IMPROVED TWO-BEAM SPECULAR HEMISPHERE METHOD FOR MEASURING THERMAL RADIATION CHARACTERISTICS OF SCATTERING MATERIALS

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The specular hemisphere method for measuring the transmittance and reflectance of light-scattering materials, which takes into account the spreading of the cross section of a narrow divergent beam of radiation in the specimen, the optical aberrations of the system, and the nonuniformity of the zonal sensitivity of the radiation detector, is examined.

In the infrared region of the spectrum the most popular method of measuring directionally hemispherical $R_\lambda(\theta;\ 2\pi)$ and $T_\lambda(\theta;\ 2\pi)$ accompanying exposure to a narrow beam of radiation directed at a low angle (θ = 5-10°) has been the specular hemisphere method [1, 3-7, 9-12, 14-16], known in the literature as the Paschen–Koblenz method.

In well-known types of attachments with a specular hemisphere for single-beam and two-beam spectrophotometers [1, 3, 4, 6, 7, 9-12, 15, 16], however, all the factors causing measurement errors are not taken into account. Some of them — radiation losses through the inlet aperture in the hemisphere and screening by the detector mounting — are usually taken into account by introducing correction factors K_R and K_T. The optical aberrations of the system are reduced to a minimum by satisfying the condition $S \leq 0.1\rho$ [3-7]. At the same time, no account is taken of the errors caused by nonideal specimen irradiation conditions, irradiation by a nonparallel divergent beam with zonal nonuniformity of the illumination of the specimen surface, and errors caused by the zonal and angular dependence of the coefficient of absorption of the coating on the sensitive element of the radiation detector and also by the reflection and absorption of radiation by the material of the detector inlet aperture. No account is taken of errors caused by the spreading of the cross section of the narrow beam of radiation emerging from the specimen and by the nonideal nature of its reflection and transmission indicatrices. The magnitudes of the correction factors K_R and K_T depending on the characteristics of the attachment and the radiation detector are assumed to be equal to 1.06-1.8 [1, 3, 4, 6, 10, 14-16] and to be constant for all wavelengths in the IR region of the spectrum, which also introduces a previously unmonitored error to the magnitudes being measured.

The complex influence of all the causes indicated on the shape and dimensions of the image and also on the density distribution of the energy flux at the image spot is investigated experimentally by a photographic method by the present authors. A special photographic film of the "Kinoinfra MRTU-43 No. 134162" type, which is sensitive to IR radiation, is placed over the surfaces of the specimen and the detector, which are installed at conjugate points of the hemisphere. The images produced on the photographic film are shown in Fig. 1. Their boundaries, calculated taking into account aberrations according to the Brandenberg formulas [14], are shown by dotted lines for comparison purposes.

As can be seen from Fig. 1, the flux density distributions at the source E_1 and detector E_2 spots are nonuniform and are dependent on the properties of the specimen. The fulfillment of the condition $S \leq 0.1\rho$ [3-7] provides an opportunity for reducing the optical aberration to a minimum. The image of the "source" of the radiation reflected from the standard–mirror observed under these conditions (Fig. 1, frame 1) has clear boundaries, but the shape of this image is distorted somewhat. Moreover, the spreading of the cross section

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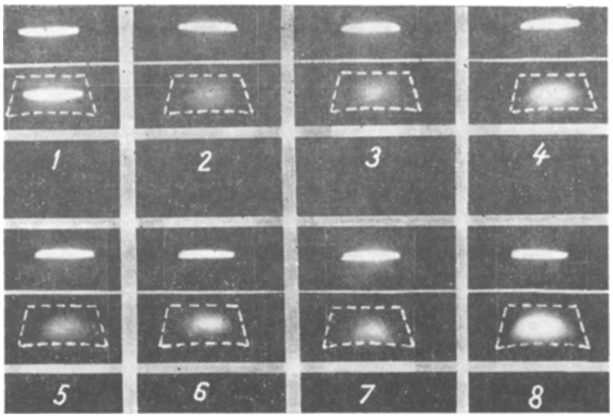

