Atomization Characteristics of Intermittent Multi-Hole Diesel Spray Using Time-Resolved PDPA Data

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The intermittent spray characteristics of a multi-hole diesel nozzle with a 2-spring nozzle holder were investigated experimentally. Without changing the total orifice exit area, the hole number of the multi-hole nozzle varied from 3 (d_n=0.42 mm) to 5 (d_n=0.32 mm). The time-resolved droplet diameters of the spray including the SMD (Sauter mean diameter) and the AMD (arithmetic mean diameter), injected intermittently from the multi-hole nozzles into still ambient air, were measured by using a 2-D PDPA (phase Doppler particle analyzer). The 5-hole nozzle spray shows the smaller spray cone angle, the decreased SMD distributions and the small difference between the SMD and the AMD, compared with that of the 3-hole nozzle spray. From the SMD distributions with the radial distance, the spray structure can be classified into the three regions : (a) the inner region showing the high SMD distribution ; (b) the mixing flow region where the shear flow structure would be constructed ; and (c) the outer region formed through the disintegration processes of the spray inner region and composed of fine droplets. Through the SMD distributions along the spray centerline, it reveals that the SMD decreases rapidly after showing the maximum value in the vicinity of the nozzle tip. The SMD remains the constant value near the Z/d_n=166 and 156.3 for the 3-hole and 5-hole nozzles, which illustrate that the disintegration processes of the 5-hole nozzle spray proceed more rapidly than that of the 3-hole nozzle spray.

Key Words : Multi-Hole Nozzle, Atomization Characteristics, Intermittent Diesel Spray, SMD (Sauter mean diameter), PDPA (phase Doppler particle analyzer)

1. Introduction

In order to atomize small droplets of the liquid fuel and increase the quality of atomization using kinetic energy, it is necessary to understand atomization characteristics of fuel sprays. In particular, the exact understanding of the transient characteristics of the fuel sprays is required to make the complete combustion of the fuel injected intermittently into a combustion chamber. In direct injection (D. I.) diesel engines, multi-hole nozzles are widely used due to their potential in the reduction of exhaust emissions. However, many of the atomization characteristics on the multi-hole diesel sprays are not clearly identified, contrary to the case of the single-hole nozzles. In addition, many experimental studies on the diesel sprays deal the intermittent spray with the case of the steady one, independent of time. Consequently, more detailed information such as the time-resolved droplet size are needed to clarify the

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atomization process of the spray injected intermittently by the multi-hole nozzles, which increase the necessity of further investigation.

Koo et al. (1990 and 1991) measured the droplet size of the intermittent diesel spray by using a PDPA system. They showed that the drop size distribution is well fitted by a log-hyperbolic distribution function, which has three or more independent variables. Ikeda et al. (1997) investigated the fuel droplet dispersion and mixture formation, including the droplet size and the velocity di -tribution of the spray, in a practical twin-fluid atomizer by using a PDPA system. They showed that the size-classified technique is suitable for understanding the droplet dispersion and momentum transfer of the spray. Ismailov et al. (1999) utilized a PDPA system to obtain the mean velocity and SMD of the high-pressure swirl-type spray. In their study, it was revealed that the time-series of the velocity and droplet size allow detailed analysis of the spray flow transitions, and the PDA technique is effective to evaluate the transient fuel spray characteristics. However, in spite of these approaches to elucidate the transient characteristics of the sprays, the quantified data that can be used in the verification of the spray formation process are not enough. Therefore, for an in-depth study of the intermittent spray, the organized data, including the time-resolved droplet size, SMD and AMD as a function of time from the start of injection, are inevitably necessary.

In this paper, the spray characteristics of the multi-hole nozzle were examined by using the time-resolved PDPA data to clarify the spray formation process. In addition, the spray structural behavior and atomization characteristics between the two nozzles were compared.

2. Experimental Apparatus and Conditions

2.1 Fuel injection system

In order to investigate the atomization characteristics of the diesel spray formed by the 3-hole and the 5-hole nozzles, an experimental apparatus composed of the fuel injection system and a

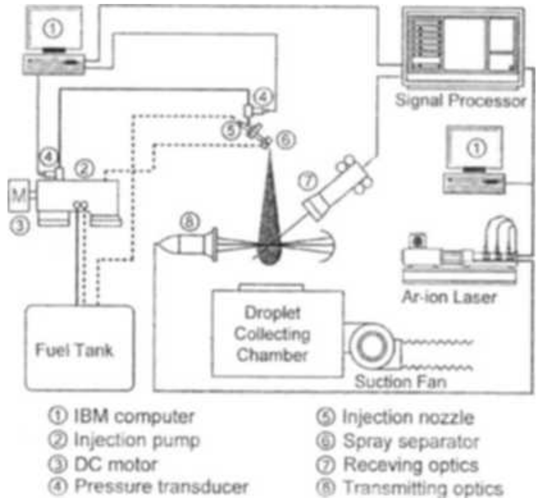


Fig. 1 Schematic diagram of experimental apparatus for droplet size measurement using 2-D PDPA system

PDPA system was used.

