Measurement of Spray Flow by an Improved Interferometric Laser Imaging Droplet Sizing (ILIDS) System

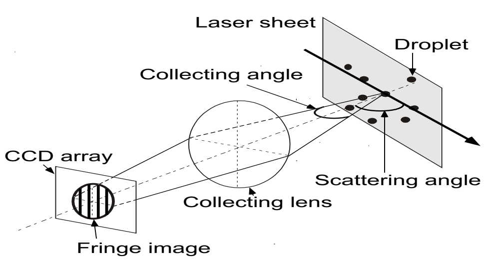
by

Toshihiro KOBAYASHI, Tatsuya KAWAGUCHI, Masanobu MAEDA

Department of System Design Engineering, Keio University,
Hiyoshi 3-14-1, Kohoku-ku, Yokohama, Japan

Abstract

This paper describes a novel technique for droplet-sizing of spray. In the field of spray analysis, various kinds of measurement techniques have been proposed. Among them the present method (ILIDS) provides instantaneous spatial distributions of droplet images in a picture as shown in the previous investigations (König *et al.* 1986, Glover *et al.* 1995, Skippon *et al.* 1996). The projected image with interferometric fringe number is correlated to its individual droplet size, the accuracy depends on the techniques used to estimate the size of the circular image and the fringe spacing as shown in Fig.1(a)(c). The previous works have employed, in this sense, high resolution photography. The present study proposes to improve this method by creating an automated system for high speed processing using high resolution CCD camera and computing system so that the validation and accurate evaluation of fringe spacing by FFT may be easily performed. Previous techniques using photographs have a disadvantage in that the fringe images overlap each other in the field where there is a higher spatial density of droplets causing the images to be defocused and enlarged in order to measure the fringe spacing. The processing system needs only line information to calculate the fringe spacing from captured images. The images were compressed optically to those of broken lines of length by defocused image and width by focused image as shown in Fig.1(b)(d). The novel technique of ILIDS receiving optics, as shown in Fig.1(b), achieves the measurements in a denser spray by avoiding overlapping of images. The accuracy of this newly developed system was about 4% for average size of 120μm droplets using a monodisperse droplet generator. The simultaneous measurement of droplet size and velocity would be possible by using a two-dimensional PIV technique.



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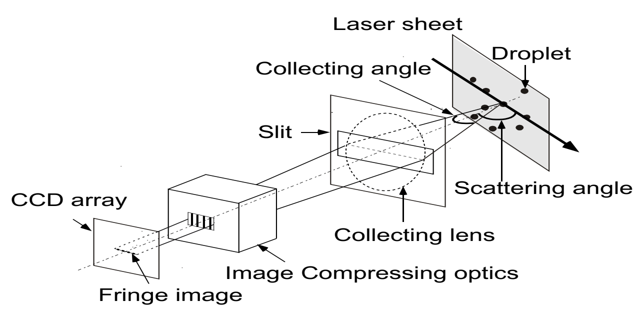

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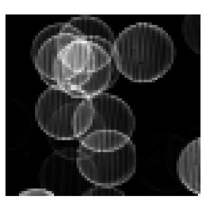

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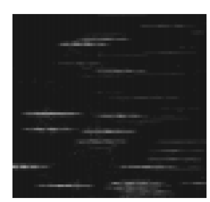


(d)

Fig.1: Basic and novel receiving optics and picture for ILIDS: (a)Classical ILIDS receiving optics, (b)Novel ILIDS receiving optics, (c)Droplet image by classical ILIDS, (d)Droplet image by novel ILIDS.

1. Introduction

In the field of spray analysis, various kinds of measurement techniques for velocity and the size of the droplets have been proposed. The most often measured properties are the velocity and the size of the droplets.

The phase-Doppler anemometry (PDA) which is an extension of Laser Doppler Velocimetry (LDV), which gives the size and velocity of individual spherical particles simultaneously, has been improved and well adapted for various applications. Several FFT based signal processing techniques for accurate velocity and size measurement have been reported (e.g. Maeda *et al.* 1988, Kobashi *et al.* 1992, Higuchi *et al.* 1994). PDA has been developed with its signal processing and determination of the size of effective measuring area and so on. Some reports illustrate that there are undesired effects due to size distribution and mass flux of droplets in order to determine the effective measuring area, namely particle size-dependent detection area, trajectory ambiguity, and slit effect (e.g. Durst *et al.*, 1994). While PDA is a point measurement technique, the imaging method (ILIDS) provides the instantaneous spatial distribution of droplets. König *et al.*(1985) showed the relation between the spatial pattern of the scattered light from the droplet and the droplet diameter in the forward scattering region based on the Mie Scattering Theory. Hesselbecher *et al.*(1991) showed the equation for the diameter and the angular fringe spacing by geometrical optics. The spatial scattered pattern is generated mainly by the interference of reflected and refracted light from the droplets.

