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Veracity of the method of detecting scattered laser radiation for content measuring of particulate matter in air

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Abstract. The problem of measuring the parameters of dust particles in the environment is currently relevant for residents of densely populated cities. Measurements of the size and size distribution function of dust particles are carried out using instruments based on the method of scattering of laser radiation. The analysis of the measurement method based on the spherical particle model and the theory of Mie diffraction theory is carried out. The indicatrices of laser radiation scattering by particles 2.5 and 10 μm in size are calculated. The size distribution function of particles is estimated under the condition that the intensity of scattered laser radiation is measured for at least two scattering angles. The possibility of erroneous indication of measurement results by widely used portable measuring devices for dust parameters is shown.

Keywords: particle concentration, air pollution, particulate matter PM2.5, Mie scattering theory, scattering indicatrix, particle size distribution

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Материалы конференции
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Надежность метода детектирования рассеянного лазерного излучения при измерении содержания твердых частиц в воздухе

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Аннотация. Проблема измерения параметров частиц пыли в окружающей среде в настоящее время актуальна для жителей густонаселенных городов. Измерения размера и функции распределения по размерам частиц пыли осуществляются с помощью приборов, работа которых основана на методе рассеяния лазерного излучения. Выполнен анализ метода измерения, базирующегося на сферической модели частиц и теории дифракции Ми. Вычислены индикатрисы рассеяния лазерного излучения на частицах размером 2,5 и 10 мкм. Проведена оценка функции распределения частиц по размерам при условии измерения интенсивности рассеянного лазерного излучения не менее чем при двух углах рассеяния. Показана возможность ошибочной индикации результатов измерений широко применяемыми портативными измерительными приборами параметров пыли.

Ключевые слова: концентрация частиц, загрязнение воздуха, частицы PM2.5, теория рассеяния Ми, индикатриса рассеяния, распределение частиц по размерам

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Introduction

In recent years, industrial production in the world is rapidly gaining momentum. The state of the environment is constantly getting worse. The number of green spaces and other natural barriers that clean up the environment is decreasing [1–3]. These negative processes lead to an increase in dust in the air [4–6]. The highest concentration of dust is formed mainly in densely populated areas of cities and poses a great danger to residents. This is due to the fact that transport, industrial emissions and smog from thermal power plants are the main sources of dust particles [3, 7–9]. Particularly dangerous to humans are particulate matter with a size of 2.5 microns ($PM_{2.5}$). They overcome the natural protective barriers of a person, penetrating the body through the mucous surface of the respiratory organs, and then spreading inside, overcoming the protective membranes of the body and penetrating directly into the cell. The problem is that the accuracy of commercial portable measuring instruments for dust parameters is not high (±15%), since the device registers particles larger than 2.5 μm, while in fact the size of the registered particles is less than 2.5 μm [10–12]. It is these particles that have a negative impact on human health.

Fig. 1 shows the concentration distribution of particulate matter in the world. Countries marked in blue are those with less than 10 μg/m^3 (safe level according to the World Health Organization). Green corresponds to countries with up to 12 μg/m^3 (safe level according to the US assessment criteria), then from yellow on a gradient to red and brown as the danger increases.

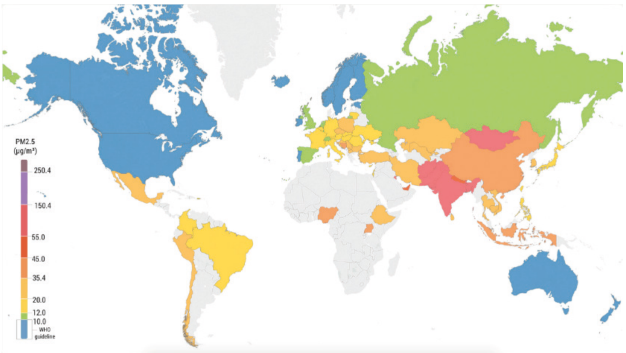

Fig. 1. Concentration of particulate matter $PM_{2.5}$ in the world

Materials and Methods

The proposed measurement method is based on the Mie diffraction theory [13, 14]. This is the most commonly used theory, which describes the scattering of laser radiation by spherical particles. Taking into account the small size of dust particles, they can be considered spherical in comparison with the distances and the volume in which the measurements are made. The radiation scattering pattern on a particle can be described over the entire angular range from 0° to 360° depending on the amplitude and wavelength. To use this theory for measurements, it is necessary to know the optical properties of the system under study (complex refractive index, its real and imaginary parts). For example, for quartz dust particles in air, this value of «n» is on the order of 1.5–0.05*i*, where *i* is an imaginary unit. The value of the imaginary part makes it possible to take into account the specificity of the particle surface structure, for example, roughness. The amplitude function of the scattered field is determined by solving the vector wave equation as a series in functions containing Legendre polynomials, and the coefficients of the scattered field series are expressed in terms of the Riccati–Bessel functions and their derivatives.