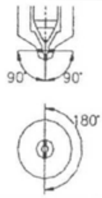
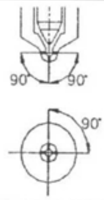
The fuel injection system was composed of the fuel injection pump, DC motor, droplet collection device and fixed frame, as shown in Fig. 1. The experiments were performed under room temperature and atmospheric pressure. The fuel injection pump was an in-line PE type, 8 barrels, and it was driven by a 15 kW DC motor that is able to rotate at maximum speed of 3600 rpm. Fuel used in this test was KS #2 diesel oil with specific gravity of 0.8315, kinematic viscosity of 3.71 cSt, refraction rate of 1.468 at 24℃

2.2 Multi-hole nozzle

The fuel injection nozzle was a mini-sac type multi-hole diesel nozzle with a 2-spring nozzle holder, as shown in Fig. 2.

There is a tested hole in the vertex of the nozzle tip. The others are located with same intervals in a plain met at right angles. The pre-lift and total lift of the nozzle needle were set up to $0.06^{\pm 0.02}$ and 0.39 mm, respectively. The first and the second needle opening pressures were set up to 150 and 220 bar, respectively. In order to investigate the effect of the hole number and corresponding variation of the hole diameter on the spray characteristics, the hole number of the multi-hole nozzle was varied from 3 (d_n=0.42 mm) to 5

Table 1 Specification of 3-hole and 5-hole nozzles

Nozzle hole number	3-hole	5-hole
Nozzle shape		
Nozzle hole diameter (mm)	Φ0.42×3	Φ0.32×5
Nozzle hole length (mm)	0.9	0.9
Length/ Diameter	2.14	2.81
Nozzle hole total area (mm^2)	0.412	0.412

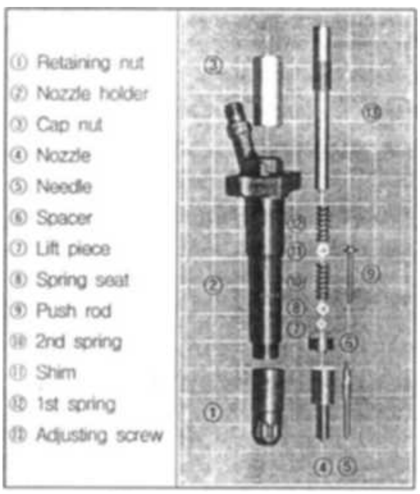


Fig. 2 Photograph of disassembled multi-hole diesel nozzle

(d_n=0.32 mm) with a same constant total nozzle hole exit area of 0.412 mm^2 and hole length of 0.9 mm. Table 1 shows the specification of the 3-hole and the 5-hole nozzles, including the schematics of the two nozzles.

In the cases of the spray imaging, the total injection quantity of the 3-hole and the 5-hole nozzles was 70 mm^3/st. The injection quantity of the tested hole, located in the vertex of the nozzle tip, was 27.2 and 14.9 mm^3/st for the 3-hole and the 5-hole nozzles, respectively. The pump speed was set to 700 rpm.

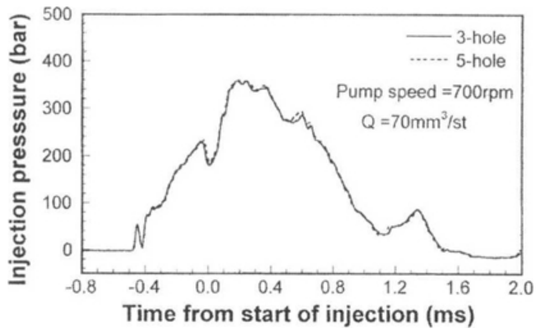


Fig. 3 Temporal variations of fuel injection pressure for 3-hole and 5-hole nozzles

Figure 3 shows the temporal variations of the fuel injection pressure, which were measured at the nozzle inlet using the piezo-type pressure sensor (Kistler 6229, −2.42 pC/bar) and charge amplifier (Kistler 5011), for the 3-hole and the 5-hole nozzles at 700 rpm and total injection quantity of 70 mm^3/st.