The current technique was further improved by Glover *et al.*(1995) and others(Skippon *et al.* 1996, Hess *et al.* 1998, Pajot *et al.* 1998) who analyzed the features of the scattered light around forward regions and applied it to spatially sparse sprays. Although their imaging technique successfully obtained the diameters of droplets from a single image, the denser part of the spray flow has hardly been investigated. The present study attempts to improve the (ILIDS) technique into an automated precision measuring system by employing a high resolution CCD camera and computing system. To make the system applicable to denser spray flow fields, the optical system was set so that the captured images were not overlapping allowing easy electronic acquisition.

2. Principle

2.1 Theoretical background

The laser sheet illuminated the spherical droplets in flow-field. The reflected (order p=0) and refracted light(order p=1) from the droplet is dominant in the wide-angle forward-scatter region, around 30 deg. to 80 deg.. The interferometric Laser Imaging Droplet Sizing (ILIDS) technique is based on the number of fringes in the interference image, made by these scattering lights.

At a view angle in off-axis alignment, scattering angle θ, two components of the scattered light appear to emanate from small spots. The two spots are observed as glare points (Fig.2) on the focal plane. From the spacing between the spots, the droplet diameter is determined (Van de Hulst *et al.* 1991). However, because of the lack of resolution and the necessity of magnification, it is not effective for real flows. On the non-focal plane, the two rays interfere each other and the regular fringes are easily observed, and their origin can be understood in terms of a simplified geometric theory. The fringe spacing is proportional to the droplet diameter, and if a set of fringes can be observed for individual droplets, they provide a potentially accurate measure of droplet diameter. Gréhan *et al.*(1998) calculated the adequate defocus length, since defocus length is necessary for doing image plane far-field.

König *et al.*(1986) describe a method for measuring the size of single droplet and the angular fringe spacing as a function of droplet size so that the particle size measurement might become independent of the absolute light intensity and only the real part of the refractive index has to be taken into account. The function (provided below) relates the number of fringes and particle diameter. It is easily expressed via the phase difference between two rays. Roth *et al.*(1991) showed the angular inter-fringe spacing $\Delta\theta$ is linked to the droplet diameter, and

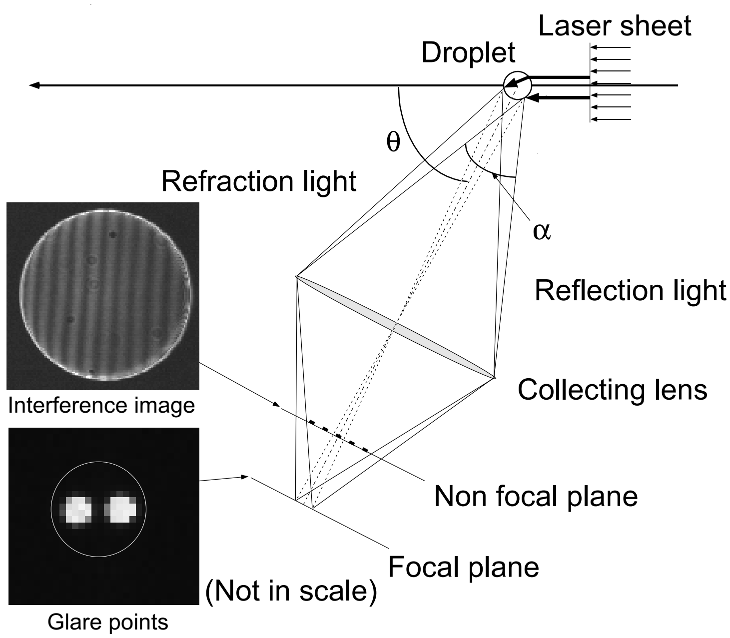


Fig.2: Basic configuration of ILIDS.

