HEAT AND MASS TRANSFER AND ENERGY TRANSPORT OF INTEGRAL RADIATION IN LIGHT-SCATTERING MATERIALS DURING EXPOSURE TO DIFFUSE AND DIRECTIONAL FLUXES

S. G. Il'yasov, N. I. Angersbakh, and A. K. Angersbakh

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Regularities are established for changes in the layer of of integrated quantities of the resultant flux density, the spatial irradiance, and the absorbed energy for solar and IR-generator KGT-220-100 radiation. Dependences of the integrated radiation flux absorption, scattering, and attenuation coefficients on the coordinate are determined. The possibility is shown of approximating the complex integrated function of the internal heat sources due to radiation absorption by a simplified exponential dependence that permits solution of the heat transfer problem top be obtained.

The heat transfer process in light-scattering materials (polymer films, paint and varnish coatings, textiles, paper, plant materials, etc.) during heat tratment and drying by solar and IR radiation occurs upon exposure to mixed diffuse and directional fluxes at a certain angle. The specific features of heat transfer are associated with penetration of solar and IR radiation in the material, acting on the structure of the substance, intensifying biochemical processes, and phase transformations and substantially influences the nature of the temperature and moisture-content field distributions [1-4].

The function of the internal heat sources due to absorption of penetrating radiation [1, 3, 4] must be known to solve heat conduction problems. Selectivity of the optical properties and multiple scattering effects on the optical inhomogeneities of the material specify a change of the radiation spectral composition and the mean integrated absorption $\bar{k}$, back-scattering s, and effective attenuation L coefficients in the coordinate [1].

Integration over the incident diffuse flux spectrum permits determination of the integrated magnitude of the absorbed radiation energy flux [1]:

$$w(x) = \int_{\lambda_1}^{\lambda_2} w_\lambda(x)\, d\lambda = \bar{k}(x)\, E_0(x), \tag{1}$$

where the magnitude of the integrated spatial irradiance is

$$E_0(x) = \int_{\lambda_1}^{\lambda_2} E_{\lambda 0}(x)\, d\lambda = \int_{\lambda_1}^{\lambda_2} E_{\lambda 1} \frac{1 + R_{\lambda\infty}}{1 - \Psi_\lambda^2} \Big[\exp(-L_\lambda x) - \frac{\Psi_\lambda^2}{R_{\lambda\infty}} \exp(L_\lambda x) \Big] d\lambda + \int_{\lambda_1}^{\lambda_2} E_{\lambda 2} \frac{1 + R_{\lambda\infty}}{1 - \Psi_\lambda^2} \Big[\exp[-L_\lambda(l - x)] - \frac{\Psi_\lambda^2}{R_{\lambda\infty}} \exp[L_\lambda(l - x)] \Big] d\lambda. \tag{2}$$

The dependence of the mean integrated absorption coefficient $\bar{k}(x)$ on the coordinate x is determined by taking the average of the total radiation flux over the spectrum of the spatial irradiance spectrum

$$\bar{k}(x) = \Big[\int_{\lambda_1}^{\lambda_2} E_{\lambda 0}(x)\, \bar{k}_\lambda d\lambda\Big]\Big[\int_{\lambda_1}^{\lambda_2} E_{\lambda 0}(x)\, d\lambda\Big]^{-1}. \tag{3}$$

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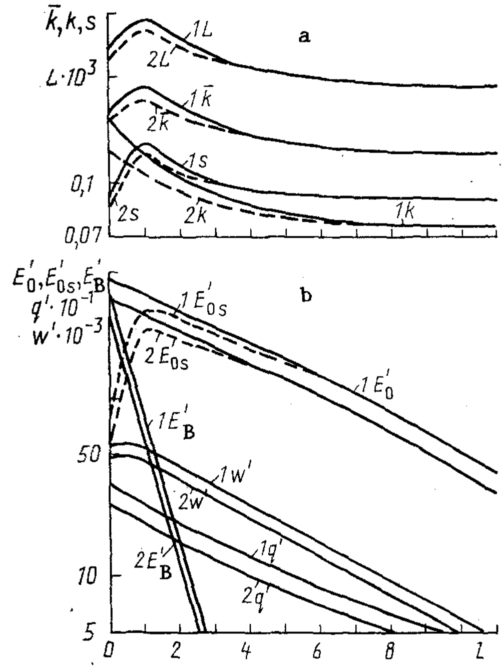

Fig. 1. Distribution of the integrated optical characteristics (a) and the radiation field characteristics (b) in a grape berry layer under unilateral directional exposure to solar radiation for different atmospheric masses m: 1) m = 1; 2) 2. $\bar{k}$, k, s, L, m^{-1}; E'_0, E'_{0S}, E'_B, q', W/m²; w', W/m³; ℓ, mm.

