DETERMINING THE CHARACTERISTICS OF THE EMISSION FIELD IN CAPILLARY-POROUS COLLOIDAL BODIES

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A method is presented for determining the layer-thickness distribution of the total emission flux and the amount of radiant energy absorbed by elementary layers at a specified depth within capillary-porous colloidal bodies. A graphical method is described for determination of the coefficients of absorption, effective radiation-flux attenuation, and reflection for a layer of infinite optical thickness on the basis of two transmission or reflection measurements.

The problem of propagation of monochromatic radiation in capillary-porous colloidal bodies has been solved in [1]. Materials are dried and heat-treated, by commercially manufactured equipment that employs the total energy flux from radiation generators ("bright" and "dark"). More than 95% of all the energy is radiated by the source within a narrow wavelength band $\lambda_1 - \lambda_2$ [2, 3, 6], while the optical properties of capillary-porous colloidal bodies are quite selective [2-5]. Thus in calculations pertaining to the drying and heat-treatment of various materials it is important to know the thermal-radiation characteristics of the layer of material with respect to the particular infrared emitter, and the distribution of the overall energy flux produced by the total radiation over the thickness of the layer.

If we consider that part of the spectrum within which the minimum values of spectral intensity do not exceed 0.1% of the maximum value, we can find the limits of the theoretical spectral region for blackbody emission from the following relationship [6]

$$0.25\lambda_{\max} < \lambda < 13\lambda_{\max}$$

or

$$917/T_e < \lambda < 47684/T_e. \tag{1}$$

For practical purposes, we need only consider the spectral region containing most of the energy (~ 95%) emitted by an actual infrared generator,

$$0.4\lambda_{\max} < \lambda < 4\lambda_{\max}. \tag{2}$$

Thus for a Nichrome helix at T_e = 1270°K, λ_{max} = 1.9 μ; it then follows from (2) that λ_1 = 0.76 μ, λ_2 = 7.6 μ, while for a type "NIK-220-1000 tr" lamp, at T_e = 2250°K, λ_{max} = 1.16 μ [3] and λ_1 = 0.51 μ, λ_2 = 5.1 μ. Thus the thermal radiation characteristics of the same material will differ with respect to different emitters, and they must be determined from the following approximate formula:

$$\bar{B} \simeq \int\limits_{\lambda_1}^{\lambda_2} I_\lambda B_\lambda d\lambda \Bigg/ \int\limits_{\lambda_1}^{\lambda_2} I_\lambda d\lambda \simeq \sum_{\lambda_1}^{\lambda_2} I_\lambda B_\lambda \Delta\lambda \Bigg/ \sum_{\lambda_1}^{\lambda_2} I_\lambda \Delta\lambda, \tag{3}$$

where B_λ is the spectral variable (A_λ, R_λ, T_λ, a_λ, σ_λ), averaged over the spectrum of the chosen emitter.

In (3) a value of 0.1 μ is adequate for the spectral range Δλ. Calculations show that a reduction of Δλ to 0.05 μ results in no substantial change in the results obtained from Eq. (3), owing to the fact that the linear dispersion of spectrophotometer monochromators is 0.100-0.200 μ/mm in the 1-15 μ infrared region, while in studying light-scattering media, it is necessary to operate with a spectral width of 0.5-2.0 mm [8]. Calculations based on the approximate formula (3) yield good agreement with experimental data. Thus for

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a 1.5 mm thick layer of wood (pine), the transmission factor found from (3) for the spectrum of a "NIK-220-1000 tr" lamp at $T_e = 2250°K$ is 5.5%, while in accordance with experimental data [5] under illumination by a "bright" radiator, the transmission factor of the same specimen is 5.2%.

At a depth x, the scalar magnitude of the resultant flux-density vector for both complete and monochromatic [1] emission is found as

$$q = Q_{1\,ef}\frac{1-R_\infty}{1-\Psi^2}\left[\exp(-\sigma x)+\frac{\Psi^2}{R_\infty}\exp(\sigma x)\right]-Q_{2\,ef}\frac{1-R_\infty}{1-\Psi^2}\left[\exp\{-\sigma(l-x)\}+\frac{\Psi^2}{R_\infty}\exp\{\sigma(l-x)\}\right], \tag{4}$$

where

$$\Psi = R_\infty\exp(-\sigma l);\quad \sigma=\sqrt{a(a+2s)}.$$

The effective radiation fluxes incident on both surfaces of the layer depend on the thermal-radiation characteristics and the relative positions of the layer, the radiators, and the chamber barriers; when $Q_{e1} = Q_{e2}$ and $R_{e1} = R_{e2}$, these fluxes can be found as

$$Q_{ef} = \frac{Q_e T_m}{1-[R+T]\,[R_c+\left(R_e\varphi_e+\sum_{i=1}^{n}R_{0i}\varphi_{0i}\right)-T_m^2]}. \tag{5}$$

