fluidizing agent; v, velocity of oscillatory motion of ball; $v_m$, maximum velocity; t, time of motion; $F_{res}$, force of resistance; $F_{el}$, elastic force; Re, Reynolds number; $Re_m$, Reynolds number corresponding to $v_m$; $\omega_0$, frequency of natural undamped oscillations; x, displacement from equilibrium position; $x_0$, amplitude of oscillations; k, elastic coefficient, N, number of oscillations after which amplitude of oscillations decreases twofold; $\xi$, dimensionless displacement; $\eta$, dimensionless velocity; Q, dimensionless parameter; T, period of oscillations; $\tau$, dimensionless time; $\tau_{1/2} = 2\pi N$; $\xi_1$, $\xi_2$, intermediate values of $\xi$.; $y = \eta^2/2$; $\Omega$, portion of volume of suspension occupied by solid phase; $\varepsilon$, porosity of bed; f, coefficient of nonsphericity; $\mu^0 = \frac{\mu_0}{\varepsilon^{1.283} + f^3 - 2(1-\varepsilon)(f-1)^{1/3}}$.

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# METHODS OF EXAMINING BEAM DIFFUSION IN AN ABSORBING AND SCATTERING MATERIAL


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An apparatus and method are presented for measuring the effective cross section of a radiation beam subject to reflection and transmission by layers of absorbing and scattering material.


Recent methods of measuring spectral characteristics for scattering materials subject to directional irradiation have made it necessary to make a detailed study of the propagation of a narrow parallel radiation beam in such a material; a particular feature here is that the beam is rapidly transformed to a purely diffuse beam on account of repeated scattering at optical nonuniformities [1-4]. The beam cross section increases considerably, and the multiple scattering makes a major contribution to the increase in cross section.

A study has been made [2] of the propagation of a narrow beam of light in a turbid medium having a highly elongated scattering indicatrix, and an analytical expression was derived for the effective radius of the beam $r_{ef}$ in relation to the optical thickness. Results have been reported [3] on the radial dependence of the flux density after passage through small Lucite spheres (the measurements were made with the photocell and set of celluloid screens). Screens coated with graphite had clear rings of internal radius up to 6 mm. The main disadvantage of this method, which introduces an uncorrected error, is that the sensitivity of the photocell varies from part to part. On the other hand, these results [3] do define the radial dependence of the flux density. So far as we are aware, no study has been made of the radial dependence of the flux density for reflected fluxes.

We have examined this topic by means of special equipment whose major components were an adjustable iris diaphragm and a photometric sphere (Fig. 1).

The iris diaphragm had blackened metal blades of thickness 0.2 mm and allowed us to alter the diameter of the back-scattered and transmitted beam from 3 to 40 mm. The two fluxes were measured for a variety of


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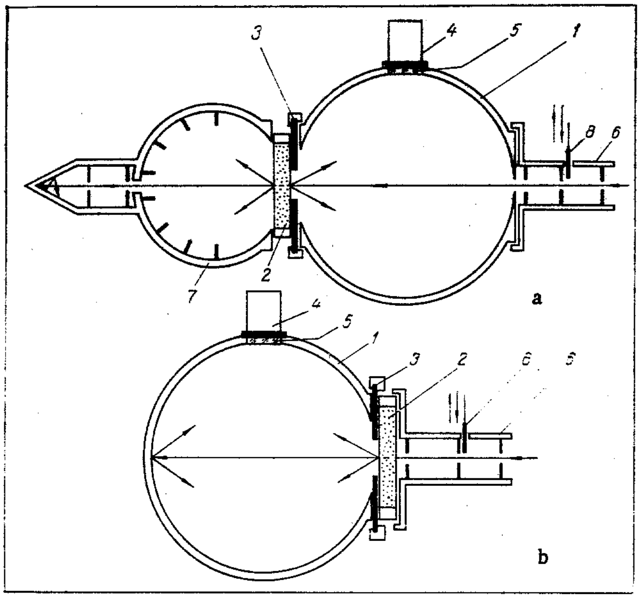


Fig. 1. Equipment for measuring the radial dependence of the flux density for back-scattered beam (a) and transmitted beam (b) from a scattering material: 1) photometric sphere; 2) specimen holder; 3) adjustable iris diaphragm; 4) FÉU-62 photomultiplier; 5) semi-transparent opal glass; 6) set of stops; 7) black-body model; 8) slide.

stop diameters by means of a photometer sphere, which eliminated the zonal nonuniformity in the detector response.

