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RADIATION TRANSPORT IN A SCATTERING MATERIAL EXPOSED TO A DIFFUSE FLUX OR ONE DIRECTED AT A CERTAIN ANGLE

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Absorbed flux densities have been calculated for a scattering material irradiated from one or both sides by a diffuse flux or a flux directed at a certain angle.

Considerable importance attaches to radiation transport in scattering material (polymer films, paint coating, textiles, paper, plant materials, etc.) on account of the need to describe heat and mass transfer during heat treatment and drying produced by diffuse or directed radiation fluxes [1-4].

To calculate the energy transport in a scattering material as affected by irradiation conditions, it is necessary to have data on the following major characteristics [1]: in diffuse irradiation, on the averaged absorption coefficients $\bar{k}_\lambda$, the effective attenuation L_λ and the two-hemisphere reflectivity of an infinitely thick layer $R_{\lambda\infty}$; with collimated radiation, one needs information on $\bar{k}_\lambda$, L_λ, $R_{\lambda\infty}$, as well as on the absorption coefficient k_λ, the extinction coefficient ε_λ, and the Dantley parameters C_1 and C_2, which incorporate the angle of incidence Θ for the collimated flux, the optimal characteristics, and the scattering indicatrix $\chi_\lambda(\gamma)$.

We have examined the scattering indicatrices of plant materials for this purpose. A scattering material has an indicatrix elongated in the forward direction [1], such as that shown in Fig. 1 for plant materials. The shape of the indicatrix can be incorporated by means of the coefficients δ_s and δ_f, which are numerically equal to the proportions of the flux scattered backwards and forwards by an elementary volume or layer on exposure to a flux in the solid angle $\omega' \leq 2\pi$ having an angular intensity distribution $B_\lambda(\Theta, \omega')$; δ_s and δ_f vary over the ranges $0 < \delta_s < 1$ and $0 < \delta_f < 1$, but the sum is always one: $\delta_s + \delta_f = 1$.

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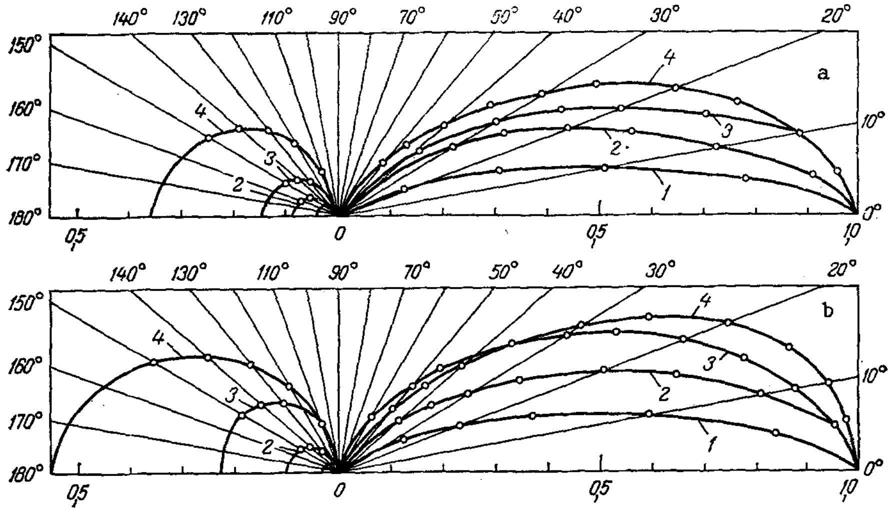

Fig. 1. Scattering indicatrices for Husayner grapes at λ = 1.1 μm (a) and λ = 0.55 μm (b): 1) peel, thickness 0.13 mm; 2-4) soft tissue with peel, thicknesses in layer 3.4, 6.5, and 10.0 mm correspondingly.

One can determine $R_{\lambda\infty}$ by experiment [1] or by graphical methods [2]; at the same time, thin layers of polymers and plant materials, paint coatings, textiles, and so on, are weakly scattering media, so it is not possible to make an optically thick layer for the purpose. Then $R_{\lambda\infty}$ is derived from nomograms from the measured R_λ and T_λ for a layer of finite thickness.