Results and Discussion

Based on the Mie scattering equations, one can calculate the dependence of the scattered light on the scattering angle for particles of different sizes. Fig. 2 shows the calculated dependences of the scattered light intensity *s* on the scattering angle θ for silica particles with sizes of 2.5 and 10 μm.

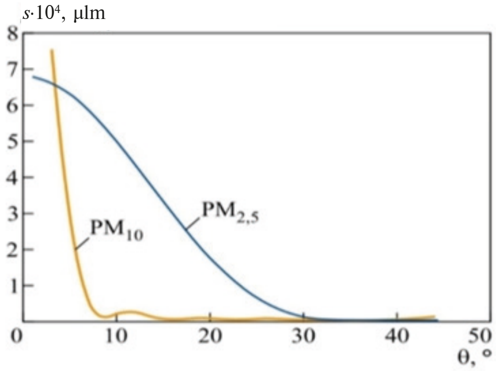

Fig. 2. Scattered light intensity as a function of the scattering angle for particles of sizes 2.5 and 10 μm

For small particle sizes, the radiation scattering indicatrix is concentrated in a sufficiently large scattering angle (θ > 20°), and for large particles, on the contrary, in a small angle (θ < 10°). At large scattering angles for very small particles, the intensities of the scattered radiation are very small, and at small angles little scattering is observed. For particles smaller than 2.5 μm, it cannot be established that the scattering intensities are extremely low compared to particles with sizes $d \geq 2.5$. It is on this fact that the selection of small particles by scattering angles is based [14–17].

Dependences of the scattered light intensity on the scattering angle can be shown on the polar diagram (Fig. 3).

For particles with a size of 2.5 μm, the intensity is maximum at θ = 45°, and for larger particles, θ ≈ 10°. When designing simple instruments for estimating particle concentration, information about these scattering angles is taken into account. To fix the photodetectors, selective angles between 10° and 45° are chosen. When using four photodetectors, it is desirable to choose the angle values at the points of the curves where the intensity derivative is maximum (Fig. 2). The highest value of the derivative for the $PM_{2.5}$ curve is achieved at θ = °20, and for the PM_{10} curve, at θ ≈ 6°. It is not without reason that we are talking about the number of photodetectors, since when using only one recorder it is impossible to obtain truthful data on the number concentration of particles. To achieve a lower measurement error, the number of sensors is usually increased to four.

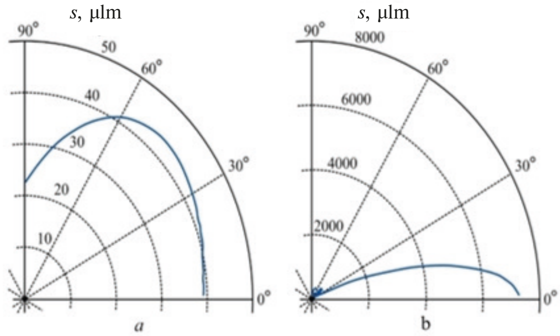

Fig. 3. Polar plot of scattering intensity for particles sized 2 μm (*a*) and 8 μm (*b*)

Thus, at a certain angle to the laser beam, the scattered radiation intensity will depend on the particle size. Scattered radiation is usually focused using a flat convex lens. A point in space where one photodiode is located registers scattered radiation not only from particles of a certain size, but also from all particles on which scattering occurs. The scattering indicatrix simply indicates that at a certain angle, a particle of a certain size has a maximum scattering intensity. However, particles of other sizes will also contribute to the total intensity of scattering at this angle. Therefore, a single photodetector, which is at an angle θ relative to the laser beam, registers scattered radiation from particles of all sizes.

To search for the distribution of particle concentration on their size using several photodetectors, we take as the calculated particle concentration, where i is the particle size, in our case n_1 denotes $PM_{2.5}$, n_2 denotes PM_4, n_3 denotes PM_6, n_4 denotes PM_8. Let s_1 be the value of the photodetector signal, which is at an angle θ to the laser beam. Then we can write

$$s_1 = \alpha_{11}n_1 + \alpha_{12}n_2 + \alpha_{13}n_3 + \alpha_{14}n_4, \tag{1}$$

where α_{11}, α_{12}, α_{13}, α_{14} are coefficients that take into account the intensity of scattered radiation for each particle size and some technical properties of photodetectors.