In addition, the start of injection was decided from the signal of the needle lift sensor (AVL 3076-A01) and carrier amplifier (AVL 3076-A01). The temporal variations of the fuel injection pressure for the two nozzles are very similar, particularly in the nozzle opening and closing pressures. The maximum pressure is 358 and 366 bar for the 3-hole and the 5-hole nozzles at 0.18 and 0.17 ms after the start of injection. The injection duration is 1.27 and 1.22 ms for the 3-hole and the 5-hole nozzles, respectively.

On the other hand, in the case of the droplet size measurement by the PDPA system, the experiments were performed at the pump speed of 500 rpm with a constant total injection quantity of 30 mm^3/st, due to the limitation of the maximum velocity range of the PDPA system used in this experiment. The injection quantity of the tested hole is 14.2 and 7.3 mm^3/st for the 3-hole and the 5-hole nozzles. The maximum pressure is 153 and 154 bar, and the injection duration is 1.0 and 1.1 ms for the 3-hole and the 5-hole nozzles, respectively.

2.3 PDPA system

The droplet size measurements were carried out by using a 2-D PDPA system (Dantec Co.). The PDPA system consists of a transmitter optics with a 750 mW air cooled Ar-ion laser as a light source, receiver optics as a scattered light collection system, a signal processing electronics (Dantec Co., 58N50), a three dimensional traverse and data acquisition system including a computer. Two laser beams, representing the wavelengths of 514.5 (green) and 488 (blue) nm, from transmitting optics cross at one point and form a measurement volume. Receiving optics detect the scattered lights, which is produced when droplets pass through the measurement volume and then transmits it to the signal processor. Therefore, the droplet size is measured by the frequency and relative phase difference of the Doppler signal.

The measurement of the droplet size was conducted in the two dimensions at axis because diesel sprays could be considered as an axi-symmetric structure. The same direction as the nozzle axis was defined as Z, and the radial direction was defined as R. The origin was located at the nozzle tip. The measurement was made at the axial distances of Z=10, 20, 30, 50, 70, 90, 120, 150 and 180 mm far from the nozzle tip. The measurement points at the radial direction were densely set near the axis because the droplet size of the spray varies sharply. However, their intervals became larger near the outer region of the spray. The number of points at the radial distance was 15. The number of measured data at each measurement position was 20,000, and the measurement mode was set not to exceed 300 sec.

3. Results and Discussion

3.1 Structural behavior of 3-hole and 5-hole nozzle sprays

Figure 4 shows the whole shape of the 5-hole nozzle spray (left-hand side) and the illustration of the typical spray structure (right-hand side), which were imaged by using a Mie scattering technique and a CCD camera (Toshiba Co., IK-627F) at 0.8 ms from the start of injection (SOI).

There are 5 sprays that are numbered onto the whole shape image of the spray. The spray tested is the one numbered as 5, which is injected from

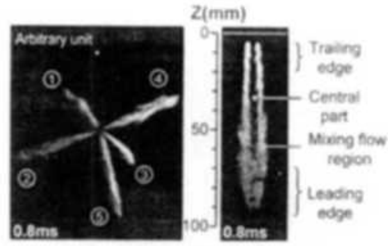


Fig. 4 Mie scattering images of 5-hole nozzle spray (left-hand side) and illustration of typical spray structure (right-hand side) at 0.8 ms from SOI

the nozzle hole located in the vertex of the nozzle tip, as shown in Table 1. In addition, the image of the number 5 spray (right-hand side) shows the typical structure of the diesel sprays. The spray consists of the three main parts: (a) the leading edge affected strongly by the ambient air; (b) the central part surrounded by the leading edge and the mixing flow region of the spray and would be scarcely affected by the ambient air; and (c) the trailing edge formed after the central part passed. The atomization process in the three parts of the spray would be different from each other because they have a different disintegration mechanism induced from its time-dependent development process.

Figure 5 shows the Mie scattering images of the 3-hole and the 5-hole nozzle sprays with time from SOI.

