SIMULTANEOUS DETERMINATION OF VELOCITY FIELD AND SIZE DISTRIBUTION OF WATER DROPLETS GENERATED BY AN ATOMIZER FROM IMAGE ANALYSIS

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ABSTRACT: A particle sizing method based on the analysis of polarization status of light scattered by targeted particles is introduced. It is combined with Interferometry Laser Imaging for Droplet Sizing method (ILIDS) to determine the size distribution of water droplets in a mist generated by an atomizer at different humidity level under different temperature. The optical setup is combined with Particle Image Velocimetry (PIV) for the simultaneous determination of particle velocity.

Introduction

Particle sizing techniques have been widely investigated and developed in a variety of industries and research laboratories, which aims at characterizing the form and the size distribution of particles ranging from several nanometers to several millimeters in a targeted group. The past several decades has seen the advancement of optical methods attribute to the application of laser techniques. Optical methods, which are based on the analysis of light-particle interaction, evidently show their advantages by providing non-intrusive and rapid measurements as well as the possibility of combination with velocity measuring devices [1].

Fig.1 illustrates light scattering by a spherical particle. The spherical polar coordinate system is centered on the particle. Theory of Lorenz-Mie provides a solution of Maxwell electromagnetic equations, which elaborates the absorption and scattering of incident light by a sphere in a linear, isotropic and homogeneous medium [2].

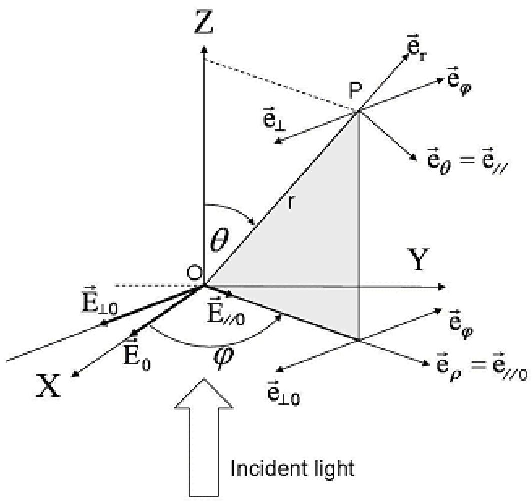


Fig.1 Light scattering by a spherical particle

A remarkable phenomenon of light scattering is the polarization of scattered light which can be characterized by four experimental parameters including the incident wavelength (λ), the angle of observation (θ), the relative refractive index of the particle and the medium (m), and the particle diameter (d). Thus when the incident light is linearly polarized at 45°, polarization ratio (P) of scattered light is calculated by the following equation:

$$P(\lambda,\theta,m,d,) = \frac{E_{\perp s}}{E_{// s}} = \frac{i_{\perp}}{i_{//}} \cdot \frac{E_{\perp i}}{E_{// i}} = \frac{i_{\perp}}{i_{//}} \qquad \text{Eq.1}$$

where E_s and E_i represent respectively the electric field of scattered light and that of incident light. $i_{\perp}$ is the scattered irradiance per unit incident irradiance given the incident light is polarized perpendicular to the scattering plane, while $i_{//}$ is its counterpart when the incident light is polarized parallel. Based on theory of Lorenz-Mie, the polarization ratio as well as the scattered irradiance per unit incident irradiance of scattered light by water droplets of different diameters is calculated by a program developed in Mathematica, as shown in Fig.2. The water droplets are dispersed in air, with a relative refractive index (m) of 1.33+0i. The incident laser light is double-pulsed laser Nd:Yag at a wavelength (λ) of 0.532µm. The measurements are performed at an observation angle (θ) of 66°.

