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DETERMINATION OF THE PARAMETERS OF PARTICLES SUSPENDED IN TWO-PHASE MEDIA BY MEANS OF PENETRATING RADIATION

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Determination of the concentration, size, and internal structure of microscopic particles suspended in two-phase media by means of contactless methods constitutes an important technological problem. If the particle sizes are on the order of the wavelength of light, methods based on light scattering by particles are widely used for this purpose. The most direct method consists in observing the optical signal scattered by an individual particle [1]. There are also several methods where the total signal from a large number of particles is recorded, but, in this case, multiple rescattering of light on particles must be negligible [2, 3]. At the same time, the complex relationship between the scattering amplitude and the refraction index, the shape of particles, etc., as well as the increasing background of multiply scattered light with greater thickness of the scattering layer, restrict the scope of application of such methods and make other measurement methods desirable, e.g., in the case of instrument calibration. Our aim is to point out the advisability of investigating two-phase media by means of penetrating radiation, which has been used successfully for radiation flaw detection [4] and for inspecting the composition and density of matter [5]. We shall mention the most important advantages of the proposed method. First, the interaction between individual particles and nonrefracted radiation is described by simple expressions, which makes the interpretation of results much easier. Second, in using the most informative scheme whereby scattering media are investigated "by transillumination," the background of multiply scattered radiation with a low information content (or, to borrow a term from radiation protection physics, the build-up factor [6]) increases with an increase in the scattering layer thickness much more slowly than it does for light. This makes it possible to use radiation methods for investigating "optically dense" two-phase media. We shall consider below the possibility of determining the distribution function of particle sizes by measuring the radiation attenuation as a function of the linear coefficient of attenuation inside the particles.

Consider the attenuation of a collimated radiation beam with the flux density I_0 which is incident perpendicularly to a uniform layer of a two-phase medium whose thickness is d. We assume that the linear attenuation factor of the liquid or the gas μ_0 is constant. We denote by the function $\mu_i(\mathbf{r}-\mathbf{r}_i)$ the difference between the linear factor inside the i-th particle and the value of μ_0, where $\mathbf{r}_i$ is the position of the center of the i-th particle, while the function $\mu_i(\mathbf{r})$ determines the internal structure of the i-th particle; it vanishes at distances larger than the particle size. For a fixed configuration of scattering particles, we write the density of the flux attenuated in conformity to the radiation exponential at the point $\boldsymbol{\rho} = (x, y)$ in the z = d plane bounding the layer in the following form:

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$$I(\rho) = I_0 e^{-\mu_0 d - \sum_{i=1}^{n} l_i(\rho - \rho_i)}, \tag{1}$$

where $l_i(\rho - \rho_i) = \int_{-\infty}^{\infty} \mu_i(x - x_i,\ y - y_i,\ z - z_i)\, dz$, while summation is performed with respect to all particles intersecting the half-line ρ = const. Expression (1) determines, from the point of view of the transport equation, the flux of radiation particles that have not experienced collisions. It holds for layer thicknesses d where the build-up factor for such a heterogeneous medium is close to unity. The values of the build-up factor for different media are given, e.g., in [6]. On the other hand, in the scattering of shortwave radiation with the wavelength λ on particles whose dimensions are a ($\lambda \ll a$), a divergent spherical wave, which interferes with the incident wave, forms as a result of coherent scattering, starting with distances of the order of a^2/λ. Consequently, if $d > a^2/\lambda$, the transport equation cannot be used, and the wave nature of radiation must be considered. This consideration (we shall not dwell upon it here) indicates that expression (1) also holds in the case $d > a^2/\lambda$ if the dimensions of the receiver R and the angle of radiation reception θ are sufficiently large ($R > \lambda d/a$, $\theta > \lambda/a$).

With changes in the configuration of particles, the flux density (1) fluctuates in the z = d plane with a correlation radius of the order of a and the correlation time a/v; v is the velocity of particles. In this case, only the statistical characteristics of radiation are of interest; they are obtained as a result of averaging with respect to the configurations of the particle system. We assume that the particles in the medium are statistically independent, in which case all the statistical characteristics of function (1) can readily be calculated [7]. In particular, the mean flux density is given by

$$\langle I(\rho)\rangle = I_0 \exp\left[-\mu_0 d + cd \int \left(e^{-l(\rho-\rho',\alpha)} - 1\right) d\rho' p(\alpha)\, d\alpha\right] = I_0 e^{-\mu_0 d - cd\langle S\rangle}. \tag{2}$$