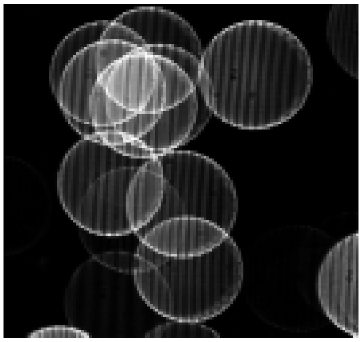
Pajot *et al.*(1998) described the relationship between diameter and the number of fringes as below function.

$$d = \frac{2\lambda N}{\alpha} \frac{1}{\cos\frac{\theta}{2} + \frac{m \sin\frac{\theta}{2}}{\sqrt{m^2 + 1 - 2m\cos\frac{\theta}{2}}}} \tag{1}$$

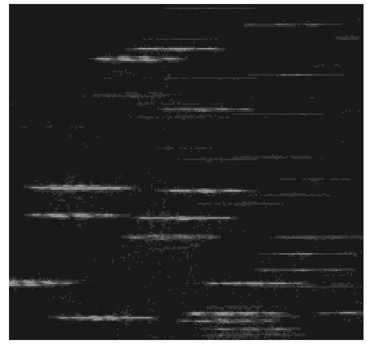
where; d is the droplet diameter, N is the number of fringe, θ is the scattering angle, α is the collecting angle(equal to $N \times \Delta\theta$), $\Delta\theta$ is the fringe space, λ is the wavelength, and m is the refractive index of water.

Equation(1) is derived from geometric analysis. Van de Hulst(1957) showed that reasonable agreement between the geometric analysis and the full Lorenz-Mie theory is generally obtained for values of $\chi = \pi d/\lambda >$10 to 20, provided that the refractive index of the droplet differs significantly from its surroundings and that rays close to grazing incidence and those close to the rainbow angles are not involved. In our case, for $\lambda = 532$nm, the lower limit is approximately 2μm. If a set of fringes can be observed, droplet size can be obtained from Eq.(1).

A picture using ILIDS is presented in Fig.3(a). In the picture, the image size of each droplet is the same and different numbers of fringes are observed. The number of fringes on each droplet image determines the droplet size. The circular fringe images are overlapped in a higher particle density region. Here, the evaluation of the individual droplet images is difficult due to the number of fringes. Thus, ILIDS is readily applied to denser sprays. By employing the receiving optics shown in Fig.4 in the next subsection, we can detect the number of fringes more easily in denser droplet concentrations.



(a)



(b)

Fig.3: Fringe images by (ILIDS) optics (a) and by the present technique (b).

2.2 Optics applicable to dense sprays

The new ILIDS receiver is able to detect the most suitable interference image in denser sprays.

Glover *et al.*(1995) use a 35mm format camera which is modified by the removal of the lens mounting ring and so on, enabling the Sheimpflug condition which is; image plane, lens plane and object plane of the cameras intersect in a common line.

We designed receiving optics to overcome the signal distortion caused by image overlapping. The droplet's fringe images are captured by optics in an out-of-focus image plane in the original techniques as Fig.1(a). The present study proposed that the image compressing lenses were set between a collecting lens and an image plane(CCD camera) in Fig.4. By using compression, the circular images are concentrated together with fringes retaining the information for circle diameter and involved fringe number. The fact that optics slide on the axis of receiving optics makes it possible to adjust to any defocus extent perpendicular to the fringes. With this novel technique, overlapping images were decreased dramatically and without the Sheimpflug condition. As mentioned above, we could detect the most suitable interference images even in denser sprays.

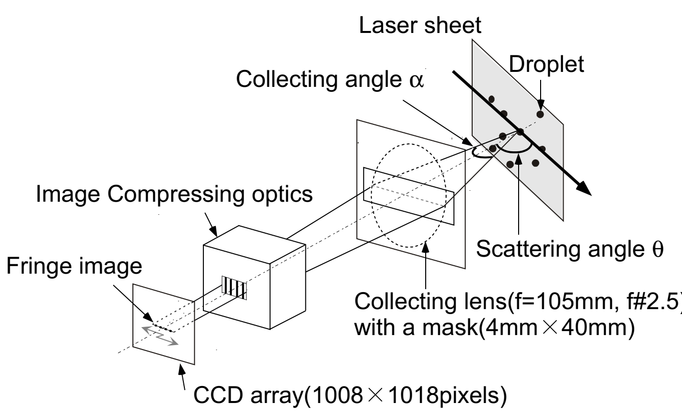


Fig.4: Feature of new receiving optics for detecting the most suitable interference image in denser spray.

