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Intermittent Atomization Characteristics of Multi-Hole and Single-Hole Diesel Nozzle

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The intermittent spray characteristics of a multi-hole and a single-hole diesel nozzle were experimentally investigated. The hole number of the multi-hole nozzle was 5, and the hole diameter of the 5-hole and the single-hole nozzle was the same as $d_n=0.32$ mm with the constant hole length to diameter ratio ($l_n/d_n=2.81$). The droplet diameters of the spray, including the time-resolved droplet diameter, SMD (Sauter mean diameter) and AMD (arithmetic mean diameter), injected intermittently from the two nozzles into the still ambient were measured by using a 2-D PDPA (phase Doppler particle analyzer). Through the time-resolved evolutions of the droplet diameter, it was found that the structure of the multi-hole and the single-hole nozzle spray consisted of the three main parts : (a) the leading edge affected by surrounding air and composed of small droplets ; (b) the central part surrounded by the leading edge and mixing flow region and scarcely affected by the resistance of air ; (c) the trailing edge formed by the passage of the central part. The SMD decreases gradually with the increase in the radial distance, and the constant value is obtained at the outer region of the radial distance (normalized by hole diameter) of 7-8 and 6 for the 5-hole and single-hole nozzle, respectively. The SMD along the centerline of the spray decrease shapely with the increase in the axial distance after showing the maximum value near the nozzle tip. The SMD remains the constant value near the axial distance (normalized by hole diameter) of 150 and 180 for the 5-hole and the single-hole nozzle, respectively.

Key Words : Atomization Characteristics, Intermittent Diesel Spray, SMD (Sauter Mean Diameter), PDPA (Phase Doppler Particle Analyzer)

1. Introduction

Recently, multi-hole nozzles are widely used in direct injection (D. I.) diesel engines, owing to its potentiality in the reduction of exhaust emissions. However, the spray characteristics of the multi-hole nozzle are not clear until now due to the sophisticated geometry and the flow structure inside the nozzle tip, contrary to the cases of single-hole nozzles. Moreover, many experimental studies on the spray characteristics deal with the intermittent spray characteristics assuming continuous sprays independent of time, and they examine mainly mean values during injection periods. Resultantly, a few time-resolved data of the intermittent sprays, which can be used to clarify the development and disintegration processes, are available. Therefore, an in-depth study to verify the disintegration process of the multi-

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hole diesel spray is needed.

There have been many studies on the diesel sprays and their formation processes but a few of the comparisons of the droplet formation process between the multi-hole and the single-hole diesel nozzles. Quoc and Brun (1994) suggested the development of the spray was governed by the three physical phenomena that are disintegration, evaporation and coherence. Safman et al. (1988) expressed the droplet velocity distributions of the single-hole diesel spray as a function of time. They classified the spray structure into the leading edge, central part and trailing edge. It was concluded that the reason for the reduction of the number density of droplets in the central part of the spray was that it was mainly composed of the ligament that was not completely atomized. Hosoya and Obokata (1993) analyzed the spray characteristics of the multi-hole and the single-hole nozzle using a LDV (laser Doppler anemometry) and a PDA (phase Doppler particle analyzer) system and suggested that the two measurement systems were efficient for analyzing the unsteady diesel spray. Arcoumanis et al. (1990) investigated the spray formation process with time. They suggested that the spray formed by the multi-hole nozzle divided into the three parts such as early injection period, main injection period and after-injection period. Hiroyasu and Aria (1990) investigated the droplet size of the intermittent spray of the single-hole nozzle using immersion liquid sampling, and they concluded it decreased with the increase in injection pressure. Arcoumanis et al. (1993) examined the atomization characteristics in a multi-hole nozzle by using a PDA system. They showed that there is a better improvement in the quality of atomization in the 2-spring nozzle than in the 1-spring nozzle during the main injection duration. Bae et al. (2002) investigated the spray characteristics from diesel injectors with various nozzle tip shapes, including a VCO and a multi-hole diesel nozzle, by an optical imaging technique. Through the microscopic image analysis, it was suggested that the droplets are formed at the end of ligament around the spray surface.