The spray structure shows unsteady intermittent characteristics. The sprays are formed and developed in the early injection periods, and they are mixed with and finally diffused to the ambient air. Hence, the atomization processes of the intermittent diesel spray have to be treated as a function of time from SOI. The spray structure of the 3-hole and the 5-hole nozzle sprays is considerably different from each other. The width of the 3-hole nozzle spray is larger than that of the 5-hole nozzle spray. In particular, the central part of the spray, mainly composed of the liquid columns under disintegrating and the large-sized ligaments, shows different width from the two sprays. The width of the 3-hole nozzle is a little larger than that of the 5-hole nozzle, especially in the leading edge of the central part. This struc-

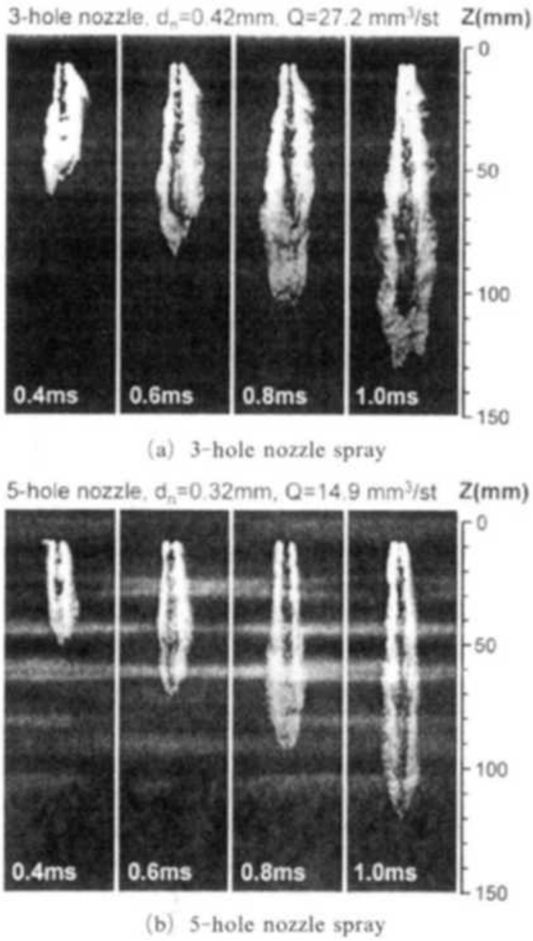


Fig. 5 Mie scattering images of 3-hole and 5-hole nozzles spray with time from SOI

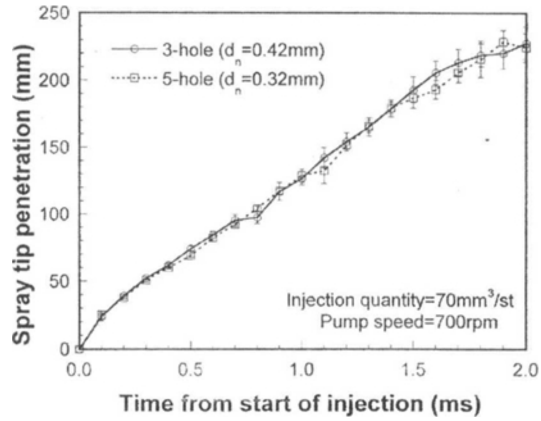


Fig. 6 Spray tip penetration with time from SOI for 3-hole and 5-hole nozzles

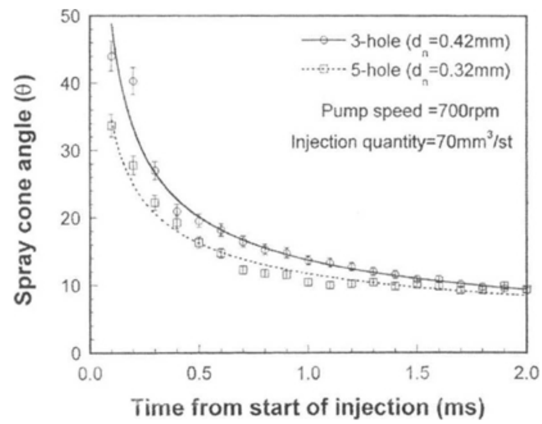


Fig. 7 Spray cone angle with time from SOI for 3-hole and 5-hole nozzles

tural behavior of the spray indicates that the atomization characteristics between the two nozzles would be quite different, and the cycle-resolved droplet size data are needed to clarify the time-dependent development process of the spray.

