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HEAT AND MASS TRANSFER IN POROUS AND DISPERSIVE MEDIA

MODELING OF NONISOTHERMAL HEAT AND MOISTURE TRANSFER IN CAPILLARY-POROUS MEDIA IN PERIODIC MICROWAVE HEATING

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The interrelated system of heat- and moisture-transfer and electrodynamic equations for modeling superhigh-frequency drying of capillary-porous materials has been formulated. An example of solving the problem of heat and moisture transfer in microwave heating of a wood sample with allowance for the influence of surface forces on the process of migration of moisture has been given.

Introduction. The electromagnetic field of a microwave range is widely used for drying porous materials [1–5]. In microwave drying, we have a rapid and uniform heating of the material and an intense evaporation of moisture; the top quality of finished products is ensured in a number of technologies.

The modeling of heat and moisture transfer in porous media with allowance for microwave heating is based on a theoretical description (developed earlier [6–8]) of nonisothermal mass transfer.

Mathematical Model. Let us consider heat and mass transfer in an undeformable capillary-porous medium, when the hypothesis of local thermodynamic equilibrium between phases holds true and by the nonequilibrium process of drying we mean the quasiequilibrium process. The Kelvin and Clausius–Clapeyron relations are valid and the experimental isotherms of sorption (desorption) of a moist material are known. Then the system of partial differential equations for describing of nonisothermal moisture transfer in a porous medium that allows for two-phase filtration, the interference of the vapor and liquid pressures, the work of surface forces, and the energy of an electromagnetic field can be represented in the following form [6–8]:

the energy equation

$$\left[(1-m)\,c_{\text{dr}}\,\rho_{\text{dr}}+m\left(\theta_{\text{v}}\,\rho_{\text{v}}c_{p\text{v}}+\theta_{\text{liq}}\,\rho_{\text{liq}}c_{p\text{liq}}\right)\right]\frac{\partial T}{\partial \tau}+m\theta_{\text{v}}\,\rho_{\text{v}}c_{p\text{v}}\left(\frac{kk_{\text{v}}}{\eta_{\text{v}}}\nabla p_{\text{v}}\nabla T\right)=$$

$$=\text{div}\,(\lambda\nabla T)+rI+Q-m\left(p_{\text{liq}}-T\left(\frac{\partial p_{\text{liq}}}{\partial T}\right)_{\theta_{\text{liq}}}\right)\frac{\partial\theta_{\text{liq}}}{\partial \tau}\,, \tag{1}$$

allowing for the heat release Q from microwave heating and for the work of surface forces of the liquid phase by means of the last term on the right-hand side [6],

the equation of transfer of the vapor

$$m\frac{\partial\,(\rho_{\text{v}}\theta_{\text{v}})}{\partial \tau}=\text{div}\,\rho_{\text{v}}\left(\frac{kk_{\text{v}}}{\eta_{\text{v}}}\nabla p_{\text{v}}\right)+I\,; \tag{2}$$

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the gas (vapor) equation

$$\rho_{\mathrm{v}} = \frac{\nu_{\mathrm{v}} p_{\mathrm{v}}}{RT}\,; \tag{3}$$

the sorption (desorption) isotherm and the expression for the vapor pressure in terms of the inverse function F

$$a = f\,(p_{\mathrm{v}}, T)\,, \quad p_{\mathrm{v}} = F\,(a, T)\,; \tag{4}$$

and the equation of transfer of the liquid

$$\frac{\partial u_{\mathrm{liq}}}{\partial \tau} = \mathrm{div}\;\rho_{\mathrm{liq}} \left(\frac{k k_{\mathrm{liq}}}{\eta_{\mathrm{liq}}}\, \nabla p_{\mathrm{liq}} \right) - I\,, \tag{5}$$

where $u_{\mathrm{liq}} = m \rho_{\mathrm{liq}} \theta_{\mathrm{liq}}$.

We use, as the closing relations, the dependences of: the pressure of the liquid's saturated vapor on the temperature (in this case we have $p_{\mathrm{s}} = f(T)$ for water), the liquid pressure on the moisture content and the temperature

$$p_{\mathrm{liq}} = p_{\mathrm{s}}\,(T) + \frac{RT}{\nu'_{\mathrm{liq}}} \ln \frac{F\,(a, T)}{p_{\mathrm{s}}\,(T)}\,, \tag{6}$$

