2-D Spatial Distribution of Droplets in a Diesel Spray by Means of Direct Photography with Super High Resolution

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Abstract

It has been very much significant information of droplets in a dense diesel spray to increase in the energy saving and to reduce the engine out emissions, for example, particulate matters and NOx. The authors have been took the information of droplets size in a dense diesel spray by means of direct photography from 1970s. The droplets were captured and their size was measured on an analogue film not by the techniques of LDA and PDPA which caught only the information of a single droplet. However, it was able for the direct photography to detect the droplets only at the spray envelope where the droplets density was small not at the dense region. It is just the weak point of this technique. The authors proposed the new lens system and applied to a diesel spray by use of an analogue film with large size. They succeeded to measure the droplets size even at the dense region. The first results were presented at ICLASS 2006 in Kyoto. This paper describes the other lens system developed which takes smaller droplets than the former one. The limit of droplet diameter measured of the old lens system is 10 [μm] and that of the new one is 5 [μm]. The experiments were carried out in a constant volume chamber where the atmosphere was high pressure at room temperature by use of both lens systems. The objective spray was formed through the pilot injection which has applied to an actual diesel engine to correspond to the severe regulation of exhaust gas. As a consequence, the vortex structure and the distribution of droplets diameter are made clearer than that captured by use of the old lens system.

Introduction

The techniques to catch the droplets in a spray are LDA, PDPA and ILIDS (Interferometric Laser Imaging for Droplet Size) [1]. The first and the second take only the spot information of a spray and the last is applied only to a thin spray like a swirl type nozzle for a gas turbine. Consequently, it is impossible for these techniques to apply to a dense diesel spray. The other one is to utilize the direct photography. It is capable of taking the droplets information in more area of a diesel spray than that obtained by a CCD camera when the telescope system and an analogue film with large size are applied to this kind of spray.

One of authors measured the droplets in a diesel spray injected into a high pressure chamber during the injection period in 1979 for the first time in the world [2]. The slit where the lens system of telescope was set was inserted in the chamber and the droplets were taken photograph of 35 [mm] film. Figure 1 displays one of examples [2], [3].Unfortunately, it was able for this technique to catch droplets at the spray envelope, that is, the mixing flow

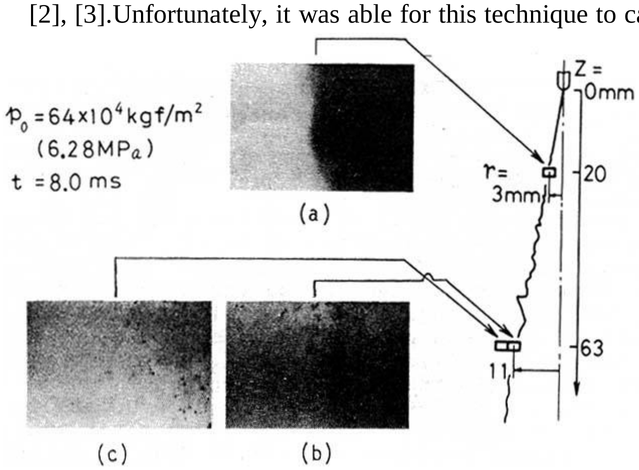
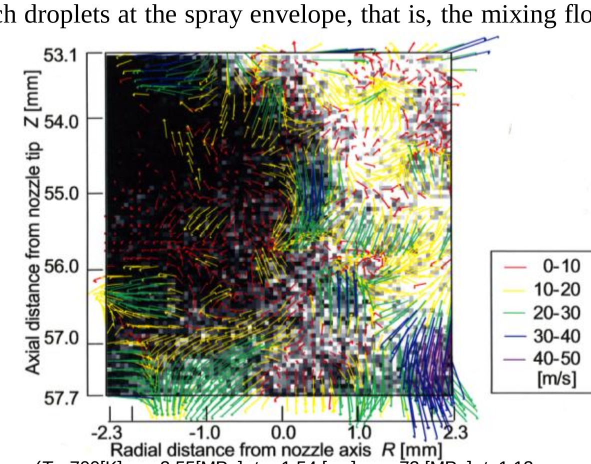


Fig. 1 One of examples of droplets photographs of a diesel spray [2], [3]



