

STRESS STATE IN GLASS BODIES DEGASSED UNDER HEATING BY INFRARED RADIATION

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A model is proposed to calculate stresses in a glass layer with gas impurities heated by thermal infrared radiation. Calculations were performed for a layer with a diatomic impurity of nitric oxide and a triatomic impurity of water. It is shown that for the radiation parameters and impurity concentrations considered, the presence of nitric oxide in the layer does not influence its stress state, whereas the presence of water leads to a certain increase of stress. The stress state of the layer is determined by the level of thermal stresses, and the concentration stresses and the stresses due to the mass forces of radiation are negligible. An increase in the rate of diffusion of the diatomic impurity due to a change of the radiation spectrum is accompanied by an increase of thermal stresses.

Introduction. The production of “pure” glass materials without gas impurities is an important technological problem of the electronic industry. It arises, in particular, in the production of electron-beam tubes, vacuum tubes, light guides, and other devices whose elements are made of glass [1, 2]. Various gas impurities in the molecular state, in particular, H₂O, CO, N₂, CO₂, H₂, etc., can be dissolved in glass [2–4]. These impurities result from both the manufacture of glass and adsorption from the ambient gas and diffusion into the material. Degassing of the glass units of the indicated devices is carried out by convective heating [4, 5]. This degassing method is based on a considerable increase in diffusion flows of a gas impurity in glass under an increase in the diffusion coefficient of the impurity $D(T) = D_0 \exp(-U_{\text{act}}/(RT))$ (D_0 is the preexponent, U_{act} is the activation energy of diffusion, and R is the universal gas constant) with rise in temperature T . Therefore, for high-quality degassing of glass, i.e., removal of gas impurities from deep layers, glass should be heated to the maximum possible temperature (determined by the temperature of transformation of glass [2], which usually does not exceed 700 K) and then held at this temperature for a time. Since the heating rate of glass elements is limited because of the high temperature stresses arising from convective heating, [5], the degassing process is lengthy and requires considerable expenditures of energy.

The possibility of increasing the unit capacity and decreasing energy expenditures in degassing electron-beam tubes has been studied theoretically and in experiments on heating their glass shells by thermal infrared radiation produced by conventional sources with various power and spectral characteristics. In particular, distributions of temperature and stress-tensor components in a glass shell heated by radiation from KG 220-1000-6 tubes were studied. Optimal (in thermal stress) combined modes of radiant-convective heating of glass shells that ensure the maximum possible heating temperature at smaller power inputs were proposed [5, 6]. Experiments showed that under radiant heating of glass shells, gas release from the glass increases considerably [6]. The indicated increase cannot be explained only by the above-mentioned temperature dependence of the diffusion coefficient of gas impurities but it is also a result of the special effect of radiation on the impurity (referred to as photo-stimulated diffusion in the literature [7]). The increase of gas release is due to the volumetric nature of infrared radiation absorption by translucent materials and due to an increase in the energy of diffusing impurity particles as a result of intense radiation absorption in definite spectral regions, in particular, in the infrared region, which contains typical absorption frequencies of gas molecules. Thus, to design rational modes of degassing for bodies made of glass materials using thermal infrared radiation, it is necessary to study the effect of heat-transfer process

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on the gas impurity concentration and glass deformation taking into account the dependence of the parameters of these processes on the external radiation spectrum, the amount and type of gas impurities, and conditions of heat and mass exchanger with the ambient medium.

1. Mathematical Model of Mechanothermodiffusion Processes in a Translucent Body with Gas Impurities on Exposure to Thermal Irradiation. We use the model proposed in [8–10] for a quantitative description of mechanothermodiffusion processes in translucent multicomponent solids (solid mixtures) exposed to external infrared electromagnetic radiation, which is based on the phenomenological theory of radiation and the continual thermodynamic theory of solid mixtures. The model assumes that the processes occurring in a solid are caused by heat release (due to absorption and radiation of electromagnetic energy by its components) and the ponderomotive (mechanical) forces of radiation effect on individual components. The energy state of the components is described by introducing additional parameters — the specific energies of the components — for which balance equations are formulated and a procedure of approximate solution is developed.

