Determination of Droplet Size Distribution and Volume Density Distribution in High-Concentration Jet Sprays Using Bi-Directional Light-Scattering Image Processing Method

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ABSTRACT

A new technique which combines the forward and backward light scattering method and an image processing method has been developed by one of the authors to measure high-concentration jet sprays. The distributions of droplet size and volume density in jet sprays are obtained by this technique from two photographs of forward and backward scattering intensities of spray injected in the collimated pulsed laser light.The method is demonstrated for measurement of Diesel fuel sprays under various injecting conditions. The distributions of the injected fuel volume obtained by this technique are compared with those calculated simply from injection rate and injecting velocity. It is recognized that this technique is very effective to measure distributions of droplet size, volume density and behavior of high-concentration spray under various operating conditions.

1. INTRODUCTION

The measurement of the time history of both the droplet size and number density in jet sprays is important to accurately assess the rate of evaporation or condensation and to diagnose the combustion in engine. Numerous methods have been employed for such purposes. The holographic technique or light scattering counter method or Fraunhofer diffraction method has been used to measure low-concentration sprays. In reality, the fuel is sprayed into a combustion chamber with the length less than 100mm. In such cases the spray is not much diffused, and its density becomes thicker. Therefore the techniques are not suitable for accurate measurements of the spatial distribution and timewise variation of the droplet size and number density in dense sprays.

A new technique using Bi-directional light scattering image processing has been developed by one of the authors to measure high-concentration jet sprays.[1] The principle of the optical method and the means of calibration of droplet size and volume density of spray have been described.[1,2] The present work applies to determine and to analize the time history of the spatial distributions of the droplet size and volume density along the entire passage of jet sprays. The comparison of the measured results for the distributions of droplet size and volume density in Diesel sprays by this method and by injection rate method is presented.

2. Experimental Apparatus and Procedure

Fig.1 shows a schematic diagram of an optical recording system and an image processing system. A Diesel fuel (No.2 Kerosine) was injected into the open atmosphere through an injector which was operated by Bosch P-type injection pump with 12mm-diameter plunger. The injector had four 0.39mm diameter nozzles with an opening pressure of 21.6 Mpa. Tests were conducted at two pump speeds: 500 and 1200rpm. The fuel injection rates were 120.0 mm^3/ stroke at 500 rpm and 135.0 mm^3/ stroke at 1200rpm. Figure 2 depicts the timewise variations of the injection rate and pressure. Photographs of each jet spray were taken at every 100 μs after the fuel injection was initiated.

A 2J-output and 20n second flash time pulsed ruby laser was used as a light source. After passing through the jet spray, the forward beam propagated straight into film A as a forward light scattering photograph. The other beam was backscattered in the jet spray and propagated into film B as a backward light scattering photograph. A Kodak photographic step tablet(or gray scale) was placed in the light path over the jet spray in order to include a calibrated gray scale on both film A and B for comparing the standard of diffuse intensity. The photographic images whose photographic density was calibrated by the gray scale were then read by a microcomputer controlled CCD camera and stored in a computer disk or memory as 256x256 image frames at 8-bit density grade.