(T_a=700[K], p_a=2.55[MPa], t_{inj}=1.54 [ms], p_{inj}=72 [MPa], t=1.12 [ms], Z=55-62.5 [mm], R=-2.5-2.5 [mm])

Fig. 2 One of results of distribution of velocity vector in an evaporating diesel spray [3], [9]

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region [3], [4] and not to take them at near the nozzle exit, that is, the initial part [3], [4] and at near the spray axis, that is, the main jet region [3], [4]. This is just the limit of this technique. The other one of authors published the droplets size through a hole nozzle and a throttle nozzle on a 35 [mm] film by use of nano light [5] and Miwa et al. [6] took photographs of an evaporating diesel spray on a 35[mm] film by use of nano spark light unit and telescopic lens assembly. However, the resolution of droplets was not always good in all the data mentioned above.

The other important data of a diesel spray is the vortex structure which generates accompanying the development of spray. One of authors measured this kind of structure applying PIV technique [7] to a non-evaporating diesel spray and an evaporating spray [8], [9]. Figure 2 is one of examples. However, it is not necessary clear the scale of vortex although its existence is definite.

The authors proposed the lens system with high spatial resolution (LHSR) as shown in Figure 3 to solve the problems pointed out above [3], [10]. The essential point was to set the speckle reduction device (Nanophoton: SK-11, ϕ10 [mm]) and to use an analogue large sized film. As a result, the photograph of droplets was very much clearer than those in the previous experiments as displayed in Figure 4. The limit of the smallest droplet measured reached 10 [μm] and the depth of field was 205 [μm]. It was just the extinguished results.

This paper describes the new lens system to spread the minimum droplet diameter measured, that is, 5 [μm] and discusses the relation between the droplet distribution and the vortex structure. The system was applied to a non-evaporating diesel spray of pilot injection.

Experimental Setup, Procedure and Condition

New lens system

Figurer 5 illustrates the new lens system with super high resolution (LSHSR). It is composed of the objective lenses, the iris diaphragm whose role is to avoid the pass of the light with large aberration and the imaging lenses. All the lenses were made by coating for all the wave lengths, thus, the smallest droplet diameter was 5 [μm] which was a half of that of LHSR. Its length is about a one fifth and the depth of field is 100 [μm] which is abut a half against LHSR [3], [10]. The magnification is ranged from 2.7 to 5.0 which are almost the same as that of LHSR. The droplets information is assessed by the equivalent droplet diameter, D, and the relative dispersion degree, L/L_o where L is the aspect ratio of droplet and L_0 means the degree of dispersion of a perfect round droplet [3],[10]. It was selected under1.2 in the data processing. L/L_0 was set 1.5 in the case of LHSR

The flow of the image processing is as same as that of the old lens system [3], [10]. The image was scanned by a film scanner (EPSON: GT-X970), the information was transferred into the CPU and was analyzed by the software developed by the authors. The input resolution was 1.85 [μm/pixel] in the case of LHSR and 0.98 [μm/pixel] in that of LSHSR. It is the problem when the faded droplets existing out of the depth of field become the obstacle against the accurate measurement of droplets size existing in it. The answer is to adopt the averaged gradient of brightness (*AGB*) [11]. The transparent glass beads with different diameter were taken by the photography through both lens systems to decide *AGB*. The field of image processing was -50 [μm] to 50 [μm] in the case of LSHSR and was -100 [μm] to 100 [μm] in the case of LHSR from the focal plane. Figure 6 is the results. The blue dashed line is the minimum bead size of 5 [μm] of LSHSR and the red one is that of 10 [μm] of LHSR. The droplet processing region is the blue zone and the green one which is extended by the new lens system.

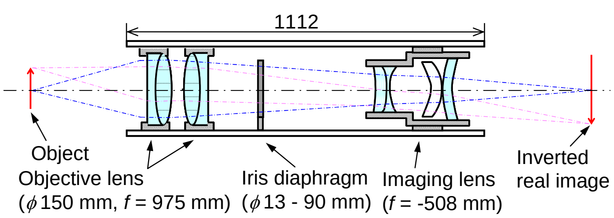


Fig. 3 Lens system with high spatial resolution(LHSR)[3], [10]

