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LASER ANALYZER OF AEROSOL PARTICLES WITH MONOTONIC CALIBRATION CURVE

Здатність малої частинки розсіювати монохроматичне світло залежить від її розміру немонотонно, що спричиняє невизначеність при вимірюванні діаметра частинки. Запропоновано нову конструкцію лазерного лічильника аерозолів, у якій ефективність збирання світла зростає при збільшенні кута розсіяння, що дозволило значно згладити градуювальну криву. На цій основі створено простий однохвильовий одноканальний лічильник частинок з точністю вимірювання розмірів близько 5%.

Рассеивающая способность малой частицы для монохроматического света немонотонно зависит от ее размера, что служит источником неопределенности при измерении ее диаметра. Предложена новая конструкция лазерного счетчика аэрозолей, в которой эффективность сбора рассеянного излучения возрастает при росте угла рассеяния, что позволило существенно сгладить форму градуировочной кривой. На этой основе создан простой одноволновой одноканальный счетчик частиц с точностью измерения размеров около 5%.

The scattering ability of a small particle, illuminated by the monochromatic light, non-monotonically depends on the particle size, which causes uncertainty in the particle sizing. A new construction of the aerosol counter is proposed in which the scattering light collection efficiency grows with the scattering angle that ensures smoothening of the calibration curve. As a result, the particle size can be measured with accuracy of about 5% in a simple single-wavelength, single-photodetector particle counter.

Optical aerosol counters are well known single-particle devices in which information on the particle size is obtained from the absolute value and angular distribution of the light scattered by a particle [1]. This principle of operation allows to create high-sensitive, fast-acting noncontact devices suitable for investigation of disperse systems as well as individual microparticles in a real time.

There are known many various constructions of such devices [1,2]. Almost all of them use a laser beam as a source of exciting light to illuminate a volume in the air stream. Once a particle carried by the stream crosses the beam, some part of the light is scattered and, by means of a certain collecting system (in Fig. 1 it is formed by a spherical mirror capturing the light scattered into the lower hemisphere) directed to a photodetector (a photodiode as a rule) producing a pulse of electrical current which is amplified and processed. The particle size determination is based on the simple concept that the scattered light power grows with the scatterer's size, so that comparison of the output electric signal with a predetermined size/scattering dependence (expressed by the calibration curve) supplies the possibility to know the particle size.

However, this simple and clear scheme possesses a fundamental defect: in the most interesting range of particle sizes ($\geq$ 1 μm) the usual characteristics of the Mie light scattering depend non-monotonically on the particle size [3] (see Fig. 2 for example). Importantly, this feature appears irrespective of which part of scattered light is collected (the energy localized within a small solid angle near a certain scattering direction **s** (Fig. 1) or the total amount of light scattered by a particle into the whole sphere). As a result, the unambiguous determination of the particle size from the scattered intensity becomes impossible. To avoid this difficulty, various approaches were applied: multi-wavelength light sources, combinations of several detectors etc. which causes complication of the counter construction, sophisticated procedures of the signal processing and, ultimately, to the growth of the device price [4–6].

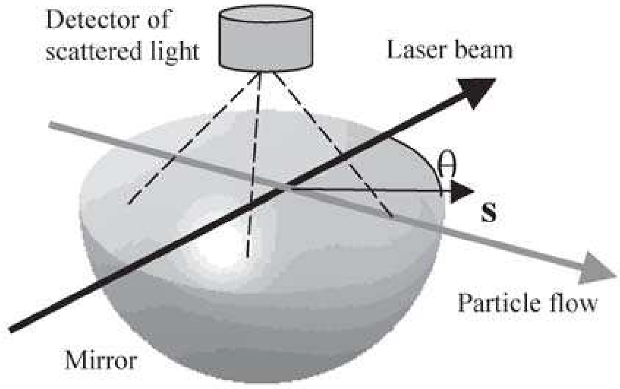

Fig. 1. Possible scheme of a laser particle counter. Laser beam crosses the particle flow, the scattered light is collected by a mirror and directed to a photodetector