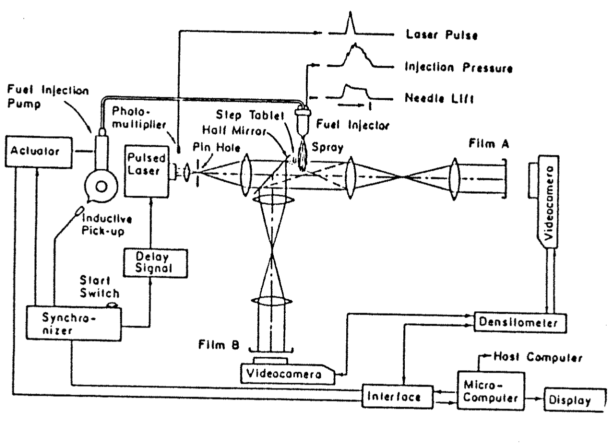

Fig. 1 Schematic diagram of apparatus

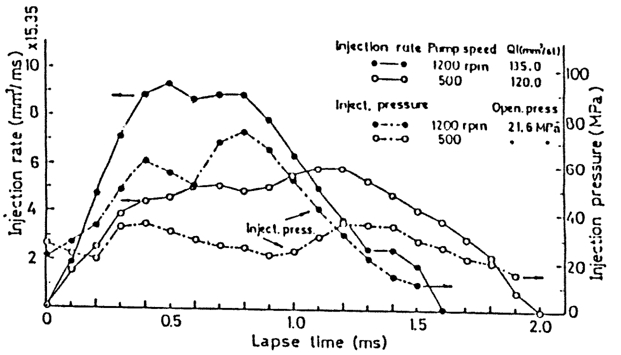

Fig.2 Time history of the injected rate and pressure

Particle size parameter α is defined as $2\pi r/\lambda$ where r is the particle radius and λ is the wavelength of the incident light. $K_s(\alpha)$ is the Mie total scattering coefficient. Let I_0 denote the incident light intensity; $n(\alpha)$, number density; ℓ, spray thickness; dx, differential length of the light passage; and R_t and R_b, collecting powers of optical system for forward and backward scattering respectively. The intensities of the forward and backward scattering can be expressed as [3,4]

$$I_t/I_o = R_t \exp\{ -\int_0^{\ell}\int_0^{\infty} K_s(\alpha)\pi r^2 n(\alpha)\,d\alpha\,dx \} \quad (1)$$

and
$$I_b/I_o = R_b \int_0^{\ell}\int_0^{\infty} S(\alpha,\pi)n(\alpha)\,d\alpha\{\exp[-\int_0^{x}\int_0^{\infty} K_s(\alpha)\pi r^2 n(\alpha)\,d\alpha\,dx]\}^2 dx \quad (2)$$

respectively.
Here, $S(\alpha,\pi)$ represents the backward scattering function and has the following relation. [4,5]

$$\int_0^{\infty} S(\alpha,\pi)n(\alpha)\,d\alpha / \int_0^{\infty} K_s(\alpha)\pi r^2 n(\alpha)\,d\alpha \propto \bar{r}_{10} \quad (3)$$

equations (1),(2) and(3) are combined to yield the average droplet radius and volume density of jet spray as,

$$\bar{r}_{10} = A_1 \frac{(I_b/I_o)}{1-(I_t/I_o)^2} \quad (4)$$

$$M = A_2\, \bar{r}_{10} \frac{[-\log (I_t/I_o)]}{\ell} \quad (5)$$

A_1 and A_2 are proportional constant.

I_t/I_o, I_b/I_o, and ℓ are determined through the image processing both the forward and backward scattering photographs with R_t and R_b evaluated by comparing the photo intensity with gray scale.

3. Measurements of spatial distributions of droplet size and Volume density

The spatial distributions of mean droplet diameter and volume density of Diesel sprays are measured as shown in Fig.3 and Fig.4 depicting the results at 0.5ms and 1.8ms after the initiation of fuel injection using a fuel pump at a speed of 500rpm. Average diameter of droplet size distribution at a distance of 5mm along the spray path from nozzle tip is about 180μm in early injecting time such as at 0.5ms after initiation of injection for the pump speed of 500rpm. The average diameter of droplet size distribution is 85μm at 25mm distance from the nozzle tip. On the top of the spray at 30mm distance, the average diameter becomes as small as the diameter of 100 μm. The average value of droplet size distribution in latter injecting spray such as at 1.8ms after initiation of injection for 500rpm at 5mm distance from the nozzle tip agrees with the value obtained at 0.5ms. At the measuring point 10mm to 25mm along the spray path from the nozzle tip, the average droplet sizes become as small as about 110 μm—160μm diameter. At over 45mm distance from the nozzle tip, the average sizes become much smaller, about 75μm diameter. The measured results for droplet size distributions for pump speed of 1200rpm have the same inclination as for 500rpm. For the measured results of the spatial distributions of the droplet sizes in Diesel sprays at both early and latter injecting time, it characterizes that the average droplet sizes show almost the same value at 5mm distance from the nozzle tip, although the volume density distributions in sprays are different from each other. As the sprays grow, experimental results show the tendency for the droplet sizes along the spray path to become smaller.

