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ANALYSIS OF A FAN-SHAPED SPRAY USING 2D ILIDS METHOD

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ABSTRACT - DI (direct injection) systems have been studied to improve thermal efficiency of gasoline engines. The analysis of spray behavior is important to examine the combustion characteristics of DI gasoline engines because fuel-air mixture formation is controlled by spray characteristics and gas motion. In this study, the characteristics of a fan-shaped spray, such as the droplet size, its velocity and the droplet-size distribution were simultaneously measured on a 2D plane by using an improved ILIDS (Interferometric Laser Imaging for Droplet Sizing) method. As a result, interesting relationships between the droplets diameter and the velocity were found. In addition, numerical analysis of a fan-shaped spray was conducted and the results were compared to the measured results. In numerical analysis, the nozzle internal flow was predicted by using VOF (Volume of Fluid) model that can simulate the two-phase flow inside the nozzle to give the liquid film formation process outside the nozzle. Using the results of VOF model for the initial conditions, numerical analysis of the spray by DDM (Discrete Droplet Model) was carried out to examine the droplets breakup process.

1. INTRODUCTION

DI (direct injection) systems have come to be used broadly with internal combustion engines for improvement of thermal efficiency. In DI gasoline engines, the injector makes air-fuel mixture distribution around a spark plug with equivalence ratio of around one and peripheral area with only air or lean mixture. In this way, stratified charge combustion can be performed. By using stratified charge combustion method, pumping loss and heat loss are reduced and specific heat ratio increases, thus thermal efficiency is improved. A slit-type injector makes a fan-shaped spray. The direction of a spray is changed to upward by piston cavity and the spray is guided around a spark plug. However, the liquid film thickness of a fan-shaped spray is not uniform in the cross section. Different phenomena of spray characteristics are observed in the width direction of fan-shaped spray. Droplet size, velocity, direction and droplet-size distribution are different in tendency in width direction. Spray formation cannot be optimized because it has been difficult to measure these parameters quantitatively. A lot of studies were conducted to measure characteristics of spray. PDPA (Phase Doppler Particle Analyzer) has been used to obtain the droplet size, the velocity of the droplet and the space distribution, as these parameters have been necessary for elucidation of atomization. However, PDPA can measure these parameters in a point section, and two-dimensional measurement in the cross-section has not been performed simultaneously.

In this study, the authors used an improved Interferometric Laser Imaging for Droplet Sizing (ILIDS) method proposed by Maeda [1,2] to measure fan-shaped spray parameters such as diameter, velocity, direction and size distribution of droplets in two-dimensional cross-section simultaneously. In addition, numerical simulation was performed. The authors compared experimental data with date of numerical simulation and examined influential parameters on atomization mechanism.

2. MEASURING PRINCIPLE

When a coherent laser light illuminates a transparent liquid droplet, the reflected and refracted lights come out of a liquid droplet. The reflective light interferes with refractive light on a defocus-plane and makes an interference image. Interference fringes with light and shade are observed in interference images made by phase difference of reflective light and refractive light. ILIDS method is a technique to measure the droplet size from number of interference fringes. In ILIDS method, an image plane of a camera is moved at a defocus-position from a focus-position of optics devices along an axis of collected light. And photographs are taken on out-of-focus-plane. ILIDS method has characteristics to observe interference fringes appearing in the overlap domain of glare points, and the reflected light and refracted light of droplet make a circular defocus image. Conventionally, PDPA method is a technique using interference of scattering light of droplet made by two incident laser lights that intersect each other. On the other hand, ILIDS method uses scattering light with one piece of laser sheet and has characteristics to be able to measure a lot of droplet's sizes and velocities in two-dimensional cross section simultaneously. The distinctness of interference fringes made by reflected light and refracted light becomes the best with the scattering angle of 73 degrees because strength of two lights becomes nearly equal. The correlation between the number of fringes in the interference image and droplet diameter is shown as the following equation that was derived from geometrical analysis [3].

$$d = \frac{2\lambda N}{\alpha} \cdot \frac{1}{\cos\frac{\theta}{2} + \frac{m\sin(\theta/2)}{\sqrt{m^2+1-2m\cos(\theta/2)}}} \quad (1)$$

$$\alpha = 2\tan\left(\frac{Wsl/2}{Dw}\right) \quad (2)$$

Where, λ is laser wavelength, α and θ are collecting angle and scattering angle respectively, and m is relative refractive index of droplets, d is droplet diameter, and N is number of fringes in the interference image. Wsl is slit width, Dw is distance between a droplet to the collecting lens. The number of fringes on each droplet image determines the droplet size.