The photometric sphere 1 of diameter 200 mm was internally coated with $BaSO_4$, which is a diffusely scattering material; the sphere had three holes. A hole of diameter 54 mm contained the specimen holder 2, which would take specimens of diameter 30 mm and thickness up to 10 mm. The adjustable iris diaphragm 3 was fitted within the sphere close to the surface of the specimen. The detector for the range 0.4-1.2 $\mu$ was an FÉU-62 photomultiplier 4, which was set up in a hole of diameter 30 mm. The hole in front of the radiation detector was closed by the semitransparent diffusely scattering opal glass 5. The signal from the detector passed to a UF-206 readout device, which was capable of handling currents up to 1 $\mu$A.

The equipment can work with any radiation source giving a narrow parallel beam. We used VSU-2P and SF-4A spectrophotometer monochromators to measure the beams in the range 0.4-1.2 $\mu$ as well as an LG-56 laser, which gave a narrow parallel beam of diameter 2 mm at 0.63 $\mu$.

The radial dependence of the back-scattered flux density was used with the system shown in Fig. 1a; the monochromatic parallel beams passed through the stop system 6 (diameter 3 mm) and the iris diaphragm 3 to fall on the specimen; the back-scattered flux passed through the iris diaphragm and was reflected repeatedly in the sphere to produce a uniform intensity of illumination in the latter. The flux transmitted by the specimen was absorbed by the black-body model 7, which consisted of a sphere of diameter 100 mm and a cylindrical cone of diameter 80 mm and length 150 mm. The inner surfaces of the sphere and cone were coated with matt black paint. Also, ring stops were placed within the sphere and cone to increase the absorption.

The radial dependence of the transmitted flux density was measured with the equipment of Fig. 1b; the adjustable iris diaphragm was placed directly by the outer surface of the specimen. The transmitted flux passed to the integrating sphere through the hole in the iris diaphragm. The sphere then recorded the flux density transmitted by the specimen as a function of stop diameter.

The intensity of illumination within the sphere is constant at all points and is related to the incident flux $F_{in}$ by the following formula [1, 5]:

$$E = \frac{F_{in}}{S} \frac{R_w}{(1-\varphi R_w)}, \tag{1}$$

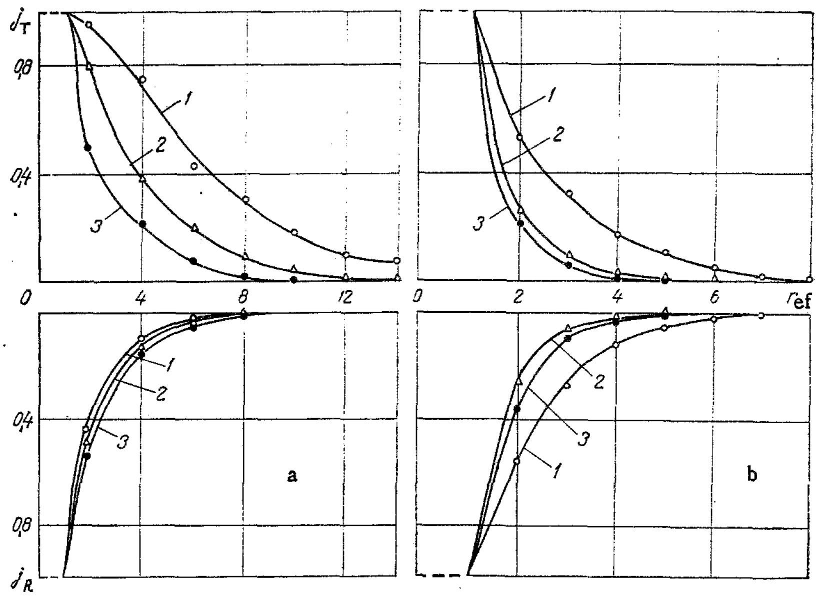


Fig. 2. Back-scattered and transmitted monochromatic fluxes ($\lambda = 0.63\,\mu$) in relation to effective cross-section radius: a) PTFE, various thicknesses; 1) 9 mm; 2) 5; 3) 3.1; b) various materials: 1) PTEE, 2.2 mm; 2) VL-548 enamel, 0.25 mm; 3) paper, 75 g/m$^2$, 0.1 mm.

where $\varphi$ is the friction of the surface of the sphere effectively involved in the multiple reflections, which also incorporates the radiation absorbed by the holes and other components:

$$\varphi = 1 - \frac{1}{S}\sum_{i=1}^{n}(1 - R_i)S_i. \tag{2}$$

Formulas (1) and (2) show that the intensity within the sphere alters not only when the specimen is replaced by a reflection standard, but also when the diameter of the iris diaphragm is altered, since the area $S_i$ of the specimen (standard) and diaphragm are affected. Therefore, it is necessary to correct for the changes in these areas in (1).