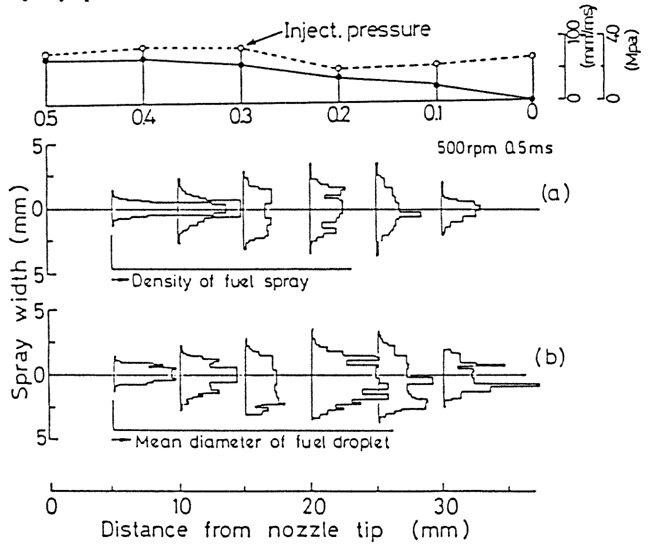

Fig. 3 Spatial distributions of mean droplet diameter and volume density of Diesel sprays at 0.5 ms after initiation of injection for 500 rpm

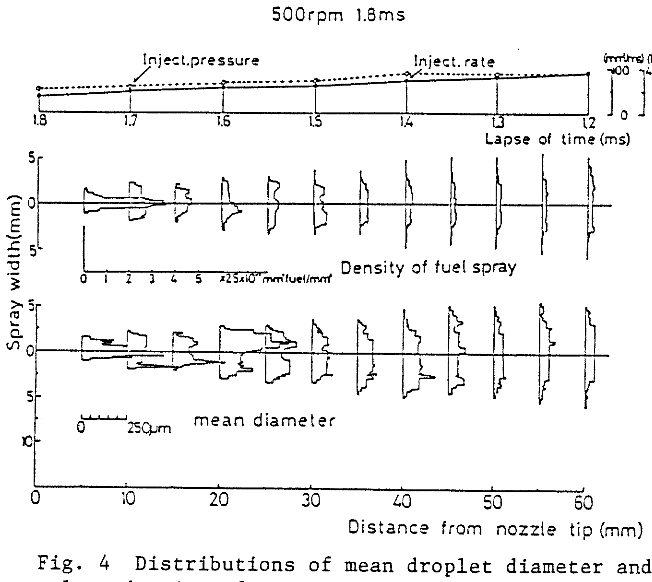

Fig. 4 Distributions of mean droplet diameter and volume density of Diesel sprays at 1.8 ms for 500 rpm

The experimental results show that the volume density in early spray at 0.5ms after initiation of injection has much higher concentration compared with that in latter spray at 1.8ms as shown in Fig.3 and 4, and that the volume densities have good correlations to injecting conditions in both sprays.

4. Spatial distribution of fuel amount of spray

4.1 The comparison with the whole amount of injected fuel obtained from the two methods

The whole amount of the injected fuel are measured by this optical method and are calculated by the injection rates under various operating conditions. Those two values obtained under the same operating condition are compared with each other. The entire sprays which are used for comparison are in the field of measuring vision, and the sprays which protrude from measuring field are not used for comparison. These experimental results are shown in Table 1.

A constant A_2 is used to calibrate the volume density in spray. The values of A_2 are compared to examine the accuracy of this optical measuring method under various operating conditions in Table 1. The constant $(A_2)_{0.6}$ is a value for pump speed of 500rpm at 0.6ms. These A_2 coincide well and have less than 20% deviations under various operating conditions. The small deviation indicates that this optical method meets the requirement for precise measurements of high-concentration sprays.