Where the incident effective fluxes are equal, Eq. (4) becomes much simpler:

$$q = Q_{ef}\frac{1-R_\infty}{1-\Psi^2}\left[\exp(-\sigma x)-\exp\{-\sigma(l-x)\}\right]. \tag{6}$$

In the optically infinite layer $\sigma l \to \infty$, the resultant flux density at a depth x is found as

$$q = Q_{ef}(1-R_\infty)\exp(-\sigma x) = q_{x=0}\exp(-\sigma x), \tag{7}$$

which yields

$$\sigma = \frac{1}{x}\ln\left(\frac{q}{q_{x=0}}\right). \tag{8}$$

Thus the coefficient σ characterizes the attenuation of the resultant flux of radiation as the latter penetrates into an optically infinite layer. If the ratio $q/q_{x=0}$ equals e at a certain depth x = L, we obtain $\sigma = L^{-1}$ from (8). As a consequence, the coefficient of effective attenuation is equal numerically to the reciprocal of the depth of the layer at which the resultant radiation flux is diminished by a factor of 2.7183. The amount of energy absorbed at the depth x by an elementary volume of thickness dx in unit time equals [1]

$$\omega = -\frac{dq}{dx} = aq^*Q_{ef}. \tag{9}$$

The quantities R_∞, σ, and a, averaged over the spectrum of the chosen emitter on the basis of Eq. (3) should be substituted into the formulas (4)-(9) for the total radiation.

The spectral reflective power $R_{\lambda\infty}$ of an optically infinite layer can be determined by one of the familiar methods [7, 8].

To determine the averaged coefficients σ and a, we can employ the familiar relationships for the spectral variables [1]:

$$\sigma = \frac{1}{l}\ln\left(\frac{1-RR_\infty}{T}\right), \tag{10}$$

$$a = \frac{1-R_\infty}{1+R_\infty}\,\sigma. \tag{11}$$

In this case, the instrumental error in measurement of R_λ and T_λ is not eliminated and, moreover, it is necessary to measure the three quantities R_λ, T_λ, and $R_{\lambda\infty}$. At present, there are no commercially produced spectrophotometers for investigation of light-scattering media in the 1-15 μ and longer infrared region [3, 7]. The literature contains descriptions of individual attachments for single-beam spectral spectrophotometers only, and then just for determination of R_λ in the infrared region [7, 8]; these devices are unsatisfactory in that the measurements take so long and the results are so difficult to process.

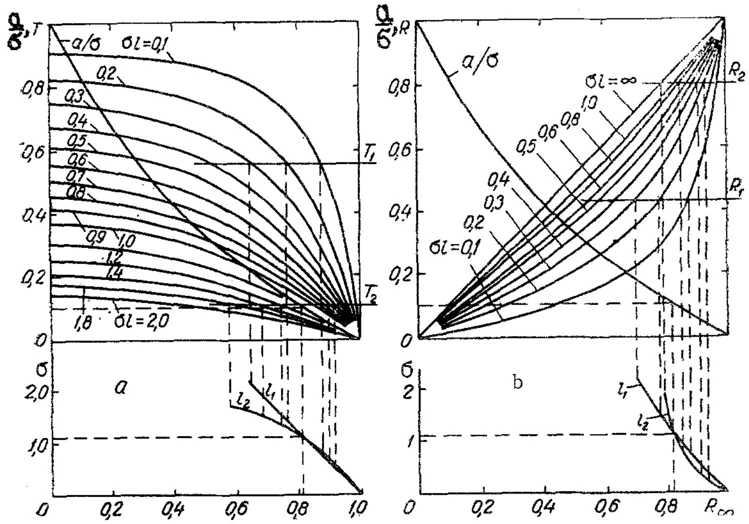

Fig. 1. Nomogram for determining a, σ, and R from measurements of transmission (a) and reflection (b) of flat layers of varying thickness.