It is not necessary to calibrate because the number of fringes does not depend on scattered light strength or the degree of the focus coming off, but is in proportion to only droplet diameter. The droplet diameter can be absolutely measured by fixing the constant of optical devices. In ILIDS technique, if the droplet diameter parameter, $\pi d/\lambda$, is ten or more, the geometrical analysis can be applied. Therefore, for instance, when the laser source of light of wavelength 532 nm is used, the lower bound of the diameter that can be measured fundamentally becomes about 5 μm. The actual range that can be detected is 10 μm or more because it should detect two fringes or more.

Defocus-images overlappe each other because the circular defocus-images were used in conventional ILIDS method. Therefore, in the method, the measurement was performed only for a single droplet and the place where the number density was remarkably low. Against this problem, Maeda et al. designed receiving optics using a rectangular slit and two cylindrical lenses. The individual droplets imaged on the CCD image plane are taken of a picture of interference image that is in focus vertically and out of focus horizontally. With this technique, only the size of the image and information of fringe spacing are left. The image is compressed vertically and changed to a linear image by receiving optics. This technique avoids an overlap of interference images in dense sprays [6].

The calculation method of the droplet velocity is similar to PTV. Two images are recorded to two different frames using a double pulse laser with a little time difference. The position and size of a droplet is decided from the first image, and is compared with the second image. The velocity of droplet is derived from the value in which the amount of movement of the obtained individual droplet was divided the difference of time between the two images.

3. EXPERIMENTAL SETUP

Table 1 shows experimental conditions. A slit-type injector for the direct injection was used in this experiment. The slit-type injector was installed in the upper part of the chamber, and the injection was controlled with the injector driver. The injection pressure of n-heptane pressurized with N_2 gas as a fuel was up to 10 MPa. The pressure in the chamber was atmospheric, and the temperature was a room temperature. Injection duration was set to 7.7 ms.

Figure 1 shows the experimental apparatus and the optical system. The double-pulse Nd-YAG laser with a wavelength of 532nm was used for the light source, and the laser sheet was made with a cylindrical lens and irradiated to spray. The thickness of laser sheet was 0.5 mm and two-dimensional images of spray were captured with a CCD camera. The pulse duration, dt, of the double-pulse laser was set to 1 μ s and the scattering angle, θ , was at 73 deg. A digital 12bit (1376 x 1024 pixel) CCD camera was used for capturing interferometric images, and the camera had a slit, detecting lenses to collect scattered light (Nikon Micro-Nikkor 105 mm (F=2.5)) and two cylindrical lenses. Because the size of slit was 18 mm × 4 mm and the working distance was set to 120mm, the collecting angle was set to an angel of 8.6 deg. The obtained image is continuously accumulated in PC. The image analysis was carried out using an analysis software, and the distribution, the diameter, and the velocity vector of individual droplets were obtained.

Table 1 Experimental conditions

Nozzle	Slit-type injector
Fuel	n-heptane
Injection pressure (MPa)	10
Ambient pressure	Atmospheric pressure
Ambient temperature	Room temperature

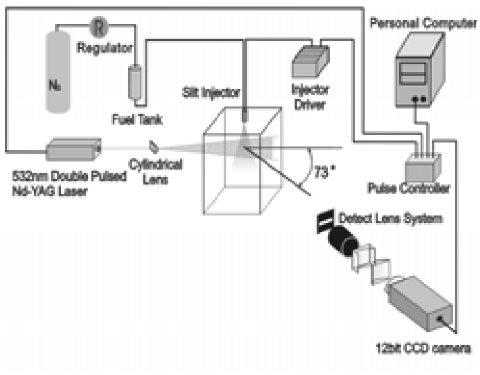
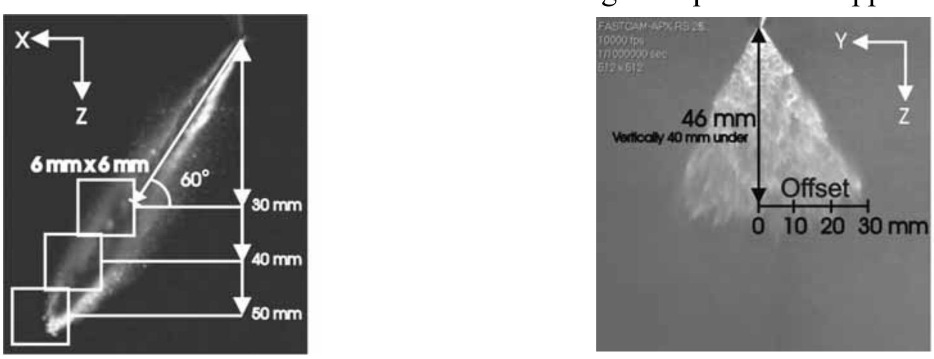


