INVESTIGATION OF THE PRIMARY THERMAL RADIATION CHARACTERISTICS OF MATERIALS BY THE METHOD OF MEASURING HEMISPHERICAL CAPACITIES

L. S. Slobodkin and Yu. M. Sotnikov-Yuzhik

UDC 536.3

A method is presented for determining the primary thermal radiation coefficients for a layer of dissipating and absorbing material. The capacities computed for layers of different thickness by using these coefficients are in good agreement with experimental measurements.

Data about the radiative (thermal radiation) characteristics of the materials participating in the heat exchange are needed for computations of radiant transfer. Since many materials are selectively absorbing and dissipating, then not taking these factors into account in the computations results in substantial errors [1, 2]. The spectral thermal radiation characteristics of the materials under consideration (T_λ, R_λ, A_λ, ε_λ) do not explicitly reflect the appropriate physical properties since they depend on the geometric dimensions of the bodies (in particular, the layer thickness) and characterize them by using primary constants [3], which might be the absorption and scattering coefficients of an elementary layer (k_λ and s_λ). Having data available on the primary optical constants, the spectral thermal radiation characteristics of materials of any thickness, the distribution of the spectral radiation fluxes within the layer, etc., can be obtained by computations. Knowledge of the primary material characteristics also permits computation of the semitransparent layer thickness, say, which is required so that it would have a definite, previously assigned,

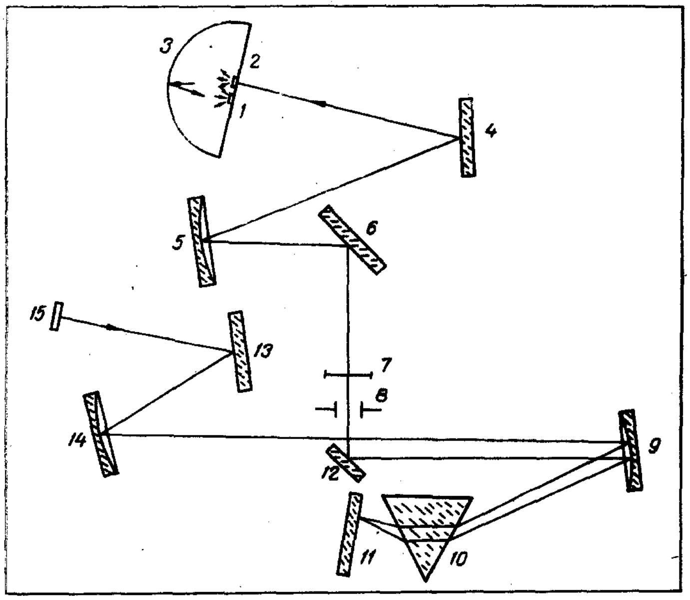

Fig. 1. Optical diagram of an IR spectrometer to measure the hemispherical capacity of dissipating materials: 1) radiation detector; 2) specimen; 3) hemispherical mirror; 4, 6) flat mirrors; 5) spherical mirror; 7) modulator; 8-15) optical elements of an IKS-12 type spectrometer.

Institute of Heat and Mass Exchange of the Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 26, No. 2, pp. 215-219, February, 1974. Original article submitted July 3, 1973.

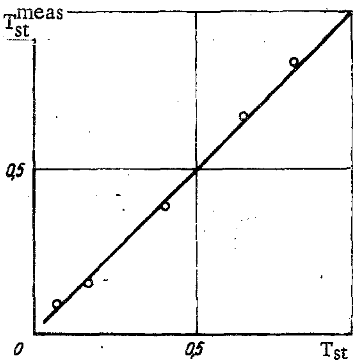

Fig. 2

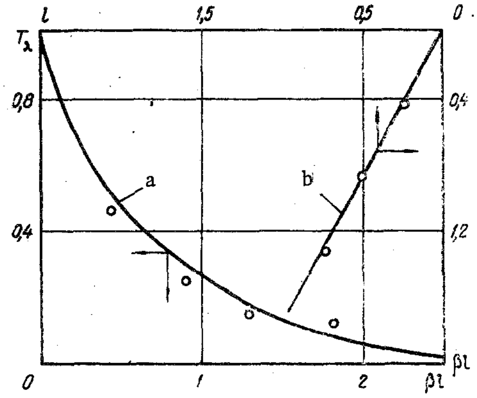

Fig. 3

Fig. 2. Dependence of the measured transmission T_{st}^{meas} on the true transmission T_{st} for the standards (wire grid).