Fig. 1. Density distribution of radiation flux at conjugate points of diametral plane of hemisphere for "source" and "image" spots accompanying reflection from various materials: 1) mirror; 2) PS-1 foam plastic, l = 3 mm; 3) VL-548 enamel, l = 0.25 mm; 4) polytetrafluoroethylene, l = 2.2 mm; 5) paper, l = 0.09 mm, 75 g/m^2; 6) apple flesh, W = 85.4%, l = 5 mm; 7) bread crumb from grade 1 flour, W = 40.7%, l = 5 mm; 8) potato starch, W = 12.3%, l = 2 mm.

of the narrow beam of radiation emerging from the specimen, aggravated by the optical aberrations of the system, exerts a considerably greater influence on the nonuniformity of the flux density distribution at the detector spot E_2 on the surface of its sensitive element (Fig. 1, frames 2-8).

For a quantitative assessment of the spreading of the cross section of the narrow beam of radiation in the specimen, measurements are made of the cross sections of the reflected flux and the flux passing through the specimen when irradiated by a parallel radiation flux using a special device comprising an integrating sphere and an iris diaphragm. The relative magnitudes of the density distributions of the reflected flux E^*_R and the flux passing through the specimen E^*_T as a function of the radius of the cross section of the emergent radiation beam shown in Fig. 2 indicate a substantial spreading of the cross section of the narrow measuring beam in the materials being investigated. This is caused by the multiple scattering of the radiation by optical inhomogeneities in the layer of material [2, 13]. The

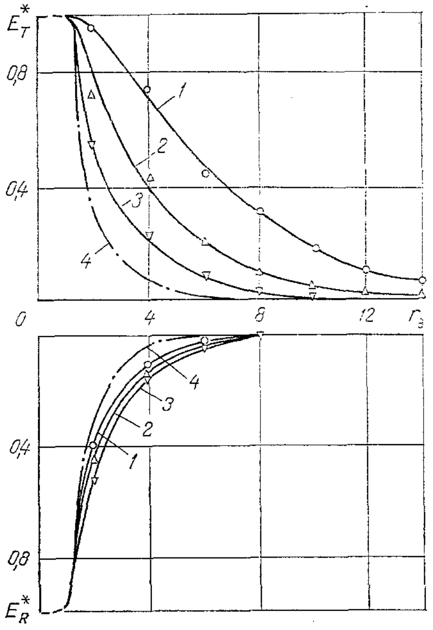

Fig. 2. Relative magnitudes of density distributions of reflected flux E^*_R and flux passing through specimen E^*_T (λ = 0.63 μ) as a function of radius r (mm) of cross section of emergent beam of radiation for various layer thicknesses l (mm): polytetrafluoroethylene — 1) l = 9.0; 2) 5.0; 3) 3.0; 4) VL-548 enamel — l = 0.25.

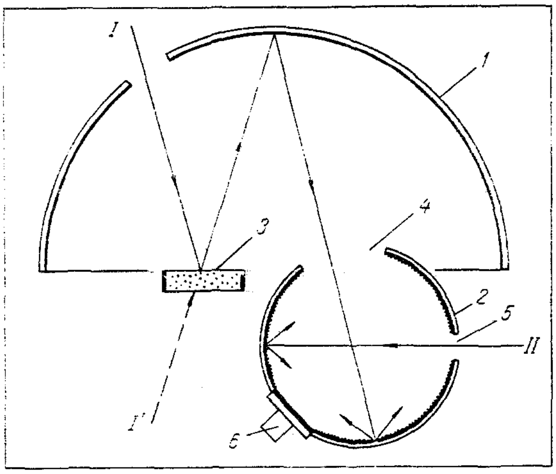

Fig. 3. Schematic diagram of optical system of improved two-beam specular hemisphere method: 1) specular hemisphere; 2) special IR integrating sphere; 3) specimen; 4) inlet aperture of integrating sphere; 5) aperture for reference beam; 6) radiation detector.

