METHOD OF SIMULTANEOUSLY MEASURING THE DOUBLE HEMISPHERICAL THERMAL RADIATION CHARACTERISTICS OF SCATTERING MATERIALS

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Methods of measuring the hemispherical reflecting and transmitting powers of radiation-scattering materials, simultaneously or as a complex operation, on subjection to hemispherical irradiation are considered.

The calculation of radiant heat transfer is quite impossible unless the spectral and integrated thermal-radiation characteristics R, T, and A of the irradiated materials, measured with due allowance for the scattering of the radiation, are known. The quantities R, T, and A depend both on the state and properties of the material and on the spatial characteristics and spectral composition of the incident flow of radiation (i.e., the irradiation conditions). The majority of published experimental data regarding the spectral reflecting and transmitting powers R_λ and T_λ of radiation-scattering materials have been obtained for irradiation by a radiant flux incident at a small angle ($\theta = 5$-$10°$) [1-4]. These values, i.e., the directional-hemispherical coefficients $R_\lambda(\theta; 2\pi)$ and $T_\lambda(\theta; 2\pi)$, may only be used in calculating radiant transfer corresponding to the actual irradiation conditions.

The authors therefore studied the manner in which $R_\lambda(\theta; 2\pi)$ and $R_\lambda(\theta; 2\pi)$ varied with the angle of incidence θ experimentally for layers of various scattering materials (Fig. 1a), such as 0.52 mm polyethylene (curves 1), 0.09 paper (curves 2), etc; the results showed that R_λ increased and T_λ diminished with increasing angle of incidence. Hence the double-hemispherical reflecting power $R_\lambda(2\pi; 2\pi)$ will be greater than the directional-hemispherical value $R_\lambda(\theta; 2\pi)$, while $T_\lambda(2\pi; 2\pi)$ will be smaller than $T_\lambda(\theta; 2\pi)$ measured for normal irradiation by a parallel flux of radiation.

The relationships shown in Fig. 1b for the double-hemispherical and directional-hemispherical thermal-radiation characteristics of polyethylene, paper, and raw potato support the foregoing considerations.

In any practical thermal-radiation installations (furnaces and closed chambers) irradiation by a diffuse or mixed (diffuse + directional) radiation flux is the rule. In view of this it is important to measure the double-hemispherical parameters $R_\lambda(2\pi; 2\pi)$ and $T_\lambda(2\pi; 2\pi)$ of the materials on subjection to a diffuse flow of radiation.

A direct method of measuring the double-hemispherical parameters $R_\lambda(2\pi; 2\pi)$ and $T_\lambda(2\pi; 2\pi)$ or radiation-scattering materials was first proposed by Duntley [7]. In this method the hemispherical irradiation of the sample and the measurement of its hemispherical reflecting and transmitting powers are

TABLE 1. Directional-Hemispherical Reflecting Power of the Sphere Coating at Various Wavelengths

λ, μ	0,5	1,0	5,0	10,0	15,0	25,0
$R_\lambda(5°; 2\pi)$	0,864	0,916	0,969	0,973	0,974	0,975

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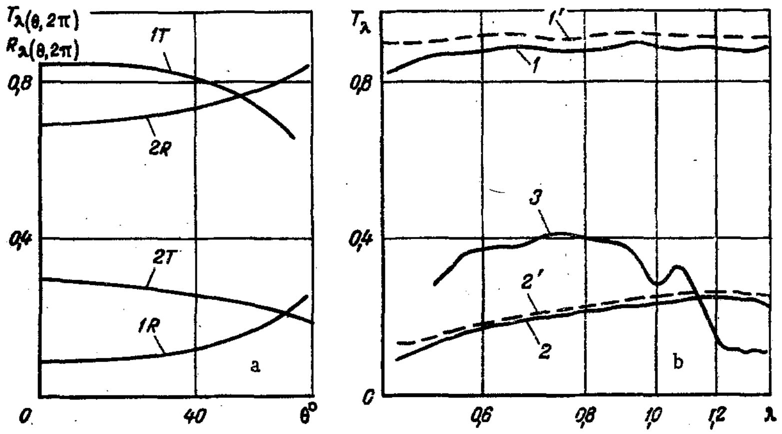

