Simultaneous determination of size and velocity of microspheres in flow by polarization analysis of the scattered light

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Abstract. A particle sizing method based on the analysis of polarization status of light scattered by targeted particles is introduced, with the polarization ratio of scattered light obtained through particle image processing. The optical setup was combined with PIV (Particle Image Velocimetry) for the simultaneous determination of particle velocity field. The presented granulometry and velocimetry method was applied to determine the size distribution of DEHS particles dispersed in ambient air generated by an aerosol generator. With the particle velocity field acquired simultaneously, the size distributions of DEHS particles under different operating pressures obtained from the presented method were compared with standard values provided by the manufacturer and showed a good correspondence, which proved it to be a promising flow field diagnostic technique.

1. 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, 2].

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 [3, 4]. Figure 1 illustrates the basic coordinate system based on which the interaction between the incident light and a spherical particle is analyzed.

According to theory of Lorenz-Mie, the linear polarization of light scattered by a sphere can be characterized by polarization ratio (P) which is determined by four 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). Given that the relative refractive index of the particle and the medium is known, with the incident wavelength and the observation angle fixed, the polarization ratio is...
determined by sphere diameter alone. The unknown diameter can thus be determined through inverse calculation when the polarization ratio is obtained from experiments.

**Figure 1.** Light scattering by a spherical particle

In the current study, $P$ is defined as the ratio of the perpendicular polarized electric intensity to its parallel polarized counterpart, as illustrated by Equation (1), where $E_\perp$ and $E_\parallel$ represent respectively the electric field of scattered light and that of incident light [5]. $i_\perp$ is the scattered irradiance per unit incident irradiance given the incident light is polarized perpendicular to the scattering plane, while $i_\parallel$ is its counterpart when the incident light is polarized parallel. Given the incident light linearly polarized at $45^\circ$, the polarization ratio $(P)$ of the scattered light is determined by the ratio of $i_\perp$ to $i_\parallel$:

$$P(\lambda, \theta, m, d) = \frac{E_{\perp}}{E_{\parallel}} = \frac{i_{\perp}}{i_{\parallel}} = \frac{E_{\perp}}{E_{\parallel}} = i_{\perp} \frac{E_{\perp}}{E_{\parallel}} = i_{\parallel}$$

(1)

Figure 2(a) shows the variation of the polarization ratio with the diameter of DEHS particle at a diffusion angle of $66^\circ$. The wavelength of incident light is $0.532\mu$m. The refractive index of DEHS particle is taken as 1.4539 [6]. The particle diameter can be determined through inverse calculation when the two polarization components of scattered light are obtained. To be noted that when the inverse calculation based on polarization ratio $P$ returns more than one diameter, which is possible when particle diameter is greater than $0.5\mu$m, the polarized scattered irradiance per unit incident irradiance is taken as reference, as shown in Figure 2(b).

**Figure 2.** (a) Variation of the polarization ratio with particle diameter; (b) Variation of the scattered irradiance per unit incident irradiance with particle diameter
2. Experimental setup

In the current study, image analysis is employed to determine the polarization ratio of light scattered by DEHS particles so that the experimental setup could be combined with PIV (Particle Image Velocimetry) to realize a simultaneous determination of velocity field.

2.1. Test rig

An optical test rig was set up to perform the acquisition of particle images, as illustrated by the sketch in Figure 3. Light scattered by the particles investigated was collected at a certain angle $\theta$, then the two polarization components of scattered light were separated by a cube polarizer and arrived 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: 4008x2672 pixels). In the presented study, double Nd:Yag laser (exposure time: 9ns) was employed to ensure the acquisition of PIV images of particle flow field. DEHS particles were generated by an aerosol generator (ATM210, Topas Gmbh) and dispersed directly into ambient air. A hot air blower was applied to reduce the concentration and agglomeration of DEHS particles.

Figure 4 shows a photo of DEHS particles obtained by CCD, with the image polarized parallel on the left and that polarized perpendicular on the right.

![Figure 3. Optical setup](image-url)

![Figure 4. Polarized image of DEHS particles in flow](image-url)
2.2. Image processing
Through image processing, the polarization ratio of light scattered by each particle can be determined. The localization of particles on images was conducted by converting the particle image into binary image. Then the two polarized components of scattered irradiance per unit incident irradiance were related respectively with the grey levels of particle images polarized parallelly and perpendicularly. Figure 5 illustrates the basic principle of the determination of particle size and velocity in the current study. For each laser pulse, two polarized images were obtained on CCD simultaneously, based on which correlation process was performed to recognize the same particle on two images. The polarization ratio \( P \) of each single particle on the image was then acquired. While with double Nd:Yag laser, the two pulses provided a pair of successive images of particles which was correlated with each other so that the particle velocity could be obtained.

![Figure 5. Determination of particle size and velocity](image)

3. Results
In the presented study, size distributions of DEHS particles under different operating pressure of the aerosol generator were examined, as illustrated in Figure 6(a)-(d). The experimental results under 0.4bar and 1.3bar were compared with those provided by the manufacturer of the aerosol generator [6], as shown in Figure 6(e)-(f). As can be seen from the figures, the DEHS particle diameter varies from 0.2μm to 1.5μm. The proportion of small particles increases when operating pressure increases to 2bar, which is logical. The comparison of experimental results with the referential values provided by the manufacturer of the aerosol generator also shows a good correspondence.
Figure 6. Size distribution of DEHS particles under different operating pressures

The velocity field of DEHS particles is shown in Figure 7. In the current study, to ensure the simple diffusion of incident light, a hot air blower was applied to reduce the concentration of DEHS particles. The particles thus showed an ascending movement with a small velocity (less than 0.04m/s).
4. Conclusion
The particle sizing method based on the analysis of polarization status of light scattered by targeted particles introduced in the current paper was applied to the determination of DEHS particle size in hot air flow. With the polarization ratio of scattered light obtained through particle image processing, the optical setup can be combined with Particle Image Velocimetry to perform the simultaneous acquisition of particle velocity in the flow. The experimental results were compared with the referential values and showed a good correspondence. The granulometry method presented is proved to be a promising flow diagnostic technique which can be applied in various research fields.

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