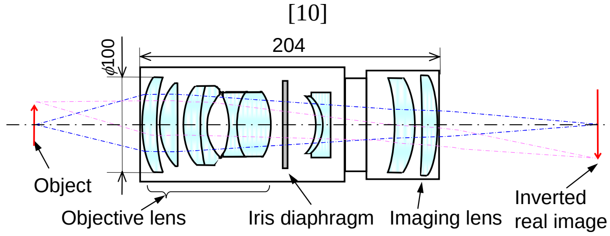
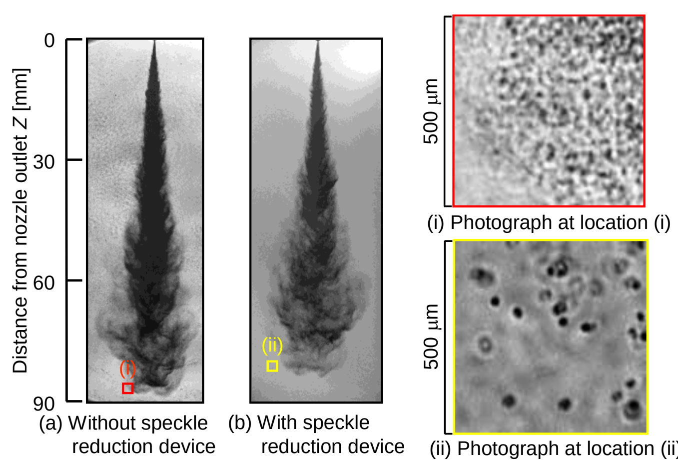


Fig. 5 Lens system with high super high spatial resolution (LSHSR)



(p_{inj} = 77.0 [MPa], ρ_a = 17.3 [kg/m^3], at end of injection, M = 2.7)

Fig. 4 Effect of speckle reduction device [3], [10]

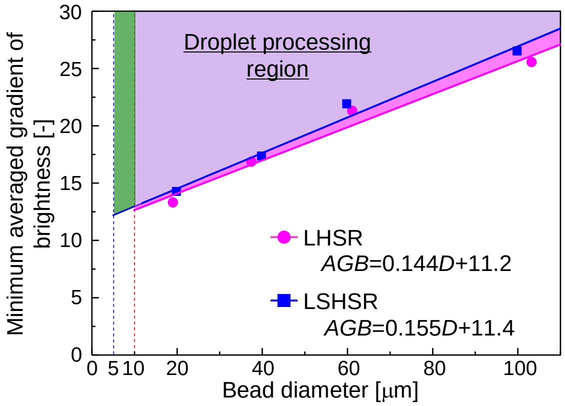


Fig. 6 Relation between bead diameter and minimum averaged gradient of brightness of bead

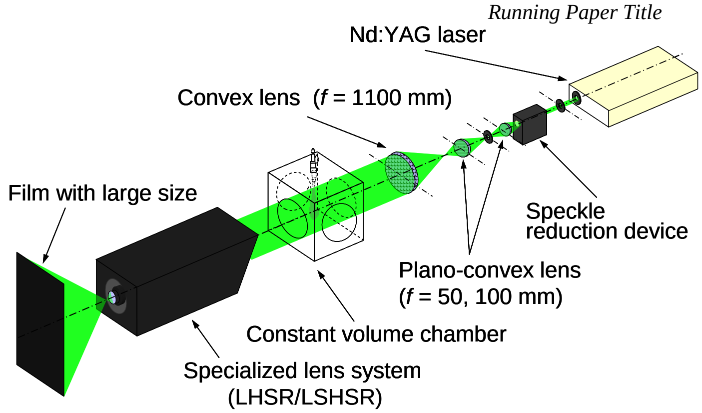


Fig. 7 Optical setup [3], [10]

Table 1 Experimental conditions

Fuel oil			n-tridecane	
Ambient gas			CO_2	
Ambient temperature	T_a	[K]	room temperature	
Ambient pressure	p_a	[MPa]	2.0	
Ambient density	ρ_a	[kg/m^3]	39.5	
Injection pressure	p_{inj}	[MPa]	87.5	
Injection duration	t_{inj}	[ms]	0.23[1)]	0.46[2)]
Injection fuel amount	m_f	[mg]	1.76	3.67
Nozzle type			Single hole nozzle	
Nozzle hole diameter	d_n	[mm]	0.20	
Nozzle hole length	L_n	[mm]	0.80	

