Photoelectric method for determination of the relative radii of microparticles

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Abstract. Experimental results of relative radii of microparticles determination by the analysis of scattered on a particle radiation are presented. Due to the monotonous dependence of the indicatrix of particle scattered radiation on particle radius at a specific angle, it becomes possible to determine the relative radii of particles in cloud of particles by one camera picture. Radii of three types of monodisperse powders of melamine formaldehyde particles with known sizes were analyzed by means of Mie theory. The results showed the possibility to determine relative radii of particles to each other in suspended clouds of particles.

1. Introduction
Plasma with dust particles is widespread in space [1–3]; it is an interesting object for study. Dusty plasma has been studied for almost a century: it was obtained for the first time in experiment by Langmuir in 1924 and recently is of a great interest [4–6].

Powders of monodisperse particles of micron and submicron sizes with known physical parameters are often used in physics of low-temperature plasma [7–10], in the particle image velocimetry research methods [11,12], in nanotechnology [13], in experimental works on particle separation [14].

Thus the task of particle size diagnostics can be useful in experiments carried out in the described studies.

The paper presents experimental results on relative radii of microparticles determination by analysis of single image of cloud of particles by means of Mie theory. The results show the possibility to determine particles radii relative to each other in suspended clouds of particles.

2. Method of particle radius determination
The method of particle radius determination by the analysis of scattered on a particle radiation is presented in figure 1(a). In the experiment particle is illuminated by the beam of laser light of known power. With known power density of the laser light in the particle region and the radial distribution of the light in the cross section of the laser beam it is possible to find the power of the incident radiation that illuminates the particle. Particle scatters incident radiation and the power of it can be presented by the equation

$$P_{\text{cam}} = \frac{(P_L j(\theta, r_p)/S_L) \pi r_p^2 \Omega}{\pi r_p^2 \Omega},$$

(1)
where $P_{\text{cam}}$ is the power of scattered illumination, $P_L$ is the power of laser light, $j(\theta, r_p)$ is the indicatrix of scattered illumination as the function of scattered angle $\theta$ and particle radius $r_p$, $S_1$ is the area of cross section of beam of the laser light in the particle region, see 4 in figure 1(a), $\pi r_p^2$ is the area of the particle projection, $\Omega$ is the solid angle of camera objective ($\Omega = a^2/(4L_a^2)$), where $a$ is the radius of camera aperture and $L_a$ is the distance from a particle to aperture.

In the experiment, the angle between optical axis of the camera and the laser beam was $\theta$. The angular size of camera aperture from the particle, see figure 1(a), was $2\Delta\theta$, so the indicatrix of scattered illumination $j(\theta, r_p)$ should be presented by the equation

$$j(\theta, r_p) = \frac{1}{4\pi} \int_{\theta-\Delta\theta}^{\theta+\Delta\theta} \int_0^{\pi} J(\theta, \phi, r_p) \sin(\theta) d\theta d\phi = \frac{1}{4} \int_{\theta-\Delta\theta}^{\theta+\Delta\theta} J(\theta, r_p) \sin(\theta) d\theta,$$

(2)

where $J(\theta, r_p)$ is the phase function of amplitude scattering. To analyze the $J(\theta, r_p)$ the MiePlot program was used.

In the experiments green laser was used with the wave length $\lambda = 532$ nm. The power of laser light $P_L$ was measured by LPM (laser power meter). Since particles were captured by camera and it could not measure the power of the light that was scattered by a particle, the power of light was determined by its brightness. To do this the camera was preliminary calibrated by means of the laser to determine the dependence of the brightness of light radiation on its power. The scheme of camera calibration is shown in figure 1(b). In experiment HiSpec Fastec Imaging camera was used with 8-bit sensor that gives 256 shades of gray (from 0 to 255). The laser beam was directed to the camera. To avoid overlight and damage of the sensor of the camera by laser light a number grey filters were used. The transition coefficients $\alpha$ of grey filters were known.

The pixelized image of the laser beam is presented in figure 2(a). Number in each pixel of the image of laser beam shows its brightness. The brightness of the whole laser beam is the sum of all brightness of all pixels of the laser beam in the image $I_{\text{spot}}$. The total brightness of laser beam was calculated by the equation $I_P = I_{\text{spot}}/(1/\alpha)$, where $\alpha$ is the product of transmission coefficients of filters used in camera calibration.