The analytic dependence (1)-(3) can be utilized to compute the integrated characteristics under exposure to diffuse flux. However, the spatial structure of IR generator and solar radiation fluxes is mixed, diffuse and directional. In this connection the necessity occurs to take into account separately the directional $E'_B(x)$ and diffuse $E'_{0S}(x)$ components of the spatial irradiance at the depth x.

The integrated magnitude of the absorbed radiation energy flux equals [1]

$$w'(x) = \int_{\lambda_1}^{\lambda_2} w'_\lambda(x)\,d\lambda = \bar{k}(x)\,E'_{0S}(x) + k(x)\,E'_B(x). \tag{4}$$

The quantities in (4) equal [1]

a) for the scattered diffuse component of spatial irradiance

$$E'_{0S}(x) = \int_{\lambda_1}^{\lambda_2} E'_{\lambda 0S}(x)\,d\lambda = \int_{\lambda_1}^{\lambda_2} \Bigg[E'_{\lambda 1} T_{\lambda 0} \frac{1+R_{\lambda\infty}}{1-\Psi_\lambda^2} \Bigg\{ C_{\lambda 2} \Big[\exp(-L_\lambda x) - \frac{\Psi_\lambda^2}{R_{\lambda\infty}} \exp(L_\lambda x) \Big] + C_{\lambda 1} \exp\Big(-\frac{\varepsilon_\lambda}{\mu} l\Big) \Big[\exp[-L_\lambda(l-x)] - \frac{\Psi_\lambda^2}{R_{\lambda\infty}} \exp[L_\lambda(l-x)] \Big] \Bigg\} - E'_{\lambda 1} T_{\lambda 0} (C_{\lambda 1} + C_{\lambda 2}) \exp\Big(-\frac{\varepsilon_\lambda}{\mu} x\Big) + E'_{\lambda 2} T_{\lambda 0} \frac{1+R_{\lambda\infty}}{1-\Psi_\lambda^2} \Bigg\{ C_{\lambda 2} \Big[\exp[-L_\lambda(l-x)] - \frac{\Psi_\lambda^2}{R_{\lambda\infty}} \exp[L_\lambda(l-x)] \Big] + C_{\lambda 1} \exp\Big(-\frac{\varepsilon_\lambda}{\mu} l\Big) \Big[\exp(-L_\lambda x) - \frac{\Psi_\lambda^2}{R_{\lambda\infty}} \exp[L_\lambda x] \Big] \Bigg\} - E'_{\lambda 2} T_{\lambda 0} (C_{\lambda 1} + C_{\lambda 2}) \exp\Big[-\frac{\varepsilon_\lambda}{\mu}(l-x)\Big] \Bigg] d\lambda, \tag{5}$$

$$\bar{k}(x) = \Big[\int_{\lambda_1}^{\lambda_2} E'_{\lambda 0S}(x)\,\bar{k}_\lambda d\lambda \Big] \Big[\int_{\lambda_1}^{\lambda_2} E'_{\lambda 0S}(x)\,d\lambda \Big]^{-1}; \tag{6}$$