the derivative of the liquid pressure on the temperature

$$\left(\frac{\partial p_{\mathrm{liq}}}{\partial T} \right)_{\theta_{\mathrm{liq}}} = \frac{\partial p_{\mathrm{s}}\,(T)}{\partial T}\,(T) + \frac{R}{\nu'_{\mathrm{liq}}} \ln \frac{F\,(a, T)}{p_{\mathrm{s}}\,(T)} + \frac{RT}{\nu'_{\mathrm{liq}}} \left(\frac{\partial \ln F\,(a, T)}{\partial T} \right)_{a}\,, \tag{7}$$

the specific heat of phase transition

$$r = \frac{RT^2}{\nu''_{\mathrm{liq}}} \left(\frac{\partial \ln F\,(a, T)}{\partial T} \right)_{u_{\mathrm{e}}} \tag{8}$$

and the intensity of mass exchange between phases

$$I = \rho_{\mathrm{liq}} \frac{\partial a}{\partial \tau} = \rho_{\mathrm{liq}} \left[\left(\frac{\partial a}{\partial p_{\mathrm{v}}} \right)_{T} \frac{\partial p_{\mathrm{v}}}{\partial \tau} + \left(\frac{\partial a}{\partial T} \right)_{p_{\mathrm{v}}} \frac{\partial T}{\partial \tau} \right]; \tag{9}$$

the initial conditions are

$$T_0 = T\,(r, 0)\,, \quad p_{\mathrm{v}0} = p_{\mathrm{v}}\,(r, 0)\,, \quad p_{\mathrm{liq}0} = p_{\mathrm{liq}}\,(r, 0)\,. \tag{10}$$

The temperature of a sample and its moisture content are usually known at the initial instant of time. Then, using the sorption (desorption) isotherm and the inverse function we easily determine the pressure of the vapor and, based on formula (6), the initial pressure of the liquid.

The boundary conditions for the simplest one-dimensional case (plate) will have the form

$$x = 0: \quad \left. \frac{\partial p_{\mathrm{p}}}{\partial x} \right|_{x=0} = 0\,, \quad \left. \frac{\partial p_{\mathrm{liq}}}{\partial x} \right|_{x=0} = 0\,, \quad \lambda \left. \frac{\partial T}{\partial x} \right|_{x=0} = 0\,, \tag{11}$$

$$x = 1: \quad \lambda \left. \frac{\partial T}{\partial x} \right|_{x=1} = \alpha\,(T_{\mathrm{m}} - T)\,, \tag{12}$$

$$p_{\mathrm{v}}(1, \tau) = \varphi(\tau)\, p_{\mathrm{s}}(T)\,, \tag{13}$$

$$p_{\mathrm{liq}}(1, \tau) = p_{\mathrm{s}}(T) + \frac{RT}{\nu'_{\mathrm{liq}}} \ln \frac{p_{\mathrm{v}}(\tau)}{p_{\mathrm{s}}(T)}\,. \tag{14}$$

Unlike the classical equations of two-phase filtration, in the system of equations (1)–(14) proposed for determination of the dependence of the liquid pressure on the moisture content and the temperature, there is no need to experimentally determine the Leverett function. Even though it may be known, it becomes difficult to prescribe the liquid pressure at the boundary of a porous body. Indeed, the Leverett function is independent of the changes in the vapor pressure and the temperature; therefore, we believe that the use of experimental sorption (desorption) isotherms whose knowledge is also necessary for determination of the intensity of mass exchange and the heat of sorption in the form of relations (8) and (9), is preferred for the problem in question.

Modeling of Nonisothermal Heat and Mass Transfer in a Wood Sample with Insulated Boundaries. *Formulation of the Problem.* A wood sample of thickness L = 0.06 m was placed in a vapor- and moisture-tight shell or film. Chamber temperature $T_{\mathrm{ch}}\big|_{x<0}$ = 330 K was maintained in the region $x < 0$, whereas $T_{\mathrm{ch}}\big|_{x>L}$ = 300 K was maintained in the region $x > L$; the coefficient of heat exchange with the ambient medium was α = 30 W/(m^2·K). The calculations were carried out for wood with a desorption isotherm of the form [9]

$$a(\varphi, T) = 10.6^{\varphi}\,(3.27 - 0.015\,(T - 273))/100\,. \tag{15}$$

At the initial instant of time (τ = 0), the moisture content of wood was u_0 = 0.3 kg/kg, and the temperature was T_0 = 300 K; the pore vapor pressure determined from the sorption isotherm was $p_{\mathrm{v}0}$ = 3791 Pa, the permeability of wood along fibers was $k = 10^{-14}$ m^2 for a porosity of m = 0.5, and the density of dry wood was ρ_{dr} = 470 kg/m^3. The relative phase permeabilities of the liquid and the vapor were calculated with a certain approximation from the S. V. Aver'yanov formulas

$$k_{\mathrm{liq}} = \left(\frac{u - u_{\min}}{u_{\max} - u_{\min}}\right)^3, \quad k_{\mathrm{v}} = \left(\frac{u_{\max} - u}{u_{\max} - u_{\min}}\right)^3,$$

where $u_{\max}$ = 1 and $u_{\min}$ = 0.1. In this case $u_{\min}$ corresponds to the limiting moisture content when the liquid with lower moisture contents is in a bound, fixed state.