spreading of the cross section and the scattering of the narrow beam of radiation, aggravated by the initial angular divergence of the incident flux, cause a significant increase in the dimensions of the cross section of the radiation flux emerging from the specimen. The cross section of the radiation flux reflected by the layer of specimen is then also significantly greater than the cross section of the incident radiation flux. For a point source of radiation the radii of the cross sections of the fluxes emerging from the specimen, depending on the properties of the material and the thickness of the specimen, reach 8-10 mm and may exceed 14 mm (Fig. 2, curves 1 and 2). As the thickness increases, the dimensions of the cross section of the radiation emerging from the specimen increase (curves 1-3) and are clearly greater than the dimensions of the receiving areas of the radiation detectors (diameter 12 mm [4], 3 × 10 mm [18] and others) normally used in the specular hemisphere method. Such radiation losses, dependent on the specimen thickness, cause significant errors which cannot be taken into account.

In order to eliminate the errors indicated above and the shortcomings of the specular hemisphere method, the authors propose a modification of the method, and an attachment for an IKS-14 type infrared spectrophotometer is designed and built using as its basic components a specular hemisphere 1 (diameter 150 mm) and a special integrating sphere 2 (diameter 50 mm) for the IR region of the spectrum (Fig. 3). The inner surface of the integrating sphere 2 has a nonselective diffusely reflecting aluminum coating with a reflectance of 0.9-0.97 in the 1- to 1000-μ range [17].

The optical system and the procedure for measuring R_λ and T_λ using the two-beam specular hemisphere method are described in detail in [4]. The modification consists of installing a special integrating sphere with three apertures in place of the radiation detector. The dimensions of the inlet aperture 4 are calculated from the Brandenberg formulas [14] taking into account the spherical aberrations. The inlet aperture 4 in the integrating sphere 2 measures 20 × 12 mm. As can be seen from Fig. 1, the cross section of the reflected radiation flux or the flux passing through the specimen at the image spot is smaller in dimensions than the inlet aperture 4. Consequently, the flux being measured falls entirely into the integrating sphere and, reflected repeatedly off the walls, generates a uniform illumination inside the sphere, which is recorded by the radiation detector. The influence on the device readings of the nonideal nature of the specimen irradiation conditions, the optical aberrations, the spreading of the cross section of the radiation beam in the specimen, and the nonuniform angular and zonal sensitivity of the radiation detector are thus eliminated. The radiation of the reference channel II falls into the integrating sphere through the aperture 5, which measures 3 × 10 mm. The detector records alternately, with a frequency of 8.8 Hz, the illumination of the inner surface of the sphere from channel I after reflection off the specimen or transmission by the specimen and from the reference channel II. The difference between the illuminations is compensated for by introducing into the reference channel II a photo-

TABLE 1. Values of R_λ and T_λ of Several Materials Measured for $\lambda = 2.5\ \mu$ by Various Methods

Material	Specular hemisphere method		Improved specular hemisphere method	
	R_λ	T_λ	R_λ	T_λ
Polytetrafluoroethylene, $l = 2.2$ mm	0,020	0,848	0,034	0,908
Paper, $l = 0.09$ mm, 75 g/m^2	0,208	0,126	0,268	0,144

TABLE 2. Values of R_λ and T_λ of Several Materials Measured for $\lambda = 0.63\ \mu$ and for Various Cross Sections of Radiation Flux Emerging from Specimen

Material	R_λ	R'_λ	ε, %	T_λ	T'_λ	ε, %
VL-548 enamel, $l = 0.15$ mm	0,914	0,451	50,1	0,044	0,026	40,9
Limewood, $l = 0.12$ mm	0,544	0,213	60,8	0,502	0,244	51,4
Polytetrafluoroethylene, $l = 9.0$ mm	0,899	0,325	63,8	0,049	0,002	95,9
Apple (flesh), $l = 8.25$ mm, W = 83.4%	0,898	0,282	68,6			
Bread crumb from grade 1 flour, $l = 14$ mm, W = 11.3%	0,780	0,118	84,9			

