Development of simultaneous measurement of droplet size and 3D velocity in spray

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ABSTRACT

In the study of spray, the some techniques regarding the characteristics of light scattered from transparent droplets illuminated by a coherent light source has been proposed. For example, LDV and PDA are applied to measurements of droplet sizing and velocity. As a relatively new technique, the mean named ILIDS (Interferometric laser imaging for droplet sizing) or IPI (Interferometric Particle Imaging) refers to determining the diameter of spherical particles from defocused images by many researchers. In this technique, the interference fringes generated by reflection and 1st order refraction ray scattered by a droplet are observed on a defocused image plane, and diameter can be determined by counting the number of the fringes. The interferometric images, however, are overlapped with dependence on number density of droplets. There are some difficulties to separate the overlapped images. Maeda et al. (2000) established ILIDS with combination of a particular optical system to 2D simultaneous measurement of droplet size and velocity. They succeed the separation of the overlapped images. In general, the behaviour of droplets is three-dimensional because of mixing with surrounding airflow entrained by high-speed spray issued from the nozzle, and droplets of various sizes are contained in the spray. Contrastively, using the in-focus image of droplets, the authors (2003) established the technique of the simultaneous measurement of droplet size and 3D components of velocity in a spray by using glare points of droplets. For measuring range in direction to relatively large particle, ILIDS depends on the spatial resolution of CCD device because of the increase number of fringes. On the other hand, the interval of glare points is enlarged. Therefore, they are trade-off in term of the measuring range.

In this report, the new technique to measure the droplet size and three-dimensional velocity simultaneously using the characteristic of light scattered from droplet and stereoscopic configuration has been proposed. In the present technique, the images of glare points and interference fringes of droplet were captured by different cameras arranged in a stereoscopic configuration. Droplet sizing has been evaluated by the image of glare points and interference fringes of droplet, and velocity has been given by two-frame 3D PTV. The optical arrangement to capture the image of glare points and interference fringes of droplet was composed. The present technique was applied to the verification of the accuracy of the size and 3D velocity measurements by using silica particles known the refractive index (2.25), and its feasibility was verified in a spray field.

1. INTRODUCTION

In a study of a spray, grasping behaviour of a droplet is important, and simultaneous measurement of size and velocity of individual droplet is desired for its quantitative evaluation. Recently, some optical techniques have been applied to engineering field with the development of laser and CCD device. The experiment analysis in the fuel spray field also is typical example, and the some techniques by using characteristic of light scattered have been proposed. For example, LDV and PDA have been applied to obtaining the size and velocity of particles as a point measurement.

In recent years, the method of size measurement determined diameter of droplet from image of interference fringe has been remarkable. When a transparent spherical particle is illuminated by coherent light, rays of reflection and 1st order refraction are imaged on a focal plane, and distribution of oscillating intensity of light scattered in the space is captured on the out of focus plane as interference fringes. (Figuer1) Hessellbacher et al. (1991) derived the relation between size and the angular fringe spacing theoretically by using a geometrical optics and verified the validation of the equation experimentally. The technique by using image of interference fringes of droplet has been applied to size measurement of droplets, which is named IPI (Interferometric Particle Imaging) or ILIDS (Interferometric Laser Imaging for Droplet sizing). However, Overlapped image of interference fringes had to be resolved in high number density of droplets. Recently, Maeda et al. (2000) established the technique based on ILIDS by optical system to separate the overlapped images, and obtained excellent results of size and 2D velocity of individual droplets. Madsen et al. (2003) proposed the new technique adopted focused and defocused images of droplets. In this technique, the same area is observed by two cameras arranged in the identical scattering angle, which is not stereoscopic configuration. The one of the cameras capture interferometric image on the defocused plane, and another one imaged glare points on focused plane. The size measurement was evaluated by interferometric image, i.e. ILIDS or IPI, and 2D velocity of individual droplets was obtained by PTV of image of glare points.

In general, it is inadequate to understand formation of spray by using 2D measurement so that behaviour of droplets in a spray is three-dimensionality. Especially, the behaviour of droplet is complicated and three-dimensionality because of the spray ejected from swirl nozzle.