Here $l(\rho-\rho', \alpha)$ is the function $l_i(\rho-\rho_i)$ for $\rho_i = \rho'$, where the dependence of the function $l_i(\rho)$ on the internal parameters, e.g., the shape, the spatial orientation, etc., is written as a function of the set of parameters α. For a fixed value of the parameter α, the integral with respect to ρ' determines the attenuation cross section for a given particle $S(\alpha)$. The function $p(\alpha)$ denotes the particle distribution density in the system with respect to the parameter α $\left(\int p(\alpha) d\alpha = 1\right)$. Thus, the integral in expression (2) constitutes the mean attenuation cross section for a single particle $\langle S\rangle$, obtained by averaging with respect to different types of particles and their spatial orientations. The theoretical concentration of particles, i.e., the mean number of particles per unit volume in a homogeneous medium, is a constant and is equal to c.

For $\mu_0 = 0$, the values of l_i and $\langle S\rangle$ are positive, and expression (2) provides the exponential attenuation of the mean intensity on a system of particles with the linear attenuation factor $(c\langle S\rangle)^{-1}$. For instance, in the propagation of radiation in a liquid with gas bubbles, the values of l_i and $\langle S\rangle$ are negative, and the ratio of the mean radiation flux densities $\langle I\rangle$ for a heterogeneous and a homogeneous layer increases exponentially. If, for the known values of d and $\langle S\rangle$, the concentration of particles is to be determined with respect to the attenuation in a layer, a lower accuracy in measuring the flux $\langle I\rangle$ will be required for determining the value of c in this case ($\langle S\rangle < 0$).

The mean attenuation cross section for particles with arbitrary shapes and an arbitrary internal structure is determined, in contrast to the case of light scattering on such particles, by the rather simple integral (2), which can be calculated either analytically or numerically. For homogeneous particles with μ = const and the dimensions a, this integral is calculated in the general form for two limiting cases. For slight attenuation in a single particle ($-1 \ll a\mu \ll 1$), the cross section is proportional to the particle volume V: $S \approx \mu V$ and $\langle S\rangle \approx \mu\langle V\rangle$. In the case of heavy attenuation ($a\mu \gg 1$), the cross section approaches the projection area S_*: $S \approx S_*$ and $\langle S\rangle \approx \langle S_*\rangle$. Since the value of $\langle S\rangle$ depends on the linear attenuation factor of particles in a certain fashion, this relationship can be used for determining the internal parameters of particles in the way the cross section of attenuation or scattering as a function of the wavelength is used in the case of light scattering [2].

We shall illustrate this possibility on the example of a system of uniform balls whose distribution with respect to radii is $p(a)$. The attenuation cross section for the given radius a and the relative linear attenuation factor μ is expressed in terms of elementary functions:

$$S(a, \mu) = -2\pi \int_0^a \left(e^{-2\mu\sqrt{a^2-x^2}} - 1\right) x\, dx = \pi a^2\left[1 - 2\left(\frac{1}{k^2} - e^{-k}\frac{k+1}{k^2}\right)\right] = \pi a^2 f(k), \tag{3}$$

where $k = 2a\mu$. The function f(k) is positive for $\mu > 0$; it increases monotonically as k increases from 0 to 1. For $\mu < 0$, the function f(k) diminishes from 0 to $(-\infty)$. The minimum negative value of $S(a, \mu)$ is obtained for $\mu = -\mu_0$.

The mean attenuation cross section is obtained by averaging expression (3) with respect to the distribution $p(a)$:

$$\langle S(\mu)\rangle = \int S(a, \mu)\, p(a)\, da. \tag{4}$$

The expression (4) can be considered as an integral transform with the kernel $S(a, \mu)$ of the distribution $p(a)$. The inverse transform of the experimentally measured function $\langle S(\mu)\rangle$ determines in principle the sought distribution $p(a)$. In practice, if we assign certain a priori distributions $p(a)$ with unknown parameters, we can determine simultaneously the concentration and the sought parameters of the size distribution of particles with respect to measurements for several values of μ. It is evident that only the form of the kernel $S(a, \mu)$ changes for inhomogeneous particles or particles with an irregular shape.

In conclusion, it should be noted that the wide ranges of the linear attenuation factors of x rays, γ rays, electron beams, and neutron beams in matter make the practical realization of this method rather promising.

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