Let us consider a glass body which contains N gas impurities. The body (solid mixture) consists of the main material (skeleton) and impurity atoms and molecules diffusing in it. The term of “gas impurity” means that in the natural state, the particles of a particular impurity form the corresponding gas. Displacements and strains of mass points of a glass body are related to displacements and strains of mass points of the skeleton, whose rate of motion is chosen as the characteristic one. At an arbitrary time t , the impurities are distributed in the bulk of the body with densities $\rho_k(\mathbf{r}, t)$ and concentrations $c_k(\mathbf{r}, t) = \rho_k(\mathbf{r}, t)/\rho(\mathbf{r}, t)$. Here $\rho = \sum_{k=1}^N \rho_k + \rho^m$ is the density of the body, $\rho^m(\mathbf{r}, t)$ is the density of the skeleton, and $\sum_{k=1}^N c_k + \frac{\rho^m}{\rho} = 1$. Let the glass body considered be exposed to external infrared radiation, which is specified in the ambient medium by the spectral intensity $I_\lambda^{\text{ext}}(\mathbf{r}, \mathbf{s}_0)$. For thermal radiation, this intensity is proportional to the spectral radiation intensity of an ideal black body $I_{\lambda b}(\lambda, T_s)$ at the temperature T_s of the radiation source [11, 12]:

$$I_\lambda^{\text{ext}}(\mathbf{r}, \mathbf{s}_0) = f_\lambda(\mathbf{r}, \mathbf{s}_0) I_{\lambda b}(\lambda, T_s).$$

Here \mathbf{r} is the radius-vector, \mathbf{s}_0 is the unit vector in the direction of beam propagation, λ is the wavelength, and $f_\lambda(\mathbf{r}, \mathbf{s}_0)$ is a proportionality constant, which depends on the position of the real radiation source relative to the body and its energy and spectral characteristics. Let us assume that the material of the examined glass body does not scatter the radiation and piezo- and electrooptical effects can be ignored. Then, radiation transport in the body (in the temperature range of interest $300 \text{ K} < T < 700 \text{ K}$) can be described by the following quasistationary transport equation in the approximation of a nonradiating material [11]:

$$\frac{\partial I_\lambda(\mathbf{r}, \mathbf{s}_0)}{\partial s} + a_\lambda(c_1, \dots, c_N) I_\lambda(\mathbf{r}, \mathbf{s}_0) = 0. \quad (1.1)$$

Here $I_\lambda(\mathbf{r}, \mathbf{s}_0)$ is the spectral radiation intensity in the body, s is the distance along the beam, and $a_\lambda(c_1, \dots, c_N)$ is the spectral absorption coefficient, which depends on the impurity concentration at a given point of the body. It should be noted that the reference literature, as a rule, gives values of this coefficient for pure glasses. From the physical meaning of the absorption coefficient (which characterizes radiation attenuation in the body as a function of the number of absorption centers [13]) taking into account well-known experimental results on spectroscopy of glasses with gas impurities, which indicate that absorption properties typical of gases are preserved in glass, for the absorption coefficient of the mixture considered, we obtain the expression

$$a_\lambda = a_\lambda^m + \sum_{k=1}^N a_\lambda^k,$$

where a_λ^m and a_λ^k are the spectral absorption coefficients of the skeleton and the k th gas impurity in the glass body. Here and below, the superscript m corresponds to the characteristics of the skeleton.

To determine the quantities a_λ^m and a_λ^k , we consider features of radiation absorption by the glass components. Solids absorb radiation practically over the entire spectrum. Therefore, the absorption coefficient of the skeleton is usually represented as a piecewise constant function: $a_\lambda^m = a_1$ for $0 \leq \lambda \leq \lambda_c$ and $a_\lambda^m = a_2$ for $\lambda_c < \lambda \leq \infty$ (λ_c is the threshold wavelength) [14]. The coefficient of radiation absorption by structural particles (atoms, molecules, ions) is determined primarily by internal processes occurring in them during interaction with radiation and by the

amount of particles. The effect of the surrounding (particles can enter in the composition of the gas, a mixture of gases or a solid body) on values of the absorption coefficient is taken into account by a correction calculated using relevant models of spectroscopy [11, 13, 15].