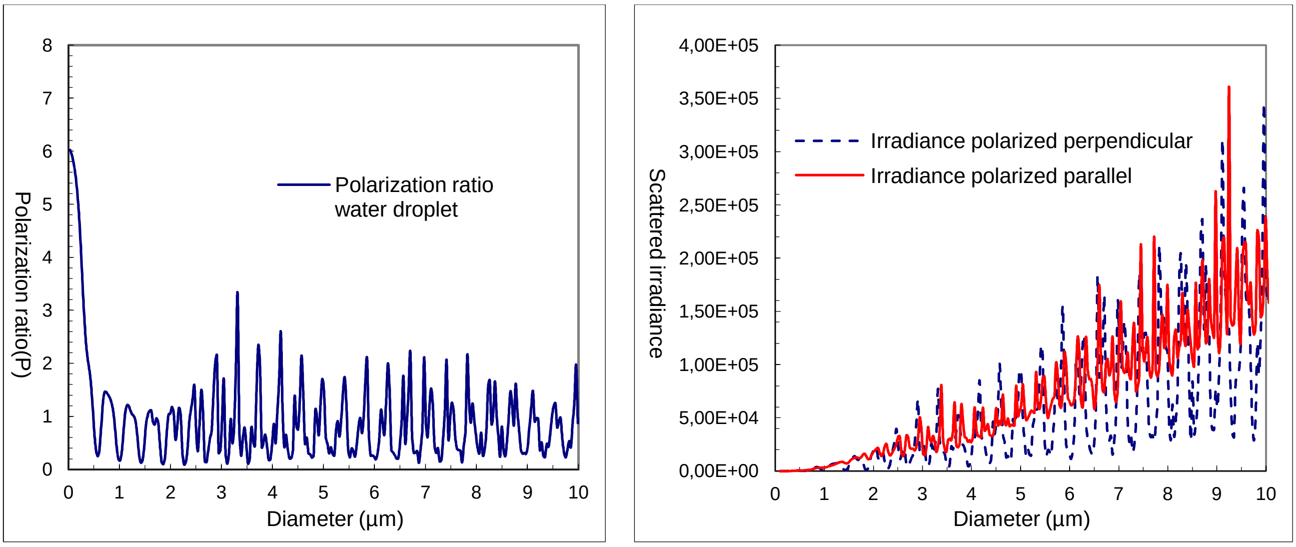


Fig.2 Polarization ratio and scattered irradiance of water droplets in air

On the other hand, the two polarized components of scattered light can be determined experimentally from the analysis of particle images respectively polarized parallel and perpendicular taken by a high resolution CCD camera. Thus the particle diameter under investigation can be obtained from inverse calculation. From Fig.2, fluctuation of the theoretical values of polarization ratio for the particles bigger than 0.5µm is observed, which causes uncertainty for the inverse calculation. Meanwhile the scattered irradiance presents an increasing tendency generally monotone with particle diameter, which provides a good reference for the inverse calculation of particle size.

Since the particles investigated seeding the flow, the experimental setup becomes a PIV device which enables the simultaneous acquisition of velocity profile when a double-pulsed Nd:Yag laser is used as incident light source. The two images illuminated by two successive laser pulses are correlated to render particle velocity in the observed field. Theoretical work and a more detailed introduction of the method of polarization ratio can be found in the authors' previous publication [3].

In the current study, method of polarization ratio is combined with Interferometry Laser Imaging for Droplet Sizing method (ILIDS) to determine the size distribution of water droplets in a mist generated by an atomizer.

Interferometry Laser Imaging for Droplet Sizing method (ILIDS)

ILIDS is a developed optical method for the determination of droplet size bigger than 10µm. According to Van de Hulst[4], when a water drop is illuminated by a wide beam, glare points can be viewed and imaged from a certain direction, respectively corresponding to the intensity maxima of the rays reflected and refracted in the forward-scatter region, around 20° to 70° [5]. Glantschnig and Chen[6] showed that regular fringes arise from interference between reflected and refracted rays of orders *p=0* and *p=1*, as shown in Fig.3.