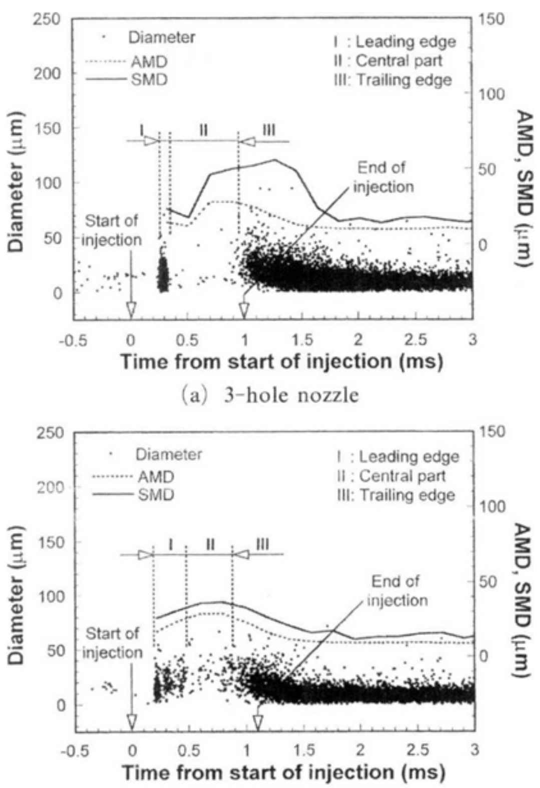
Figure 6 shows the spray tip penetration with time from SOI for the 3-hole and the 5-hole nozzles. The spray tip penetration increases linearly with time from SOI, and it shows the similar distribution within the range of the cycle-to-cycle variation. Therefore, it is not easy to find the effect of the hole number on the spray tip penetration.

Figure 7 shows the spray cone angle with time from SOI for the 3-hole and the 5-hole nozzles. The spray cone angle, which is decided from the linear curve fit of the spray outer boundary and the nozzle tip, decreases rapidly with time from SOI, and it remains the constant value of 9.51° and 9.32° at 1.5 and 1.0 ms for the 3-hole and the 5-hole nozzles, respectively. The spray cone angle of the 3-hole nozzle spray is larger than that of the 5-hole nozzle spray. The timing, showing the constant value, is also longer at the 3-hole nozzle spray. These constant values of 9.51° and 9.32° for the 3-hole and the 5-hole nozzles approximately agree with the 11.33° and 10.24° proposed by Arai et al. (1991) who derived the spray cone angle from the dimensional analysis using the experimental results. On the other hand, the spray cone angles are a little smaller than 15.40° proposed by Abramobich (1963) who derived the spray cone angle from the turbulent jet theory. In addition, they are larger than 3.5°~4.5° proposed by Bracco et al. (1974) who used the Taylor's surface wave growth theory in the derivation of the spray cone angle.

3.2 Time-resolved droplet size distributions

Figure 8 shows the time-resolved evolution of the droplet diameter, the AMD and the SMD at the axial distance of 30 mm and at the centerline of the spray for the 3-hole and the 5-hole nozzles.

Time window, which is a time interval for calculating the mean droplet sizes such as AMD and SMD, was 0.15 ms. It was carefully selected to represent the time-dependent intermittent characteristics as well as the mean droplet sizes of the spray. If the time window gradually increases, the intermittent characteristics of the spray disappear so that it is difficult to get the information about the intermittent characteristics. On the contrary, if the time window is set too small, the mean characteristics within the selected time window disappear, and the fluctuating characteristics induced from the low data rate appear. There are several studies on the selection of the time window. Pitcher et al. (1992) set the time window at 0.04 ms. Arcoumains et al. (1990) set the time window at 0.1 ms to calculate the mean velocity of the spray.



(a) 3-hole nozzle

(b) 5-hole nozzle

Fig. 8 Time-resolved evolutions of droplet diameter, AMD and SMD at axial distance of 30 mm and at centerline of spray for (Z=30 mm, R=0 mm) (a) 3-hole and (b) 5-hole nozzle

On the other hand, through the time-resolved evolution of the droplet size, information on the internal structure of the spray injected intermittently would be found. The fuel is injected with the relative short injection durations of 1.0 and 1.1 ms for the 3-hole and the 5-hole nozzles. Moreover, the droplet sizes are measured at the centerline of the spray. Therefore, the time-resolved evolutions of the droplet diameter with time from SOI could well show the time-dependent development process of the internal structure of the spray.

Just after the leading edge of the spray arrived there, comparatively small-sized droplets, which can be distinguished from the floating droplets around the measurement point, are detected. After the leading edge passed, the detecting frequency of the droplets is remarkably decreased in a certain period. This duration is a period in which the central part enclosed the leading edge and the mixing flow region, as shown in Fig. 4, passes through the measurement point. The results indicate that the shape of the droplet passing through the measurement point during this period is not spherical at least. Namely, the low detecting frequency of the droplets in the central part of the spray does not mean there is no droplets but there are a few spherical droplets. Since the PDPA system evaluates the droplet size based on the phase difference of the scattered lights from the droplets, it recognizes the droplets as the spherical droplets when the phase difference detected in different positions were the same or within 10%. Therefore, it is concluded that there are ligaments, non-spherical droplets or large droplets that exceed the measurement range of the PDPA system used near the central part of the spray. Meanwhile, after the central part of the spray passes through the measurement point, the detecting frequency of the droplets increases prominently.