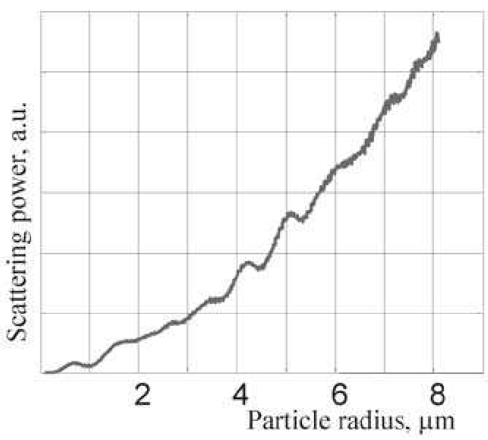

Fig. 2. Typical calibration curve of a laser particle counter (water particles, radiation wavelength 0.63 μm): for small particles the sizing inaccuracy can reach 50%

Nevertheless, it is known that maxima and minima of calibration curves for scattering at different angles θ generally do not coincide. In this view, attempts to get a smoother calibration curve by means of combination of the scattering signals obtained at different scattering angles seem to be productive. For example, the authors of Ref. [7] have proposed to collect the light scattered into angle intervals 10° – 30° (signal of forward scattering S_f) and 145° – 170° (signal of back scattering S_b). Then processing the signals S_f and S_b separately allows not only to unambiguously determine the particle size but also to find its refraction index, which, as well, affects the counter calibration curve.

Further development of this idea leads to expect that proper combination of light portions scattered under different angles can produce the resultant scattering signal showing a much more smooth angular dependence that is usually observed and presented in Fig. 2.

We have studied this problem theoretically on the ground of the Mie theory [3], assuming the spherical particle shape. For a non-polarized incident plane wave, the pattern of scattering is symmetric with respect to the incident beam axis so that the light power scattered by a particle with radius a into the solid angle between θ_1 and θ_2 equals to

$$P(a) = \frac{\lambda^2}{2\pi} I_i \int_{\theta_1}^{\theta_2} S_{11}(a,\theta) \sin\theta \, d\theta \qquad (1)$$

where λ is the wavelength of incident light, I_i is its intensity and $S_{11}(a,\theta)$ is the element of the Mueller matrix describing transformation of the Stokes vector upon scattering [3]. Our main idea is to combine the light portions scattered at different angles with different weights that leads, instead of Eq. (1), to the following representation of the collected light power

$$P_f(a) = \frac{\lambda^2}{2\pi} I_i \int_{\theta_1}^{\theta_2} f(\theta) S_{11}(a,\theta) \sin\theta \, d\theta \qquad (2)$$

where $f(\theta)$ is the weight function which should be chosen from the condition of maximal smoothness of the dependence P_f (a). This problem can be considered in a regular mathematical way but on this stage we have used a simple trial method which however has yielded relevant results. In particular, quite appropriate effect may be obtained when choosing the linear weight function, $f(\theta) \propto \theta$. In this case, the strong forward scattering, growing with the particle size, is taken into account with very small weight while the weak back scattering obtains maximum weight. Corresponding calibration curve (Fig. 3) contains some residual oscillations but their magnitude is efficiently depressed, especially for small particles providing high sizing accuracy (compare Fig. 2).

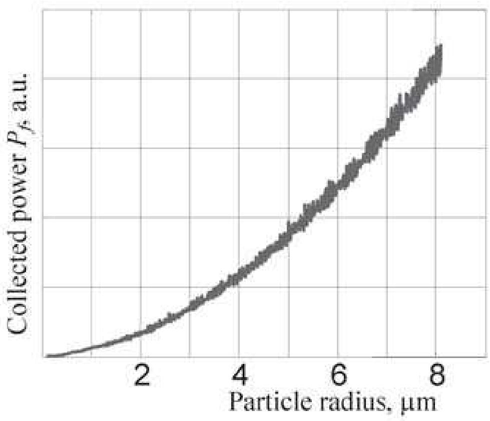

Fig. 3. Collected light power (2) vs size of water droplets for linearly variable collecting efficiency $f(\theta)$: the potential sizing inaccuracy does not exceed 5%

The most direct method for realization of the required weight function lies in creation of collecting systems whose collecting efficiency varies with the scattering angle θ. This can be reached, for example, due to special shape of the collecting mirror enabling the linear growth of the efficiency

$$f(\theta) = \frac{\theta}{2\pi} \tag{3}$$

(see Fig. 4a). Such a construction provides also an additional advantage. As the particle size increases, the forward scattering (at small θ) grows very rapidly while the back scattering grows moderately or even falls down [3]. In this situation, the collecting system, whose efficiency increases with θ, allows to soften the steepness of calibration curve making it almost linear for particle radii exceeding ~ 5 μm (Fig. 3).