C_1 and C_2 are related to the basic and averaged optical characteristics [1] as follows:

$$C_1 = \frac{\mu s'\varepsilon_e - s'\varepsilon + \mu f's}{\varepsilon^2 - \mu^2 L^2}. \tag{1}$$

$$C_2 = \frac{\mu f'\varepsilon_e + f'\varepsilon + \mu s's}{\varepsilon^2 - \mu^2 L^2}, \tag{2}$$

where

$$\varepsilon_e = \bar{k} + s; \quad \varepsilon = k + \sigma; \quad L = \sqrt{\bar{k}\,(\bar{k} + 2s)}. \tag{3}$$

With collimated irradiation, if one knows R_λ' and T_λ' for a layer, one can derive C_1 and C_2 from the nomogram of [3], where one determines also $\bar{k}_\lambda$ and s_λ. Information on $\chi_\lambda(\gamma)$ and $B_\lambda(\Theta, \omega')$ is incorporated into $\bar{k}_\lambda$ and s_λ by means of the coefficient for the spatial distribution of the incident radiation flux m ($1 < m < \infty$) and δ_s [1]:

$$s = \delta_s \sigma m; \quad s' = \delta_s \sigma; \quad f = \delta_f \sigma m; \quad f' = \delta_f \sigma; \quad \bar{k} = mk. \tag{4}$$

The optical characteristics on diffuse illumination are derived from measurements on R_λ, T_λ, and $R_{\lambda\infty}$:

$$L_\lambda = \frac{1}{l} \ln\left(\frac{1 - R_\lambda R_{\lambda\infty}}{T_\lambda}\right), \tag{5}$$

$$\bar{k}_\lambda = \frac{1 - R_{\lambda\infty}}{1 + R_{\lambda\infty}} L_\lambda. \tag{6}$$

The extinction coefficient is given by

$$\varepsilon = \frac{1}{m}\left(\varepsilon_e + s\,\frac{\delta_f}{\delta_s}\right). \tag{7}$$

To calculate the transport of monochromatic radiation, the material can be represented as a model consisting of three absorbing and scattering layers: a shell, the material, and a shell. The boundary reflection affects the energy distribution and the radiation characteristics, which complicates the calculations considerably. To simplify calculating the absorbed energy the collimated radiation, one can take the shell as a boundary that reflects, absorbs, and transmits radiation, and one can assume that it is penetrated by radiation fluxes of density $E_1'\,T_{sh}$ and $E_2'\,T_{sh}'$.

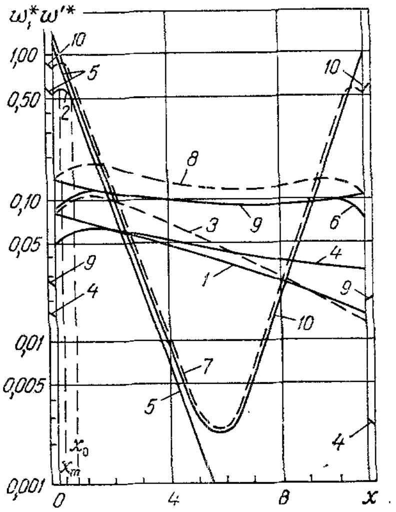

Fig. 2

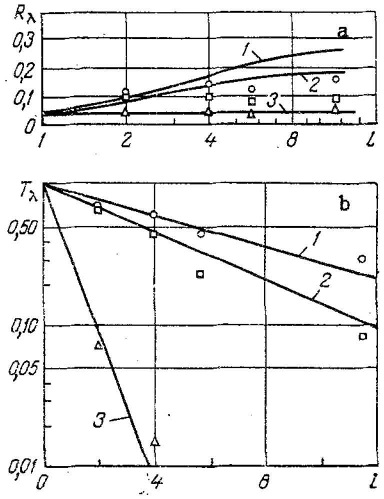

Fig. 3

Fig. 2. Distribution of the absorbed energy in an individual graph under various irradiation conditions at different wavelengths: 1-3) one-sided irradiation by a collimated flux; 4, 5) one-sided irradiation by a diffuse flux; 6-8) two-sided collimated fluxes; 9 and 10) two-sided diffuse fluxes; 1, 4, 6, and 9) λ = 1.1 μm; 2, 5, 7, 10) λ = 0.55 μm; 3 and 8) λ = 1.2 μm; w* and w'* in mm^{-1} and x in mm.

Fig. 3. Effects of layer thickness ℓ at various wavelengths on the spectral hemispherical reflectivity R_λ (a) and transmissivity T_λ (b) for wavelengths in μm of: 1) 1.1; 2) 1.2; 3) 0.55; ℓ in mm.