Figure 8(a) shows the results for the 3-hole nozzle. Few droplets are detected at the central part. The large droplets above 50 μm are detected near the starting point of the trailing edge. After 1.5 ms from SOI, the size of most droplets is below 25 μm, but large droplets are detected irregularly. The AMD is approximately 25 μm during the injection period, and it maintains the value of about 12 μm after 1.5 ms from SOI. The difference between the AMD and the SMD is large within 1.7 ms. It means that the droplet distribution is not uniform because the SMD, which is defined as the ratio of volume (d^3) to surface area (d^2), has the weighting effect to the large droplets, so that the difference between the AMD and the SMD increases when the droplet size shows the widely dispersed distribution.

Figure 8(b) shows the results for the 5-hole nozzle. Although the trend of the size distribution with time is similar to that for the 3-hole nozzle, the thickness of the leading edge is relatively thick. In addition, the detecting frequency of droplets in the central part of the spray is a little increased, compared with that of the 3-hole nozzle. After the central part passes through the measurement point, the detecting frequency of the droplet increases considerably, and many of large-sized droplets over 40 μm are detected. The AMD is approximately 20 μm during injection period, but it maintains the size of about 10 μm after 1.5 ms from SOI. The SMD tends to change more uniformly than that of the 3-hole nozzle, and the value of approximately 30 μm is distributed within 2 ms from SOI.

Figure 9 shows the time-resolved evolution of the droplet diameter, the AMD and the SMD at the radial distance of R=2.9 mm and at the fixed axial distance of Z=30 mm. This radial position, which was selected after investigating the axial velocity distributions corresponding to the mixing flow region, as shown in Fig. 4.

Simultaneously with the reach of leading edge

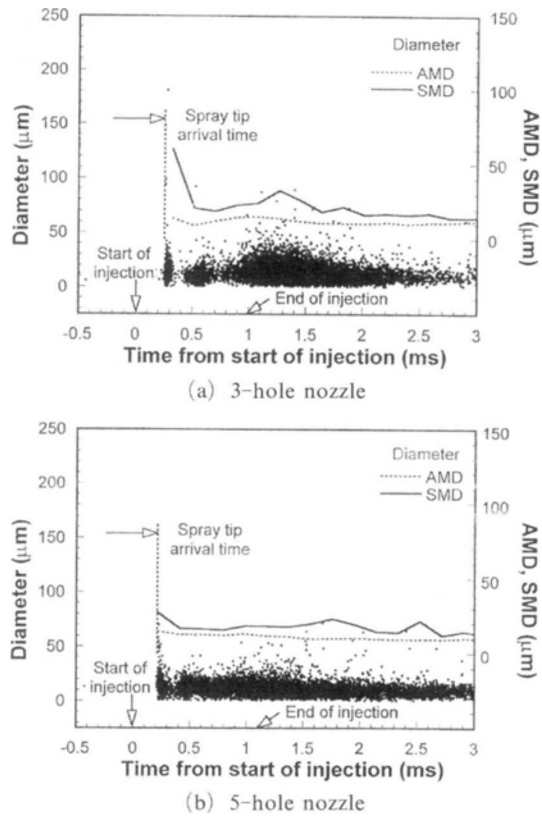


Fig. 9 Time-resolved evolutions of droplet diameter, AMD and SMD at axial distance of 30 mm and at radial distance of 2.9 mm (Z=30 mm, R=2.9 mm) for (a) 3-hole and (b) 5-hole nozzle

of the spray at the measure point, the droplet detecting frequency is considerably increased. Moreover, the drop size distribution is more uniform than that at the central part, as shown in Fig. 8.

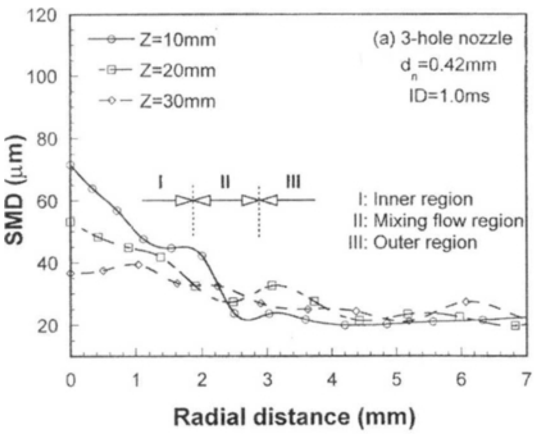
In Fig. 9(b) for the 5-hole nozzle, the detecting frequency of the droplets is prominently increased to an extent that it is difficult to discriminate the boundary between the leading edge and the central part of the spray. The SMD distribution is uniform, and the difference between the SMD and the AMD is small, compared with that of the 3-hole nozzle.