The effects of the stop on the intensity within the sphere can be calculated as follows. The intensity of illumination $E_1$ at the surface of the sphere for the stop fully open and $E_2$ (the same with the stop closed) are given by

$$E_1^* = \frac{R_W}{1 - \varphi_1 R_W}; \quad E_2^* = \frac{R_W}{1 - \varphi_2 R_W}, \tag{3}$$

where

$$\varphi_1 = 1 - \frac{1}{S_{sp}}[(1 - R_O)S_O + (1 - R_D)S_D + (1 - R_0)S_s + (1 - R_{ea})S_{ea}];$$

$$\varphi_2 = 1 - \frac{1}{S_{sp}}[(1 - R_O)S_O + (1 - R_D)S_D' + (1 - R_0)S_s' + (1 - R_{ea})S_{ea}];$$

$S_D$ and $S_D'$ are the areas of the completely open and completely closed stop. The effects of the stop area on the intensity within the sphere are defined by

$$\frac{E_1}{E_2} = \frac{1 - \varphi_2 R_W}{1 - \varphi_1 R_W}. \tag{4}$$

Calculations based on (4) showed that the intensity within the sphere altered by only 0.8% in measurements on reflection from an MS-14 standard for maximal change in the stop diameter from 3 to 30 mm, which was confirmed by the measurements.

The distribution of the back-scattered flux density over the surface is determined as follows (Fig. 1a).

A parallel beam of diameter 2 mm passes through the entrance hole and strikes the specimen; the initial setting of the iris diaphragm represents a hole of diameter 3 mm. The proportion of the back-scattered flux passed by the diaphragm increases with the diameter. The intensity of illumination within the sphere will increase until the area of the stop becomes equal to the effective cross section of the back-scattered beam. The transmitted flux is absorbed completely by the black-body model. The back-scattered flux was measured for preset values of the stop diameter in the range 3 to 30 mm, step 2 mm.

The radial dependence of the flux density on the transmitted side was measured similarly; the equipment was as shown in Fig. 1b, with the adjustable stop and sphere used to examine the transmitted intensity. The stop is opened up until the signal becomes maximal.

The relative flux density back-scattered or transmitted by an annular surface element $\Delta S_i = S_i - S_{i-1}$ between radii $r_i > r_{i-1}$ is given by

$$j_{i(R,T)} = \frac{1}{j_0}\left(\frac{N_i - N_{i-1}}{S_i - S_{i-1}}\right), \tag{5}$$

where $N_i$ and $N_{i-1}$ are the signals given by the detector for holes of area $S_i$ and $S_{i-1}$, which correspond to radii of $r_i$ and $r_{i-1}$, where $j_0$ is the flux density transmitted by a stop of radius $r_0 = 3$ mm, which corresponds to an area $S_0$, $j_0 = N_0/S_0$.

Figure 2a shows measurements on the back-scattered and transmitted fluxes as functions of radius for PTFE specimens of various thicknesses; the effective cross section of the back-scattered flux is largely independent of the thickness, whereas the effective cross section of the transmitted flux increases appreciably with the thickness. At a radius of 4 mm, the difference between the flux densities transmitted by specimens of thickness 3.1 and 9 mm was 58%. This ratio applied fairly closely as the radius of the stop was varied for PTFE specimens of various thicknesses. The diameter of the effective emergent flux exceeded 30 mm for specimens of thickness 5 and 9 mm, while it was 20 mm for a specimen of 3.1 mm.

Figure 2b shows the densities of the back-scattered and transmitted fluxes in relation to the stop radius for various materials; it is clear that the effective cross sections vary for PTFE, VL-548 enamel, and paper. The effective diameter for the back-scattered beam from the PTFE was 14 mm, while that of the transmitted beam was 16 mm. Paper showed rather less broadening of the transmitted beam than did VL-548 enamel; the diameters of the beams in back-scattering and transmission were in the range 10-12 mm when the incident beam had a diameter d = 2 mm (from the LG-56 laser).

This equipment also enables one to examine the effective diameter $d_{ef}$ for the back-scattered and transmitted beams for various absorbing and scattering materials; if $d_{ef}$ is known, it is possible to choose a correct method of measuring the characteristics of such a material, as well as the minimum specimen size, the dimensions of the major measuring elements, and the possible errors due to the method arising from scattering and beam broadening.

## NOTATION

E, intensity of illumination at the internal surface of photometric sphere; F, radiation flux; r, radius; d, diameter; R, reflectivity; S, area; j, relative flux density; $S_s$, $S_s'$, areas of surface of specimen with stop completely open and with stop closed down to 3 mm diameter. Indices: i, incident; ef, effective; w, wall; o, semitransparent opal glass; D, diaphragm; s, specimen; ea, entrance aperture; sp, sphere.

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