Palero et al. (2002) proposed the technique given the distribution of three-components of velocity in the classified droplets by using SPIV applied that the information of the intensity of the light scattered from droplets is related to the droplet size. However, the technique cannot obtain the velocity and size of individual droplets. Nishino et al. (2000) reported the simultaneous measurement of size and velocity of particles by using stereo imaging. In this technique, the particles were observed directly by stereoscopic configuration, and the profile of the particles was detected by the image processing and interpolation. Therefore, the assumption was embraced to determine the size and the centre of particles, and the spatial resolution depends on the accuracy of the measurement. Damaschke et al. (2002) has been reported the technique based on IPI for simultaneous measurement of size and 3D velocity of the particles. In this method, the optical configuration is similar to the mean reported by Jesper et al., and the interferometric fringes and glare points of droplets are imaged in the common area of cameras. The particle position in the direction of out of plane is determined by the size of the interferometric image. The size of particles is given from interferometric image, and the 3D velocity is obtained by tracking of focused image, i.e. PTV, and the size of the interferometric image. They reported that there were some difficulties to identification of the focused and defocused images. The authors (2003) developed the technique based on SPIV and glare points imaging for simultaneous measurement of size and three-components of velocity and optical

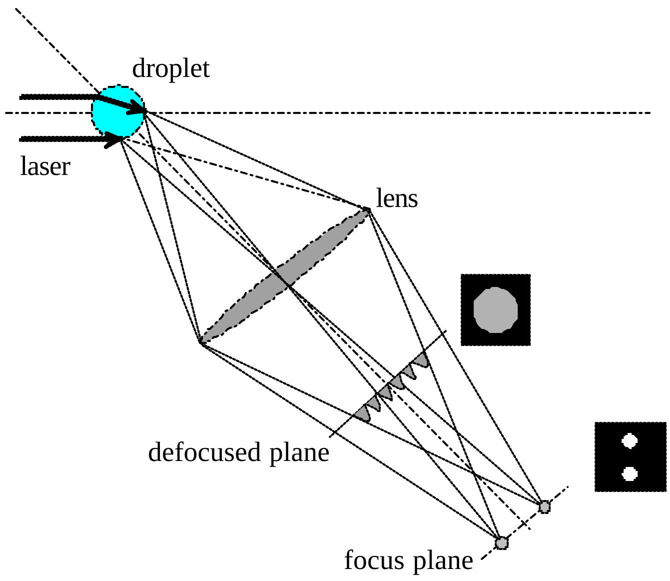


Figure1 Fundamental optics

configuration to make it possible. The size was evaluated by glare point separation that has information of diameter of droplet on the captured image, and the three-components of velocity was given from the cluster of doublet image. The dynamic range of size measurement depends on the spatial resolution of receiving system, because the glare points separation is proportional to the diameter.

Whereas IPI can obtain the diameter of droplet accurately, the fringes of large particle cannot be resolved on the CCD element so that number of the fringes is proportional to the diameter. The fringes can be imaged with enlarging the size of defocused image, however the interferometric images are overlapped. Therefore, the size of the droplets can be evaluated from image of interference fringes and glare points within the dynamic range depending on the resolution and magnification of CCD camera. Consequently, the size measurement with high dynamic range can be carried out with combination of interference fringes and glare points separation.

In this report, the new technique combined 3DPTV and characteristic of scattered light for simultaneous measurement of the size and 3D velocity of individual droplets was proposed. In the technique, interferometric and glare points image are captured by stereoscopic configuration. The size and 3D velocity are evaluated by both images simultaneously. And, the accuracy of the present technique was verified by using silica particle in order to apply into a spray.

2. Optical Principle of Measurement of Size

Figure1 shows the relationship of optical ray tracing of droplet imaging on the focusing plane and defocused plane. When a transparent spherical droplet is illuminated by a parallel laser light, the scattered rays of 0th order reflection and 1st order refraction are dominant in the forward region of scattering angle at Mie scattering. The relation between an object and image plane is defined by the familiar equation (1), wherefore the doublet image of glare points is obtained on the focused plane by 0th order reflection and 1st order refraction by the droplet.

$$\frac{1}{R}+\frac{1}{S}=\frac{1}{f} \qquad (1)$$

Where, R is the distance between a droplet and lens, S is the distance between lens and image plane and f is the focal distance of the lens.