The dependence of laser beam brightness on the power of laser light is presented in figure 2(b). The step in figure 2(b) can be explained by different sets of grey filters that were used to determine the brightness of laser beam. The dependence of $I$ on $P$ is linear and could be presented by equation $I = AP$, where $A = 1.87\times10^{11}$ W$^{-1}$ with rms deviation $\sigma = 81$.

3. Experiment on relative radii of microparticles determination

In the experiment the injector with calibrated particles was installed above the laser beam figure 1(a). Particles fell from the injector into the laser beam where they were captured by the camera. In the experiment 3 types of monodisperse particles of melamine formaldehyde were used with $r_m = 0.88$, 2.24 and 4.48 $\mu$m. Particles were analyzed by microscope before they were installed in the injector. Due to small sizes of particles the falling speed was small enough that the camera could capture them, figure 3.

To analyze the large number of particles (more than 100) the program was developed that allowed registering particles, determining two-dimensional coordinates of each particle in the picture and brightness of particles. Particle that has even one pixel with brightness 255 was not analyzed as the light-striked particle. Particles of all three types were injected separately. During the experiment camera settings (size of the aperture of the camera, the ISO, the exposure time) were fixed while the power of the laser light was selected for the certain type of particles to prevent their light exposure. Laser parameters (the power of laser light, the area of cross section of the laser beam in particle region, the wavelength) were taken into account. As the power of the laser light can be set by the brightness, the power of scattered by a particle light $P_{\text{cam}}$ should be changed by the equation $P_{\text{cam}} = I_{\text{cam}}/A$, see figure 2(b).
Figure 1. (a) Method of particle radius determination by analyzing of scattered by the particle illumination: 1—the particle; 2—the laser; 3—the beam of laser light; 4—the cross section of laser beam in the particle region; 5—the camera; 6—the solid angle; 7—the injector and falling particles from it. (b) The scheme of camera calibration: 1—the camera; 2—a number of grey filters; 3—the laser.

Figure 2. (a) The pixelized image of the spot of the laser beam. Number in each pixel of the laser beam image corresponds to its brightness. The sum brightness of the beam was $I_{\text{spot}} = 2278$ that corresponds to the laser beam power 0.057 W. The number of grey filters were used with transmission coefficients $\alpha = 0.3788, 0.0197, 0.0036$ and 0.0079. (b) The dependence of brightness $I_P$ on the power of light $P_L$. Grey line is approximation line.

In the experiment $a = 1.4$ mm, $L_a = 21$ cm, $\theta = 90^\circ$ and $\Delta \theta = 3.8^\circ$, so $j(\theta, r_p)$ can be replaced by the function of only one parameter $r_p$: $j(r_p)$ (2).
Figure 3. The cloud of particles.

Figure 4. (a) The monotonous dependence of indicatrix of scattered illumination \( j(r_p) \) on particle radius \( r_p \) at \( \theta = 90^\circ \). (b) The linear dependence between the radii of particles determined by the microscope \( r_m \) and the radii of the particles defined by the method \( r_p \).

The result equation to determine each particle radius is

\[
    r_p^2 j(r_p) = \frac{I_{cam} A^4 L_a^2 S_L}{AP_L}.
\]

where \( I_p \) is the brightness of particle.

The dependence of \( j(r_p) \) on \( r_p \) is presented in figure 4(a). The dependence in figure 4(a) is monotonic and in the first approximation can be presented as the linear function \( j(r_p) = -0.001r_p + 0.009 \) with rms deviation \( \sigma = 10^{-6} \). Unfortunately, the particle radii determined by the method are strongly depend on the approximation function and only relative to each other.
particle radii can be determined. To find the radius of each particle the equation (3) should be solved. The result is presented in figure 4(b). One can see that there is the linear dependence between the radii of the particles determined by the microscope $r_m$ and the particles radii defined by means equation (3) $r_p$ (rms deviation $\sigma = 0.9$). Changing the approximation function for the dependence in figure 4(a) the linear dependence in figure 4(b) remains but the inclination of linear dependence changes. Since particles radii obtained by this method are sensitive to the approximation equation for dependence in figure 4(a), the only relative particle radii relative to each other can be determined by this method.

4. Conclusion
The experimental results on particle radius determination by analysis of scattered on particles radiation are presented. Due to the monotonous dependence of the indicatrix of scattered by particle radiation on particle radius at a specific angle, it was possible to determine the relative particles radii in particle cloud by one camera picture. Experimentally 3 types of monodisperse powders of melamine formaldehyde particles were studied. Since particles radii obtained by this method were sensitive to the approximation equation for dependence of the indicatrix of scattered by particle radiation on particle radius, the only relative particle radii relative to each other can be determined by this method.

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