b) For the directional flux component

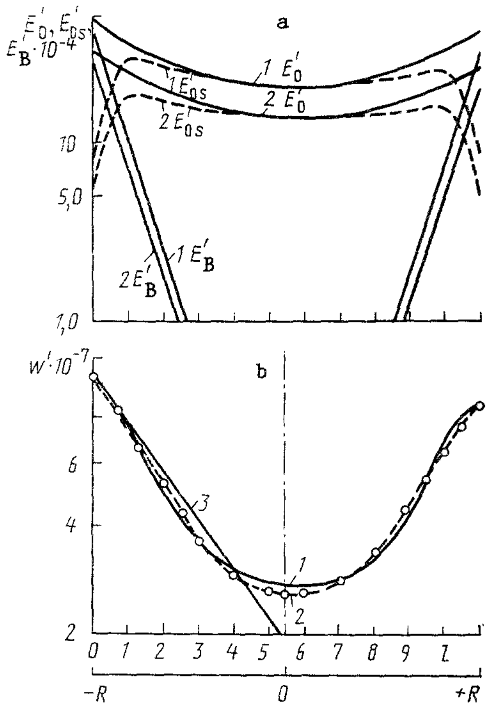

Fig. 2. Distribution of the spatial irradiance (a) and the absorbed radiation energy flux: (b) in a grape berry layer under bilateral directional exposure to KGT-200-1000 lamps: a: 1) T = 2600 K; 2) 2400; b: 1, 2, 3,) T = 2600 K; 1) integration over the spectrum (formula (4)); 2, 3) over the approximating function (formulas (13) and (10)).

$$E_B'(x)=\int_{\lambda_1}^{\lambda_2}E_{\lambda B}'(x)\,d\lambda=\int_{\lambda_1}^{\lambda_2}\left[E_{\lambda 1}'T_{\lambda 0}\exp\left(-\frac{\varepsilon_\lambda}{\mu}x\right)+E_{\lambda 2}'T_{\lambda 0}\exp\left[-\frac{\varepsilon_\lambda}{\mu}(l-x)\right]\right]d\lambda, \tag{7}$$

$$k(x)=\left[\int_{\lambda_1}^{\lambda_2}E_{\lambda B}'(x)\,k_\lambda d\lambda\right]\left[\int_{\lambda_1}^{\lambda_2}E_{\lambda B}(x)\,d\lambda\right]^{-1}. \tag{8}$$

Integrated optical characteristics and radiation field characteristics in a layer of a typical colloidal capillary-porous light-scattering material, grape berries under exposure to solar (for atmospheric masseds m = 1 and m = 2) and IR radiation (KGT-220-1000 for T = 2400 and 2600 K).

In order to simplify the computations during the integration of the sufficiently complex spectral functions (1)-(8) over the radiation spectrum bounded by the wavelength interval $\lambda_1-\lambda_2$ taken, the integration is replaced by summation with a finite spectrum step $\Delta\lambda$ equal to 0.05 μm. The case of energy transport under unilateral exposure conditions $E_2 = 0$ is examined for solar radiation and under bilateral nonsymmetric exposure $E_2 = 0.8E_1$ in the case of the IR generator KGT-220-1000.

It is established (Fig. 1a) that the integrated optical characteristics of the material change with the coordinate x within the layer. Their magnitudes reach maximal values here at a certain depth x = 1 mm. Analysis of the characteristics w', E_0', E_{0S}', E_B' (Fig. 1b, 2a) shows that under bilateral exposure heating of a layer of light-scattering material occurs more uniformly as compared with unilateral exposure ($E_0' = E_{0S}' + E_B'$). Moreover, for a higher IR generator spiral temperature (T = 2600 K) the material layer is heated better and the main fraction of radiation is absorbed in the surface layer.

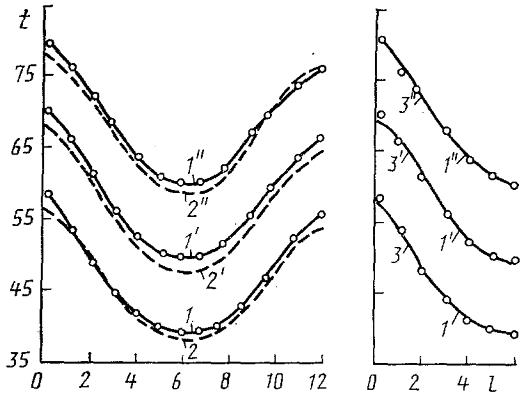

Fig. 3. Comparison of experimental and computed data of the temperature distribution in a grape berry layer under IR exposure at different times: 1, 2, 3) τ = 30 sec; 1', 2', 3') 45; 1", 2", 3") 60; 1, 1', 1") average experimental; 2, 2', 2") computed by formula (34) p. 334 in [3]; 3, 3', 3") computed by formula (15).