The doublet image has information of a size of a droplet. The evaluation of the size was suggested by Van de Hulst et al. (1991) that it is evaluated by the spacing of the doublet image observed on the focusing plane. Van de Hulst (1981) described that the geometrical optics can be applied instead of full Lorenz-Mie theory, when the size parameter ($\alpha=\pi d/\lambda$) is lager than 10-20. Equation (2) can be derived by the geometrical relationship between the optical pass of 0th order reflection and 1st order refraction ray on a focused plane shown in Figure1, and it shows that the droplet size d is proportional to the spacing of the glare points L.

$$d = 2\frac{L}{M}\left[\sin\left\{\tan^{-1}\left(\frac{\sin\left(\frac{\theta}{2}\right)}{\cos\left(\frac{\theta}{2}\right)-\frac{1}{n}}\right)\right\}+\cos\left(\frac{\theta}{2}\right)\right]^{-1} \qquad (2)$$

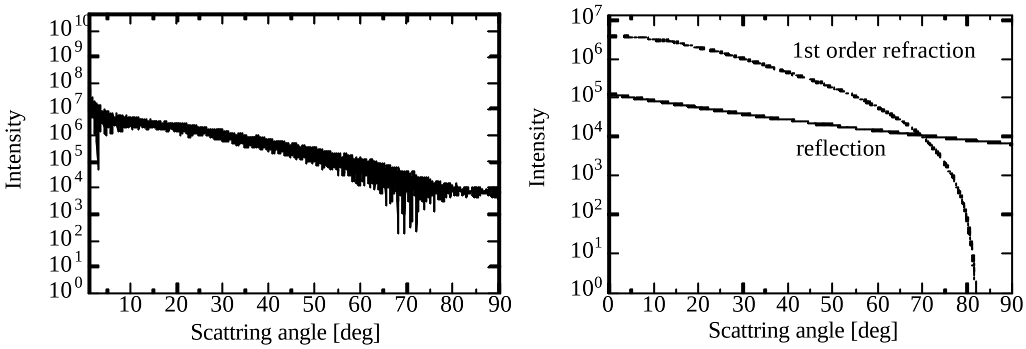
Where θ is scattering angle, n is the refractive index of droplet and M is the magnification of optical system. On the other hand, on defocusing plane, a fringe pattern of the droplet generated by interference between 0th order reflection and 1st order refraction ray is observed. Hessellbacher et al. (1991) showed a relationship between the droplet size and the fringe spacing. The method by Maeda et al. (2000) is based on the same principal, but the additional optical technique for image separation of the overlapping droplets and the image tracking method for velocity measurement are used.

$$d = \frac{2\lambda N}{\alpha}\left\{\cos\left(\frac{\theta}{2}\right)+\frac{n\sin\left(\frac{\theta}{2}\right)}{\sqrt{n^2-2n\cos\left(\frac{\theta}{2}\right)+1}}\right\}^{-1} \qquad (n>1) \qquad (3)$$

$$d = \frac{2\lambda N}{\alpha}\left\{n\cos\left(\frac{\theta}{2}\right)-\frac{n\sin\left(\frac{\theta}{2}\right)}{\sqrt{n^2-2n\cos\left(\frac{\theta}{2}\right)+1}}\right\}^{-1} \qquad (n<1) \qquad (4)$$

The equations (3), (4) between droplet diameter and the number of fringes are as follows. Where d is the droplet size, λ is the wavelength, N is the number of fringes, α is the collect angle of the lens, n is the refractive index and θ is the scattering angle for receiving optics. In the case of the geometrical optics, a scattering of light is expressed by summation of reflection, refraction and diffraction on a surface of a droplet.