1) Case of LSHSR 2) Case of LHSR

Experimental setup and condition

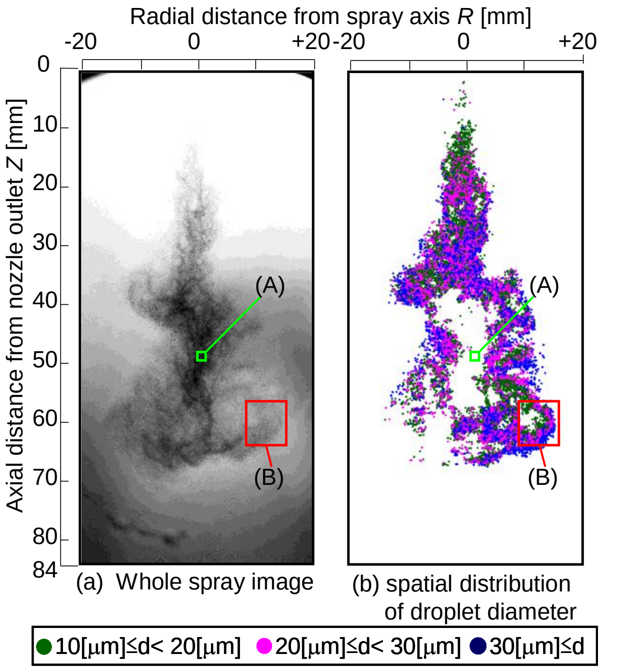
Figure 7 illustrates optical setup. The light of 2nd harmonic of 532 [nm] through an Nd:YAG laser (Spectra Physics: PIV 400, half width of oscillation: 8 [ns/pulse]) passes through a pin hole of a speckle reduction device, a plano-convex lens (*f* 50 [mm]), the other pin hole, the other plano-convex lens (*f* 100 [mm]) and a convex lens (*f* 1000 [mm]), then, it becomes parallel whose diameter is 100 [mm]. It goes into the diesel spray injected into a constant volume chamber. The spray is formed through the pilot injection. Its droplets density is leaner than that of the spray of the main injection, however, it shows the same characteristics as those of the latter. The droplets image is taken on am analogue film with large size (Kodak: TMAX100, width 202 [mm], height 254 [mm], line resolution 63 [line/mm]) after passing through the specialized system shown in Figures 3 and 5.

The chamber used was the same as that in the previous experiments [3], [10]. Its inner dimensions were 205 [mm] in diameter and 180 [mm] in height. Two sheets of artificial quartz glass were set in both sides of the chamber. The carbon dioxide was charged to elevate the ambient pressure. The ambient density, ρ_a, was set considering the gas condition in the combustion chamber in an actual engine with a super charger. The experimental conditions are listed in Table 1. The data were taken at the dimensionless time, t/t_{inj}, of 10.0 where t was the photographing timing and t_{inj} was the injection duration. The spray at this timing is too lean comparing to the normal spray during the injection duration. However, its vortex structure is almost the same as that of the normal spray [8], [9]. The magnification was 2.7 on a film.

Experimental Result and Discussion

Decision of measuring area

Figure 8 is the spray image (a) captured through LHSR and the spatial distribution of droplet diameter (b) for their diameter range, that is, more than and equal to 10 [μm] and less than 20 [μm], more than and equal to 20 [μm] and less than 30 [μm] and more than 30 [μm]. It is much clear that the vortex with large size is taken in (B). Figure 9 is the enlarged spray image (i) and the binary image (ii) of (i) at the area (A) shown in Figure 8. It is clear that the droplets density is too much and it is not distinguished among individual droplet. As a result, the white zone appears in the area (A) in Figure 7 where the droplets crowd exceeding the resolution of LHSR. Figure 10 displays the enlarged spray image (i) and the spatial distribution of droplet diameter (ii) at the area (B) in Figure 7. The individual droplet image is clear and the image of the vortex with large scale is marked in both figures. Generally speaking, the large droplets move to the spray envelope due to their large momentum, the small droplets exist inside the vortex and the droplets with medium scale locate between the large ones and the small ones. It is estimated that the smaller droplets whose diameter is less than 10 [μm] exist inside the vortex, in other words, in the white area, however, it is unable to capture by LHSR. The following figures show the data in the area where it is capable of processing, that is, inside the vortex with large size.