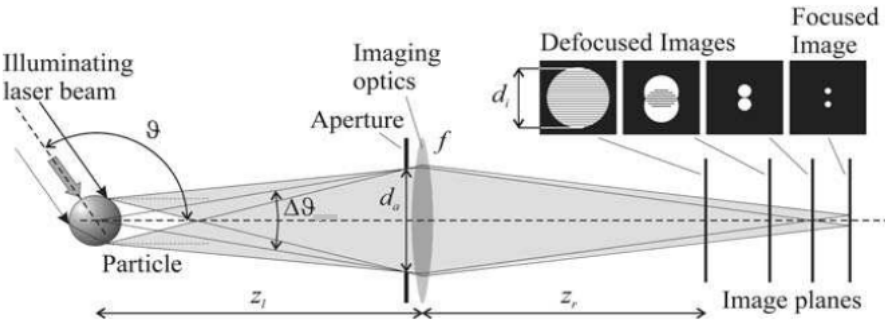


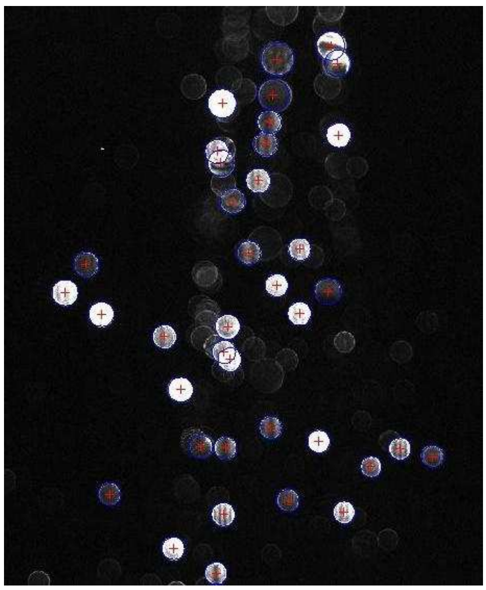
Fig.3 Principle of Interferometry Laser Imaging for Droplet Sizing method (Albrecht[7])

The angular frequency of the fringes is proportional to droplet diameter, as illustrated by the following formula[8] :

$$d = \frac{2\lambda N}{\Delta\theta}\left(\cos\frac{\theta}{2} + \frac{m\sin\frac{\theta}{2}}{\sqrt{m^2+1-2m\cos\frac{\theta}{2}}}\right) \qquad \text{Eq.2}$$

where N is the fringe number, and λ is the wavelength of the light incident. θ is the scattering angle and $\Delta\theta$ is the collecting angle, while m is the refractive index of the droplet.

(a)



(b)

Fig.4 Defocused water droplets image and particle detection

Fig.4(a) presents a defocused snapshot of water droplets generated by an atomizer. The fringe number of each particle corresponds to different particle diameter. A circular Hough transform was applied to locate circles in the image from edge-strength information, which rendered the size and position of each circle detected, as shown in Fig.4(b). Since the fringe-intensity within a circle has the form of a periodic function that resembles a sine wave, the number of peaks, i.e. the fringe number, was obtained by fitting the intensity information to a parametric model. Thus the particle diameter can be calculated through Eq.2.

Experimental setup

An optical test rig has been set up to perform the acquisition of particle images, as illustrated by the sketch in Fig.5. Light scattered by the particles investigated is collected at a certain angle θ, then the two components polarized are separated by a cube polarizer and arrive at the camera after a couple of reflections on the mirrors. Particle images polarized respectively parallel and perpendicular are taken by a CCD camera (TSI 630062: 4008×2672 pixels). According to the basic principle of ILIDS, defocused images have been taken for the sizing of water droplets.

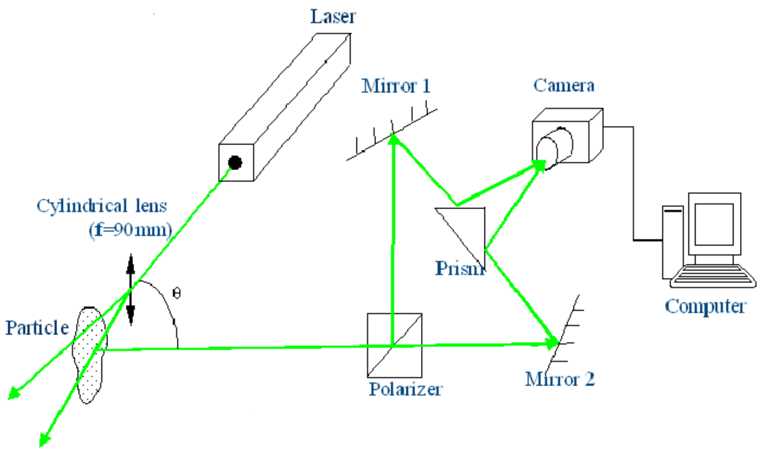
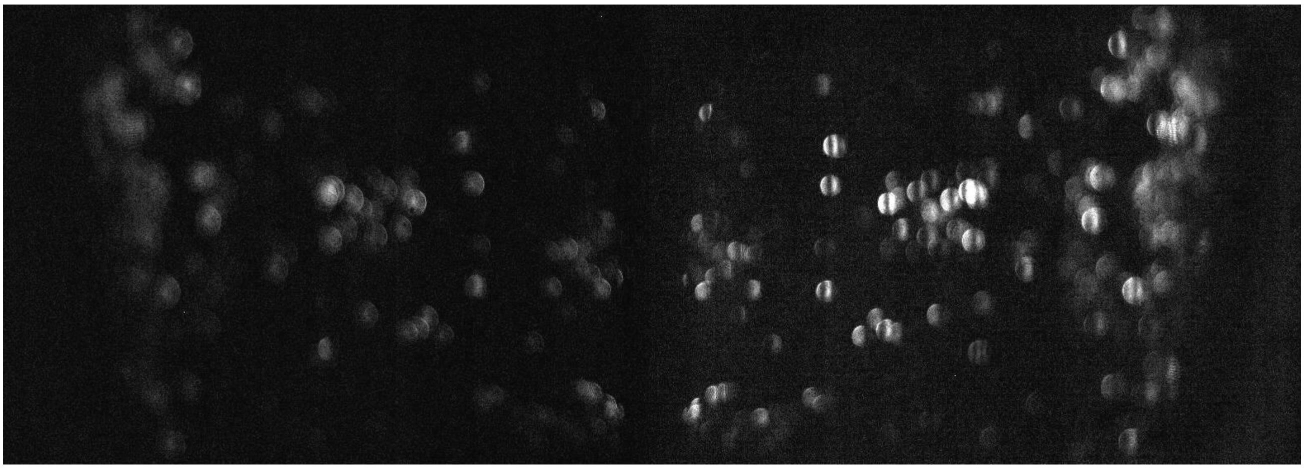