In this paper, the intermittent atomization characteristics of a multi-hole and a single-hole diesel spray were experimentally examined to investigate the development process of the diesel spray, and the comparisons of AMD (arithmetic mean diameter, D_{10}) and SMD (Sauter mean diameter, D_{32}) between the two nozzles were made.

2. Experimental Apparatus

2.1 Fuel injection system

In order to investigate experimentally the atomization characteristics of the diesel spray formed by the 5-hole and the single-hole nozzle, an experimental apparatus composed of the fuel injection system and 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 Fuel injection nozzle

The fuel injection nozzle was a mini-sac type multi-hole diesel nozzle with a 2-spring nozzle

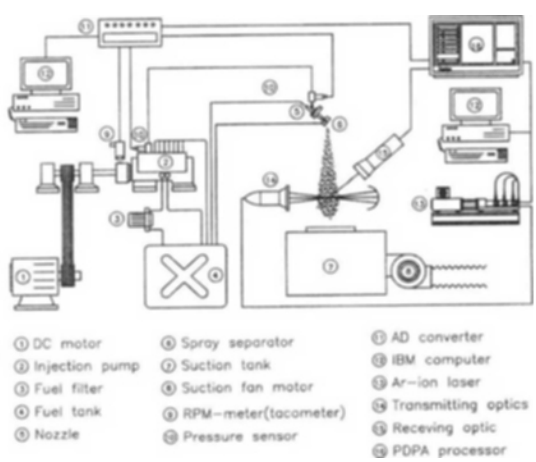


Fig. 1 Schematic diagram of experimental apparatus

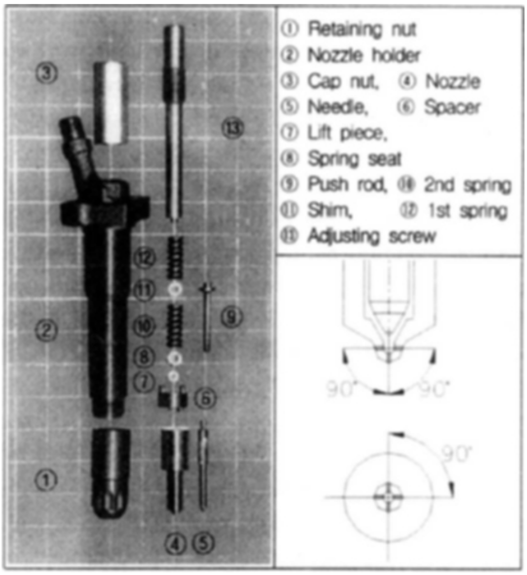


Fig. 2 Photograph of disassembled 5-hole diesel nozzle and schematic diagram of nozzle tip

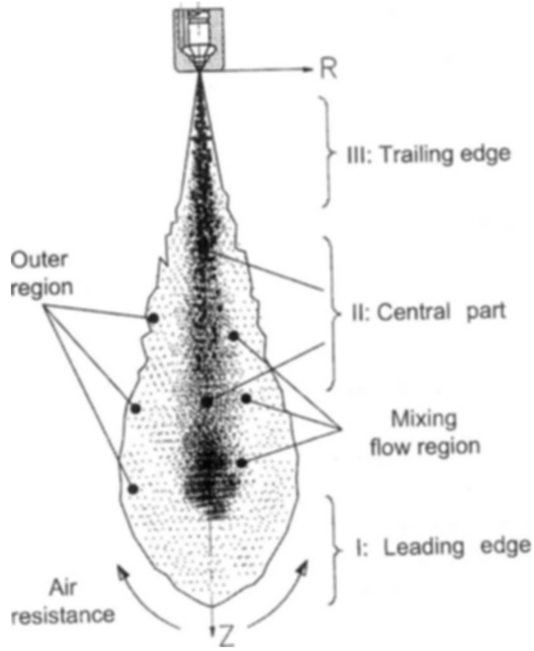


Fig. 3 Illustration of typical structure of spray formed by diesel nozzle and definitions of coordinate system in spray flow field

holder, as shown in Fig. 2.