Molecular (atomic) gases absorb radiation in narrow segments of the spectrum — bands (lines). The number of absorption bands n_k for the k th gas is determined by the number of atoms in its molecule. The absorption coefficient of the k th gas in a band l can be expressed in terms of well-known characteristics of bands by the formula [13] $a_{\lambda_l}^k = J_l^k / \Delta\lambda_l^{k(\text{eff})}$, where J_l^k is the band intensity and $\Delta\lambda_l^{k(\text{eff})}$ is its effective width. Within the framework of the exponential wide-band model [13, 15], the indicated characteristics can be calculated for a constituent gas of a gas mixture at various temperatures and pressures. For gas impurities in solids, such models are not available. However, taking into account collisions, described by hydrostatic or phonon pressure, the relations of the exponential wide-band model can be used to calculate the absorption characteristics of gas particles in a solid. Because of the linear dependence of the absorption coefficient of a gas on its density, the absorption coefficient of a gas impurity as a component of a multicomponent body can be written as $a_{\lambda_*}^k = a_{\lambda_*, \text{atm}}^k c_k$, where $a_{\lambda_*}^k = a_{\lambda_*, \text{atm}}^k \rho / \rho_{\text{atm}}^k$ ($a_{\lambda_*, \text{atm}}^k$ and ρ_{atm}^k are the absorption coefficient and density of the gas particles at atmospheric pressure, respectively). Thus, the absorption coefficient of glass under irradiation is written as

$$a_{\lambda} = a_{\lambda}^m + \sum_{k=1}^N a_{\lambda_*}^k c_k. \quad (1.2)$$

From the equations of energy balance and radiation momentum [11, 16], we determine the volume densities of heat release

$$Q(\mathbf{r}) = \int_0^{\infty} a_{\lambda}(c_1, \dots, c_N) \left(\int_{\Omega=4\pi} I_{\lambda}(\mathbf{r}, \mathbf{s}_0) d\Omega \right) d\lambda \quad (1.3)$$

and the ponderomotive forces

$$\mathbf{F}(\mathbf{r}) = \frac{1}{c_0} \int_0^{\infty} a_{\lambda}(c_1, \dots, c_N) \left(\int_{\Omega=4\pi} I_{\lambda}(\mathbf{r}, \mathbf{s}_0) \mathbf{n}_{\Omega} d\Omega \right) d\lambda \quad (1.4)$$

in glass. Here Ω is the solid angle and c_0 is the electrodynamic constant. In the continual model of a solid mixture, the magnitudes of volume heat releases and forces in the body are related to similar quantities Q_k and \mathbf{f}_k calculated per unit mass of the components by the relations

$$Q = \rho \left((1-c)Q^m + \sum_{k=1}^N c_k Q_k \right), \quad \mathbf{F} = \rho \left((1-c)\mathbf{f}^m + \sum_{k=1}^N c_k \mathbf{f}_k \right), \quad (1.5)$$

where $c = \sum_{k=1}^N c_k$. Using relations (1.3)–(1.5) and representation (1.2) for the absorption coefficient, we obtain expressions for the specific (per unit mass) densities Q_k and Q^m of the energy absorbed by the impurities and the skeleton and the ponderomotive forces \mathbf{f}_k and \mathbf{f}^m of radiation effects on the impurity and the skeleton, respectively.

To describe the diffusion of gas impurities in glass, we use the equations of mass balance for the components of a solid mixture. Then, in the absence of chemical reactions in glass, for the gas components we obtain the equations

$$\rho \frac{\partial c_k}{\partial t} = -\text{div } \mathbf{J}^k, \quad (1.6)$$

which relate the mass flow of the k th gas around the skeleton \mathbf{J}^k to the change of its concentration. According to the model of diffusion under irradiation proposed in [9, 10, 17], we assume that transport of the gas impurity is due to the following:

(a) nonuniform distribution of the impurity concentration

$$\mathbf{J}_c^k = -\rho D_c^r(E^k) \text{grad } c_k, \quad (1.7)$$

where $D_c^r(E^k) = D_k(T) \exp[U_{\text{act}}^k / (RT(1 - RT/E^k))]$ is the diffusion coefficient under irradiation, $E^k(\mathbf{r}, t)$ is the mean energy of 1 mole of the k th gas which absorbs radiation, whose value is larger than the mean energy RT of thermal oscillations in the body;

(b) nonuniform temperature distribution in the body (thermal diffusion) and the corresponding thermal-diffusion flux

$$\mathbf{J}_T^k = -\rho D_k^r (\alpha_k^T/T) \text{grad } T,$$

where α_k^T is the thermal-diffusion ratio for the k th impurity;

(c) the action of ponderomotive forces on the impurity (“forced diffusion”) and the corresponding flux

$$\mathbf{J}_f^k = -(\rho D_k^r (E^k)/E^k) M_k M^m c_k c^m (c_k/M_k + c^m/M^m) (\mathbf{f}_k - \mathbf{f}^m),$$

where M^m and M_k are the molecular masses of the skeleton and the impurity.

Substituting relation (1.7) into Eq. (1.6), we obtain diffusion equations for the gas impurities in the glass body under infrared irradiation.