Note. Magnitudes of R_λ and T_λ obtained for diaphragm diameter 30 mm; R'_λ and T'_λ, for 3 mm.

metric wedge, which is connected mechanically to the pen of the recording device and, thus, a reflection or transmission spectrum is produced on the diagram in percentages relative to the standard.

A mirror with an outer coating of aluminum sputtered onto a glass surface is used as the reflection standard and an empty cuvette, a transparent substrate, etc. (depending on the type of specimen being investigated), are used as the transmission standard. Photoresistances of the 6AN, 40AN, etc., types are used as the radiation detectors.

The device described can be used to measure the spectral reflectance and transmittance of various materials: free-flowing solids, solids, and liquids. Table 1 gives values of the R_λ and T_λ of several materials measured using the two-beam specular hemisphere method [4] and the improved two-beam specular hemisphere method for $\lambda = 2.5\ \mu$ without introducing the correction factors K_R and K_T. It is clear from a comparison of the results obtained that the improved method makes it possible to significantly reduce the magnitudes of the correction factors.

The presence of the inlet aperture in the hemisphere requires the introduction of a correction factor, equal to 1.05, when calculating R_λ and T_λ.

In order to evaluate the errors generated solely due to the spreading of the cross section of the narrow beam of radiation without the influence of the spherical aberrations in measurements using a thermopile with a receiving area of 3 × 10 mm, the authors measured the R_λ and T_λ of materials for various cross sections of the beam of radiation emerging from the specimen (Table 2). The measurements are made using a special device comprising an integrating sphere, an iris diaphragm, and an LG-56 laser giving a narrow parallel beam 2 mm in diameter when $\lambda = 0.63\ \mu$. The magnitudes of R'_λ and T'_λ are measured for a diaphragm aperture diameter of 3 mm, which corresponds to the width of the receiving area of the thermopile of the radiation detector (3 × 10 mm) usually used in the specular hemisphere method. The magnitudes of R_λ and T_λ are measured for a totally open diaphragm (diameter 30 mm). The relative error is calculated by the formula

$$\varepsilon = \frac{R_\lambda - R'_\lambda}{R_\lambda} \cdot 100\%. \quad (1)$$

As can be seen from Table 2, the magnitudes of the relative error, caused solely by the spreading of the cross section of the radiation flux emerging from the specimen, reach 96%. Consequently, the accuracy of R_λ and T_λ measured by the improved method is greater than the accuracy of measurements by the well-known specular hemisphere method. The use of an integrating sphere with an inlet aperture of 20 × 12 mm makes it possible to eliminate the errors due to the nonideal specimen irradiation conditions, the scattering and spreading of the cross section of the narrow beam of radiation emerging from the specimen, the optical aberrations, and the nonuniformity of the angular and zonal sensitivities of the radiation detector. The reproducibility of the magnitudes R_λ and T_λ for the same specimen is obtained with a scatter of not more than ±1.0%.

Thus, using the improved two-beam specular hemisphere method described it is possible to obtain more accurate data on the spectral and integral characteristics of materials which scatter radiation.

NOTATION

R, T, reflectance and transmittance of layer of material; $R(\theta;\ 2\pi)$, $T(\theta;\ 2\pi)$, directionally hemispherical reflection and transmission of layer of material; θ, angle of incidence; E^*, relative magnitude of flux density; λ, wavelength, μ; l, specimen thickness, mm; $E(\rho, \alpha)$, flux density, W/m^2; S, displacement from center of hemisphere, mm; ρ, radius of hemisphere, mm; K, correction factor. Indices: λ, spectral; R, reflection; T, transmission.

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