The hole number of the multi-hole nozzle was 5, and there was a tested hole in the vertex. Other holes were located with same intervals in a plain met at right angles. The diameter of a hole, length to diameter ratio (l_n/d_n) of the nozzle and nozzle hole total area were 0.32 mm, 2.81 and 0.412 mm^2, respectively. The diameter and l_n/d_n of the single-hole were 0.32 mm and 2.81, which are the same as those of the multi-hole nozzle. The rotating speed of the pump in this experiment was set up to 500 rpm with constant total injection quantity of 30 mm^3/st. The injection quantity of a tested hole was 7.31 mm^3/st, and that of the single-hole nozzle was the same. The injection duration was 1.1 and 0.8 ms for the 5-hole and the single-hole nozzle, respectively.

2.3 PDPA system

The droplet size measurements of the fuel spray were carried out by a 2-dimensional PDPA (Dantec Co.) system. 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 detects the scattered lights, which is produced when droplets pass through the measurement volume, and then transmits them to the signal processor. Therefore, the droplet size is measured by the frequency and relative phase difference of the Doppler signal.

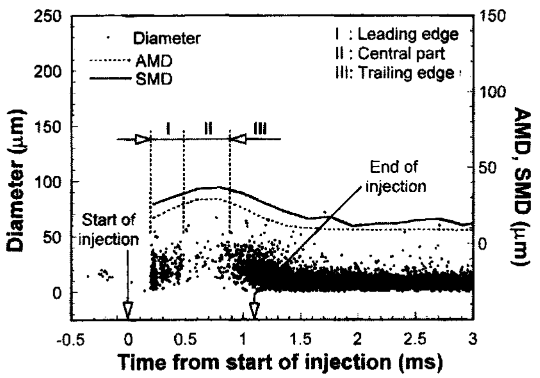
The measurement of the droplet size was conducted in the two dimensions at axis because the sprays would be considered as an axi-symmetric structure in the spray flow field. Figure 3 shows the schematic diagram of the typical structure of the spray formed by diesel nozzles and the definitions of the coordinate system in the spray flow field. 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 performed at the non-dimensional axial positions of $Z/d_n=31$, 63, 94, 156, 219, 281, 375, 469, and 562 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 point was 20,000, and the measurement mode was set not to exceed 300 sec.

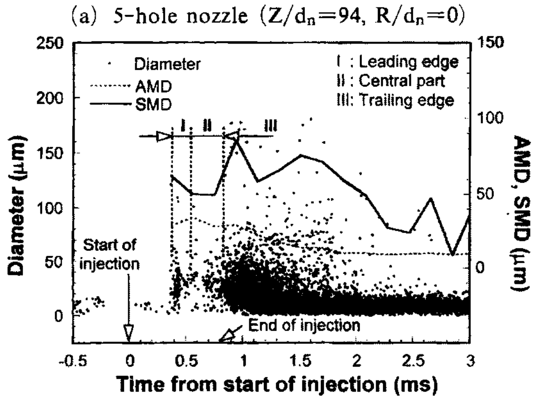
3. Results and Discussion

3.1 Time-resolved evolution of droplet size

Figure 4 shows the time-resolved evolution of the droplet diameter, the AMD and the SMD at the axial position of $Z/d_n=94$ and at the centerline of the spray for the 5-hole and the single-hole nozzle. 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.



(a) 5-hole nozzle ($Z/d_n=94$, $R/d_n=0$)



(b) Single-hole nozzle ($Z/d_n=94$, $R/d_n=0$)

Fig. 4 Time-resolved evolution of droplet diameter, AMD and SMD at axial position of $Z/d_n=94$ and at centerline of spray for 5-hole and single-hole nozzle

Through the time-resolved evolutions of the droplet size, information on the internal structure of the spray injected intermittently would be found. That is, the fuel was injected with the relatively short injection durations of 1.1 and 0.8 ms for the 5-hole and the single-hole nozzle. Moreover, the droplet sizes were measured at the centerline of the spray. Therefore, the time-resolved evolutions of the droplet diameter with time from the start of injection (SOI) could well show the time-dependent development process of the internal structure of the spray.

