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ATTACHMENT TO THE IKS-21 SPECTROPHOTOMETER FOR MEASURING THE ANGULAR CHARACTERISTICS OF DIFFUSELY SCATTERING MATERIALS SUBJECT TO HEMISPHEREICAL IRRADIATION

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An attachment to the standard-manufacture IKS-21 spectrophotometer is described; it is designed for measuring the spectral and integrated reflecting powers of diffusely reflecting materials in relation to the angle of observation for the case of hemispherical irradiation in an integrated flow of long- and short-wave infrared radiation.

Data relating to the spectral and integrated characteristics of diffusely reflecting materials subjected to diffuse irradiation in a flow of long- and short-wave infrared radiation, expressed as functions of the angle of observation, are essential for calculating the radiation fields in various materials, for spectral analysis, and for selecting generators to be used in various irradiating infrared installations and furnaces. For thermal engineers' calculations of thermal-radiation installations it is also essential to possess information regarding the hemispherical characteristics $R_\lambda(2\pi)$ and $T_\lambda(2\pi)$ of the materials under consideration under various irradiation conditions. These characteristics are usually measured by methods based on a specular hemisphere of integrating sphere [1-9, 11]. These devices differ from one another as regards the conditions of irradiating the sample and also the means of obtaining the diffuse flow of radiation. The main disadvantage of the majority of such instruments is the limited spectral range of measurements (0.25-3.0 μ). The use of a special integrating sphere [4] enables us to extend the range of the spectrum to 15 μ, but the preparation of such spheres is extremely troublesome. The device mentioned in [5] enables us to

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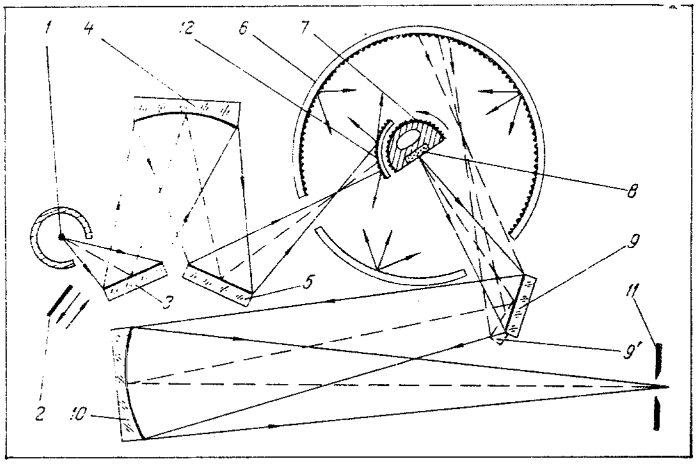

Fig. 1. Optical arrangement of the attachment for the IKS-21 spectrophotometer.

measure the hemispherical brightness coefficient for any angle of observation in the range 0-70°, but the use of monochromatic radiation transmitted through milk glass for irradiating the sample, which in the method under consideration seriously reduces the light power (transmission) of the apparatus, restricts the working range of the spectrum to 0.75-1.1 μ. In another investigation [6] the sample is illuminated with a diffuse integrated flux arriving from a half-space, but it is only viewed in one particular direction through an aperture in a hemisphere. The attachment to the IKS-21 indicated in [7] enables us to determine the reflection and transmission coefficients of samples at four observation angles. A common shortcoming of the systems of [6] and [7] is the severe heating of the sample in the course of measurement; this prevents thermally labile materials from being studied. The device mentioned in [3] serves adequately for absolute measurements of R_λ in the spectral range 0.25-2.6 μ, the angle of observation being varied over a wide interval. However, in this case the identity of the sample irradiation conditions for any angles of observation cannot be ensured because of the rotation of the cylindrical scattering surface of the sample holder. This may involve errors associated with the nonuniformity of the surfacing, inconstant geometrical-optical properties, and the selectivity of the coating on the cylindrical, diffusely reflecting surface of the sample holder.