2.3 Image processing

The present study proposes an automated computed aided image processing technique.

Image analysis was carried out using original code written in C and run on a PC. The software identifies the individual lined fringe images and their location and their length in the frame. The shape of signals acquired scanning the captured frame are similar to Doppler Burst signals and the signal processing can employ FFT for LDV/PDA with a higher accuracy to evaluate fringe spacing by the adjusted Gaussian fitting, i.e. whereas the power spectrum is interpolated by adjusted Gaussian fitting within that data. This interpolation realizes bias error of less than 0.2% for fundamental frequency. The equation of adjusted Gaussian fitting is presented as follows;

$$a = \frac{1}{2}\left[\frac{\log\left(\frac{P_{peak-1}}{P_{peak}}\right) - \log\left(\frac{P_{peak+1}}{P_{peak}}\right)}{\log\left(\frac{P_{peak-1}}{P_{peak}}\right) + \log\left(\frac{P_{peak+1}}{P_{peak}}\right)}\right] \quad (2)$$

$$f* = K_{peak} + 0.9169a + 0.3326a^3 \quad (3)$$

where; K_{peak} is the position of maximum amplitude in the discrete spectrum and $f*$ is a signal frequency normalized by the fundamental frequency(Kobashi *et al.* 1990).

Glover *et al.*(1995) detected fringe spacing by edge detection, Hough transform, and so on. Their detection ratio is 72% to 95% for faint or bright fringe images, and typical run times are 5 to 6 minutes with 30 to 40 fringe images. Compared with their performance, the present processing achieved about a 90% detection ratio and about 300 images in a frame within 30 seconds.

3. Experiments

3.1 Experimental setup

The experimental setup for this study is illustrated in Fig.5. A thin pulsed laser sheet about 0.5mm (NEW WAVE Nd:YAG Laser, 100mJ/pulse) illuminated droplets of the spray area and light scattered fringed images were recorded in the high resolution CCD camera (KODAK MEGAPLUS ES1.0/10BIT 1008×1018pixels) which acquires digital images directly providing time series measurements and avoiding development errors on film. The spatial pattern of the images was observed by focusing out the collecting system. The projected circular images with fringes have been optically compressed to line images and converted to digitized data by line scanning as shown in Fig.3(b) so that the images might not interfere with each other. Now, circular polarized incident light is applied for better recognition of the fringe and background. The scattering angle is 73 deg. and for p=0 and p=1 light is almost the same intensity. The collecting angle is 11.7 deg. which is calculated by the distance from the collecting lens to the center of object plane and the collecting lens effective diameter.

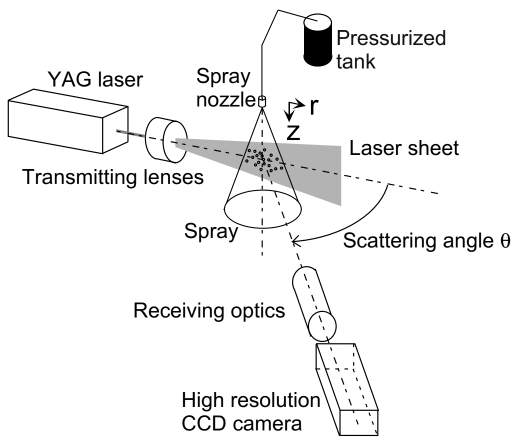


Fig.5: Schematic view of the measurement set-up.

3.2 Results and discussion

3.2.1 Evaluation with Monodisperse droplet generator

Evaluating the system, a microscopic measurement of 120μm droplets generated by Monodisperse droplet generator operated at 68.2kHz was performed. The microscope lens used is a Nikon 20×/0.40. The monodisperse droplet generator was set up on the laser beam axis to the CCD camera. The calibrations plate had a scale of 20μm/div.. The resolution was about 1.6μm. The comparison with microscopic measurements and the present automated ILIDS measurement system is shown in Fig.6. The x-axis is the droplet diameter and the y-axis is PDF. It is obvious that both peaks of PDF agree well. The difference is about 3% at each peak and is about