Fig. 1. Reflecting and transmitting capacities as functions of angle of incidence for $\lambda = 1.0\ \mu$ (a) and as functions of the conditions of irradiation (b) for various materials: 1) polyethylene 0.52 mm thick; 2) paper, 0.09 mm, 75 g/m^2; 3) raw potato, 5.75 mm; the continuous lines 1-3 give the double-hemispherical transmitting power $T_\lambda(2\pi;\ 2\pi)$; the broken lines 1' and 2' give the directional-hemispherical transmitting power $T_\lambda(\theta;\ 2\pi)$. λ, μ

carried out with the aid of two identical integrating spheres containing three apertures. The advantage of this method lies in the possibility of carrying out absolute measurements of $R_\lambda(2\pi;\ 2\pi)$ and $T_\lambda(2\pi;\ 2\pi)$; however, it imposes strict requirements upon the accuracy of photometric measurement, covers only a limited spectral range 0.40-0.75 μ, and involves a complex measuring technique [7].

A simpler method of measuring the double-hemispherical transmitting power $T_\lambda(2\pi;\ 2\pi)$ was described and an attachment to the SF-4A spectrophotometer, offering a spectral range of 0.4-1.4 μ, was proposed by the authors in an earlier paper [3]. In order to obtain hemispherical irradiation of the sample this system uses an MS-14 reflection standard and a specular ellipsoid, while for measuring the hemispherical radiation passing through the sample a receiver with a large receiving area is employed (an FÉSS-U10 photocell).

For measuring the double-hemispherical reflecting power $R_\lambda(2\pi;\ 2\pi)$ in the infrared part of the spectrum 1-38 μ, Sherrell and Sharhrokhi [8] developed a spectrophotometer attachment with a CsBr prism in the form of an integrating sphere. The surfaces of the sphere and reflecting standard are coated with gold having a diffuse reflecting power $R_\lambda \approx 0.95$. The value of $R_\lambda(2\pi;\ 2\pi)$ is measured relative to the standard. This method also makes severe demands upon the accuracy of the photometric measurements. The accuracy of the measurements is less than ±2% [8].

Experimental-analytical methods of determining the double-hemispherical parameters $R_\lambda(2\pi;\ 2\pi)$ and $T_\lambda(2\pi;\ 2\pi)$ are based on an experimental determination of the hemispherical brightness coefficients (radiance) $\rho_\lambda(2\pi;\ \theta_R,\ \varphi_R)$ and $t_\lambda(2\pi;\ \theta_T;\ \varphi_T)$ or the reflection coefficients $R_\lambda(\theta,\ \varphi;\ 2\pi)$ and $T_\lambda(\theta;\ \varphi;\ 2\pi)$ for various angles of observation θ_R, φ_R and θ_T, φ_T or angles of incidence of the radiant flux θ, φ and the analytical relationships between these [2, 3, 5]:

$$R_\lambda(2\pi;\ 2\pi) = \frac{1}{\pi}\int\limits_{2\pi} \rho_\lambda(2\pi;\ \theta_R;\ \varphi_R)\cos\theta_R d\omega_R, \qquad (1)$$

where $d\omega_R = \cos\theta_R d\theta_R d\varphi_R$;

TABLE 2. Spectral Reflection Indicatrices of the Sphere Coating for Normal Irradiation

Wavelength, μ	Reflection angle, deg							
	10	20	30	40	50	60	70	80
1,0	0,992	0,965	0,666	0,450	0,360	0,298	0,280	0,212
2,0	0,993	0,962	0,642	0,450	0,360	0,308	0,282	0,218
15,0	0,991	0,961	0,587	0,361	0,287	0,239	0,209	0,122