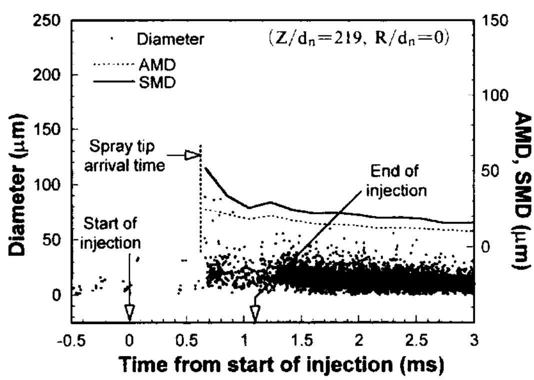
There is a certain period, usually called the spray tip arrival time, in which droplets are not detected before the leading edge of the spray reaches the measurement point. Just after the leading edge of the spray arrived at the measurement point, comparatively small-sized droplets, which can be distinguished from the floating droplets around the measurement point, are detected. After the leading edge of the spray passed, there is a certain period in which the detecting frequency of the droplets is remarkably decreased. This duration is a period in which the central part enclosing the leading edge and the mixing flow region of the spray, as shown in Fig. 3, passes through the measurement point. This result, showing the low detecting frequency, indicates that the shape of the droplets passing through the measurement point during this period is not spherical at least. However, the boundary between the leading edge and the central part of the spray is not clear. It is also difficult to make clear definition of the end part of central part of the spray.

The low detecting frequency of the droplets in the central part of the spray does not mean there are no droplets but there are a few spherical droplets. The PDPA system, which was used to measure the droplet size, evaluates the droplet size based on the phase difference of the scattered lights produced when the spherical droplets pass through the measurement volume. In this study, when the droplet sizes, calculated from the phase difference detected in different positions, were the same or their differences were within 10%, we regarded them as the spherical droplets. Therefore, it is found that there are ligaments, non-spherical droplets or large-sized 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. From these time-resolved evolutions of the droplet size, the structure of the diesel spray can be divided into the three main parts, as depicted in Fig. 3 : (a) the leading edge affected by the surrounding air and composed of small droplets ; (b) the central part surrounded by the leading edge and mixing flow region, and scarcely affected by the surrounding air ; (c) the trailing edge formed after the central part passed.

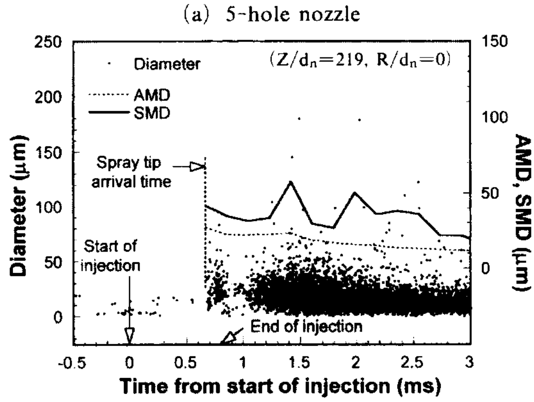
Figure 4(a) shows the results for the 5-hole nozzle. Slightly large-sized droplets are detected at the leading edge and central part of the spray, and the detecting frequency of the droplets is low. Numerous droplets over $D>40$ μm are measured in the beginning region of the trailing edge of the spray. After 1.51 ms from SOI, the size of most droplets shows below 25 μm, but large-sized droplets are detected irregularly. The AMD is approximately 25 μm during the injection period, but it maintains the value of about 10 μm after 1.5 ms from SOI. The trend of the SMD variation is quietly similar to that of the AMD, and the difference between the AMD and the SMD is not so large. It means that the droplet distribution is quietly uniform because the SMD, which is defined as the ratio of volume (d^3) to surface area (d^2), has the weighting factor to the large-sized droplets, so that the difference between the AMD and the SMD decreases when the droplet size shows the quietly uniform distribution.