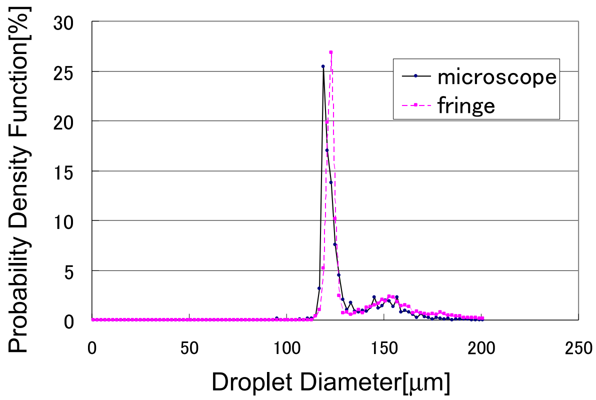


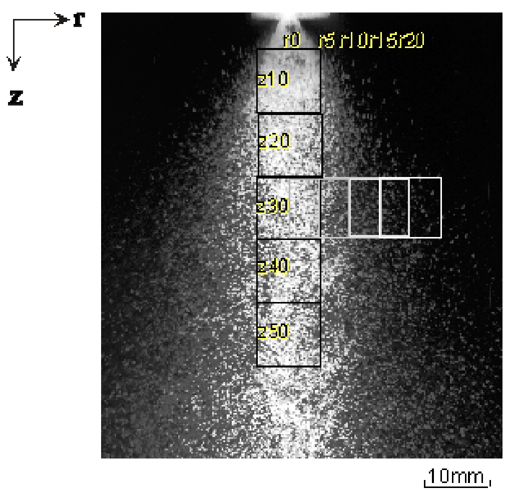
Fig.6: Microscopic and ILIDS measurement on monodisperse droplet generator.

4% for each average.

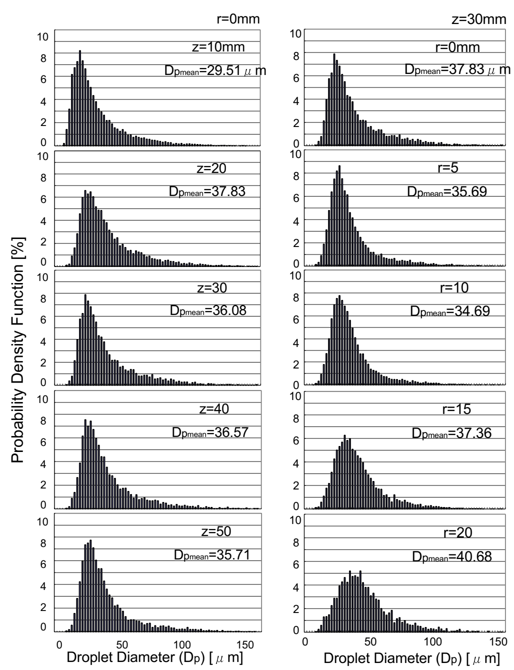
3.2.2 Droplet size distribution in a higher concentration spray

Measurements of the droplet size distribution are described in this subsection.

The measurement regions are shown in Fig.7(a). The experimental results are shown in Fig.7(b). It shows the distributions of droplet-size at the axial position z=30mm, and the radial positions r=0,5,10,15,20mm, individually below the spray nozzle. A Delavan nozzle (type B, 0.50 GPH, solid cone) was employed with a pressure of 0.8 MPa. The results show robust features of droplet distribution similar to our previous PDA work (Maeda *et al.* 1988). The sampled number of droplets per PDF was 10000 from 30 frame images. The data rate was 300 droplets per frame in 1/30s using at 10mm×10mm square cross-section. The laser sheet had a thickness of 0.5mm, so that the droplet was able to be measured even in denser regions. The number of particles in a cubic centimeter was estimated as about 6000. The validation ratio was approximately 90%.



(a)



(b)

Fig.7: Solid cone spray of Delavan nozzle (type B45deg., 0.5GPH) pictured for whole area: (a)Measuring view area is 10mm×10mm square cross-section, (b)PDFs of droplet size distribution.

3.2.3 Simultaneous measurement of droplet size and velocity

The present method can be easily employed by the small modification of the PIV/PTV system and the velocity vectors of individual droplets would be available with an additional modification. The measurements were obtained with a KODAK MEGAPLUS ES1.0/10 camera using a Triggered Double Exposure and the frame changing timing controlled to within 1μs to 5μs. The pulsed laser source illuminated each frame.