A. Ungut et al. (1981) compared a geometrical optics to a Lorenz-Mie theory numerically, and a comparison of them from water droplet was also investigated by Warner (1981).
Figure2 (a) shows the characteristic of scattering light of a water droplet of a diameter of 60μm with calculated by a geometric optics based on the equation proposed by Warner, and (b) shows the comparison of the intensities between 0th order reflection and 1st order refraction ray obtained from (a). The intensities of 0th order reflection ray correspond to the one of 1st order refraction ray at approximately 69° of scattering angle. Therefore, glare points and interference fringes are imaged clearly at its scattering angle.



(a) (b)

Figure2 characteristic of scattered light for water droplet (a) and relation of intensity between reflection and 1st order refraction ray (b) (refractive index: 1.33, diameter: 60[mm], wavelength: 532[nm])

3. EXPERIMENT AND RESULTS

3-1 Experimental set-up

Figure3 shows the optical arrangement of simultaneous measurement of size and 3D velocity of individual droplets in a spray. The two CCD cameras, which are Kodak Es1.0 (1008(H)×1016(V)), were arranged in the stereoscopic view angel in the direction of flow axis, and the angular set-up was applied. Furthermore, they were tilted at the scattering angle corresponding to both intensities of reflection and 1st order refraction ray to the light sheet supplied by Nd:YAG laser (New Wave Reserch) outputting 50[mJ/pulsed]. One of the cameras captures glare points on the focused plane, and another one observes the interference fringes of droplets on the defocused plane. In this configuration, both cameras can observe the common area at the same direction of scattering angle. Then effect of stereoscopic view angle must be considered to scattering angle of optical receiver. Figure4 illustrates a geometrical relation of observed direction with stereoscopic view angle. Camera allocated to θ of scattering angle with stereoscopic angle ϕ observes *P*. Then, the scattering angle coincides with the intensity of scattered light at *P'*. Therefore, setting angle of cameras has to be considered δθ to preserve the equivalent light intensity of reflection and 1st order refraction ray. Figure5 shows raw images captured by the optical configuration illustrated in fgure3 for the spray issued from swirl nozzle. Interference fringes and glare points imaged by the present technique was confirmed. In this configuration, the size can be evaluated from both images of interference fringe and glare points so that their images can be captured by a stereoscopic

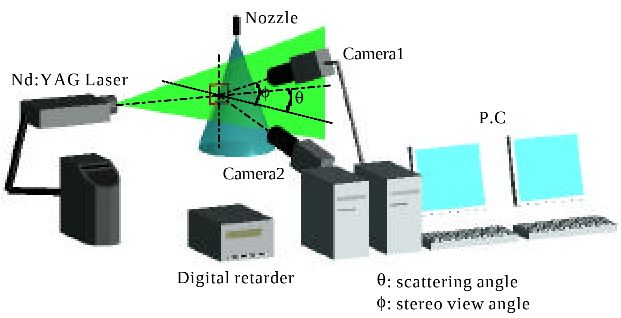


Figure3 optical configuration for application of spray

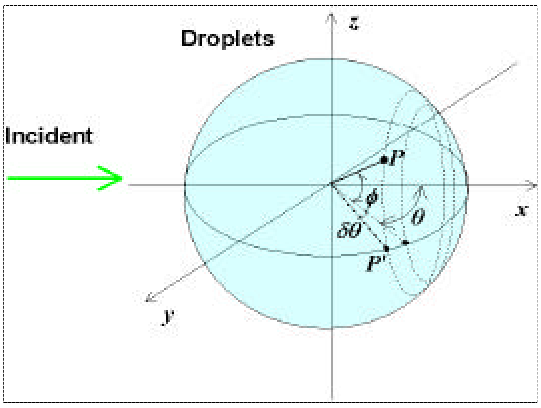


Figure4 geometrical relation of scattering angle

configuration.
In the case of IPI, the dynamic range of the size measurement depends on the performance resolving the fringes on the image. According to equation (3) and (4), the diameter is proportional to a number of fringes (figure6). Therefore, the fringes generated by large particle cannot be resolved on the image.
Certainly, the fringes can be resolved by enlarging the size of defocused image, however the overlapped images increase. e. g. Damaschke et al. (2002). In this technique, the size of the particles not to able to resolve the fringes using IPI was evaluated by the glare points separation, and the dynamic range of the size measurement can be improved.