The authors have developed an attachment for the SF-4A device [9] and for the two-beam IKS-14 infrared spectrophotometer that makes it possible to measure R_λ and T_λ for light-scattering media; they make it possible to reduce experimental time by a factor of 5-10, which is very important when moist materials are studied. Such devices have been used to measure R_λ and T_λ for various capillary-porous colloidal bodies (paste, starch, potato, wood, etc.).

To eliminate instrumental error, R_λ or T_λ should be measured for two thicknesses l_1 and l_2, and a system of type (12) or (13) must be solved for the unknowns σ and R_∞:

$$R = R_\infty \frac{1 - \exp(-2\sigma l)}{1 - R_\infty^2 \exp(-2\sigma l)}, \tag{12}$$

$$T = \exp(-\sigma l) \frac{1 - R_\infty^2}{1 - R_\infty^2 \exp(-2\sigma l)}. \tag{13}$$

However, it is difficult to solve such systems exactly. A similar problem is encountered when we determine the absorption and reflection coefficients from the surface of a flat layer of absorbing semiconductor material [10]. Thus such systems can be treated as follows: 1) by finding approximate solutions and estimating the permissible errors [11]; 2) by developing graphical solution methods [12-14].

For light-scattering media, it is best to use the graphical method proposed by A. P. Prishivalko for absorbing (but not scattering) media [10].

This idea has been embodied in a simple and convenient method for graphical solution of such problems, with the three variables a, σ, and R_∞ of the light-scattering media being determined. The method is based on the use of nomograms on which several $T(R_\infty)$ and $a/\sigma(R_\infty)$, or $R(R_\infty)$ and $a/\sigma(R_\infty)$ curves are drawn. Such nomograms are illustrated in Fig. 1. They were constructed with the aid of Eqs. (11), (12), and (13).

The coefficients of absorption a, effective attenuation σ, and reflection R_∞ for an optically infinite layer are found from the nomogram in the following manner. The relationships obtained between R_λ or T_λ and the wavelength for two or more specimens are averaged over the spectrum of the chosen emitter by means of (3). Next the line T = const or R = const is drawn for the first specimen. The values σl for the curves cut must be divided by the specimen thickness l_1. The resulting values of σ are plotted on a supplementary graph as a function of the R_∞ values corresponding to the points at which the given straight line intersects the $R(R_\infty)$ or $T(R_\infty)$ curves. These points are joined by a smooth curve. In like manner, we obtain the $\sigma(R_\infty)$ curve for the second specimen. The coordinates of the points of intersection of these curves give the desired values of σ and R_∞. The desired ratio a/σ is given by the ordinate of the point at which a straight line parallel to the axis of ordinates through the value found for R_∞ intersects the $a/\sigma(R_\infty)$ curve.

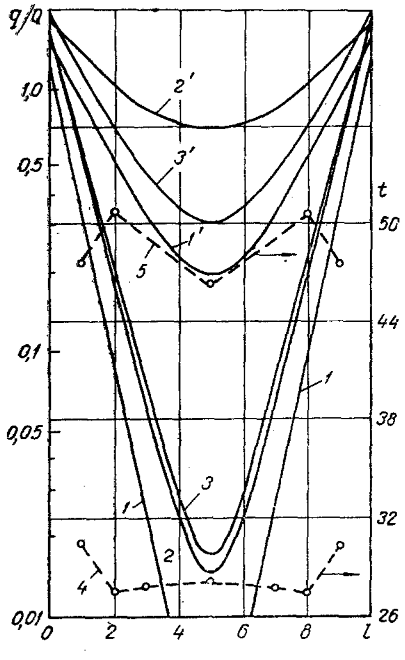

Fig. 2

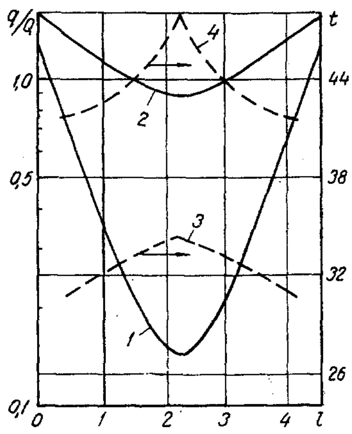

Fig. 3

Fig. 2. Distribution of dimensionless total (curves 1, 2, 3) and spectral ($\lambda = 1.1\ \mu$) (curves 1', 2', 3') fluxes and temperature [3] (curves 4, 5) over layer thickness for various materials eliminated by "NIK-220-1000 tr" lamps: 1, 1') macaroni dough, W = 31.2%; 2, 2') candy after setting, W = 30.0%; 3, 3') wood (pine), W = 6.2%; 4, 5) temperature in sheet of macaroni dough at 5 and 60 min, respectively.