Fig. 3. Dependence of the hemispherical transmission of wood (pine) (curve a) on the dimensionless parameter βl ($\lambda = 0.91\ \mu$) and dependence of the factor βl (b) on the layer thickness l (mm).

value of T, R, A and ε for a given wavelength λ or within any spectrum band $\Delta\lambda$. Moreover, such data are needed for the solution of complex radiation heat exchange problems.

A considerable number of papers are devoted to theoretical investigations of radiation transfer in dissipating and absorbing media. The method of the two-flux approximation, worked out and developed in [4-8] and others has become especially widespread. Solutions for the layer of a capillary-porous body are presented in [9-11] the basis of the most widely used form of the two-constant system of equations. The authors have proposed two methods for determining the internal optical constants k_λ and s_λ, where the former is based on an experimental determination of the hemispherical thermal radiation coefficients R_λ, T_λ and $R_{\lambda\infty}$, and the latter is determined by the graphical solution of transcendental relationships. In practice, the realization of the mentioned methods is governed in the first case by the complexity of eliminating the instrumental error in measurements of three diverse quantities, and in the second by its being time-consuming.

We use the general solution of the known, initial two-constant system of equations [4-9] in the form proposed in [12]:

$$I_+ = A_1(1-\alpha)\exp(\beta x) + A_2(1+\alpha)\exp(-\beta x), \tag{1}$$

$$I_- = A_1(1+\alpha)\exp(\beta x) + A_2(1-\alpha)\exp(-\beta x), \tag{2}$$

to find the primary optical characteristics of a dissipating and absorbing layer, where A_1 and A_2 are integration constants.

There are new constants α and β in this solution which are related uniquely to the initial constants, the absorption k and "back"-scattering s coefficients of an elementary layer. Therefore, if the pair of constants α and β is determined, then this is equivalent to determining the constants k and s since

$$k = \alpha\beta \text{ and } s = \frac{\beta}{2\alpha}(1-\alpha^2). \tag{3}$$

It has been shown in [12] that the constant β has the physical meaning of a radiation attenuation factor during propagation within an absorbing and dissipating layer, and the quantity α is the optical constant of a layer of unit thickness.

The boundary conditions for the system (1) and (2) are determined by selecting an appropriate physical model of the object under investigation from the viewpoint of thermal radiation propagation therein. Let us assume that a plane-parallel layer being investigated has no continuous interface between dissipating and non-dissipating media. In this case the reflection from the interface itself can be assumed zero and the layer reflection actually observed will be substantially spatial. As analysis has shown, among such objects might be layers of various colloidal capillary-porous bodies (powdery compounds, etc.).

In this case the relationships

$$I_{+}^{(x=0)} = I_t \text{ and } I_{-}^{(x=l)} = 0 \tag{4}$$

will be the boundary conditions for (1) and (2).

Solving the system (1) and (2) with (4) taken into account, we find expressions for the fluxes I_+ and I_-, after which an expression can be written for the hemispherical transmission coefficient of a layer of thickness l:

$$T_t = \frac{I_{+}^{(x=l)}}{I_t} = \frac{2\alpha}{\frac{1}{2}\,(\alpha^2+1)\left[\exp(\beta l) - \exp(-\beta l)\right] + \alpha\left[\exp(\beta l) + \exp(-\beta l)\right]} \tag{5}$$

Having written (5) for two material specimens of thickness l_1 and l_2, where $l_2 = 2l_1$, we finally arrive at the relationship

$$\exp(\beta l_1) + \exp(-\beta l_1) = \left(1 + \frac{1}{T_2}\right) T_1 \tag{6}$$

by manipulations which are not presented here because of awkwardness. By using (6) one of the desired constants, the attenuation factor $\beta\lambda$, is easily determined (by means of tables of hyperbolic functions) if there exist experimentally measured hemispherical transmission coefficients for the two specimens of different thickness. The other quantity desired, the optical constant, is determined from (5) which is an ordinary quadratic equation in $\alpha\lambda$.