Using the equation of the energy E^k of the k th impurity and modeling the interaction of gas impurity with external radiation by collisions with photons and the interaction of the impurity with the skeleton by collisions with phonons, and employing the theory of random walks (jumps) of diffusing impurity particles between nodes of the skeleton [20], Gachkevich et al. [17–19] obtained the following approximate expressions for E^k :

$$E^k(\mathbf{r}, t) = \begin{cases} (Q_k(\mathbf{r}, t)/\gamma_0)t + RT_0(\mathbf{r}) & \text{for } L_k(\mathbf{r}, t) \gg 1, \\ RT(\mathbf{r}, t) & \text{for } L_k(\mathbf{r}, t) \leq 1. \end{cases} \quad (1.8)$$

Here

$$L_k(\mathbf{r}, t) = \sum_{l=1}^{N_k} \frac{I_{\lambda_l^k}(\mathbf{r}, t) \Delta \lambda_l^{k(\text{eff})} d_k^2}{\hbar \omega_l^k p_k} = \frac{N_k^{pt}(\mathbf{r}, t) d_k^2}{p_k}, \quad (1.9)$$

where $I_{\lambda_l^k}(\mathbf{r}, t)$ is the radiation intensity at a given point of the body at a frequency ω_l^k of the l th absorption band of the k th gas impurity, $\omega = 2\pi v/\lambda$, v is the rate of radiation propagation in the examined material, \hbar is the Planck constant, d_k is the molecular diameter of the k th gas, p_k is the frequency of interaction of molecules of the k th impurity with phonons, which is set equal to the frequency of their diffusion jumps, N_k^{pt} is the number of absorption bands of the k th gas, and γ_0 is a coefficient. The accumulation of energy by an impurity, i.e., an increase in the value of E^k continues until the energy absorbed by the impurity becomes equal to the energy dispersed in thermal oscillations of the skeleton (or until the frequencies of photon and phonon interactions become equal) [17, 18]. Therefore, the maximum value of E^k that can be determined from relations (1.8) and (1.9) should satisfy the condition

$$N_k^{pt} d_k^2 = (D_{0k}/(z_k l_k^2)) \exp(-U_{\text{act}}^k/E^k),$$

where l_k is the length of a diffusion jump of particles of the k th impurity, determined by the average distance between the nodes in the skeleton and z_k is a geometrical coefficient that depends on the structure of the skeleton and the number of possible equivalent positions for the jump [20, 21]. Because the values of l_k and z_k differ little for different types of glass, the values of E^k are determined by the known experimental characteristics D_{0k} and U_{act}^k .

The equations of radiation transport (1.1) and diffusion of the gas impurity (1.6) and the relations for the energy of the impurity E^k (1.8) and (1.9) together with the equations of quasistatic thermoelasticity [22] (in which the quantities Q and \mathbf{F} are volume sources of heat and volume forces) and constitutive relations for a linear thermoelastic body with impurities [23, 24]

$$\sigma_{ij} = 2G\varepsilon_{ij} + \left[\left(K - \frac{2}{3}G \right) e - K \left(\alpha(T - T_0) + \sum_{k=1}^N \beta_k (c_k - c_{0k}) \right) \right] \delta_{ij}$$

(σ_{ij} and ε_{ij} are the stress- and strain-tensor components, $e = \varepsilon_{\alpha\alpha}$, K and G are elastic constants, α and β_k are the thermal- and concentration-expansion coefficients, and δ_{ij} is the Kronecker delta) form a complete system of equations describing the heating and deformation of a glass body and diffusion of gas impurities in it on exposure to thermal infrared irradiation. The indicated equations are supplemented by boundary and initial conditions. The initial conditions specify the temperature distribution $T_0(\mathbf{r})$ and the impurity concentration $c_{0k}(\mathbf{r})$ at the initial time.