Fig. 3. Distribution of dimensionless total (curve 1) and spectral ($\lambda = 1.1\ \mu$) (curve 2) fluxes and temperature [3] (curve 3, 4) over layer thickness for macaroni dough irradiated by "NIK-220-1000 tr" lamps; 3, 4) temperature at 8 and 12 min, respectively.

Thus the nomogram yields all values of a, σ, and R_∞ needed to compute q(x) or ω(x) from (4)-(9), and for determining the thermal-radiation characteristics of a material layer of any thickness l from (12), (13).

Figure 1 illustrates the determination of a, σ, and R_∞. Specimens of wood (pine) of thickness $l_1 = 0.14$ mm, $l_2 = 1.05$ mm, have values of $T_{1\lambda} = 0.56$, $T_{2\lambda} = 0.11$, and $R_{1\lambda} = 0.43$, $R_{2\lambda} = 0.80$ for a wavelength $\lambda = 0.8\ \mu$. From Fig. 1 we obtain $\sigma_\lambda = 1.12\ \mathrm{mm}^{-1}$, $a_\lambda/\sigma_\lambda = 0.1$, $a_\lambda = 0.112\ \mathrm{mm}^{-1}$.

The nomogram can also be used if we know T and R_∞ or R and R_∞.

On the basis of the accuracy with which T or R is measured, the nomogram scale must be so selected that in graphical determination of a, σ, and R_∞, the error per millimeter does not exceed the experimental error. Where necessary, (12), (13) can be used to obtain additional $R(R_\infty)$ and $T(R_\infty)$ curves. The slope and angle of intersection of the $\sigma(R_\infty)$ curves on the supplementary graph will depend on the thicknesses selected for the investigated specimens. For a more reliable determination of a, σ, and R_∞ it is desirable to measure R or T for several specimens of varying thicknesses; here the thickness ratio l_2/l_1 must exceed 3 [14]. The supplementary curves must intersect at distances determined by the experimental error.

At present, R can be measured more reliably for light-scattering media than T, so that we should use the $R(R_\infty)$ nomogram shown in Fig. 1b, even though R is less sensitive to variations in the optical properties of the material.

The method described was used to determine the spectral and spectrally averaged coefficients a, σ, and R_∞ for various emitters and several typical capillary-porous colloidal materials. Using these coefficients and (3), we can establish the distribution of the spectral and total energy fluxes over the depth of the material for a given emitter.

From the distributions of the dimensionless (q/Q_{ef}) spectral and total fluxes (Figs. 2, 3) over the depth of various materials, we can draw the important conclusion that anomalous temperature distributions (Fig. 2, curve 5 [3]) found by many investigators in drying and heat-treatment of various materials [3, 15, 16] cannot be explained by penetration of infrared radiation to a certain depth where it is converted into heat energy. As we see from Figs. 2, 3, the density of the resultant total and monochromatic fluxes in the surface layers of various capillary-porous colloidal materials is several times that found at a depth of 2 mm [3, 15] and 5 mm [16], where the maximum temperature is ordinarily found. Thus more heat is liberated in the surface layer owing to absorption of radiant energy than in the layer lying 2-5 mm deep, as is observed at the initial instant (Fig. 2, curve 4).

The method proposed for determining the distribution of total-radiation fluxes in capillary-porous colloidal materials on the basis of experimentally obtained R_λ and T_λ characteristics associated with the spectrum of an infrared emitter makes it possible for us to analyze internal heat-exchange processes during drying and heating by infrared.

NOTATION

T_e	is the emitter temperature, °K;
t	is the temperature of the medium, °C;
I_λ	is the spectral intensity, $W/m^2 \cdot sr$;
A, R, and T	are the absorption, reflection, and transmission factors for a layer of finite thickness;
a and σ	are the absorption and effective-attenuation factors for a layer of unit thickness, mm^{-1};
q	is the resultant flux density at a depth x, W/m^2;
R_∞	is the reflective power of an optically infinite layer;
φ	is the irradiation factor;
W	is the moisture, %;
l	is the layer thickness, mm.

Subscripts

e	is the emitter;
b	is the barrier;
λ	is spectral;
ef	is effective;
i	is incident;
m	is the steam–air mixture.

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