On two-sided irradiation by collimated beams directed at angles Θ = arc cos μ, which have densities E_I' and E_{II}', the energy absorbed by unit volume in unit time at depth x is given [1] by

$$w_\lambda'(x) = \bar{k}E_1'T_{sh}'\frac{1+R_\infty}{1-\Psi^2}\left\{C_2\left[\exp\ (-Lx) - \frac{\Psi^2}{R_\infty}\exp(Lx)\right] + \right.$$
$$+ C_1\exp\left(-\frac{\varepsilon}{\mu}\ l\right)\left[\exp[-L(l-x)] - \frac{\Psi^2}{R_\infty}\exp[L(l-x)]\right]\Bigg\} - [\bar{k}(C_1+C_2)-k]\,E_1'T_{sh}'\exp\left(-\frac{\varepsilon}{\mu}\ x\right) + \quad (8)$$
$$+\bar{k}E_2'T_{sh}'\ \frac{1+R_\infty}{1-\Psi^2}\left\{C_2\left[\exp[-L(l-x)] - \frac{\Psi^2}{R_\infty}\exp[L(l-x)]\right] + \right.$$
$$\left. + C_1\exp\left(-\frac{\varepsilon}{\mu}\ l\right)\left[\exp(-Lx) - \frac{\Psi^2}{R_\infty}\exp(Lx)\right]\right\} - [\bar{k}(C_1+C_2)-k]\,E_2'T_{sh}'\exp\left[-\frac{\varepsilon}{\mu}(l-x)\right],$$

where

$$\Psi = R_\infty\exp(-Ll). \quad (9)$$

On two-sided exposure to diffuse fluxes, the absorbed energy for an individual layer in a multilayer system is

$$w_i(x_i) = L_iE_{i,1}\frac{1-R_{\infty i}}{1-\Psi_i^2}\left[\exp(-L_ix_i) - \frac{\Psi_i^2}{R_{\infty i}}\exp(L_ix_i)\right] +$$
$$+L_iE_{i,2}\frac{1-R_{\infty i}}{1-\Psi_i^2}\left\{\exp[-L_i(l_i-x_i)] - \frac{\Psi_i^2}{R_{\infty i}}\exp[L_i(l_i-x_i)]\right\}. \quad (10)$$

The flux incident on layer i is determined with the following boundary conditions: for the first layer

$$x_1=0,\quad E_{1,1}=E_I\ , \quad (11)$$

$$x_1=l_1,\quad E_{1,2}=(E_{II}T_{3+2}+E_I\ T_1R_{2+3})\,M_{1,2+3}; \quad (12)$$

for the second

$$x_2=0, \quad E_{2,1}=(E_{\rm I}\,T_1+E_{\rm II}T_{3+2}R_1)\,M_{1,2+3}\,, \tag{13}$$

$$x_2=l_2, \quad E_{2,2}=(E_{\rm II}T_3+E_{\rm I}\,T_{1+2}R_3)\,M_{3,2+1}, \tag{14}$$

and for the third

$$x_3=0, \quad E_{3,1}=(E_{\rm I}\,T_{1+2}+E_{\rm II}T_3R_{2+1})\,M_{3,2+1}\,, \tag{15}$$

$$x_3=l_3, \quad E_{3,2}=E_{\rm II}. \tag{16}$$

If the irradiation is one-sided ($E_{II} = 0$), then (8) and (10) simplify considerably.

One derives the radiation pattern from (10) with the boundary conditions of (11)-(16) for the three-layer system by deriving the transmission and reflection with allowance for the boundary reflection by combining the layers from the formulas

$$R_{i+j}=R_i+\frac{T_i^2\,R_j}{1-R_iR_j}, \tag{17}$$

$$T_{i+j}=\frac{T_iT_j}{1-R_iR_j}, \tag{18}$$

$$M_{i,j}=\frac{1}{1-R_iR_j}. \tag{19}$$

These formulas have been used to examine R_λ' and T_λ' for the skins and flesh sections of various types of grapes (Kishmish black, Toyfi pink) in the visible and near infrared regions, 0.4-5.0 μm. The optical and thermal characteristics were calculated for points within the fruit for one-sided and two-sided unsymmetrical irradiation ($E_I/E_{II} = 1.5$) for wavelengths corresponding to the peaks in the spectra of the sun ($\lambda = 0.55$ μm) and of a KG-220-1000 IR source ($\lambda = 1.1$ μm), as well as for the absorption bands of water ($\lambda = 1.2$ μm). Two-sided exposure to diffuse or collimated fluxes (Fig. 2) produces more uniform heating than one-sided exposure. With collimated radiation, the energy absorbed per unit time attains its maximum at a certain depth x_m, while with diffuse irradiation, the maximum absorption occurs in the surface layer at $x = 0$. For x larger than a certain x_0, the x dependence of w' and w is much the same for the various irradiation conditions (curves 5 and 2). On the other hand, the relationships differ for $x < x_0$. The absorption peak with collimated radiation is due to differences in the absorption coefficients for the collimated and scattered fluxes: $\bar{k}$ is greater than k by a factor m.