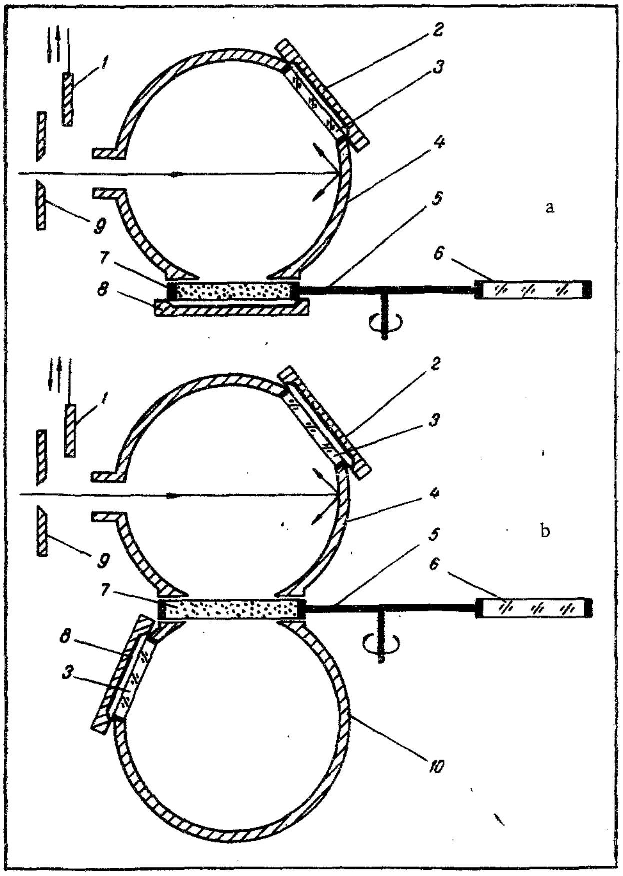

Fig. 2. Basic arrangement of the attachments to the SF-4A monochromator for the simultaneous (a) and separate (b) measurement of the double-hemispherical reflecting and transmitting powers of scattering materials: 1) cover; 2, 8) FÉSS-U10 photocells; 3) scattering opal glass; 4, 10) integrating spheres; 5) holder; 6) standard; 7) sample; 9) monochromator slit.

$$R_\lambda(2\pi;\ 2\pi) = \frac{1}{\pi}\int_{2\pi} R_\lambda(\theta,\ \varphi;\ 2\pi)\cos\theta d\omega, \qquad (2)$$

where $d\omega = \cos\theta d\theta d\varphi$.

Devices for measuring the hemispherical brightness coefficient $\rho_\lambda(2\pi;\ \theta_R,\ \varphi_R)$ have been developed by many authors [3, 5]. The quantities $R_\lambda(\theta,\ \varphi;\ 2\pi)$ and $(T_\lambda(\theta,\ \varphi;\ 2\pi)$ may be measured by means of special attachments to spectrophotometers. The main disadvantage of experimental-analytical methods, impeding their practical use, is the complexity involved in integrating the functions $\rho_\lambda(2\pi;\ \theta_R,\ \varphi_R)$ and $R_\lambda(\theta,\ \varphi;\ 2\pi)$ with respect to the solid angle 2π, even for cases of a symmetrical reflection indicatrix.

The authors have now developed a method of measuring the double-hemispherical reflecting and transmitting powers of radiation-scattering materials, either simultaneously or as a complex operation.

For simultaneously measuring the absolute double-hemispherical transmitting and reflecting powers $T_\lambda(2\pi;\ 2\pi)$ and $R_\lambda(2\pi;\ 2\pi)$ in the spectral range 0.4-1.4 μ we developed and manufactured a special attachment, based on an integrating sphere (ϕ 65 mm) with three apertures (Fig. 2a). The inner surface of the sphere 4 is coated with diffusely scattering $BaSO_4$. A monochromatic flow of radiation emerging from the slit 9 of an SF-4A monochromator passes through the entrance aperture (ϕ 12 mm) to fall on the inner surface of the sphere and, as a result of multiple reflections from its surface and the surface of the sample 7 (φ 20 mm), creates a uniform illumination, which is recorded by the photocell 2. The aperture (ϕ 18 mm) in front of the stationary photocell 2 is covered with a semitransparent, diffusely scattering opal glass 3.

TABLE 3. Comparison between the Integrated Double-Hemispherical and Directional-Hemispherical Reflecting Powers of Various Materials

Material	$R(2\pi;\ 2\pi)$ for globar radiation	Published data regarding $R(\theta;\ 2\pi)$
Black mat enamel	0,085	0,074—0,055 [6]
Silver	0,990	0,978—0,950 [6]
Pine wood, 3.05 mm	0,307	0,312, calculated by averaging

The mobile photocell 8 with a large receiving area (ϕ 32 mm) measuring the radiation flux passing through the sample 7 maybe set directly under the lower surface of the sample, or else under the 20-mm-diameter aperture of the sphere 4. The signals of the (FÉSS-U10) photocells are measured with a reading instrument UF-206 designed for measuring currents down to 1 μA.

For these dimensions of the sphere and sample aperture, the additional illumination $\Delta E = 3.0R_0E$ inside the sphere [8] created by the flow of radiation reflected from the sample is 2.25 times greater than in the Sherrell apparatus [8] ($\Delta E = 1.33\ R_0E$). This enables us to increase the signal of the radiation receiver for a better spectral resolution of the instrument, and to increase the accuracy of the measurements. A shortcoming of the device under consideration is a certain difference in the conditions of illuminating the surface of the photocell 8 (Fig. 2a) recording the radiation passing through the sample and the standard. This results in errors due to the dependence of the photocurrent on the angle of incidence and the nonuniform sensitivity of the photosensitive layer at different points on the surface and under different conditions of irradiation.