(p_{inj} = 87.5 [MPa], ρ_a = 39.5 [kg/m^3], t= 0.43[ms], t/t$_{inj}$= 10.0)

Fig. 8 Spray image and distribution and spatial distribution of droplet diameter (LHSR)

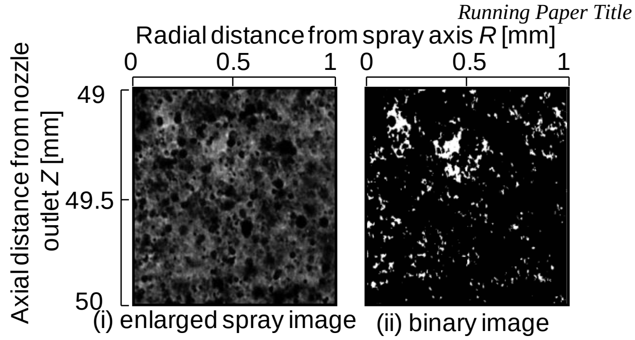


Fig. 9 Enlarged spray image and binary image at area (A) in Fig. 8

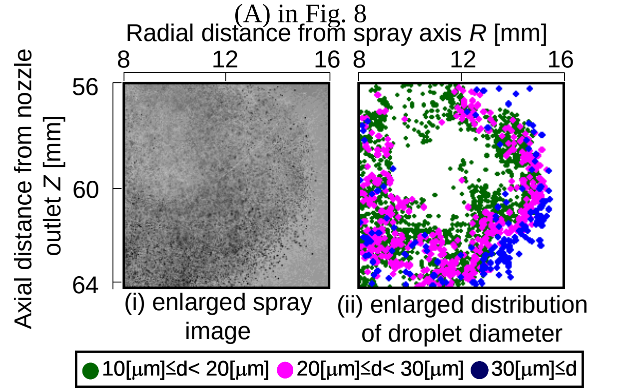


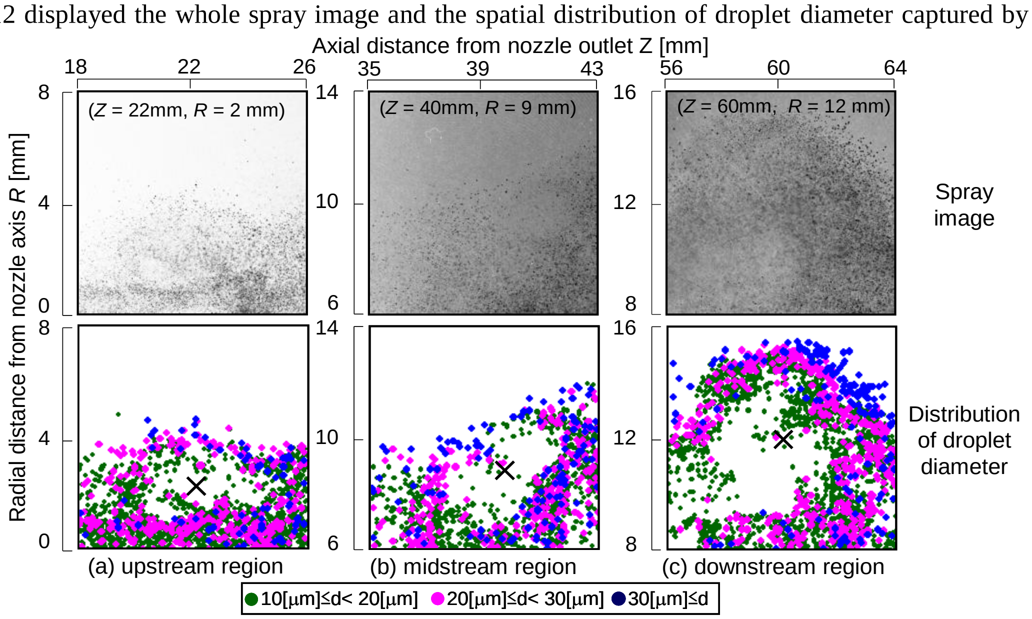
Fig. 10 Enlarged spray image and binary image at area (B) in Fig. 8

Spatial distribution of droplet diameter inside vortex taken by LHSR

Figure 11 demonstrates the spray image taken by LHSR and the distribution of droplet diameter at the upstream region (i), at the midstream region (ii) and at the down stream region (iii). The black cross means the center of the vortex. The larger the vortex scale is, the farther the location from the nozzle outlet is. The nearer the location of the vortex center from the spray axis is, the nearer the measuring location from the nozzle exit is. At the downstream region the number of large droplets gathered is large comparing with the other regions. At the other region this trend is not so clear, namely, classified droplets distribute relatively uniform.