Figure 4(b) shows the results for the single-hole nozzle. The trend of the droplet diameter distribution with time from SOI is similar to that for the 5-hole nozzle, but large-sized droplets are measured irregularly. After the central part passes through the measurement point, the detecting frequency of the droplet increases considerably, and many of large-sized droplets over 100 μm are detected. The AMD is about 40 μm during injection period, but it maintains the value of 10–15 μm after 2 ms from SOI. The SMD tends to change irregularly, and the value of about 100 μm is distributed within 2 ms from SOI. It indicates that the trailing edge of the spray, which is mainly formed after the end of injection and in which numerous large-sized droplets are measured, is also important part in the evaluation of the atomization characteristics.

Figure 5 shows the time-resolved evolution of the droplet diameter, the AMD and the SMD at the axial position of $Z/d_n=219$ and at the centerline of the spray for the 5-hole and the single-



(a) 5-hole nozzle



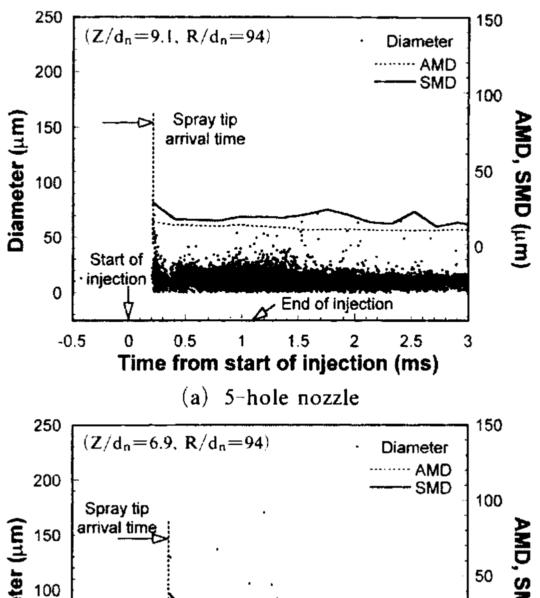
(b) Single-hole nozzle

Fig. 5 Time-resolved evolution of droplet diameter, AMD and SMD at axial position of $Z/d_n=219$ and at centerline of spray for 5-hole and single-hole nozzle hole nozzle.

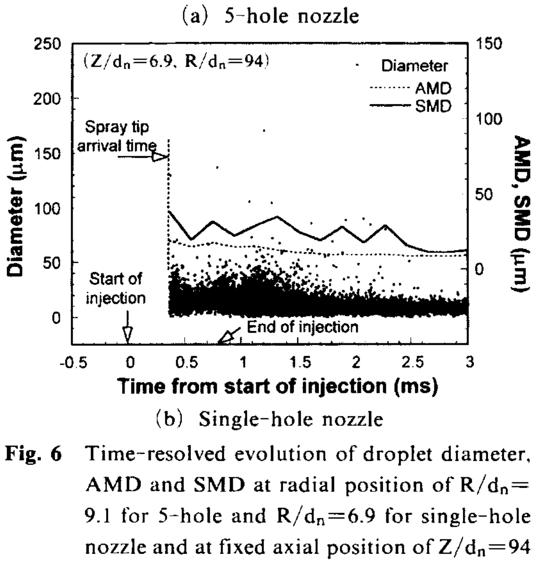
In Fig. 5(a) for the 5-hole nozzle, the detecting frequency of the droplets in the leading edge and the central part of the spray is considerably increased, so that it is difficult to discriminate the boundary among the three parts mentioned in Fig. 4. The AMD maintains the value of 10-15 μm after showing the range of 10-20 μm at the leading edge and the central part of the spray. The SMD tends to change irregularly, and the value of 25-50 μm is distributed within 2 ms from SOI. In Fig. 5(b) for the single-hole nozzle, unlike that of the 5-hole nozzle, the detecting frequency of the droplets at the central part of the spray is still low. In addition, the fluctuation of the SMD distribution is observed.