Numerical simulations have shown that exact form of the weight function in (2) is not critical, provided that the collecting efficiency grows from forward to back directions. In particular, this growth may be stepwise, for example, with the N-step weight function

$$f(\theta) = (1/2N)\, j\,, \quad (\pi/N)(j-1) < \theta < (\pi/N)\, j \quad (j = 1 \ldots N). \tag{4}$$

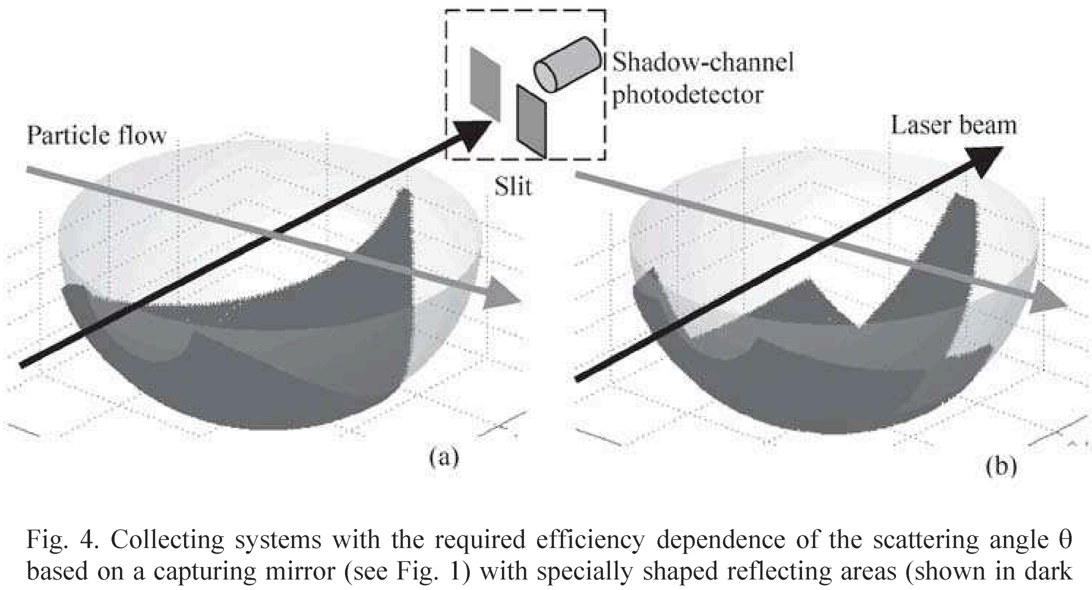

Fig. 4. Collecting systems with the required efficiency dependence of the scattering angle θ based on a capturing mirror (see Fig. 1) with specially shaped reflecting areas (shown in dark tone): (a) exact linear dependence (3); (b) stepwise dependence (4) with N = 3. The small "deviations" in the mirror shapes near the laser beam serve as inlet and outlet

Corresponding modification of the reflecting beam shape can be seen in Fig. 4b. The appearance of calibration curve for the case of 3-step mirror depicted in Fig. 4b is presented in Fig. 5. Visually it is almost identical to that of Fig. 3; however, quantitative potential accuracy of the particle sizing falls down noticeably.

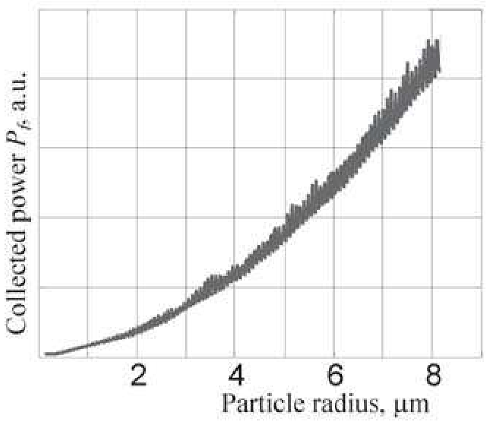

Fig. 5. Calibration curve of a particle counter with a stepwise mirror of figure 4b: the potential sizing inaccuracy ~10%