For four photodetectors, we denote the signals as s_1, s_2, s_3, s_4 and write down the system of linear inhomogeneous equations:

$$\begin{cases} s_1 = \alpha_{11}n_1 + \alpha_{12}n_2 + \alpha_{13}n_3 + \alpha_{14}n_4 \\ s_2 = \alpha_{21}n_1 + \alpha_{22}n_2 + \alpha_{23}n_3 + \alpha_{24}n_4 \\ s_3 = \alpha_{31}n_1 + \alpha_{32}n_2 + \alpha_{33}n_3 + \alpha_{34}n_4 \\ s_4 = \alpha_{41}n_1 + \alpha_{42}n_2 + \alpha_{43}n_3 + \alpha_{44}n_4, \end{cases} \tag{2}$$

Considering that each counter receives scattered light only from a particle of a certain size, the distribution is calculated using four values s_1, s_2, s_3, s_4:

$$\begin{cases} s_1 = \alpha_{11}n_1 \\ s_2 = \alpha_{22}n_2 \\ s_3 = \alpha_{33}n_3 \\ s_4 = \alpha_{44}n_4, \end{cases} \tag{3}$$

But the actual signals correspond to the solution of the system of inhomogeneous linear equations (2). The difference between these values is the reason for the errors in estimates of the calculated concentration. Fig. 4 shows two distribution functions of particles, actual and calculated from the readings of photodetectors. For particles of different concentrations, readings based only on the signals of the photodetector do not match the actual concentrations. It follows from Fig. 4 that the particle sizes obtained from instrument readings based on only certain signals from four photodetectors in accordance with the system of equations (3) differ significantly from the actual sizes of the same particles calculated from (2). In any of the two experiments, the estimate of the concentration of $PM_{2.5}$ particles only from the signals of photodetectors (ignoring equation (2)) will be much higher than the actual one. The above analysis indicates that the readings of portable devices with several photodetectors do not correspond to the real concentration of particles.

To obtain a smoother curve of the distribution function, it is necessary to increase the number of laser counters in the device located at a small distance from each other. However, the concentration values will be relative, since they are expressed in units of photodetector readings. To obtain actual mass concentration values, it is necessary to collect the particles after they have passed the laser beam and weigh them. Only after these actions, it is possible to construct the particle size distribution function depending on their mass concentration.

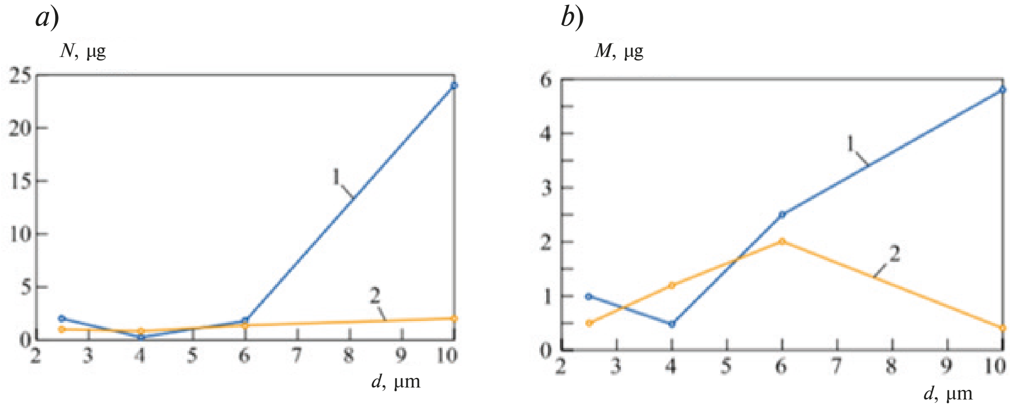

Fig. 4. Theoretical (1) and actual (2) particle distribution using one (*a*) and four (*b*) sensors

Conclusion

The revealed measurement errors are inherent in both simple and complex devices designed to determine the number concentration of particles. Instruments based on the simple correspondence of a particular angle to a particle size can have measurement errors of almost 100%, in particular for $PM_{2.5}$ hazardous particles. The particle size distribution can be easily obtained from the readings of several photodetectors at selected scattering angles. But an increase in the number of counters does not guarantee the authenticity of the results, since there are other errors due to the size of the angle, the finite size of the aperture in the working gap, as well as changes in the nature of the particles, which manifest themselves in a change in the imaginary part of the refractive index.

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