Figure 6 shows the time-resolved evolution of the droplet diameter, the AMD and the SMD at the radial position of $R/d_n=9.1$ for the 5-hole and $R/d_n=6.9$ for the single-hole nozzle and at the fixed axial position of $Z/d_n=94$. These radial positions, which were selected after investigating the axial velocity distribution, correspond to the mixing flow region, as shown in Fig. 3. Since the diffusion processes of the 5-hole spray are more active, the radial position of the 5-hole nozzle is a little longer than that of the single-hole nozzle.

In the case of Fig. 6(a) for the 5-hole nozzle, the central part of the spray, showing the low detecting frequency of the droplets on the spray axis, as shown in Figs. 4 and 5, is not observed any more. It indicates that the droplets, separated from the leading edge and the central part of the spray, construct the mixing flow region. In the case of the single-hole nozzle, as shown in Fig. 6 (b), the fluctuation of the SMD distribution is observed due to the irregularly large-sized droplets.



(a) 5-hole nozzle



(b) Single-hole nozzle

Fig. 6 Time-resolved evolution of droplet diameter, AMD and SMD at radial position of $R/d_n=9.1$ for 5-hole and $R/d_n=6.9$ for single-hole nozzle and at fixed axial position of $Z/d_n=94$

3.2 Mean droplet size of intermittent spray

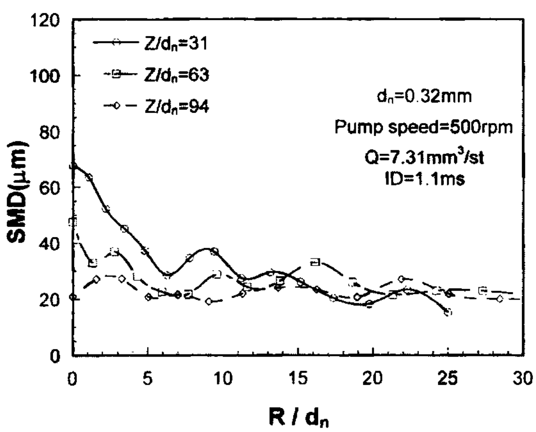
Figure 7 shows the SMD of the 5-hole and the single-hole nozzle with radial distance at the three axial positions of $Z/d_n=31$, 63 and 94. Here, the time window, applied for calculating the SMD, is 20 ms from SOI. This time window of 20 ms is relatively longer duration than the injection periods of 1.1 and 0.8 ms for the 5-hole and the single-hole nozzle, respectively. Hence, the SMD distribution shown in Fig. 7 would represent the whole spray characteristics during the single injection event.

In the case of the 5-hole nozzle, as shown in Fig. 7(a), the SMD decrease with the increase in the axial distance, and finally, at $Z/d_n=94$, it reaches approximately 30 μm near the spray axis. In addition, the SMD decreases gradually with the increase in the radial distance and shows about 20 μm from at $R/d_n>7$-8. In the case of the single-hole nozzle, as shown in Fig. 7(b), the SMD decrease with the increase in the axial distance, but it is quite high near the spray axis, compared with that of the 5-hole nozzle. In the variation of the SMD along with the radial distance, the SMD decreases rapidly with the increase in the radial distance, and the constant value is obtained at $R/d_n>6$, which is a little smaller than that in the 5-hole nozzle. There is the large difference between the inner region, which is defined as the region near the spray axis including the central part and trailing edge of the spray, and the outer region of the spray in the SMD, especially near the nozzle tip. These smaller SMD distributions near the outer region of the spray indicate that the fine droplets are produced through the disintegration processes of the inner region of the spray.

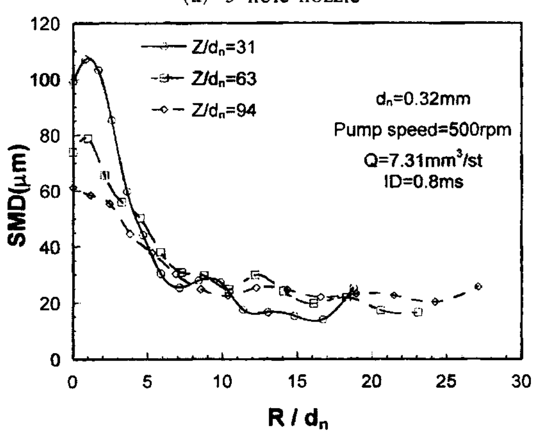
Figure 8 shows the SMD along the centerline of the spray for the 5-hole and single-hole nozzle. The time window of 20 ms was used to calculate the SMD at the given axial positions.