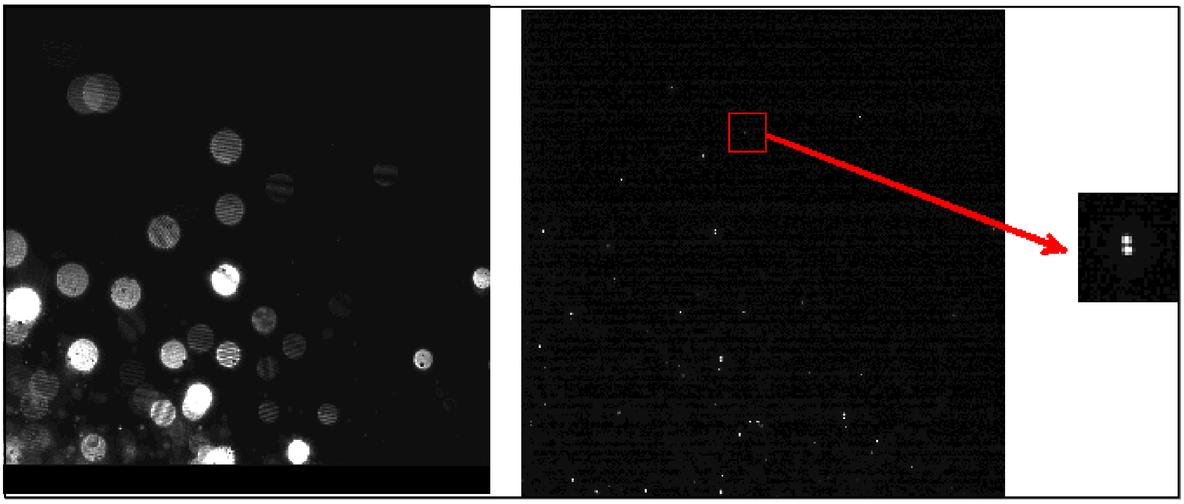


Figure5 Raw images of spray on defocused and focused plane

(Observation area: 20[mm] ´ 20[mm], q: 69°, f: 20°)

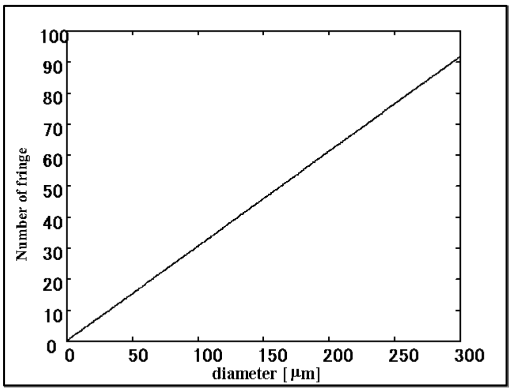


Figure6 Number of fringes vs. diameter

3.2 Calibration procedure

In this technique, calibration procedures of cameras are necessary in order to obtain 3D velocity from imaged droplets. In general, a calibrator known dimension between grids or dots accurately is put in test section, and its common area is captured by cameras. And relation of camera and object coordinate is derived by using its images. Prasad (2000) reported its methods in detail as review of stereoscopic PIV. Focused plane of cameras observing with stereoscopic view is set in the test section. There, however, is a focused plane of a camera captured interference fringes at out of observation area. Therefore, procedures for camera calibration were carried out by the manner illustrated in figure7.
Camera1 that is captured glare points was implemented its calibration by using calibrator images given in test section. On the other hand, calibration of camera2, which is captured interference fringes, was carried out by using image of the calibrator moved to focused plane of camear2. Then both cameras can be defined on the common object coordinate by measuring the displacement *l* between in-focus planes of both cameras. The colinearity condition equation proposed by Dho et al. (2001) was applied as relation between camera and object coordinate. The accuracy of the reconstruction was verified by using the grids on the calibrator image located at Z=0mm and Z=0.1mm. SPIV was applied in order to obtain the displacement of the grids. The accuracy of the reconstruction is evaluated approximately 3% of standard deviation.