In order to eliminate the disadvantages of the foregoing devices and expand the working range of the spectrum, we have developed a new attachment to the standard IKS-21 spectrophotometer designed for measuring the spectral and integrated reflecting powers of diffusely reflecting materials in relation to the angle of observation subject to hemispherical irradiation with an integrated flux of long- and short-wave infrared radiation. In developing the optical scheme for the attachment to the IKS-21 we used the basic principles of construction employed in [3] and a special integrating sphere of the kind proposed in [8], with a coated surface reflecting diffusely in the infrared part of the spectrum 1-1000 μ. The optical scheme of the attachment is shown in Fig. 1. The surface of the integrating sphere 6 and screen 12 is made with a special undulating geometry, having a double structure of microasperities commensurable with the wavelengths 1 and 1000 μ in the near- and far-infrared regions, respectively. Aluminum, which possesses a nonselective high reflection of infrared radiation, is deposited on this surface in a high vacuum. The spectral and angular characteristics of this nonselective, diffusely reflecting surface of the sphere and screen were given in [8]. In order to ensure identical conditions of irradiation for any angles of observation (so as to eliminate any possible errors on rotating the sample holders in front of the samples), in contrast to the arrangement of [3], an immovable screen 12 is employed. This eliminates errors associated with possible nonuniform surfacing and inconstancy of the geometrical-optical properties or selectivity of the coating on the cylindrical, diffusely reflecting surface of the sample holder; furthermore, the heating of the sample is also reduced.

The integrated flux of radiation entering into the integrating sphere is twice reflected from the same parts of the stationary screen 12 and the sphere 6 and illuminates the surface uniformly. For any angles of observation the sample surface thus receives a diffuse flux of constant characteristics, reflected three times from the surfaces of the scattering system

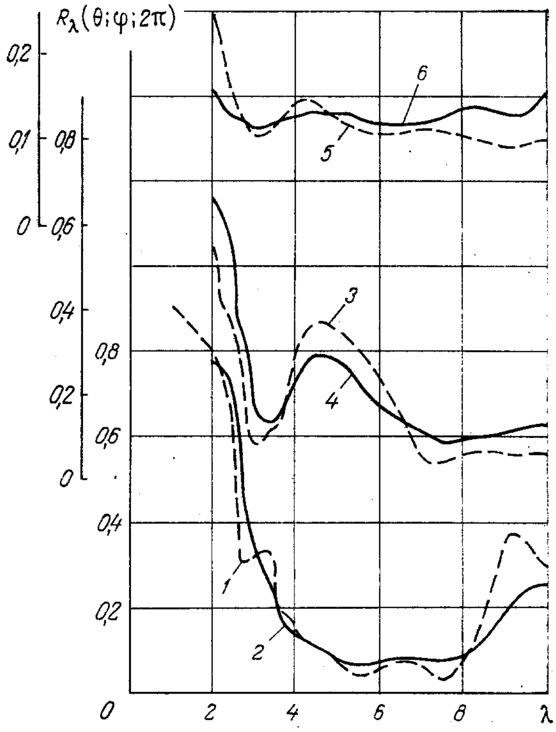

Fig. 2. Hemispherical reflection coefficients $R_\lambda(\theta;\ 2\pi)$ of milky glass MS-14 (1, 2), VL-548 enamel (3, 4), and bread crust h = 10 mm (5, 6) as functions of wavelength λ for θ = 10° obtained by different methods: continuous lines) by the method here described, using the attachment to the IKS-21 with the integrating sphere; dashed lines) specular-hemisphere method [14, 15]; λ in μ.

and the sphere. By virtue of the threefold reflection, an almost perfect diffuse spatial distribution of the flux of radiation falling on the sample surface is achieved. In contrast to earlier cases [6, 7], the heating of the sample during the measurements is greatly reduced. Furthermore, the rotating sample holder 7 is fixed in a hollow tube 8 mm in diameter and arranged in such a way that water may be made to circulate inside it in order to keep the sample temperature constant. This enables us to measure the hemispherical brightness coefficient as a function of sample temperature.

We see from Fig. 1 that the attachment to the IKS-21 consists of three plane mirrors 3, 5, and 9, one spherical mirror 4, a special integrating sphere (diameter 120 mm) 6 for the infrared part of the spectrum 1-1000 μ, a rotating holder 7, and a stationary screen 12. The rotating sample holder 7 may be turned through a polar angle θ between 0 and 90°. The rotating angle may also be changed in fixed steps of 5°. For measuring purposes the sample 8 may be rotated around an axis perpendicular to its surface to an extent depending on the azimuthal angle φ. The image of the radiation source (globar) 1 is projected via the plane mirror 3, the spherical mirror 4, and the plane mirror 5 through the 16 × 30-mm entrance aperture in the integrating sphere 6 into an image of normal size on the diffusely reflecting cylindrical surface of the stationary screen 12. Being repeatedly reflected, the diffuse flow of radiation creates uniform illumination on the inner surface of the sphere and the sample surface under examination. In order to eliminate the influence of the intrinsic radiation of the sample on the readings of the instrument, the integrated flux of radiation from the globar falling on the surface of the stationary screen is modulated by means of the interrupter 2. The radiation reflected from the sample 8 is directed through the exit aperture (14 × 28 mm) in the sphere by means of the plane and spherical mirrors 9 and 10 onto the entrance slit 11 of the IKS-21 monochromator. The surface of the integrating sphere acts as a standard. A slight displacement of the mirror 9 into the position 9' (dashed lines in Fig. 1) enables us to direct radiation monochromatically reflected from the surface of the integrating sphere onto the entrance slit 11. The ray from the sample and the comparison ray travel within identical solid angles, cut out by the exit aperture in the sphere and the