After showing the maximum value near the nozzle tip, the SMD distributions show a rapid decrease, and it remains at a constant value near $Z/d_n=150$ for the 5-hole nozzle and $Z/d_n=180$ for the single-hole nozzle. It indicates that the inner region of the 5-hole and the single-hole spray is dramatically changed within the near field of the nozzle tip, and the disintegration processes of those sprays take place actively within this region. In addition, the disintegration processes of the 5-hole spray proceed more rapidly than that of the single-hole spray.

Figure 9 shows the cross-section mean value of



(a) 5-hole nozzle



(b) Single-hole nozzle

Fig. 7 SMD distributions of 5-hole and single-hole nozzle with radial distance at three axial positions of $Z/d_n=31$, 63 and 94 (time windows of 20 ms)

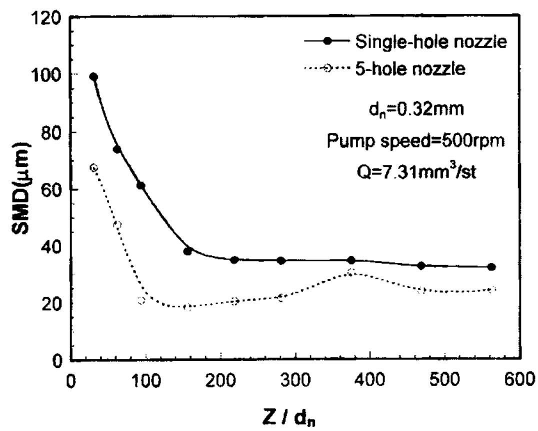


Fig. 8 SMD distribution along centerline of spray for 5-hole and single-hole nozzles (time windows of 20 ms)

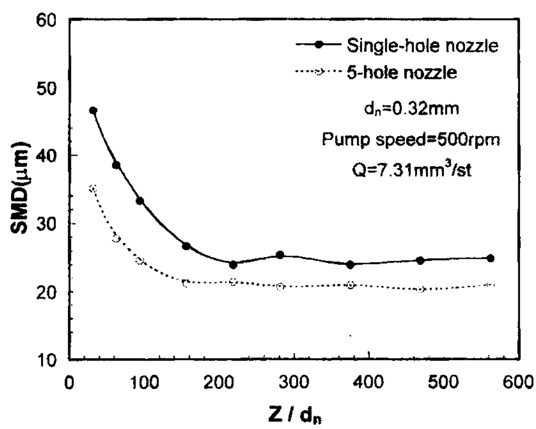


Fig. 9 Cross-section mean value of SMD along axial distance (time windows of 20 ms)

the SMD along the axial distance. Here, the cross-section mean value of the SMD is the mean value of the SMD, calculated at all radial measurement points of the given axial position, during the time window of 20 ms. Since this result, differently from that in Fig. 8, is the mean value of the SMD including the inner region, the mixing flow region and the outer region of the spray, it would give useful information to understand the time-dependent development process of the spray along the axial distance.

Similarly to Fig. 8, after the mean SMD shows a high value near the nozzle tip, it decreases rapidly and then remains the constant value in the downstream of the spray. The SMD decreases with the increase in the axial distance and reaches the minimum value at $Z/d_n=156$ for the 5-hole nozzle and $Z/d_n=218\text{-}250$ for the single-hole nozzle. It indicates that the 5-hole diesel spray develops faster than the single-hole spray.

3.3 Time-resolved SMD distributions of intermittent spray

Figure 10 shows the SMD distributions, which were calculat the time window of 1.15 ms to all measurement points (144 points) of the spray flow fields (from $Z/d_n=31$ to 562), with the time from SOI. Namely, the SMD to the whole flow field implies the overall mean value of the SMD.