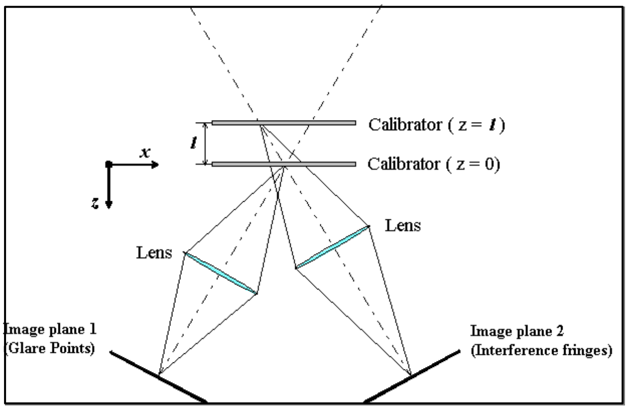


Figure7 schematic of calibration procedures

3.3 Image processing and verification on size measurement

The size measurement applied in this technique was evaluated by image, which is captured by stereoscopic configuration, of glare points and interference fringes. The dynamic range of the size measurement obtained from respective images is relation of trade-off for special resolution of optical system. The droplet that cannot resolve the fringes on the image, i.e. large droplet comparatively, can be measured the size by glare points separation.

The verification of accuracy on the size measurement given from image of glare points was carried out using the silica particle fixed on the glass plate as shown in figure8. In the case of doublets image, the size is evaluated by glare points separation according to equation (2), and its separation was obtained by evaluation of auto-correlation with sub-pixel accuracy. The doublet image captured of silica particle, which is shown in figure9 (a), gives the distribution of auto-correlation value shown in figure9 (b), and the interval between 0th and 1st peak corresponds to the glare points separation. Before the experiment, the diameter of the silica particle was measured using the microscope, and the diameter obtained is 64[μm]. The result obtained is 63[μm], and the error of measurement is verified 1.5%. And, the interferometric image, which was captured by another camera, of the same calibrated silica particle is shown in figure9(c). The size was determined from signal processing by using Fourier analysis of the spatial frequency in the fringes, e.g. Maeda et al. (2000). The size obtained was 64.2[μm], and the error was estimated by less than 1%.

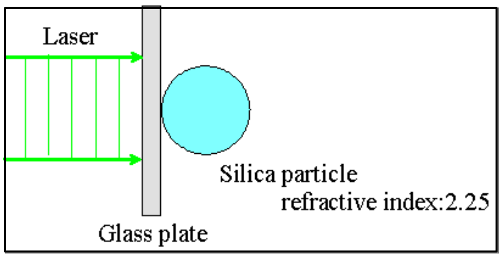
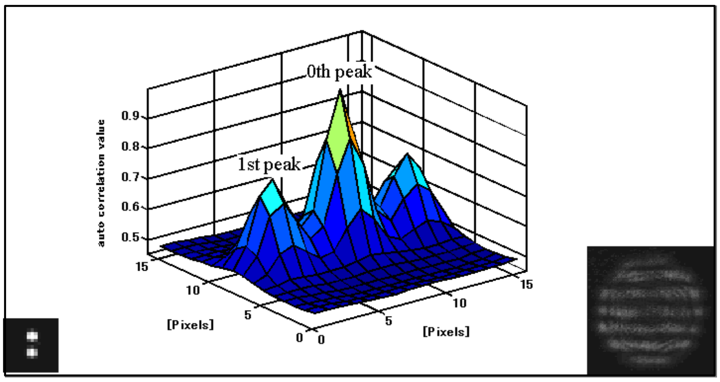


Figure8 schematic configuration in verification on size measurement



(a) (b) (c)

Figure9 doublet image of calibrated silica particle (a), distribution of auto-correlation value (b) and interferometric image (c)