In order to estimate and eliminate these errors we developed another method: the complex measurement of $T_\lambda(2\pi;\ 2\pi)$ and $R_\lambda(2\pi;\ 2\pi)$.

For the complex measurements the attachment to the SF-4A monochromator (Fig. 2b), like that of Duntley [7], includes two integrating spheres 4 and 10 with identical characteristics. For measuring the illuminations of the speres we use two radiation receivers 2 and 8. The lower sphere 10 may be replaced by the model of an absolutely absorbing body, also made in the form of a sphere, with a blackened inner surface. The reflection and transmission samples 7 and standards 6 are fixed in a special rotating holder 5. As reflection standard we use MS-14 opal glass. The cover 1 serves for closing the entrance aperture of the sphere.

The integrating sphere 10 and the semitransparent diffusely scattering glass 3 create identical conditions of illumination of the photocell 8, whether the radiant flux passes through the sample or through the standard, and hence avoids the errors already discussed in relation to the single-sphere instrument.

The method of measuring the double-hemispherical parameters $R_\lambda(2\pi;\ 2\pi)$, $T_\lambda(2\pi;\ 2\pi)$ is based on the dependence of the state of illumination of the inside of the sphere on the dimensions and reflecting powers of all its elements and apertures.

In the reflection of the incident flux F_{in} from the surface of the sphere, the illumination E within the latter is constant for any point and may be determined by means of the Taylor equation [3, 5]

$$E = \frac{F_{in}}{s}\,\frac{R_s}{(1-\varphi R_s)}, \tag{3}$$

where φ is a coefficient determining the actual proportion of the whole surface of the sphere taking part in the multiple reflections and allowing for the absorption of radiation by the apertures and other elements:

$$\varphi = 1 - \frac{1}{s}\sum_{i=1}^{n}(1-R_i)\,s_i. \tag{4}$$

It follows from Eq. (3) with due allowance for Eq. (4) that the illumination of the surface of the sphere only changes after replacing the sample by the reflection standard or the blackened sphere. Hence Eq. (4) may be conveniently expressed in the following way:

$$\varphi = \varphi' + R_0\frac{s_0}{s}, \tag{5}$$

where φ' is a coefficient constant for the particular sphere and independent of the R_0 of the sample,

$$\varphi' = 1 - \frac{1}{s}\sum_{i=1}^{n}(1-R_i)s_i - \frac{s_0}{s}. \quad (6)$$

For the illumination of the inner surface of the sphere, on allowing for Eqs. (3) and (5), we obtain a relationship for the double-hemispherical reflecting power R_0 of the sample in the following form:

$$E(R_0) = \frac{F_{in}}{s} \cdot \frac{R_s}{(1-\varphi' R_s) - R_0 R_s \frac{s_0}{s}}. \quad (7)$$

The method of simultaneously measuring $R_\lambda(2\pi; 2\pi)$ and $T_\lambda(2\pi; 2\pi)$ with a single integrating sphere and two photocells (Fig. 2a) is as follows.

1. In the absence of the sample 7, the lower photocell 8 is placed directly in the aperture of the sphere 4, and the signals N_{pR} and N_{pT} of the upper and lower photocells 2 and 8, proportional to the illumination of the sphere $E(R_p)$ (which depends on R_p, the reflecting power of the photocell), are measured:

$$E(R_p) = \frac{F_{in}}{s} \frac{R_s}{(1-\varphi' R_s) - R_p R_s \frac{s_0}{s}}, \quad (8)$$

$$N_{pR} = \alpha E(R_p), \quad N_{pT} = \beta E(R_p). \quad (9)$$

2. The sample 7 is placed in the aperture of the sphere 4 and the signals N_R and N_T of the upper and lower photocells 2 and 8, proportional to the illumination of the sphere, are measured at the same time:

$$E(R_0) = \frac{F_{in}}{s} \cdot \frac{R_s}{(1-\varphi' R_s) - R_0 R_s \frac{s_0}{s}}, \quad (10)$$

$$N_R = \alpha E(R_0), \quad N_T = \beta E(R_0) T_0. \quad (11)$$

In the majority of cases air is the transmission standard, so that $N_{pT} = N_{stT}$ and by the simultaneous solution of Eqs. (8)-(11) we obtain the following absolute value of the double-hemispherical transmitting power of the sample:

$$T_\lambda(2\pi; 2\pi) = \frac{N_T}{N_{pT}} \cdot \frac{N_{pR}}{N_R}. \quad (12)$$

