentration.

measured at room temperature. But the actual temperature of the surrounding gas in the cylinder is higher than room temperature. Under the higher temperature of surrounding gas, it is considered that the cross-sectional area of the spray injected from the slit nozzle is expanded by vaporization of the spray and this expansion results in the penetration being lower than that at room temperature. A study on the mixture formation under higher temperatures of the surrounding gas should be carried out in the future.

## 5.Conclusions

The spray characteristics of the slit nozzle developed for direct injection gasoline engines were evaluated and compared with those of the swirl nozzle. The following results were obtained.

(1) The spray tip penetration increases with increasing slit thickness.

(2) The effect of the slit thickness on the Sauter mean diameter is small at the higher surrounding gas pressure.

(3) The features of the slit nozzle are high spray penetration, widely diffuse spray and fine atomization.

The following empirical equations were obtained.

Spray tip penetration:

For the first stage of penetration: t<tc

$$y = c \cdot \left(\frac{\rho_a}{\rho_0}\right)^{-0.25} \cdot \sqrt{2 \cdot \frac{\Delta P}{\rho_f}} \cdot t$$

For the second stage of penetration: t>tc

$$y = \left(\frac{4 \cdot c \cdot A_e \cdot \Delta P}{\rho_a \cdot \tan\theta \cdot \psi}\right)^{0.25} \cdot t^{0.5}$$

$$t_c = \sqrt{\frac{c \cdot Ae}{\rho_a \cdot \tan\theta \cdot \psi \cdot \Delta P} \cdot \frac{\rho_f}{c_s^2}}$$

Sauter mean diameter:

For lower injection pressure ΔP=0.1 to 0.3 MPa,

$$d_{32} \propto \Delta P^{-0.25} \cdot H^{0.3}$$

For higher injection pressure ΔP=6 to 12 MPa,

$$d_{32} \propto \Delta P^{-0.5} \cdot H^{0.1} \cdot \rho_a^{0.33}$$

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