It is expedient to use the Lykov–Mikhailov solution of the heat conduction equation with an internal heat source described by on exponential function [3, 4]

$$\mathrm{Po}(X,\ \mathrm{Fo}) = \mathrm{Po_c}\exp(-KX), \tag{9}$$

where $K = L\mathcal{R}$, $\mathcal{R} = l/2$ when describing the heat and mass transfer process for the solar and IR radiation exposure case under consideration.

Meanwhile, the integrated functionsl (1)-(8) obtained that describe the internal heat source distribution w(x) due to absorption of IR radiation from the selected generator that penetrates the material layer, include up to 12 components and have a sufficiently complex form. In this connection, it is proposed to approximate the exact integrated distribution function of the adsorbed radiation energy flux w(x) by using one exponential (Fig. 2, curve 3) of the form

$$w(x) = E_{\mathrm{p}}L\frac{1-R_\infty}{1+\Psi}\exp(-Lx)\quad(0<x<0.5l). \tag{10}$$

in order to apply the known solution [3, 4].

In this case the relationship for the Pomerantsev criterion [4] takes the form

$$\mathrm{Po} = \mathrm{Po_c}\exp(-Lx), \tag{11}$$

where

$$\mathrm{Po_c} = \frac{E_{\mathrm{p}}(1-R_\infty)L\mathcal{R}^2}{\lambda t_0[1-R_\infty\exp(-Ll)]}. \tag{12}$$

It is seen form Fig. 2b that the relative error of the proposed approximation of the function w(x) is 16% in the interval 0 < x < 5 mm according to (10), and reaches 28% at the center of the layer.

The following approximating function (Fig. 2b, curve 2)

$$w(x) = E_{\mathrm{p}}L_1\frac{1-R_\infty}{1+\Psi}\{\exp(-L_1x)+\exp[-L_1(l-x)]\},\quad 0<x<l \tag{13}$$

is proposed for a more accurate description of the heat transfer under bilateral directional irradiation of a layer of finite thickness.

The relative error of the approximation of the quantity w(y) according to (13) does not exceed 5%, which is sufficient for engineering computations (Fig. 2b).

Taking account of (13) the Pomerantsev criterion takes the form

$$\mathrm{Po}(X,\ \mathrm{Fo}) = \mathrm{Po_c}\{\exp(-KX) + \exp[-K(2-X)]\}. \quad (14)$$

The solution of the heat conduction equation for an unbounded plate of thickness $2\mathscr{R}$ under boundary conditions of the second kind is obtained for the internal heat source function w(x) in (13) by the method of [3]:

$$\Theta(X,\ \mathrm{Fo}) = \mathrm{Ki}\left[\mathrm{Fo} - \frac{1}{6}(1-3X^2) - \sum_{n=1}^{\infty}(-1)^n \frac{2}{\mu_n^2}\cos\mu_n X \exp(-\mu_n^2 \mathrm{Fo})\right] + \mathrm{Po_c}[1-\exp(-2K)] \times \left\{\frac{\mathrm{Fo}}{K} + \sum_{n=1}^{\infty}\frac{2K\cos\mu_n X}{(\mu_n^2+K^2)\mu_n^2}[1-\exp(-\mu_n^2\mathrm{Fo})]\right\}, \quad (15)$$

where $\Theta = (t - t_0)/t_0$, $\mu_n = n\pi$ (n = 1, 2, 3, ...).

Temperature fields (Fig. 3) were computed on an electronic computer to compare the efficiency of the proposed approximations and the solutions obtained by (10), (13), and (15). It is established that the solution (15) agrees most accurately with the experimental data. Meanwhile, an internal source function with one exponential (10) that permits direct utilization of the known solution [3] can be used to simplify engineering computations.

NOTATION

L, $\bar{k}$, s, ε are optical characteristics, the effective attenuation, absorption, "back" scattering, and extinction factors, m^{-1}, C_1 and C_2 are Dantley parameters, E_λ is the density of diffuse, and E'_λ, the density of directional monochromatic radiation flux incident at a certain angle Θ, W/m^2, w' and w is the magnitude of the absorbed radiation energy flux under directional and diffuse exposure, W/m^3, E'_B and E'_{0S} are magnitudes of the directional and diffuse components of spatial irradiance E'_0, W/m^2.

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