The radiation boundary conditions are formulated using the balance of all radiation fluxes delivered to the body surface (including those rereflected inside it) [12]. These conditions relate the radiation intensity on the surface to the given intensity of the thermal radiation source in the ambient medium $I_{\lambda}^{\text{ext}}(\mathbf{r}, \mathbf{s}_0)$ for known spectral

reflectivity R_λ and refractive index n_λ . Thermal boundary conditions are formulated with allowance for conditions of heat exchange between the glass body and the ambient medium. These conditions have the form of known thermal conditions of the first, second, and third kind. Accurate boundary conditions of mass transfer are obtained from the balance of fluxes of the gas impurity on the body surface [3] and allow for the adsorption and desorption of gases. However, these conditions can be replaced by the Newton mass-transfer conditions

$$\mathbf{J}^k \cdot \mathbf{n} = \bar{\beta}_k (c_k - c_k^*),$$

where \mathbf{n} is the outward normal to the surface of the glass body, $\bar{\beta}_k$ is a known constant expressed in terms of the characteristics of the ambient medium and the body surface, and c_k^* is a quantity that depends on the concentration of the k th impurity in the ambient medium. Under conditions of evacuation of gases, low pressure occurs in the ambient gas medium, which can be treated as vacuum. Then, on the part of the body surface in contact with vacuum, we set $c_k^* = 0$. It is assumed that on this surface, heat insulation conditions are satisfied because of small convection fluxes [6].

The formulation of mechanical boundary conditions on the surface of the glass body depends on the method of fastening the body and the external loads applied.

2. Numerical Calculations. We consider an infinite glass layer of thickness h_0 which contains impurities of nitrogen oxide (NO) and water (H₂O) (distributed uniformly over the layer thickness with concentrations c_{01} and c_{02} at the initial time $t = 0$) and is exposed to the thermal infrared radiation generated by a plane surface (plane) which is parallel to the layer and heated to a temperature T_s . The surface is at a distance h_* from the basis of the layer in the region $z^* < 0$ (z^* is the coordinate along the layer thickness) of the ambient medium, which is considered transparent to radiation [11, 12]. Free convective heat and mass exchange with the ambient gaseous medium containing gas impurities considered occurs through the surface of the layer $z^* = 0$, and the surface $z^* = h_0$ is contact with vacuum. The surfaces of the layer $z^* = 0$ and $z^* = h_0$ are free of loading, and its edges ($x \rightarrow \pm\infty$ and $y \rightarrow \pm\infty$) are rigidly fastened. The thermal radiation of the heated surface is considered diffusive, and its intensity is equal to

$$I_\lambda^{\text{ext}} = f_\lambda I_{\lambda b}(\lambda, T_s), \quad I_{\lambda b}(\lambda, T_s) = 2\pi C_1 / \{\lambda^5 [\exp(C_2/(\lambda T_s)) - 1]\}, \quad (2.1)$$

where $C_1 = \hbar c_0$ and $C_2 = \hbar c_0/k^*$ (k^* is the Boltzmann constant).

From the above equations of the model, we obtain a complete system of equations describing radiation transport and mechanothermodiffusion processes in the layer. If in the heat equation, we ignore thermoelastic dissipation of energy, the heat transferred by impurity particles during diffusion, and the effect of ponderomotive forces on the stress state [16], this system takes the form

$$I_\lambda^+(z, v) = I_\lambda^+(0, v) \exp(-z\theta_\lambda/v), \quad I_\lambda^-(z, v) = I_\lambda^-(1, v) \exp(-(1-z)\theta_\lambda/v); \quad (2.2)$$

$$I_\lambda^+(0, v) - 2R_\lambda \int_0^1 v_0 I_\lambda^-(1, v_0) \exp\left(-\frac{\theta_\lambda(1-z)}{v_0}\right) dv_0 = n_\lambda^2(1-R_\lambda)I_\lambda^{\text{ext}}(\xi), \quad (2.3)$$

$$I_\lambda^-(1, v) - 2R_\lambda \int_0^1 v_0 I_\lambda^+(0, v_0) \exp\left(-\frac{\theta_\lambda z}{v_0}\right) dv_0 = 0;$$

$$\frac{\partial^2 T}{\partial z^2} - \frac{\partial T}{\partial \tau_0} = \frac{h_0^2}{\eta} Q(c_k, z),$$

$$Q(c_k, z) = \rho(1-c)Q^m(z) + \rho \sum_{k=1}^N c_k Q_k(c_k, z),$$

$$Q^m(z) = \frac{2\pi}{\rho(1-c)} \int_0^\infty \int_0^1 a_\lambda^m (I_\lambda^+(z, v) + I_\lambda^-(z, v)) dv d\lambda,$$

$$Q_k(c_k, z) = \frac{2\pi}{\rho c_k} \int_0^\infty \int_0^1 a_\lambda^k (I_\lambda^+(z, v) + I_\lambda^-(z, v)) dv d\lambda,$$

$$f^m(z) = \frac{1}{c_0 \rho (1-c)} \int_0^\infty \int_0^1 a_\lambda^m (I_\lambda^+(z, v) - I_\lambda^-(z, v)) v dv d\lambda, \quad (2.4)$$