3.4 3DPTV and its verification

Particle tracking was carried out from continuous two-frame image captured glare points and interference fringes. The positions of the droplets on the images was determined by particle mask correlation method, e.g., Takehara et al. (1999), and the technique based on cross-correlation operation was applied to particle tracking, e.g., Cowen et al. (1997). In this technique, the difference between general PTV is that the doublet images of glare points and interference images are tracked. The position of particle on the images was defined the centre between doublet image and the fringe image because of the point being on the particle, which the position is not exactly the centre of the particle. Stereo pair matching is determined by the cross of the lines given by co linearity condition equation going through the particle positions on the images of each camera, and the decision is that the evaluation of the difference between the particle position of the image and the position transformed the midpoint of shortest segment between the lines to the image. 3D position was defined as the midpoint. And figure 12 shows the vector map reconstructed by the result of 2D PTV. In this verification, the error versus exact displacement of 0.1[mm] was estimated approximately 3% by a standard deviation. Table1 shows the averaged displacement of each component (x, y, z) and the magnitude. The error of the displacement contains approximately 0.5[Pixels] on the image plane. Therefore, the analysis of sub-pixels accuracy contribute to it error.

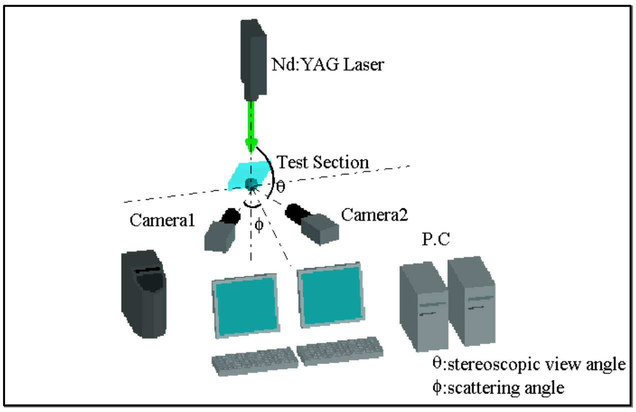
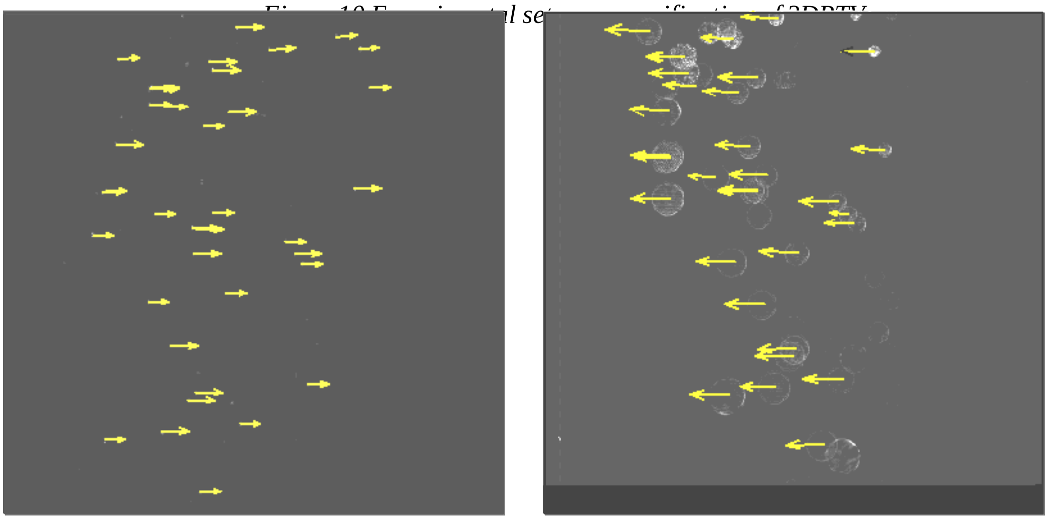


Figure10 Experimental se[illegible]f 3DPTV



(a) (b)

Figure11 Results obtained by 2DPTV from the doublet and interferometric images snapped in stereoscopic configuration (a), (b), respectively.

4. CONCLUSIONS

As the new technique of a simultaneous measurement of the size and 3D velocity in a spray, the method in order to capture the image of glare points and interference fringes by standard stereoscopic configuration was proposed. In the verification of accuracy of the present technique, the measurements of size and 3D displacement of calibrated silica particles was carried out. And the error was evaluated by less than 2% for the diameter and estimated 3% for 3D displacement. Furthermore, the technique was applied to the spray issued from swirl nozzle. And, that the stereoscopic images of glare points and interference fringes of droplets can be captured by the proposed optical configuration was verified, and its feasibility was confirmed.