Velocity measurements are carried out by two-dimensional conventional PIV measurements to get overall mean velocities in the cross section. The interval of laser emission, Δt, is 35μs. Fig.8(a) is z-axial mean velocity and mean droplet diameter and Fig.8(b) is the vector map for two dimensions. The quality of the data was acceptable, and the experiment demonstrates the capability to measure velocity of spray flow field. However, since a spray flow is dispersed two-phase flow, strictly speaking, a measurement by PIV that is spatially averaging for velocity is not sufficient to obtain information of individual particle size and velocity. We have recently been applying Novel ILIDS to measure individual droplet size and velocity simultaneously performing, spatial and time series measurements by using the interferometric image technique. The interference image is captured at intervals of 10μs. The displacement of these fringe images is calculated by cross-correlation. Moreover, the information of droplet diameter is used for the surveying the particle paring. This method enables a measurement system for individual droplets by searching droplet fringe pattern using a cross-correlation method that are levitated and aides in analyzing a spray flow completely.

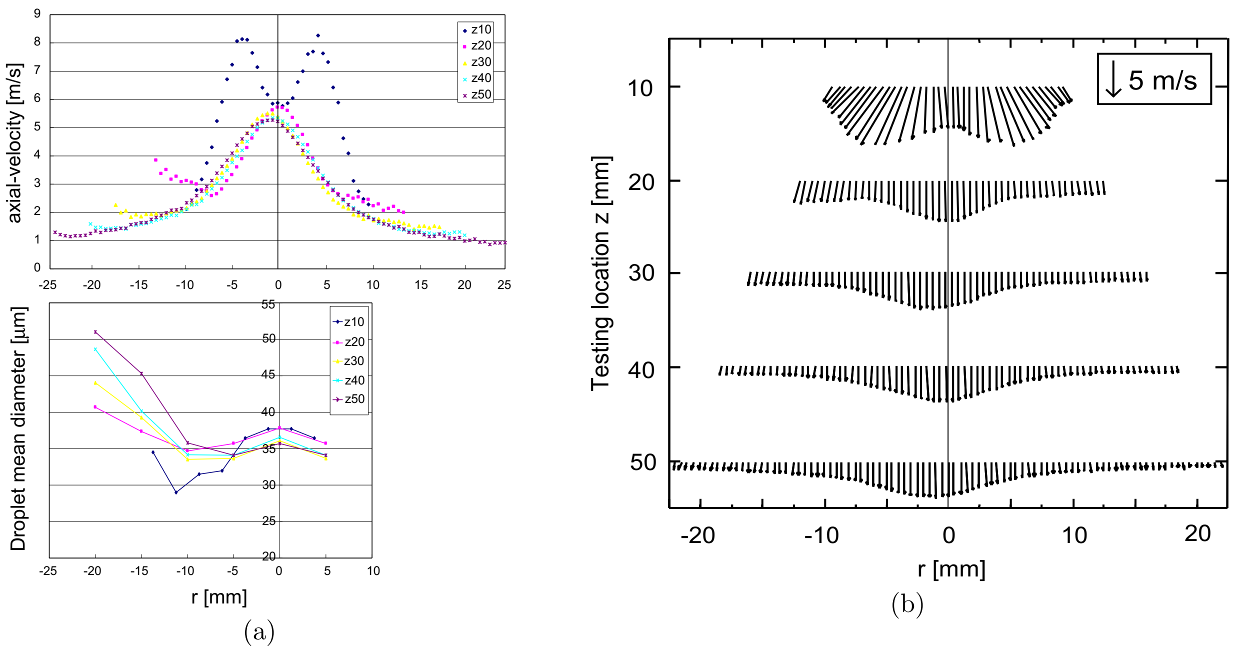


Fig.8: Average velocity and diameter and a technique for velocity of individual droplet: (a)Average axial-velocity and diameter in spray, (b)Average velocity of spray flow.

4. Conclusions

This newly developed ILIDS technique is useful for the analysis of spray flows. By redesigning receiving optics, an improvement of spatial resolution was achieved even for the case of many fringes and a wide dynamic range of droplet diameter. Then this system makes it possible to measure the droplet-size and droplet-size distributions in denser sprays. The error of this system was 4% on mean diameter by measurement using MDG. This system provides effective measurement for droplet sizes ranging from a few micrometer to several hundred micrometers. The data rate was 300 droplets for each frame viewing at the measuring area of 10mm×10mm square cross-section, which provides approximately 10000 droplets with using 30 exposures per sec. Using a digital CCD camera, simultaneous droplet-size, position, and velocity measurements have been demonstrated by two-dimensional PIV. Also, a measurement of individual particle diameter will be accomplished.

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