Fig. 1 Experimental apparatus



(a) (b)

Fig. 2 Measurement areas

Figure 2 shows the image captured with a high-speed camera (Photoron FASTCAM APX RS, 10000 f.p.s.). Fig. 2(a) shows the side-view of sectional photograph of the fan-shaped spray while Fig. 2(b) shows the front-view of sectional photograph captured at the nozzle center position. The measurement positions were the areas 30, 40, and 50 mm left in the perpendicular direction as shown in Fig. 2(a). Because the spray orificial angle of injector was set to 60 deg, the measurement positions where 30, 40 and 50 mm left in the perpendicular direction became the area 35, 46 and 57 mm left from the nozzle tip, respectively. Moreover, as shown in Fig. 2(b), the authors made measurements in three points that are offset from the nozzle center section by 10, 20 and 30 mm. The measurement timing was adopted the time when the tip of spray enters the area, namely, the time was 550 μs after the start of injection in the area of 30 mm left in the perpendicular direction, 750 μs after SOI in the area of 40 mm left and 1100 μs after SOI in the area of 50 mm left. The measurement area size was set to 6 mm × 6 mm.

4. EXPERIMENTAL RESULTS AND DISCUSSION

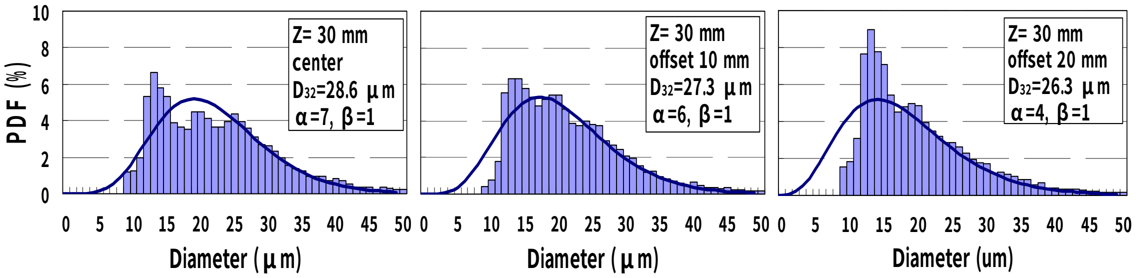
4.1 Droplet Size Distribution

Figure 3 shows the change of droplet-size distribution with a various amount of offset from the center. The figure shows the droplet-size distribution at the position where 30mm left from the nozzle tip in the perpendicular direction. These distributions were measured in three different areas, the section of nozzle center, offset 10 mm and 20 mm. The droplet-size distributions were indicated as P.D.F. The values of Sauter mean diameter (SMD: D_{32}) under each condition are indicated in figures. SMD has become slightly small with increasing the amount of the offset and going outside spray. While the amount of offset increasing and going outside the nozzle center section, the shape of the droplet-size distribution has shifted to small diameter side, decreasing the number of droplets with large diameter. It was considered that the atomization was promoted in the early stage by the shear with surrounding gas because the outside area was far from the nozzle tip than the nozzle center area and the droplet velocity in outside of the fan-shaped spray was fast as will be indicated.