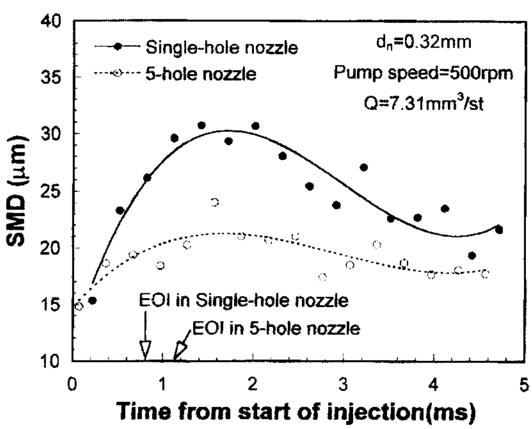


Fig. 10 SMD distribution with time from start of injection, which was calculated with time window of 0.15 ms to all measurement points of spray flow fields

Therefore, it would help to clarify the development and disintegration processes of the spray injected intermittently.

The SMD for the single-hole nozzle increases gradually with time, and then it tends to decrease after reaching the maximum value of approximately 30 μm near 1.5 ms from SOI. The trend for the 5-hole nozzle is similar to that for the single-hole nozzle, but the level of the SMD is relatively low.

These increases of the SMD within 1.5 ms from SOI are a little different from those of the general disintegration processes of the solid cone spray: that is, the liquid columns or the ligaments change into the fine droplets so that the SMD decreases with the time from SOI. These phenomena would be closely related with the characteristics of the PDPA system that was used to measure the droplet size. As mentioned in Fig. 4, the PDPA system calculates the droplet size only in the case that the phase difference detected in different positions was the same or their differences were within 10%. Hence, the ligaments, non-spherical droplets or large droplets that exceed the measurement range near the central part of the spray were not considered in Fig. 10. Reversely, it is concluded that a certain period is needed to change the ligaments or large-sized droplets into the small-sized spherical droplets. This duration is about 1.5 and 2.0 times of the injection duration for the 5-hole and the single-hole nozzle, respectively. Consequently, the disintegration processes of the 5-hole and the single-hole nozzle are continued after the end of injection. The mean value of the SMD from SOI to 4.5 ms is 19.2 and 25.0 μm for the 5-hole and the single-hole nozzle, respectively.

4. Conclusions

The intermittent atomization characteristics of a multi-hole and a single-hole diesel spray were experimentally examined by using a 2-D PDPA (phase Doppler particle analyzer) system. The time-resolved evolution of the droplet diameters, including the SMD and the AMD, were measured. Concluding remarks can be summarized as follows.

(1) Through the time-resolved evolution of the droplet diameter, it was found that the internal structure of the multi-hole and the single-hole nozzle sprays consisted of three main parts : (a) the leading edge affected by surrounding air and composed of small droplets ; (b) the central part surrounded by the leading edge and mixing flow region and scarcely affected by the resistance of air ; (c) the trailing edge formed by the passage of the central part.

(2) The SMD decreases gradually with the increase in the radial distance, and the constant value is obtained at $R/d_n > 7$-8 and $R/d_n > 6$ for the 5-hole and single-hole nozzle, respectively.

(3) The SMD along the centerline of the spray decrease shapely with the increase in the axial distance after showing the maximum value near the nozzle tip. The SMD remains the constant value near $Z/d_n = 150$ for the 5-hole nozzle and $Z/d_n = 180$ for the single-hole nozzle. It indicates that the inner region of the 5-hole and the single-hole spray is dramatically changed within the near field of the nozzle tip, and the disintegration processes of the 5-hole spray proceed more rapidly than that of the single-hole spray.

(4) In both the 5-hole and the single-hole nozzle spray, a certain period is needed to change the ligaments or large-sized droplets into the small-sized spherical droplets. This duration is about 1.5 and 2.0 times of the injection duration for the 5-hole and the single-hole nozzle, respectively.

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