Experimental condition		Measured value			Comparison	
Pump Speed	Lapse of Time	Fuel Volume by Picture	Injected Fuel Volume		A_2 Value	$\frac{A_2 - (A_2)_{0.6}}{(A_2)_{0.6}}$
rpm	ms	$\cdot A_2$ mm³fuel	mm³	%	mm³fuel/mm³	%
500	0.5	23.1	22.4	-24.8	0.97	-3
	0.6	29.8	29.8	0	1.00	0
	0.7	36.5	37.5	+25.8	1.03	+3
	0.8	42.6	45.2	+51.7	1.06	+6
1200	0.4	30.9	28.2	-5.4	0.91	-9
	0.5	47.8	42.2	+41.6	0.88	-12

Table 1 The constant A_2 evaluated by equating the total volume of injected liquid obtained from the measured injection rates and from this method

4.2 Spatial distribution of fuel amount of spray

The spatial distribution of fuel amount of spray measured by this optical method and that assumed with injection rate and average spray velocity are compared at 5mm increment along the spray path as shown in Figures5-10. Assuming from the injection rate and spray velocity, the fuel amounts of spray are devided with the injection rate along the spray path by the average spray velocity. Figures5-8 show the comparisons with the distributions of fuel amount calculated by both methods in early injecting sprays. Fig.9 and 10 show the comparisons with that in latter injecting sprays. By using this optical method for the measurements of spray progressing, it clearly and quantitatively comes out that at the tip of the spray, the following group of droplets in spray overtake the head group of droplets by resistance of atmosphere and they accumulate at that point. Although the whole amounts of spray obtained by the two methods agree well as shown in Table 1, the spatial distributions of spray amount in early spray measured by this optical method do not agree with those empirically determined from spray velocity and injection rates. On the other hand, the fuel amount of distributions in latter sprays obtained by both methods coincides well as shown in Fig. 9 and 10. In the latter injected spray, the tip of spray comes away from the view field covering 60mm distance from the nozzle tip, and the portion of spray in the view field moves in the air flow accelerated by the preceding spray droplets, and the resistance of atmosphere decreases, and it is assumed that the following droplets in spray will move with near average velocity of preceding droplets. Therefore, the fuel amount distributions in the latter spray coincide with those disposed from injection rates in the view field near the nozzle tip. Under the operating condition as shown in Fig.9. and 10, the entire value of fuel amount obtained by both methods differs less than about ±15%.

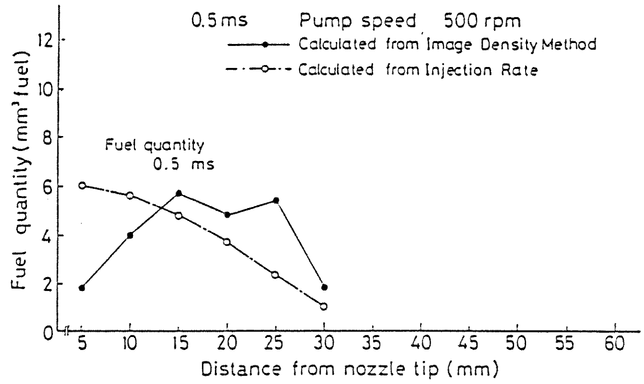

Fig. 5 The comparison with the distribution of fuel amount calculated by two methods at 0.5 ms