$$f_k(c_k, z) = \frac{1}{c_0 \rho c_k} \int_0^\infty \int_0^1 a_\lambda^k (I_\lambda^+(z, v) - I_\lambda^-(z, v)) v dv d\lambda,$$

$$\frac{\partial c_k}{\partial \tau_k} = -\frac{\partial}{\partial z} \left\{ D_k^r \left[\frac{M_k M^m}{E^k} c_k c^m \left(\frac{c_k}{M_k} + \frac{c^m}{M^m} \right) (f_k^z - f_z^m) - \frac{\partial c_k}{\partial z} - \frac{\alpha_k^T}{T} \frac{\partial T}{\partial z} \right] \right\},$$

$$\sigma_{xx} = \sigma_{yy} = \frac{E}{1-\nu} \left(\alpha(T^* - T) + \frac{1+\nu}{3(1-2\nu)} \sum_{k=1}^2 (c_k^* - c_k) \right),$$

$$T^* = \frac{1}{2} \int_0^1 T(z, \tau_0) dz, \quad c_k^* = \frac{1}{2} \int_0^1 c_k(z, \tau_k) dz,$$

$$E^k(z, \tau_0) = \begin{cases} (Q_k(c_k, z)/\gamma_0)\tau_0 + RT_0(z) & \text{for } L_k(z, \tau_0) \gg 1, \\ RT(z, \tau_0) & \text{for } L_k(z, \tau_0) \leq 1, \end{cases}$$

$$N_k^{pt} d_k^2 = (D_{0k}/(z_k l_k^2)) \exp(-U_{act}^k/E^k), \quad k = \overline{1, N}.$$

Here $I_\lambda^+(z, v)$ and $I_\lambda^-(z, v)$ are the spectral radiation intensity in the layer in the directions that form an acute angle β and an angle $\pi - \beta$ with the z^* axis, $z = z^*/h_0$ is the dimensionless coordinate along the layer thickness, $v = \cos \beta$, $\xi = \arcsin(n_\lambda \sqrt{1-v^2})$, $\theta_\lambda = a_\lambda h_0$ is the optical thickness of the layer, R_λ and n_λ are the spectral coefficients of diffusive reflection and refraction on the surface of the layer, respectively, $\tau_0 = \chi t/h_0^2$ and $\tau_k = D_{0k} t/h_0^2$ are the Fourier criteria, η and χ are the thermal conductivity and diffusivity, and E , ν , and α are the elastic modulus, Poisson's ratio, and the linear temperature-expansion coefficient, respectively.

Under the assumptions on features of heat and mass transfer, the boundary conditions of heat and mass transfer on the surfaces of the layer $z = 0$ and $z = 1$ take the form

$$\frac{\partial T(0, \tau_0)}{\partial z} - \text{Bi}(T(0, \tau_0) - T_{\text{ext}}) = 0, \quad \frac{\partial T(1, \tau_0)}{\partial z} = 0,$$

$$\left[h_0 \frac{M_k}{E^k} (f_k(0) - f^m(0)) - \text{Bi}_k^*(0) \right] c_k(0) - \frac{\partial c_k(0)}{\partial z} = -\text{Bi}_k^*(0) c_k^*(0) - \alpha_k^T \frac{\partial T(0)}{\partial z}, \quad (2.5)$$

$$\left[h_0 \frac{M_k}{E^k} (f_k(1) - f^m(1)) + \text{Bi}_k^*(0) \right] c_k(1) - \frac{\partial c_k(1)}{\partial z} = 0.$$

Here Bi and $\text{Bi}_k^* = \bar{\beta}_k h_0 / (\rho D_k^r)$ are the Biot criteria for heat and mass transfer, respectively; the quantities $\bar{\beta}_k$ and c_k^* are expressed in terms of known characteristics of absorption and desorption processes on the surface of the material considered and the impurity concentration in the ambient medium [3].