3.3 Mean droplet size distributions

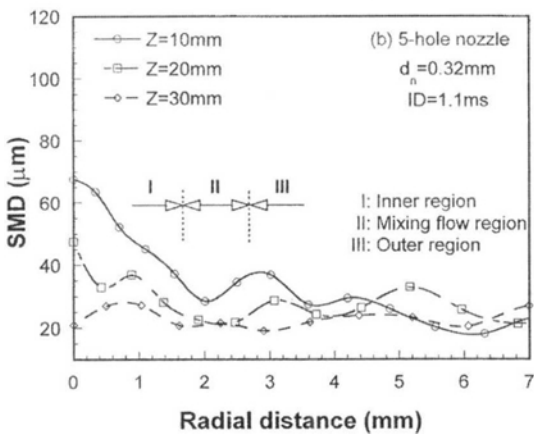
Figure 10 shows the SMD distributions with the radial distance at the three axial positions of

Z=10, 20 and 30 mm for the 3-hole and the 5-hole nozzles. The time window, applied for calculating the SMD, is 20 ms. This time window is relatively longer duration than the injection periods of 1.0 and 1.1 ms for the 3-hole and the 5-hole nozzles, respectively. Thus, the SMD distributions represent the whole spray characteristics during the single injection event.

In the case of the 3-hole nozzle, as shown in Fig. 10(a), the SMD decreases with the increase in the axial distance, and finally, at Z=30 mm, it reaches approximately 38 μm near the spray axis. In addition, the SMD decreases rapidly with the increase in the radial distance and shows the constant value in the range of 20 to 30 μm from at R>2-3 mm. In the case of the 5-hole nozzle, as shown in Fig. 10(b), the SMD decreases with the increase in the axial distance, but it shows lower value about 20 μm near the spray axis than that of the 3-hole nozzle. In the variation of the SMD along with the radial distance, the SMD decreases gradually with the increase in the radial distance, and the constant value is obtained at R>2-3 mm. In the cases of both the 3-hole and the 5-hole nozzles, the droplets of the outer region of the spray show the uniform SMD distributions. From the SMD distributions with the radial distance, the spray structure of the spray can be classified into three regions: (a) the inner region showing the high SMD distribution; (b) the mixing flow region where the shear flow structure would be constructed; and (c) the outer region formed through the disintegration processes of the spray inner region and composed of the fine droplets.



(a) 3-hole nozzle (d_n=0.42 mm, ID=1.1 ms)



(b) 5-hole nozzle (d_n=0.32 mm, ID=1.1 ms)

Fig. 10 SMD distributions with radial distance at three axial positions of Z=10, 20 and 30 mm for (a) 3-hole and (b) 5-hole nozzle

Figure 11 shows the SMD along the centerline of the spray for the 3-hole and the 5-hole nozzles. The time window of 20 ms was used for calculating the SMD at the given axial positions.

After showing the maximum value in the vicinity of the nozzle tip, the SMD distribution shows a rapid decrease, and it remains the constant value near Z=50 mm (Z/d_n=156.3) for the 5-hole nozzle and Z=70 mm (Z/d_n=166.6) for the 3-hole nozzle. It indicates that the inner region of the 3-hole and the 5-hole spray is dramatically

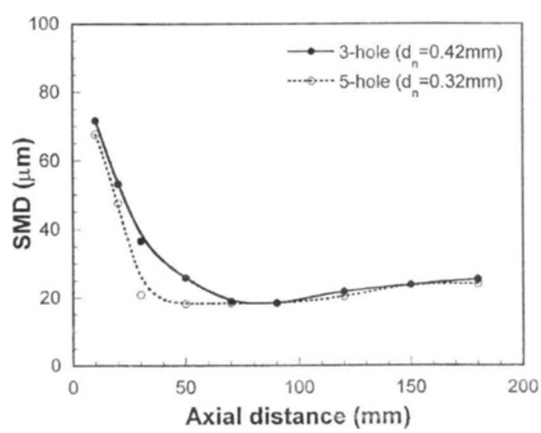


Fig. 11 SMD distributions along centerline of spray for (a) 3-hole and (b) 5-hole nozzle

changed within the near-field of the nozzle tip, and the disintegration processes of those sprays take place actively within this region. The disintegration processes of the 5-hole nozzle spray proceed more rapidly than that of the 3-hole nozzle spray.