The monotonic calibration curve enables unambiguous particle sizing so that a particle of higher size produces a higher scattering signal. However, to have a possibility of quantitative measurements, one must perform the absolute calibration procedure: at least for one particle the size must be measured independently, and this known size being associated with the scattering signal from this particle, gives the scale factor determining absolute value of the calibration curve. To this purpose, the shadow channel is designed (Fig. 4a). It consists of an additional photodetector provided with a small (10 – 20 μm width) slit positioned so that when a particle crosses the laser beam, its shadow "crosses" the slit. The particle shadow decreases the light power approaching the photodetector by the amount directly related to the particle radius. The signal shape in the shadow channel can be easily calculated. Results for water particles are presented in Fig. 6 (for particles of a different nature, the pattern is quite similar and even quantitatively coincides within 5%).

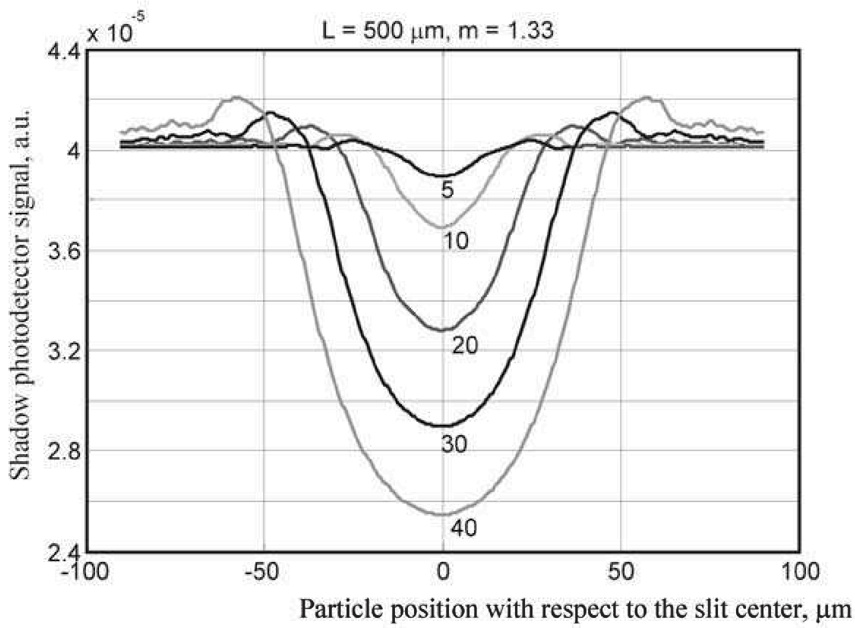

Fig. 6. The shadow signal shapes for different particle sizes (indicated in micrometers). A 20 μm wide slit is positioned at 500 μm from the particle flow immediately in front of the detector

So the absolute counter calibration is performed as follows. Before measuring a sample aerosol, relatively coarse (10 – 20 μm) particles are pumped through the counter. Each particle produces interrelated signals in both scattering and shadow channels. The analysis of the shadow signal enables to determine the particle size, after which this size has been associated with the corresponding signal in the scattering channel. This gives the necessary absolute value of the calibration curve of Figs. 3 or 5 which then can be used for sizing of particles within wide size range, including small particles (< 1 μm) that cannot be measured efficiently with the shadow method.

Conclusion. It is shown that proper combinations of light scattered at different angles provides essential smoothening of the known large-scale oscillations in the scattered power dependence on the scattering particle size (the counter calibration curve). The decrease of oscillations down to less than 5% can be achieved if the collecting efficiency grows linearly with the scattering angle; the stepwise efficiency change is also profitable. For the absolute counter calibration, an additional channel employing the shadow principle of sizing can be used. This approach enables to avoid the tedious and ambiguous procedure of the counter calibration within the fine particle range. It allows to combine, in a single device, the accuracy of particle sizing methods based on the light scattering with the simplicity and the conceptual clarity of calibration procedures using the shadow methodology.

The principles described have been used in construction of a working device with following basic characteristics: measurable particle size range 0,5 to 5 μm; admissible concentration of particles ≤ 2000 per liter; volume aspiration rate 0,1 to 0,5 l/min; measurement time 1 min; overall dimensions 100×200×300 mm; total mass 4 kg.

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