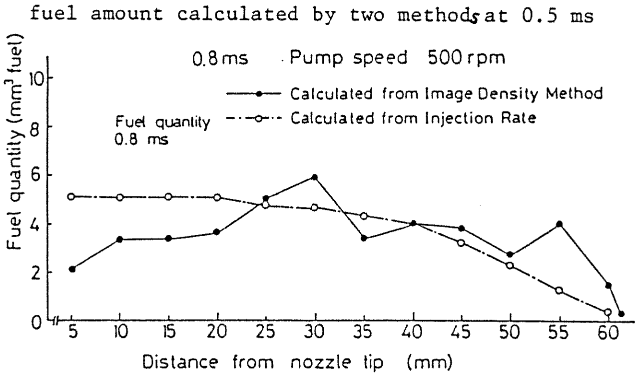

Fig. 6 Distribution of fuel amount at 0.8 ms for 500 rpm

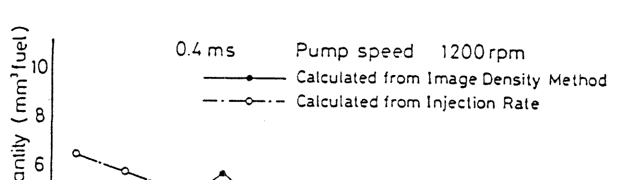

Fig. 7 Distribution of fuel amount at 0.4 ms for 1200 rpm

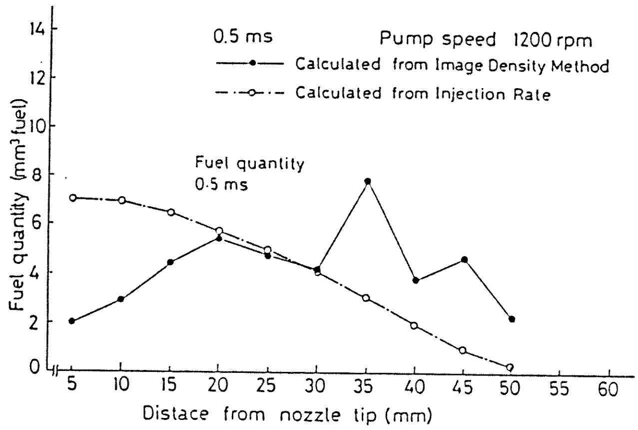

Fig. 8 Distribution of fuel amount at 0.5 ms for 1200 rpm

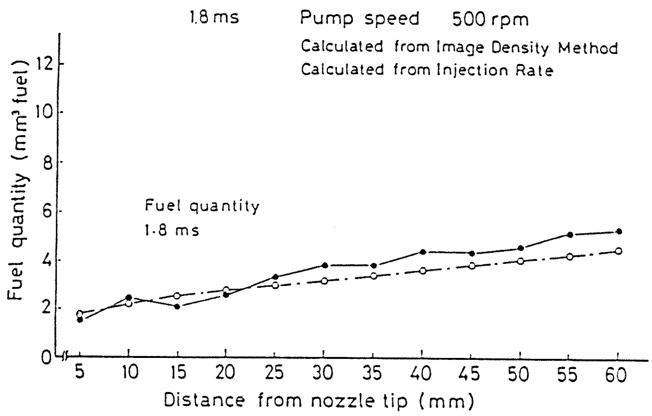

Fig. 9 Distribution of fuel amount at 1.8 ms for 500 rpm

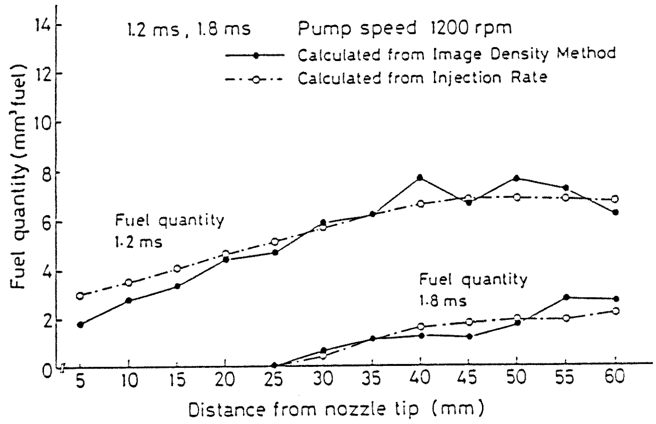

Fig. 10 Distribution of fuel amount at 1.2 ms and 1.8 ms for 1200 rpm

5. Spatial distributions of volume density

5.1 Average volume density distributions in the early spray

The average values of the volume densities in the early spray at 0.4 ms — 0.8 ms after initiation of injection for pump speed of 500 rpm are obtained along the spray path from the nozzle tip as shown in Fig. 11. The measured results indicate that the head of the spray has higher density at every injecting time, that the volume density is given quantitatively and that the influence of the air resistance at the head of spray cleary comes out. In the case that the volume density in spray at a distance of 5 mm from the nozzle tip is compared with each of the volume densities at 0.4 ms — 0.8 ms after initiation of injection for 500 rpm pump speed, the comparison indicates that the changes of the volume densities correspond to the changes of injection rate and injection pressure as shown in Fig.2. The measured results of volume density indicate that the volume density near the nozzle tip becomes higher in propotion to increase of injection rate and decrease of injection pressere.