The obtained coupled system (2.1), (2.2), (2.4) with boundary conditions (2.3) and (2.5) was solved by iterations using the finite-difference method in each approximation. As a zero approximation, we used the solution of the system obtained for the absorption and diffusion coefficients and the values of Q_k , Q^m , f_k , and f^m calculated from known initial distributions of temperature and impurity concentrations. Numerical calculations were carried out for a layer of S93 glass 1 cm thick. The thermal and radiative characteristics of the glass were taken from [2, 3, 14]. The characteristics of the absorption bands of gases were calculated using the data of [15]. The diffusion characteristics of nitric oxide were calculated with satisfactory accuracy from the results obtained in [25], and the diffusion characteristics of water were taken from [26]. We assumed that the initial impurity concentrations were constant along the thickness and equal to $c_{01} = c_{02} = 0.001$, the quantities c_k^* were equal to zero, and $\text{Bi} = \text{Bi}^* = 1$ on both surfaces of the layer. The initial temperature of the body and the ambient temperature were considered equal: $T_{\text{ext}} = T_0 = 300$ K. To study the effect of the radiation spectrum on the examined processes in the body, we considered the action of sources with temperatures $T_s = 1000, 2000, 3000$ K, and in all cases, the integral radiant

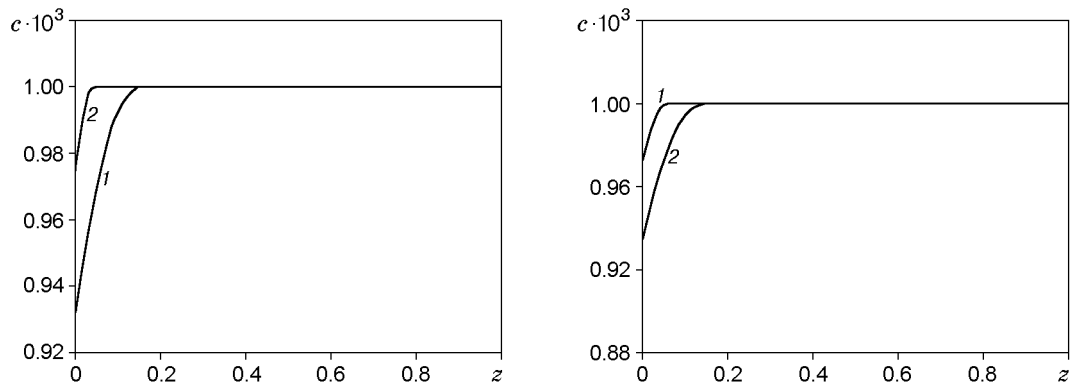


Fig. 1

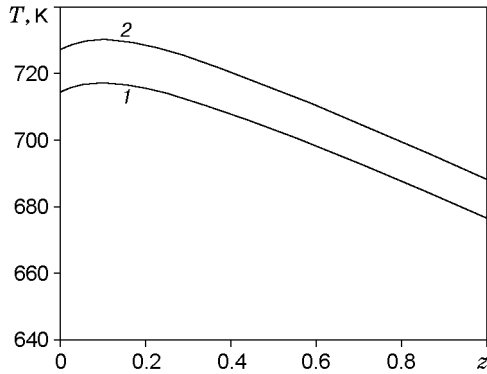


Fig. 2

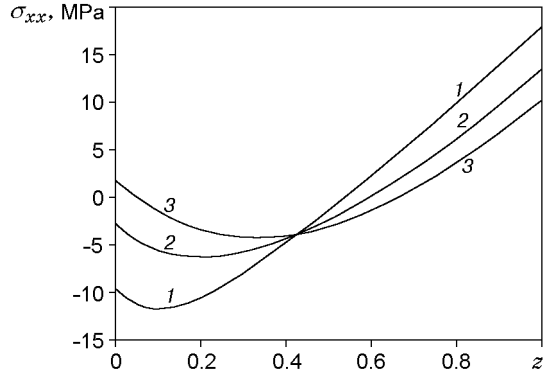


Fig. 3

flux into the body was identical by a proper choice of the coefficient f_λ . In all cases, the duration of the radiation effect was 2 h.

Figure 1a shows concentration distributions for the diatomic nitric oxide impurity along the layer thickness under irradiation whose spectrum corresponds to source temperatures $T_s = 1000$ (curve 1) and 3000 K (curve 2). From Fig. 1a it follows that the diffusion rate depends on the radiation spectrum and is maximal at $T_s = 1000$ K. This is explained by the fact that for diatomic molecules of nitric oxide there is one fundamental absorption band at a wavelength of $5.3 \mu\text{m}$. More radiation energy falls in this absorption band at $T_s = 1000$ K than at $T_s = 3000$ K, because of which the energy of nitric oxide E^k and its diffusion coefficient $D(E^{\text{NO}})$ are maximal. It should be noted that the diffusion rate is much lower if the layer is heated convectively to the maximum possible temperature [2] at the maximum possible heating rate (which is determined by the strength properties of glass) and then is held until the total heating time becomes equal to 2 h.