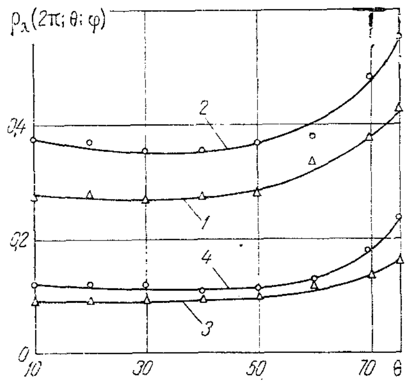

Fig. 3. Dependence of the hemispherical brightness coefficients $\rho_\lambda(2\pi;\ \theta;\ \varphi)$ on the observation angle θ for barium sulfate (1, 3) and VL-548 enamel (2, 4) at various wavelengths: 1, 2) λ = 5 μ; 3, 4) λ = 8 μ. θ, deg.

mirror 10 of the IKS-21 illumination system. The modulated signals reaching the receiver are recorded by the ÉPP-09M3 automatic recorder of the IKS-21 instrument. For monitoring the temperature during the measurements, a Chromel—Copel thermocouple 0.1 mm thick is placed in the sample and the temperature is recorded by means of a PP-63 potentiometer.

By measuring the brightness coefficient at various observation angles we may determine the hemispherical characteristic $R_\lambda(2\pi)$ under various conditions of irradiation. On the basis of the Helmholtz theorem as to the reversibility of radiant flux for isotropic media [10], for equal angles of incidence θ, φ and reflection θ_R, φ_R we have

$$\rho_\lambda(2\pi;\ \theta_R;\ \varphi_R) = R_\lambda(\theta;\ \varphi;\ 2\pi). \tag{1}$$

Equation (1) constitutes a theoretical basis for the method of measuring the coefficients of imperfectly diffuse reflection $R_\lambda(\theta;\ \varphi;\ 2\pi)$ in the case of directional irradiation (determined by the angles θ and φ) with a narrow beam of radiation lying within the solid angle dω.

The intensity of the monochromatic radiation falling on unit area of the sample ds from the area ds_i of the sphere close to a certain point visible from the center of the sample in the direction θ', φ' is by definition [3] equal to

$$dJ_{\lambda,i} = B_{\lambda,i}(\theta',\ \varphi')\cos\theta' d\omega_i, \tag{2}$$

where $B_{\lambda,i}(\theta',\ \varphi')$ is the brightness of the surface of the sphere at the point (r, θ', φ') in the direction of the normal to the element ds_i; $d\omega_i = ds_i/r^2$ is the solid angle. The intensity of the monochromatic radiation reflected from the sample and from the standard surface in the direction of the exit aperture is given by the equations

$$dJ_{\lambda,R} = B_\lambda(\theta,\ \varphi)\,d\omega, \tag{3}$$

$$dJ_{\lambda,s} = B'_{\lambda,s}(\theta'_s,\ \varphi'_s,\ \alpha)\,d\omega'. \tag{4}$$

where $B_\lambda(\theta,\ \varphi)$ is the brightness of the sample surface in the direction θ, φ; $B'_{\lambda,s}(\theta'_s,\ \varphi'_s,\ \alpha)$ is the brightness of the surface of the sphere at the point (r, θ'_s, φ'_s) in the direction α of the comparison ray at the exit aperture; and α is the angle between the comparison ray and the normal to the surface of the sphere at the point (r, θ'_s, φ'_s).