Spatial distribution of droplet diameter inside vortex captured by LSHSR

Figure 12 displayed the whole spray image and the spatial distribution of droplet diameter captured by LSHSR.



(p_{inj} = 87.5 [MPa], ρ_a = 39.5 [kg/m^3], t= 0.43[ms], t/t$_{inj}$= 10.0)

Fig. 11 Spray image and spatial distribution of droplet diameter at upstream, midstream and downstream region of spray (LHSR)

The white zone of LSHSR is smaller than that of LHSR due to the increase in the resolution. The larger droplets over 30 [μm] appears at the spray envelope, in other words, at the vortex envelope because of their larger momentum. Figure 13 is the enlarged spray image and the spatial distribution of droplet diameter in this image. It is very remarkable matter that the small size and mid size droplets distribute inside the vortex. It is the clear evidence of the existence vortices with small scale inside the vortex with large scale [8], [9].

Conclusions

The new lens system with high spatial resolution (LHSR)and that with super high spatial resolution (LSHSR) were applied a dense diesel spray by use of a large sized analogue film to make clear the spatial distribution of droplet diameter and the vortex structure. The following conclusions are drawn from the experiments:

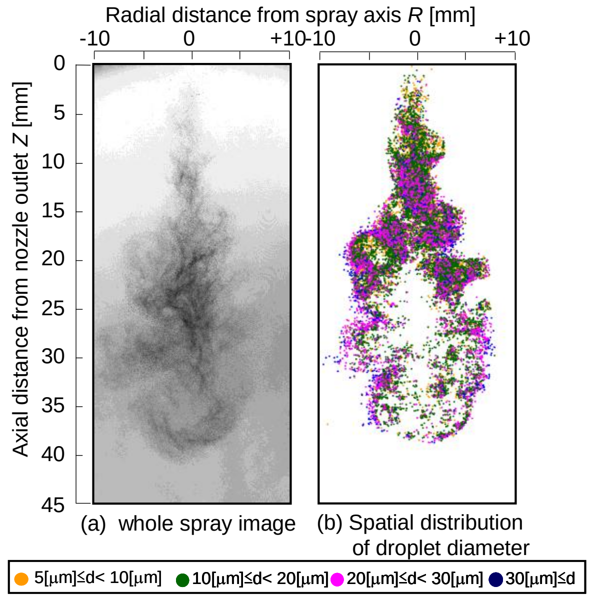
(1) It is able to catch the droplets whose diameter is more than 10 [μm] in the case of LHSR and those whose diameter is more than 5 [μm] in the case of LSHSR.

(2) The zone where droplets are not captured decreases when the resolution of lens system increases.

(3) The larger droplets gather at the spray envelope, in other words, at the vortex envelope due to their larger momentum.

(4) It is possible to catch the small sized vortices which exist inside the large sized vortex. The small droplets appear in these small sized vortices when the resolution of lens system increases.

(5) The center of vortex with large size appears at near the spray axis when this vortex locates at near the nozzle outlet.



(p_{inj} = 87.5 [MPa], ρ_a = 39.5 [kg/m^3], t= 0.23[ms], t/t$_{inj}$= 10.0)

Fig. 12 Whole image of spray and spatial distribution of droplet diameter (LSHSR)

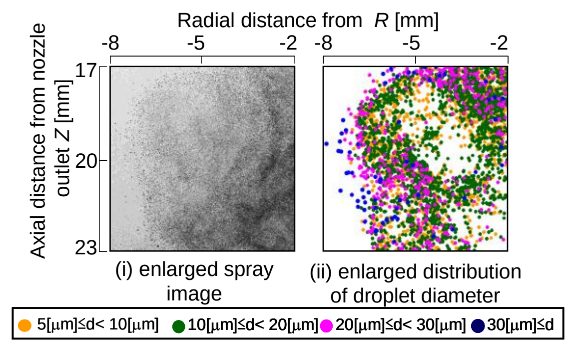


Fig. 13 Enlarged spray image and spatial distribution of droplet diameter (LSHSR)

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