The absolute value of the double-hemispherical reflecting power of the sample is determined from Eqs. (8) and (10) with the aid of (9) and (11):

$$R_\lambda(2\pi; 2\pi) = \left(1 - \frac{N_p}{N_R}\right) \frac{1-\varphi' R_s}{R_s \frac{s_0}{s}} + R_p \frac{N_p}{N_R} - \Delta R, \quad (13)$$

where ΔR is a correction allowing for the reflection of the radiation which has passed through the sample from the lower photocell.

The magnitude of the correction may be taken as approximately

$$\Delta R = T_\lambda^2(2\pi; 2\pi) R_p. \quad (14)$$

For relative measurements of the sample reflecting power we determine the signal of the upper photocell 2 for the case in which the reflection standard 6 (opal glass MS-14) is placed in the aperture of the sphere.

$$N_{stR} = \alpha E(R_{st}) = \alpha \frac{F_{in}}{s} \cdot \frac{R_s}{(1-\varphi' R_s) - R_{st} R_s \frac{s_0}{s}}. \quad (15)$$

The quantity $R_\lambda(2\pi; 2\pi)$ for the sample may be determined, after allowing for (9)-(11) and (15), from the equation

$$R_\lambda(2\pi; 2\pi) = \left(\frac{N_R - N_{pR}}{N_{stR} - N_{pR}}\right) \frac{N_{stR}}{N_R} R_{\lambda st}(2\pi; 2\pi) + \Delta R. \quad (16)$$

The correction ΔR in this case equals

$$\Delta R = R_p\left[1 - T_\lambda^2(2\pi;\ 2\pi) - \left(\frac{N_R - N_{pR}}{N_{stR} - N_{pR}}\right)\frac{N_{stR}}{N_R}\right]. \tag{17}$$

It follows from (17) that for large values of the T_λ or R_λ parameters of the sample (greater than 0.8) the correction ΔR is negligible owing to the small value of the reflecting power of the photocell ($R_p \leq 0.05$), since the difference term in the square brackets then assumes values smaller than 0.2, so that $\Delta R < 0.001$.

The complex measurement of $T_\lambda(2\pi;\ 2\pi)$ and $R_\lambda(2\pi;\ 2\pi)$ by means of two integrating spheres (Fig. 2b) is carried out as follows.

1. In the absence of the sample 7, the apertures (20 mm in diameter) in spheres 4 and 10 are brought together and the signals N_{sR} and N_{stT} of the upper and lower photocells 2 and 8, proportional to the illuminations, are measured:

for the upper sphere

$$N_{sR} = \alpha E_u(R_s') = \alpha \frac{F_{in}}{s} \cdot \frac{R_s}{(1 - \varphi' R_s) - R_s' R_s \frac{s_0}{s}}, \tag{18}$$

for the lower sphere

$$N_{stT} = \beta E_l(R_s') = \beta \frac{E^2(R_s')}{F_{in}} s_0, \tag{19}$$

where R_s' is the effective coefficient characterizing the proportion of reflected radiation from the sphere 10 passing through the aperture of area S_0 into the sphere 4.

2. The sample 7 is placed in the apertures of spheres 4 and 10 (Fig. 2b) and the signals N_R and N_T of the upper and lower photocells are measured:

$$N = \alpha E_u(R_0') = \alpha \frac{F_{in}}{s} \cdot \frac{R_s}{(1 - \varphi' R_s) - R_0' R_s \frac{s_0}{s}}, \tag{20}$$

$$N_T = \beta E_l(T_0,\ R_0') = \beta T_0 \frac{E_u^2(R_0')}{F_{in}} s_0. \tag{21}$$

The absolute value of the double-hemispherical transmitting power is determined, after allowing for (18)-(21), from the equation

$$T_\lambda(2\pi;\ 2\pi) = \frac{N_T}{N_{stT}} \cdot \frac{N_{sR}^2}{N_R^2}. \tag{22}$$

In order to determine the reflecting power $R_\lambda(2\pi;\ 2\pi)$ we still have to carry out the following measurements.