If equality of the solid angles dω = dω' determined by the optical scheme is ensured, the reflecting power of the sample will according to (1), (3), and (4) be equal to the brightness ratio

$$\frac{dJ_{\lambda,R}}{dJ_{\lambda,s}} = \frac{B_\lambda(\theta,\ \varphi)}{B'_{\lambda,s}(\theta'_s,\ \varphi'_s,\ \alpha)} = \rho_\lambda(2\pi;\ \theta_R;\ \varphi_R) = R_\lambda(\theta;\ \varphi;\ 2\pi). \tag{5}$$

Thus by using the proposed attachment we may measure the brightness of the radiation reflected by the sample in the direction of the angle θ_R in the case of hemispherical irradiation and compare it with the brightness of the radiation falling on the sample surface. The ratio of the signals from the radiation receiver is proportional to the hemispherical brightness coefficient $\rho_\lambda(2\pi;\ \theta_R;\ \varphi_R)$ and the hemispherical reflecting power $R_\lambda(\theta;\ \varphi;\ 2\pi)$.

Equation (5) enables us to determine the true value of the reflecting power of the sample for any angles θ, φ, but only when the brightness of the surface of the sphere $B'_{\lambda,s}$ is the same at all points of the hemisphere facing the sample and when the radiation falling on the sample is completely diffuse. On deviating from these conditions R_λ will be subject to error. The extent of the error will depend on the scattering properties of the sample, the polarization of the radiation by the sample and the monochromator, and the presence of the exit window in the integrating sphere. On measuring the R_λ of specular samples, the ratio of the brightnesses of the sample and the wall of the sphere will, on the basis of the reflection law, be

$$R'_\lambda = \frac{B_\lambda(\theta, \varphi)}{B'_{\lambda,s}(\theta', \varphi')} \tag{6}$$

for $\theta = \theta'$ and $\varphi = \varphi'$.

If we substitute the brightness of the sample from (5) into (6), we obtain [3]

$$R'_\lambda = R_\lambda \frac{B'_{\lambda,s}(\theta'_s;\ \varphi'_s,\ \alpha)}{B_{\lambda,s}(\theta';\ \varphi')} = R_\lambda \gamma_\lambda. \tag{7}$$

The brightness ratio γ_λ describes the brightness distribution inside the sphere. If the brightness distribution is completely diffuse, then $\gamma_\lambda = 1$ and $R'_\lambda = R_\lambda(\theta, \varphi, 2\pi)$, i.e., we obtain the true reflecting power of the sample.

If we measure the R_λ of a diffuse sample, its brightness will be the same for all observation angles. The intensity of the radiation falling on the sample, averaged over the hemisphere in accordance with Eq. (2), will be equal to

$$J_{\lambda,i} = \frac{\int\limits_{(2\pi)} dJ_{\lambda,i}}{\int\limits_{(2\pi)} \cos\theta' d\omega'} = \frac{1}{\pi}\int\limits_{(2\pi)} B_\lambda(\theta';\ \varphi')\cos\theta' d\omega'. \tag{8}$$

In Eq. (8) the integration is carried out over a hemisphere embracing the sample surface. The reflecting power of the diffuse sample, on allowing for (3), (5), and (8), is given by

$$R'_\lambda = \frac{dJ_{\lambda,R}}{J_{\lambda,i} d\omega} = \frac{\pi B_\lambda(\theta, \varphi)}{\int\limits_{(2\pi)} B_\lambda(\theta';\ \varphi')\cos\theta' d\omega'} = \frac{R_\lambda(\theta, \varphi, 2\pi)}{\frac{1}{\pi}\int\limits_{(2\pi)} \frac{1}{\gamma_\lambda}\cos\theta' d\omega'}. \tag{9}$$

We see from Eq. (9) that the true reflecting power is equal to the measured value if the brightness ratio γ_λ is equal to unity for all angles. The following condition is then satisfied:

$$\frac{1}{\pi}\int\limits_{(2\pi)} \frac{1}{\gamma_\lambda}\cos\theta' d\omega' = 1. \tag{10}$$

For an incompletely diffuse sample it is impossible to obtain a simple formula, but the error δ of the measurements may be estimated from the inequality [3]

$$\left(1 - \frac{1}{\pi}\int\limits_{(2\pi)} \frac{1}{\gamma_\lambda}\cos\theta' d\omega'\right) < \delta < \left(1 - \frac{1}{\gamma_\lambda}\right). \tag{11}$$

The error δ in the measurements of R_λ is smaller for incompletely diffuse samples than for specular samples, but greater than for completely diffuse samples.