To check this model for w', we measured R_λ' and T_λ' for layers of various thicknesses made up of grapes and compared the values with those given as functions of layer thickness by the formulas [1]

$$R_\lambda'=C_2R_\lambda-C_1(1-T_{\lambda B}'T_\lambda), \tag{20}$$

$$T_\lambda'=C_2T_\lambda+T_{\lambda B}'(1+C_1R_\lambda-C_2), \tag{21}$$

where

$$R_\lambda=R_{\lambda\infty}\frac{1-\exp(-2L_\lambda l)}{1-R_{\lambda\infty}^2\exp(-2L_\lambda l)}; \tag{22}$$

$$T_\lambda=\frac{(1-R_{\lambda\infty}^2)\exp(-L_\lambda l)}{1-R_{\lambda\infty}^2\exp(-2L_\lambda l)}; \tag{23}$$

$$T_{\lambda B}'=\exp(-\varepsilon_\lambda l). \tag{24}$$

Figure 3 shows that R_λ' and T_λ' given by (20)-(24) differ by 1-7% from the measurements, which shows that the method is quite accurate.

NOTATION

k_λ, σ_λ, absorption and scattering factors, 1/m; $\chi_\lambda(\gamma)$, scattering indicatrix; $\bar{k}_\lambda$, f_λ, s_λ, averaged absorption and forward and backward scattering factors, 1/m; R_λ, T_λ, reflecting and transmitting powers of a plane layer with thickness ℓ; $R_{\lambda\infty}$, reflecting power of optically infinitely thick layer; ε_λ, extinction factor; Θ, angle of incidence; E_λ, density of diffuse and E_λ', density of monochromatic radiant flux falling on layer at angle Θ, W/m²; $w'^* = w'/E_\lambda'$ and $w^* = w/E_\lambda$, relative absorbed flux densities for directed irradiation w'^* and diffuse w^*.

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INTEGRAL HEMISPHERICAL ABSORPTIVITIES OF METALS AT 4.2-293°K

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UDC 536.3

On the basis of experimental data the authors obtained an empirical formula enabling them to determine the integral absorptivity of metal with an optically smooth surface from the magnitude of its electrical resistivity.

The most effective types of protection of cryogenic equipment operating in the temperature range 4.2-293°K against heat influx from the environment are high-vacuum and vacuum-multilayer heat insulation. The former is an evacuated space between heat-exchanging surfaces which reflects well thermal (infrared) radiation, the latter is a set of reflecting screens placed in such a space and divided by heat-insulating distance packings. The screens in vacuum-multilayer insulation are various foils and metallized polymer films with high reflectivity of the surface.

For the calculation of radiative heat exchange in such systems it is indispensable to know the integral hemispherical absorptivities (relative to heat radiation) of the metallic surfaces. The dependence of the above parameter, especially at lower temperatures, on a number of factors including technological ones makes it difficult to find reliably the theoretical values of the absorptivity of real surfaces. The experimental study of the optical properties of metals is therefore of great practical interest.

The published experimental data on the optical properties of metals at low temperatures [1-4] are very limited, often contradictory, and it is difficult to compare them with each other because of lack of information on the technology of preparing the specimens.

The present work involved the experimental investigation of the absorptivities of metals including those used as screen materials and for coatings reflecting heat radiation, in the temperature range 4.2-293°K.

At 293°K the measurements were carried out by the radiation method with the use of a thermoradiometer marque TIS. The operating principle of the instrument is based on the use of the method of comparison where the absorptivity of the investigated surface is compared with the known absorptivity of a standard. The maximal error of measurement was 25% with an absorptivity $A = 0.02\text{-}0.025$, and it decreased with increasing A.

Measurements at low temperatures were carried out by the calorimetric method in an experimental vessel whose diagram is shown in Fig. 1. The vessel has an inner spherical cavity 1 with a capacity of 10 liters, and on its outer surface the investigated specimen is applied. Cavity 1 is surrounded by copper screen 2 which is cooled by a cryogenic liquid

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