Figure 1b shows concentration distributions for water (curve 1) and nitric oxide (curve 2) at $T_s = 1000$ K. For triatomic molecules of water there are several absorption bands in the infrared region, as a result of which they absorb more radiation energy than diatomic molecules of nitric oxide. However, because the diffusion coefficient of water is much smaller than the diffusion coefficient of nitric oxide, the diffusion rate of nitric oxide is higher. The diffusion of diatomic NO molecules depends on the radiation spectrum. In contrast, for H_2O molecules, which have several absorption bands in the infrared range, variation of the radiation spectrum (with variation in T_s from 1000 to 3000 K) practically does not influence the diffusion rate, and their concentration distribution in the layer is the same (curve 1).

Temperature distributions along the layer thickness are shown in Fig. 2. Curve 1 corresponds to a pure layer exposed to a thermal radiation source whose temperature is $T_s = 1000$ K. It should be noted that the temperature in the layer, just as the concentration of the diatomic NO impurity, depends on the radiation spectrum: as the source temperature decreases, the absolute value of temperature increases and its distribution along the thickness becomes more nonuniform. The presence of the diatomic nitric oxide impurity at the examined initial concentration $c_0 = 0.001$ practically does not influence the temperature in the layer, and its distribution is also represented by

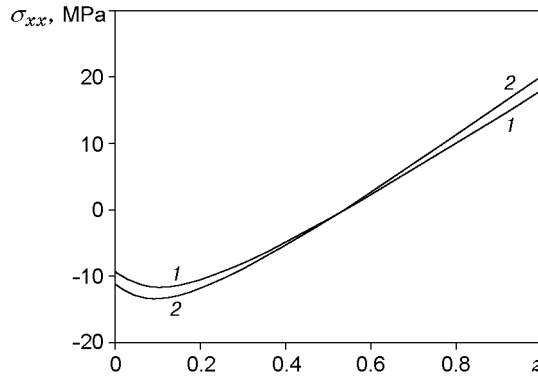


Fig. 4

curve 1. However, if in the layer there is a triatomic impurity of water at the same concentration, the temperature in the layer increases (curve 2) compared to the temperature of the pure layer. This is due to the fact that the total amount of radiation energy absorbed by the triatomic impurity is much larger than that absorbed by the diatomic impurity.

Figure 3 shows distributions of stresses $\sigma_{xx} = \sigma_{yy}$ in a layer with an impurity of NO at $T_s = 1000$ (curve 1), 2000 (curve 2), and 3000 K (curve 3). From Fig. 3 it follows that the stresses in the layer depend on the radiation spectrum. However, their values do not depend on the presence of nitric oxide with concentration $c_0 = 0.001$; therefore, curves 1–3 also correspond to the stress distribution in the pure layer. It should be noted that the stress state of the layer is determined by the level of thermal stresses and the concentration stresses and the stresses due to the action of mass forces of radiation are negligibly small. Hence, because the temperature in the layer practically does not depend on the presence of the diatomic NO impurity, the thermal stresses also do not depend on it.

Figure 4 shows distributions of stresses $\sigma_{xx} = \sigma_{yy}$ in a pure layer (curve 1) and a layer with a water impurity (curve 2) at $T_s = 1000$ K. From Fig. 4 it follows that unlike in the case where the layer contains diatomic nitric oxide, the presence of triatomic water leads to an increase of stresses in the layer.

For real thermal-radiation parameters, determined by the temperature of the radiation source ($f_\lambda \leq 1$ at $T_s < 5000$ K), and the absorption characteristics of the impurities considered, thermal diffusion phenomena and ponderomotive forces practically do not influence the impurity concentration distribution in glass. This is due to the insignificant temperature gradient of glass (see Fig. 2) and the forces $f_k \sim \alpha_\lambda^k (I_\lambda^+ - I_\lambda^-) \Delta \lambda^{k(\text{eff})} / (c_0 \rho)$. Thus, for the impurities considered, the force f_k has values of 0.1–10.0 N/kg, i.e., it does not induce diffusion processes [27].

An analysis of the numerical results leads to the following conclusions. As in a pure glass layer, thermal stresses in a glass layer with impurities increase as the temperature of the thermal radiation source decreases from 3000 to 1000 K under the same integral radiation flux delivered into the layer. In this case, the diffusion rate of a diatomic impurity increases, whereas for a triatomic impurity, it remains practically constant. The increase in the diffusion rate of a diatomic impurity due to the change of the radiation spectrum is accompanied by an increase of thermal stresses.

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