The existence of an exit aperture also introduces error when measuring R_λ, since the irradiation of the sample is less than hemispherical by an amount equal to the proportion of the flux passing out through the exit aperture. For a diffuse sample the error in determining R_λ associated with the loss of radiation through the exit aperture may be found from Eq. (9) [3]:

$$\delta = 1 - \frac{1}{\pi}\int\limits_{(2\pi)} \frac{1}{\gamma_\lambda}\cos\theta' d\omega'. \tag{12}$$

In the integration in (12) it is important to remember that $1/\gamma_\lambda$ is equal to zero within the exit aperture. For our present sphere, 120 mm in diameter, with an exit aperture of 14 × 28 mm, the error δ is under 1.5%. For specular or almost-specular samples, the error is negligibly small if the specular component of the reflected radiation does not fall into the aperture. This condition limits the range in which the angular dependence of specularly reflecting samples may be studied to angles of incidence less than 13.5°. It is in fact well known that the reflection of specular samples remains practically identical for angles of incidence less than 15-20°.

TABLE 1. Brightness Coefficients of MS-14 for $\theta = 10°$ and Various Wavelengths

λ, μ	$\rho_\lambda(\theta;\ 2\pi)$ for $\theta = 10°$	
	measured on the IKS-21	according to [16]
2,0	0,77	0,78
2,1	0,76	0,75
2,2	0,75	0,73
2,3	0,73	0,71
2,4	0,70	0,69

On reflection from the surface of the mirrors in the illuminating system and the monochromator, the radiation of both rays is identically part-polarized on the way to the radiation receiver. Rays which have traveled identical paths and undergone reflection at identical angles are also identically part-polarized. However, the sample creates additional polarization of the radiation, and this introduces an error into the measurement of R_λ. The polarization effects may be determined experimentally and taken into account for any given spectrometer.

Apart from absolute measurements, the attachment to the IKS-21 enables us to carry out relative measurements of the spectral R_λ as well as integrated R values. For this purpose a plane mirror directing the integrated flux straight to the exit slit has to be placed behind the entrance slit of the IKS-21 monochromator. The method of measuring the integrated R will then be analogous to the method of measuring R_λ.

As the reflection standard we may use mirrors with various coatings: aluminum, gold, silver, etc. The reflecting powers of aluminum and other mirrors are quite well known [12, 13]. The spectral reflection coefficient of the sample for a given observation angle in relative measurements is calculated from the equation

$$R_\lambda = \frac{N_o}{N_{st}} R_{st}, \tag{13}$$

where N_o and N_{st} are the readings of the recording instrument corresponding to the reflection of the sample and standard; R_{st} is the reflection coefficient of the standard.

Using the attachment here described, we measured the hemispherical brightness coefficient as a function of the observation angle and wavelength for VL-548 enamel, MS-14 milky (opal) glass, barium sulfate, and a number of food products and other materials scattering radiation. By way of example, Fig. 2 and Table 1 present data obtained in various ways. The R_λ relationships (1, 3, 5) were obtained by the specular-hemisphere method in the IKS-12 spectrophotometer [14, 15], using an LiF prism in the wavelength interval 2-5 μ and NaCl in the interval 5-10 μ. The correction factor for the whole spectral range 2-10 μ was taken as 1.5. The R_λ relationships (2, 4, 6) were obtained by means of the attachment to the IKS-21, using only the NaCl prism, and without introducing any correction factor. We see from Fig. 2 and Table 1 that the experimental data obtained by the different methods agree quite closely. There is nevertheless a slight difference which may be explained by the fact that the correction factor taken as constant and equal to 1.5 for the measurements on the IKS-12 does in fact vary with wavelength. This quantity depends on the variation of the sample reflection indicatrix with wavelength and also varies over the cross section of the reflected radiant flux emerging from the surface due to the scattering and blurring of the narrow beam of radiation in the sample layer. Thus the losses of reflected radiation not recorded by the receiver depend on the wavelength of the radiation.

The angular dependence of the hemispherical brightness coefficient of various materials at $\lambda = 5$ and 8 μ is illustrated in Fig. 3. We see from this figure that the hemispherical brightness coefficients of $BaSO_4$ and VL-548 enamel vary very little with increasing angle of observation up to $\theta = 60°$. A sharp rise in ρ_λ only appears at $\theta > 60°$. This indicates that the reflection indicatrices of these materials in the infrared part of the spectrum are very nearly diffuse.

NOTATION

R, reflecting power of the layer of material; φ, θ, angles of incidence or observation; ω, solid angle; ρ, brightness coefficient; S, area, m^2; J, intensity of monochromatic radiation; B, surface brightness; λ, wavelength, μ. Indices: λ, spectra; R, reflection; s, sphere; o, sample; st, standard.

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