ACNOLEGEMENT

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REFERENCES

Maeda, M. Kawaguchi, T. and Hishida, K. (2000) "Novel interferometric measurement of size and velocity distributions of spherical particles in fluid flows", Meas. Sci. Technol., 11, L13-L18

Zama, Y. Kawahashi, M. and H, Hirahara. (2003) "Three-dimensional velocity and droplets size measurements of spray flow", 4th ASME&JSME, joint fluid Conf., July, 6th-10th, Hawaii U.S.A

Hesselbacher, K. H. Anders, K. and Frohn, A. (1991) "Experimental investigation of gaussian beam effects on the accuracy of a droplet sizing method", Appl. Opt. 30, pp.4930-4935

Madsen, J. Harbo, J. Nonn, T.I. Blondel, D. Hjertager, B.H. and Solberg, T.(2003) "Measurement of droplet size and velocity distribution in spray using Interferometric Particle Imaging(IPI) and Particle Tracking Velocimetry(PTV)", ICLASS, July, 13th-17th, Sorrento, Italy

Palero, V.R. and Ikeda, Y. (2002) "Droplet-size-classified stereoscopic PIV for spray characterization", Meas. Sci. Technol., 13, pp.1050-1057

Nishino, K. Hiroyuki, K. Torii, K. (2000) "Stereo imaging for simultaneous measurement of size and velocity of particles in dispersed two-phase flow", Meas.Sci.Technol,11, pp.633-645.

Damaschke, N. Nobach, H. Nonn, T.I. Semidetnov, N. and Tropea, C. (2002) " Size and velocity measurements with the global phase Doppler technique", Proc. 11th Intl. Symp. On Appl. Of Laser Technique to Fluid Mechanics, July, 8th-11th, Lisbon Portugal

Van de Hulst, H. C. Wang, R. T. (1991) "Glare Points", Appl. Opt. 30, pp.4755-4763

Van de Hulst, H.C. (1981) "Light Scattering by small particles", Dover, New-York

Ungut, A. Grehan, G. and Gouesbet, G. (1981) "Comparison between geometrical optics and Lorenz-Mie theory", Appl. Opt. 20, pp.2911-2918

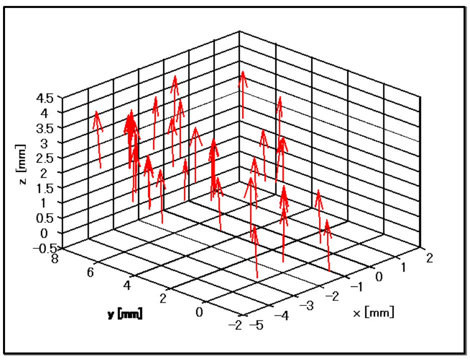

Figure12 The 3D displacement of silica particles

Table1 Calculated displacement

Component	x	y	z
Averaged displacement[mm]	0.0004	0.0003	0.1030

Glantschnig, W. J. and Chen, S. H., (1981) “Light scattering from water droplets in the geometrical optics approximation”, Appl. Opt. 20, pp.2499-2509

Damaschke, N. Nobach, Tropea, C. (2002) “Optical limits of particle concentration for multi-dimensional particle sizing techniques in fluid mechanics”, Experiment in Fluids, 32, pp.143-152

Prasad, A.K. (2000) “Stereoscopic particle image velocimetry”, Experiment in Fluid, 29, pp.103-116

Dho,H.D. Kim, D.H. Cho, K.R. Cho, Y.B. Saga, T. Kobayashi, T. (2001) “3D-PTV using Genetic Algorithm”, 4th Intl. Symp. On PIV

Takehara, K. and Etoh, T. (1999) “A study on particle identification in PTV: Particle mask correlation method”, Journal of Visualization, 1, pp.313-323

Cowen, E.A. and Monismith S. G. (1997) “ A hybrid digital particle tracking velocimetry technique”, Experiment in Fluid, 22, pp.199-211