3.4 Time-dependent analysis of development process of intermittent spray

Figure 12 shows the SMD distribution, which is the mean value of the SMD calculated at each measurement point of the whole spray flow field during the time window of 0.15 ms, with time from SOI. That is, the SMD to the whole flow field indicates the overall mean value of the SMD. Therefore, it helps to clear up the development and atomization processes of the spray injected intermittently.

The SMD for the 3-hole and the 5-hole nozzles increases gradually with time, and then it tends to decrease after reaching the maximum value of approximately 25 μm near 1.5 ms from SOI. The increasing trends within 1.5 ms from SOI, denoted as the region "I", are a little different from the general tendency on the disintegration processes of the diesel spray. The liquid columns or the ligaments change into the droplets so that the SMD decreases with time from SOI. The increase within 1.5 ms would be closely related with the characteristics of the PDPA system that was used

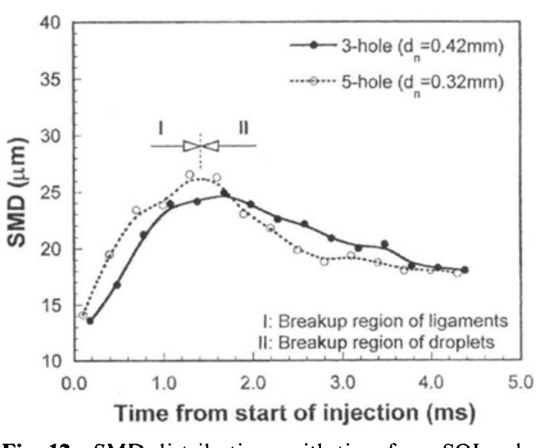


Fig. 12 SMD distributions with time from SOI, calculated with the time window of 0.15 ms to all measurement points of spray flow fields

to measure the droplet size. As mentioned in Fig. 8, the PDPA system calculates only in the case that the phase difference detected in different positions are the same or their differences are within 10%. Consequently, the ligaments, non-spherical droplets or large-sized droplets that exceed the measurement range near the central part of the spray are not considered in Fig. 12. Reversely, it is concluded that the 1.5 ms from SOI is the time required to change the ligaments or larger droplets change into the spherical droplets. On the other hand, after 1.5 ms, denoted as the region "II", the SMD distributions show the decreasing tendency with time from SOI. This is considered that the droplets formed through the disintegration of the ligaments or large droplets within the region "I" disintegrate to the more fine droplets through the 2nd atomization due to the resistance to the ambient air.

In the comparison between the two nozzles, the 3-hole nozzle shows the low SMD within 1.5 ms, and reversely after 1.5 ms it shows the higher SMD. It means that, within 1.5 ms, the droplet formation process of the 3-hole, through the disintegration of the spray central parts, proceeds more slowly than that of the 5-hole, so that the number of droplets measurable by the PDPA system is small, compared with that of the 5-hole nozzle. Consequently, the disintegration processes of the multi-hole nozzle are continued after the end of injection. The mean value of the SMD from the start of injection to 4.5 ms is 20.1 and 19.2 μm for the 3-hole and the 5-hole nozzle, respectively.

4. Conclusions

The atomization characteristics of the 3-hole and the 5-hole sprays, injected intermittently into still ambient, were investigated using the time-resolved PDPA data to clarify the spray formation processes. The spray structural behavior and atomization characteristics between the two nozzles were compared. Concluding remarks can be summarized as follow.

(1) The 5-hole nozzle spray shows the smaller spray cone angle, the decreased SMD distribu-

tions and the small difference between the SMD and the AMD, compared with that of the 3-hole nozzle spray.

(2) From the SMD distributions with the radial distance, the spray structure of the spray can be classified into the three regions : (a) the inner region showing the high SMD distribution ; (b) the mixing flow region where the shear flow structure would be constructed ; and (c) the outer region formed through the disintegration processes of the spray inner region and composed of the fine droplets.

(3) Through the SMD along the centerline of the spray, it reveals that the SMD decreases rapidly after showing the maximum value in the vicinity of the nozzle tip. The SMD remains the constant value near $Z=70$ $(Z/d_n=166.6)$ and 50 mm $(Z/d_n=156.3)$ for the 3-hole and the 5-hole nozzles. Consequently, the disintegration processes of the 5-hole nozzle spray proceed more rapidly than that of the 3-hole nozzle spray.

(4) In the time-dependent analysis of the SMD to the whole flow fields, there are two regions : (a) the liquid columns or the ligaments change into the droplets so that the SMD increases with time from SOI ; (b) the droplets formed through the disintegration of the ligaments or large droplets disintegrate to the more fine droplets so that the SMD decreases with time from SOI.

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