The authors fabricated a special adapter to a single-beam infrared spectrometer, whose main element is a hemispherical mirror, to determine the directional hemispherical capacities of dissipating materials. The instrument permits measurement of the hemispherical $R\lambda$ and $T\lambda$ in the thermal range of the spectrum.

Let us examine the operation of the instrument mounted in a position to measure $T\lambda$ (Fig. 1). Radiation flux from the exit slit 8 of the monochromator is focused on the surface of the specimen 2 by using a spherical 5 and flat 6 and 4 mirrors. The radiation which has passed through the specimen is collected by the hemisphere 3 at the radiation detector 1.

The use of the hemispherical mirror, which collects radiation reflected by or transmitted through the specimen in a large solid angle reaching 2π, imposes strict constraints on the selection of the radiation detector [13]. This latter should have high sensitivity, large size of the detecting area, and a large input aperture (up to 2π). Meanwhile, as a rule the fabrication of a detector corresponding to the first two constraints is a difficult task since the threshold response of a majority of detector types is inversely proportional to the area of the detecting area [14].

We selected a photo-resistor based on lead sulfide and lead selenide as detector. The former permits conducting measurements in the 0.8-3 μ range with high sensitivity, while the domain of satisfactory response of the second detector extends to 5 μ.

Radiation modulated at a 20 Hz frequencey, which has passed through the specimen, is incident on the detector. The variable signal taken off from the detector was amplified by a selective microvoltmeter B6-4 with a synchronized detector. In combination with the low noise, the high detector response permits operating with small slits, and therefore, with great resolution. The slit width in the region of maximum response of the PbS detector (2.7 μ) was on the order of 0.05 mm.

The transmission coefficients $T\lambda$ of a number of metal grids used as transmission standards (λ = 2.5 μ) were measured to verify the linearity of the whole detecting-recording system of the instrument. Transmission coefficients of the standards were measured to 1% accuracy at the same wavelength λ on a UR-20 infrared spectrometer. Presented in Fig. 2 is a dependence of T_{st}^{meas} on T_{st}, from which it is seen that the linearity of the detecting-recording system is conserved with satisfactory accuracy.

The instrument described permitted verification of the relationships presented to determine the primary thermal radiation characteristics. A typical colloidal capillary-porous material, wood, was taken as the subject of investigation. The measured values of the hemispherical capacities are presented as a function of thickness in Fig. 3 (curve a) and agree well with data in the literature [9]. The specimens had the following thickness l: 0.25; 0.5; 0.75 and 1.0 mm (the magnitude of l was kept within 0.01 mm accuracy). Also presented in Fig. 3 is the dependence of βl on the specimen thickness l. The linearity of this dependence indicates the constancy of the effective attenuation factor. The values of the constants α and β calculated by means of (12) and (8) afforded the possibility of constructing a computational dependence of the capacity of wood as a function of the dimensionless parameter (the optical thickness) βl. A computation of the curve (a) by means of (8) is in good agreement with the experimental values of the capacity (Fig. 3).

Therefore, in combination with the experimental method proposed the relationships presented afford the possibility of determining the primary thermal radiation characteristics of the semitransparent dissipating and absorbing materials under consideration in the thermal spectrum range comparatively simply and with the accuracy needed.

NOTATION

R_λ, T_λ, A_λ	are the spectrum reflexivity, transmissivity, and absorptivity, respectively, for a layer of thickness l;
ε_λ	is the spectral radiativity of the material;
k_λ, s_λ	are the spectral absorption and "back"-scattering coefficients for an elementary layer;
I_+ and I_-	are the radiation fluxes at depth x in positive and negative directions;
I_{II}	is the incident flux at $x = 0$;
α, β	are the optical constants for layer of unit thickness;
$R_{\lambda\infty}$	is the spectral reflexivity of an optically infinitely dense layer.

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