3. The sphere 10 under the sample is replaced by an absorbing sphere, in which case the illumination depends on the reflecting power of the sample, and the photocell signal is equal to

$$N_{R0} = \alpha E_u(R_0). \tag{23}$$

4. The sample 7 is removed and the illumination of the sphere 4, depending on the reflection R_A of the absorbing blackened sphere, is measured. The photocell signal is then

$$N_{RA} = \alpha E_u(R_A). \tag{24}$$

The double-hemispherical reflecting power of the sample may be determined, after allowing for (18)-(20), (23), and (24), from

$$R_\lambda(2\pi;\ 2\pi) = \left(1 - \frac{N_{RA}}{N_{R0}}\right) \frac{1 - \varphi' R_s}{R_s \frac{s_0}{s}}. \tag{25}$$

In the case of relative measurements the absolute value of $R_\lambda(2\pi;\ 2\pi)$ must be calculated from the equation

$$R_\lambda(2\pi;\ 2\pi) = \left(\frac{N_{R0} - N_{RA}}{N_{Rst} - N_{RA}}\right) \frac{N_{Rst}}{N_{R0}} R_{\lambda st}(2\pi;\ 2\pi), \tag{26}$$

where N_{Rst} is the signal obtained from photocell 2 on placing the reflection standard in the aperture of sphere 4.

Using these methods we made some direct measurements of the double-hemispherical parameters $R_\lambda(2\pi;\ 2\pi)$ and $T_\lambda(2\pi;\ 2\pi)$ for selectively absorbing and scattering materials (Fig. 1b). Checks showed that the values of the double-hemispherical reflecting and transmitting powers of the materials measured with one and two spheres (Fig. 2a and b, respectively) differed on average by ±0.005, which indicated that the one-sphere measurement of $T_\lambda(2\pi;\ 2\pi)$ using a large receiving area was fairly accurate. An advantage of this method by comparison with the method of two spheres and the Duntley method [7] lies in the fact that the signals of the reflection and transmission receivers are of the same order, since they measure the illumination inside a single sphere. In devices with two spheres the illumination inside the second sphere is two orders of magnitude lower than in the first, and hence the photocell signal in the measurements of $T_\lambda(2\pi;\ 2\pi)$ is much lower (by a factor of 100), which imposes severe conditions on the accuracy of the photometer measurements. In the present case of the diffuse irradiation of various weakly scattering (polyethylene) and strongly scattering (paper) materials, the receiver 8 is subject to almost constant conditions of irradiation (Fig. 2a), and the errors due to the nonuniformity of the photolayer properties are no greater than 0.5%. Only for samples having a hemispherical-irradiation transmission indicatrix deviating sharply from the diffuse condition does the error in measuring $T_\lambda(2\pi;\ 2\pi)$ by the single-sphere method become substantial. The majority of real scattering materials transmit a hemispherical radiation flux diffusely and may be studied by the simple method here described.

The proposed methods for the simultaneous and complex measurement of the double-hemispherical transmitting and reflecting powers may also be used in the infrared part of the spectrum. For this purpose we developed a special integrating sphere with a diffusely reflecting aluminum coating; the reflecting power was 0.9-0.97 in the near and medium infrared parts of the spectrum for a diffuse reflection indicatrix.

The spectral characteristics of the special coating of the integrating sphere are shown in Tables 1 and 2 for the infrared part of the spectrum. Using a sphere of this kind we measured the integrated reflecting powers $R(2\pi;\ 2\pi)$ of various materials irradiated in globar radiation. As the radiation receiver we used a thermocell of the Kozyrev type [4] with a receiving area of $3 \times 10\ mm^2$ and a KRS-5 entrance window. On comparing the measured values of the integrated double-hemispherical reflecting powers of various materials (Table 3) with published data and data calculated from the directional-hemispherical parameters $R(\theta;\ 2\pi)$, the reliability of the results obtained by the sphere method is excellently confirmed.

NOTATION

R, T, and A, reflecting, transmitting, and absorbing powers of the layer of material; $R_0 = R(2\pi;\ 2\pi)$ and $T_0 = T(2\pi;\ 2\pi)$ double-hemispherical reflecting and transmitting powers of the sample; E, illumination of the surface of the sphere, W/m^2; s, area of the sphere, m^2; s_i, area of the i-th aperture of the sphere, m^2; F, radiation flux, W; N, photocell signal; α, β, sensitivities of the photocells. Indices: λ, spectral; R, reflection; T, transmission; 0, sample; in, incident; p, photocell; s, sphere; st, standard; l, lower; u, upper; A, black-body; i, element or aperture in the sphere.

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