Moreover, the curve-fittings of the droplet-diameter distribution were carried out for the measurement results. In the figure, solid line is a curve fitted result using Nukiyama-Tanasawa's droplet-diameter distribution function [4]. Equation (3) describes the droplet-size distribution function proposed by Tanasawa [7].

$$\frac{dn}{n} = Ax^{\alpha}\left(-Bx^{\beta}\right)dx \qquad (3)$$

Usually, it is recommended that β is 1.0 when Nukiyama-Tanasawa's droplet-diameter distribution function of the liquid spray is calculated [12]. Thus, curve-fittings were made with changing α as a parameter, while β was fixed at 1.0. The curve-fittings were carried out corresponding to the droplet-distribution of larger droplets. As a result, the curve-fittings are able to correspond to the droplet-distribution at large droplets side though the agreement of the curve on the small droplets side is not good. The mode diameter becomes small with going away from the nozzle center in Nukiyama-Tanasawa's droplet-diameter distribution function. It can be confirmed that the droplet-distribution shifts to small diameter side by number of large droplets decreasing with going away from the nozzle center. The droplet-distribution cannot be fitted on small diameter side, because number of detected fringes of small droplets was a little compared with large droplets and the margin of error was large, and small droplets by the last spray remain though sprays were injected continuously by 1Hz.



Solid line: curve fitting using Nukiyama-Tanazawa's droplet-diameter distribution
Bar graph: measured PDF of droplet diameter
Fig. 3 Normalized droplet-size distributions at z=30 mm