Fig.5 Sketch of optical setup

Fig.6 shows a defocused image of water droplets generated by an atomizer, with the image perpendicular polarized at left and that parallel polarized at right. For the experimental results presented, measurements were carried out at a scattering angle of 66°. Double-pulsed Nd:Yag laser was employed at a wavelength of 0.532µm, which was inclined at 45° to render an incident beam linearly polarized at 45°. With a 16-bit grayscale CCD camera of 4008×2672 pixels, the size of each pixel was 9×9 μm^2. The size of measuring area was 4×4 cm^2 and the magnification ratio the optical system is 1:10. Thus, the diameter of a droplet producing exactly one fringe across the observed circle would be 15.7µm at f2.8. To determine the particle size, the fringe number of each detected particle was calculated. Those with a fringe number less than 1 were taken out to perform the calculation of polarization ratio, based on which their diameters were obtained.



$I_{\perp}$ $I_{//}$

Fig.6 Defocused images of water droplets parallel and perpendicular polarized

Experimental results

Measurements were carried out to determine the size distribution of water droplets generated by an atomizer under different heating temperature at different humidity level. Experimental results shown in Fig.7 were drawn based on 30 images successively taken by CCD camera. Particle size decreased evidently when the water droplets were heated under a higher temperature, whereas larger particles became more important in the mist when humidity level was increased.