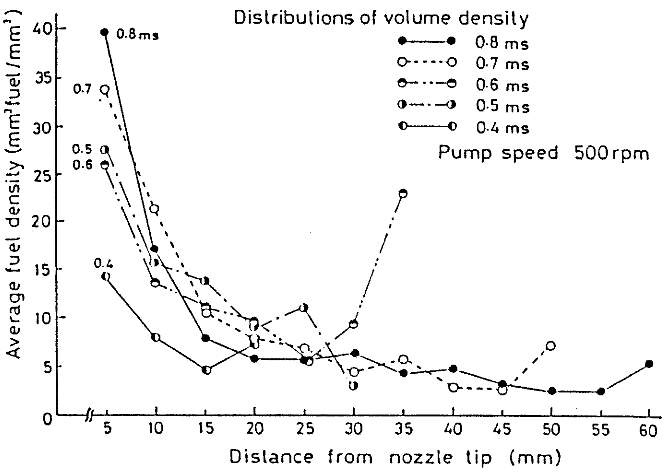

Fig. 11 Volume density distributions in the early spray

5.2 Change of the volume densities in sprays all through the elapsed time

The distribution of volume densities measured for the tipical spray,that is, the early, the middle and the latter sprays in the view field near the nozzle tip, is compared with each other as shown in Fig. 12. In that Figure, the widths and densities of spray measured simultaneously are presented. The experimental results show that the volume densities

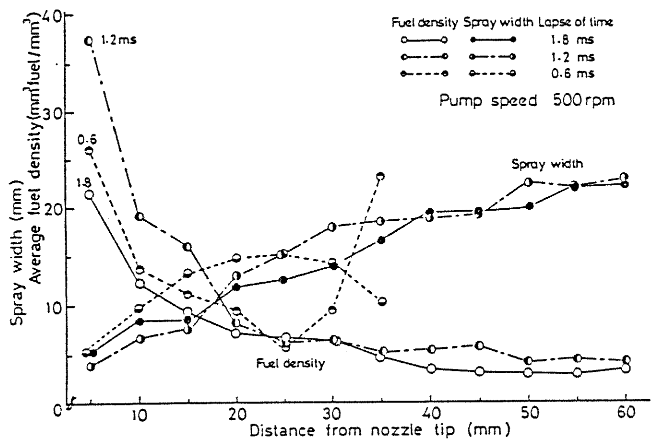

Fig. 12 Change of the volume densities in spray all through the elapsed time

of each spray at a distance of 5mm from the tip of nozzle are arranged in order of magnitude at 1.2ms, 0.6ms, and 1.8ms after initiation of injection. The magnitude of the average values of the volume densities is approximately proportional to the magnitude of the injected fuel amount during 0.1ms calculated from injection rate curve as shown in Fig.2.

6. Conclusions

The spatial distributions of the mean droplet diameter and volume density in high concentration jet sprays are determined by the Bi- Directional Light-Scattering Image Processing Method. It is concluded that

1. The instantaneous and spatial distributions of droplet size and volume density of spray are quantitatively determined in Diesel sprays.
2. The mean droplet diameters of spray in the region close to the nozzle tip are large,but,the mean diameters in the same region become smaller as the spray progresses.
3. Mean droplet diameters in the spray which has low density at the latter injecting time are small and these show nearly constant values at each increment apart from the nozzle tip along the spray path.
4. In the case that the whole sprays are in the field of vision, the whole amounts of spray measured by this image processing method agree well with those calculated from injection rate under various operating conditions of sprays.
5. The distribution of fuel amount of spray along the spray path measured by this image processing method does not agree with those calculated from injection rate and velocity in the early spray, but agree well in the latter spray.
6. It is quantitatively detected from the measured results of spatial distributions of spray density that the density in the tip of spray becomes large by air resistance.
7. Density of spray close to the tip of nozzle has a good correlation to the change of injection rate and pressure.
8. The characteristics of spatial distributions of volume density in the spray of the early, the middle and the latter injection are clearly detected by this image processing method. The value of the volume density close to the nozzle tip in these injecting time has good correlation to injection rate.

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