4.2 Relation between Diameter and Velocity of Droplets

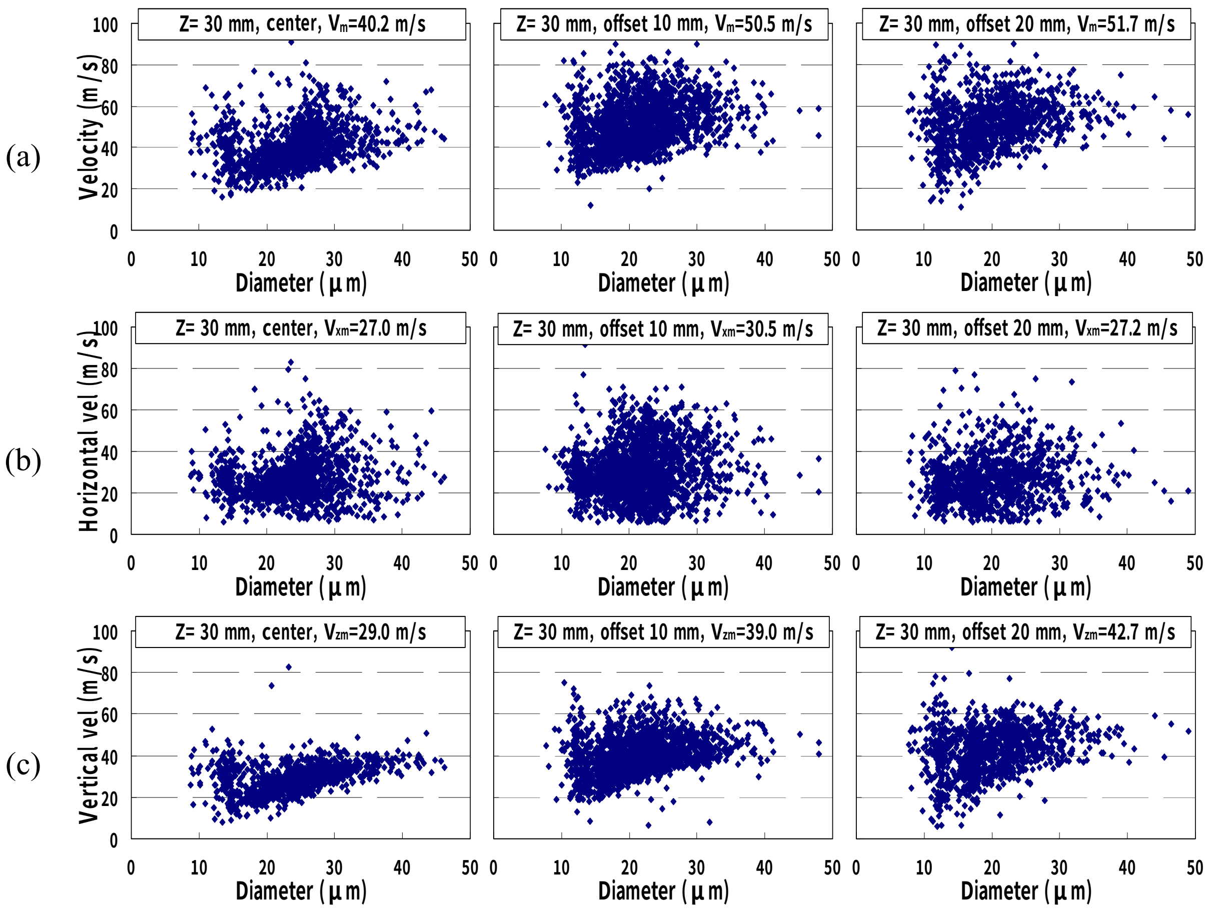


Fig. 4 Relations between diameter and velocity at z=30 mm

Figure 4 shows the correlation between the droplet diameter and velocity. First three graphs of Fig. 4 (a) are the diameter-velocity correlations on three conditions with different amount of offset at the position of z=30 mm. V_m shows an arithmetic mean velocity of droplets. As shown in these graphs, V_m increased with going outside from the nozzle center. Under each condition, the velocity of small droplets is scattered while the unevenness of the velocity of large droplets is small and the velocity of large droplets is close to V_m. The large diameter droplets with strong inertial force have a speed close to V_m, however, small droplets which experienced atomization may receive a strong influence of turbulence. Thus, small droplets indicate a large velocity distribution.

The velocity measured at the position of z=30 mm was divided into the velocity components of horizontal and vertical directions, and the correlation between the horizontal velocity, V_{xm}, or the vertical velocity, V_{zm}, and the droplet diameter are shown in Fig. 4 (b) and (c) respectively. A strong correlation was not found between the horizontal velocity and the droplet diameter. On the other hand, there is a tendency similar to the case of (a) in the correlation between the vertical velocity and the droplet diameter. Small droplets have various velocities, while large droplets indicate a small unevenness. In addition, V_m increases with going away from the nozzle center section. From these results, it was found that the vertical velocity strongly influences the correlation between the droplet diameter and the velocity.

5. NUMERICAL CALCULATION

5.1 Calculation Conditions

A fan-shaped spray was calculated with DDM by using detailed numerical calculation result of the internal flow in the nozzle using VOF model. Under the same condition as the experiment, the velocity of spray calculated with VOF model was assumed to be the initial condition of DDM. An initial velocity was about 150 m/s. The spray angle (fan-side) was assumed to be 60 deg as well as the experiment. The fuel that injected from the slit-type injector forms a liquid film and becomes a liquid column, and takes atomization processes of droplets [11]. The liquid film length was assumed to be 1.5mm from the experimental result, and it was assumed that the drag force does not work in this region. In this way, the authors imitated the liquid film. Wave breakup model [9] was used as the breakup model in the liquid film part, while TAB model [10] was used in the droplet part downstream. Nukiyama-Tanasawa's droplet-diameter distribution function (α=2, β=1) was used for the droplet size distribution after droplets were divided. Table 2 shows the conditions of calculation. The ambient pressure was set to the atmospheric pressure as well as the experimental conditions while the ambient temperature was set to the room temperature. The timing when 550 ms after start of injection was chosen as the condition of comparisons with experimental results. SMD of droplets in the position of z=27~33 mm was calculated. In Cases1~3, the initial droplet size was assumed to 150 μm that is the thickness of nozzle orifice. In Case6, the droplet film thickness was assumed to 150 μm and 37.5 μm, which was deduced by in-nozzle flow results using VOF model. The oval body model [5] was used for the drag force model. Fuel was assumed non-evaporative and the calculation was performed without droplet collision model.

5.2 Calculation Results and Discussion

The spray shapes at 550 μs after start of injection in each condition are shown in Fig. 5. The overall SMD and SMD of droplets at z=27~33 mm are shown in Fig. 6. The effect of coefficients in the breakup models was examined in Cases1~3. In Wave model used for calculation of break-up in the liquid film region, there are a coefficient B_0 to calculate the droplet diameter after breakup and a coefficient B_1 to define the breakup time. TAB model used for the breakup in the droplet region has a coefficient K to calculate the droplet diameter after breakup. Among these three coefficients concerning the breakup, the coefficients B_0 and K relate directly to the droplet diameter. As the coefficient K in TAB model was changed, there was little change in the spray shape between Case1 and Case2. However, Overall SMD decreases from 42 μm to 19 μm in these cases. The coefficient B_0 in Wave model was changed from 1.0 to 0.85 in Case3. The influence on the spray shape was small.

Next, the initial liquid film thickness was changed in Case 4 and Case 5. There was little influence on the spray shape. However, it was found that the overall SMD decreased to 19.12 μm→15.89 μm→10.5 μm proportionally as the liquid film thickness decreased to 150 μm→ 112.5 μm→75 μm.