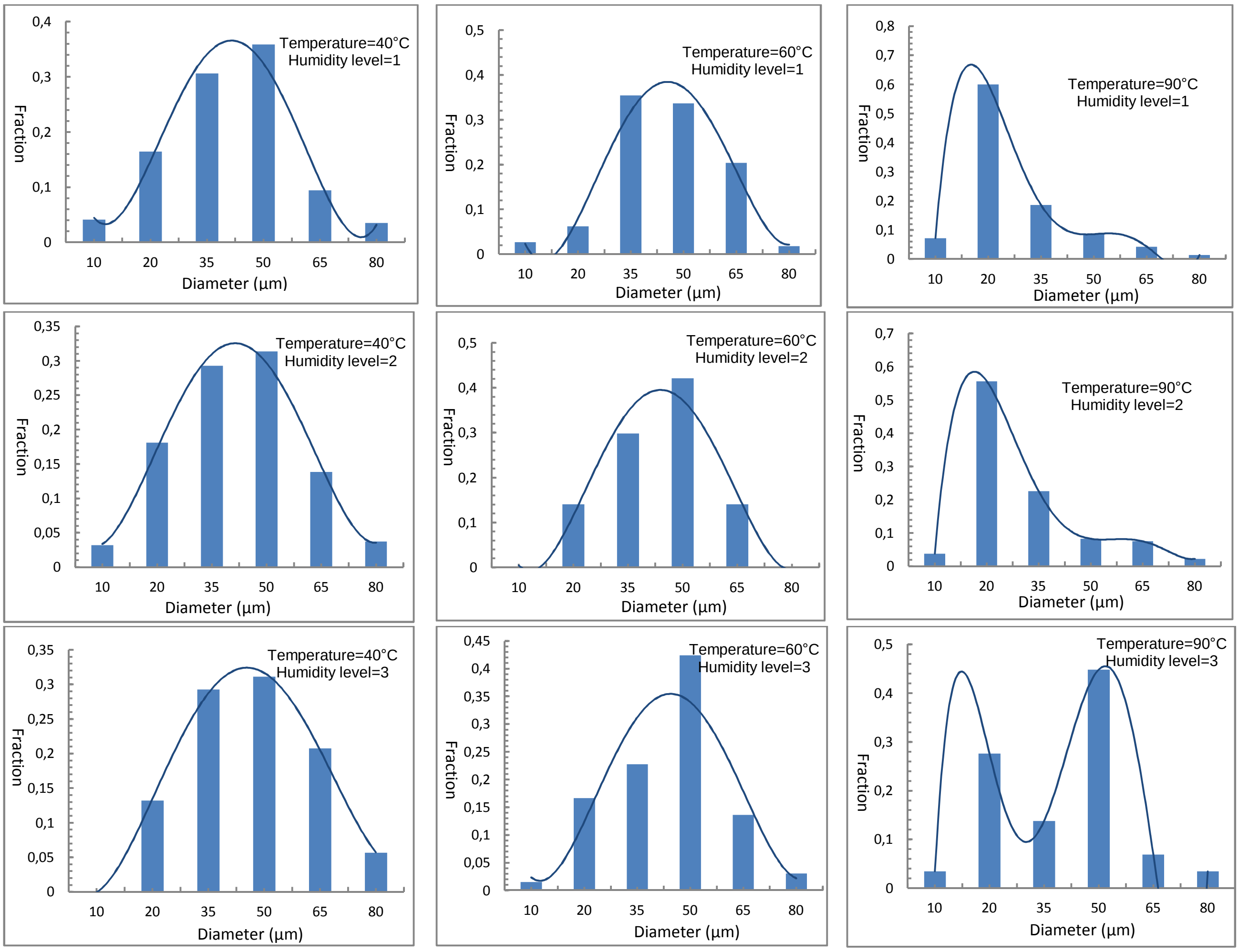


Fig.7 Size distributions of water droplets in a mist generated by atomizer under different conditions

In the current study, particle velocity was obtained by Particle Image Velocimetry from the analysis of two successive images of particles illuminated by double-pulsed laser sheet. Here we take the image polarized parallel (left half of Fig.**6**) for the determination velocity field. Le flow direction of the water droplets ascending naturally is influenced by the hot air flow blowing downward, as shown in Fig.8.

Conclusion

The optical method of polarization ratio provides a non-intrusive particle sizing technique for spherical particles in two-phase flow under low concentration. The combination with velocity measurements (PIV) makes it possible to determine the particle velocity simultaneously. The optical setup also allows the combination with other particle sizing methods for the application to particles of a larger size range.

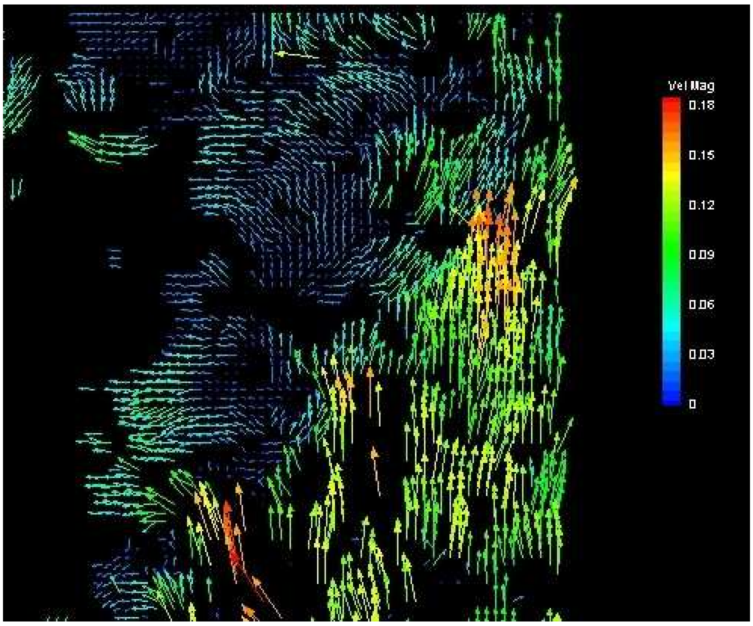


Fig.8 Velocity field of water droplets under investigation

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