In Case6, the result of VOF of the liquid film thickness was used. There was little influence on the spray shape. Fig. 7 shows the spatial distribution of SMD in horizontal direction at z=30 mm. The experimental result was also indicated in the figure for comparison. Compared with the experimental result, it was found that droplet size was evaluated larger in the calculation result. But the tendency that the droplet diameter became small with going away from nozzle center was reproduced. It will be necessary to examine these models further in the future.

Table 2 Conditions of numerical calculation

		Case1	Case2	Case3	Case4	Case5	Case6
Wave model	B_0	1.0	1.0	0.85	1.0	1.0	1.0
	B_1	20	20	20	20	20	20
TAB model	K	5/6	1.0	1.0	1.0	1.0	1.0
Liquid sheet thickness	h [μm]	150	150	150	75	112.5	VOF

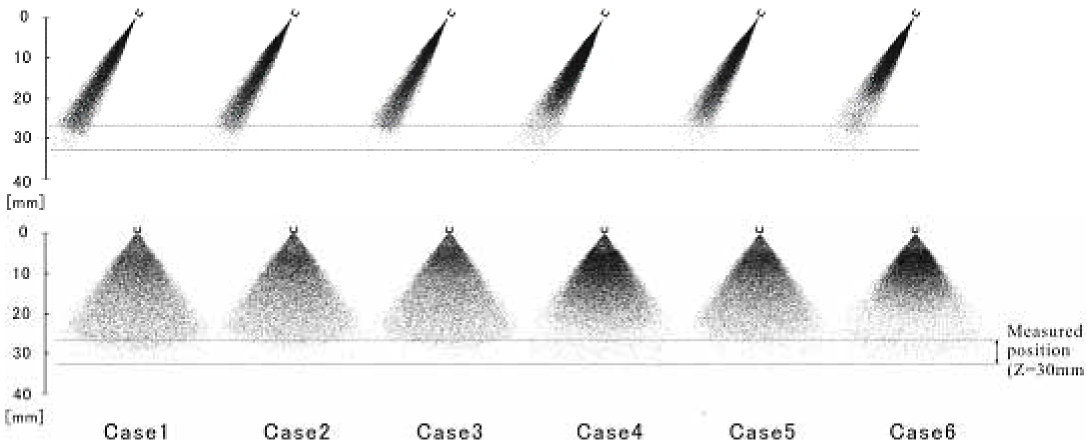


Fig. 5 Shapes of sprays obtained in calculations (t_{inj}=550 μs)

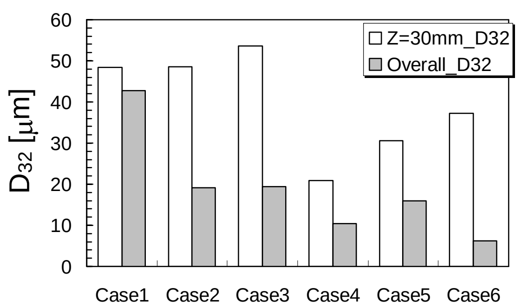


Fig. 6 Calculated SMD in each cases

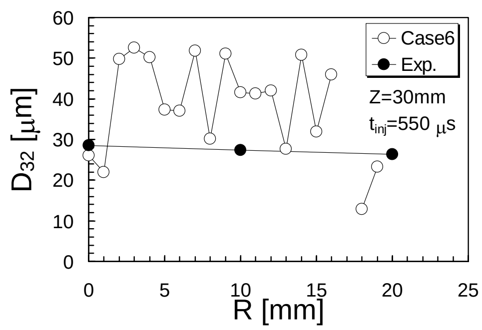


Fig.7 Correlation of amount of offset and SMD

6. CONCLUSIONS

(1) SMD of droplets becomes small with going from the nozzle center section to the outside because atomization is promoted by the shear with the surrounding gas.
(2) The arithmetic mean velocity in the outside of fan-shaped spray is faster than that in the nozzle center section. However, this tendency is not clear in the downstream region.
(3) The velocity of small droplets is uneven and largely scattered while the unevenness of velocity of large droplets is small and the velocity of large droplets approaches to the arithmetic mean velocity.
(4) A numerical calculation was carried out in the same condition as the experiment. As a result, SMD has become small with going away from the nozzle center section that is the same tendency as the experiment.

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