The saturated-vapor pressure as a function of the temperature was calculated with an approximation of 5–10% to a value of 140°C from the formula

$$p_{\mathrm{s}}(T) = 10^5\,(T/373)^{15}\,. \tag{16}$$

It is necessary to find the dynamics of distribution of the temperature, the moisture, and the vapor pressure in the sample with time.

Solution. For solution we used the system of equations (1)–(5) for a one-dimensional case. Determining the vapor pressure from isotherm (4) in explicit form and using the Clapeyron and Kelvin formulas, we obtain the expressions for the liquid pressure and the heat of sorption as functions of the moisture content and the temperature

$$p_{\mathrm{liq}}(u, T) = \frac{RT}{\nu'_{\mathrm{liq}}} \ln\left(0.4257 \ln\left(\frac{-6666.7u}{T - 491}\right)\right),$$

$$r(u, T) = \frac{RT^2}{\nu''_{\mathrm{liq}}}\left(\frac{1}{(491 - T)\ln(6666.7u/(491 - T))} + \frac{15}{T}\right). \tag{17}$$

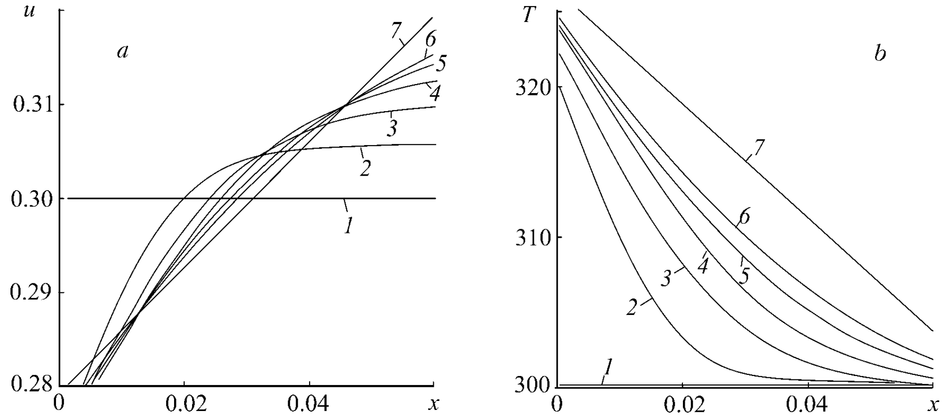

Fig. 1. Distribution of the moisture content of wood u (a) and the temperature T (b) in the sample for different instants of time: 1) 0, 2) 1000, 3) 2000, 4) 3000, 5) 4000, 6) 5000, and 7) 20,000 sec. u, kg/kg; T, K; x, m.

The initial and boundary conditions are

$$\tau = 0: \quad T(x, 0) = T_0, \quad p_{\rm v}(x, 0) = p_{\rm v0}, \quad u(x, 0) = u_0,$$

$$\rho_{\rm liq}\left(\frac{kk_{\rm liq}}{\eta_{\rm liq}}\right)\frac{\partial p_{\rm liq}}{\partial x}\Bigg|_{\substack{x=0\\x=L}} = -\rho_{\rm v}\left(\frac{kk_{\rm v}}{\eta_{\rm v}}\right)\frac{\partial p_{\rm v}}{\partial x}, \quad \lambda\frac{\partial T}{\partial x}\Bigg|_{x=0} = \alpha(T_{\rm ch} - T), \quad \lambda\frac{\partial T}{\partial x}\Bigg|_{x=L} = \alpha(T_{\rm ch} - T). \tag{18}$$

They reflect the equality of the vapor and liquid flows at the boundary, since the total mass flux through the boundary is equal to zero. i.e., $\mathbf{q}_{\rm v} + \mathbf{q}_{\rm liq} = 0$. We assume the boundaries to be impermeable to the total mass flux. The thermal conductivities and the effective heat capacity are determined from the following empirical dependences [4, 9]:

$$\lambda = 0.00222u\,(T - 273) + 10^{0.295\log(100u) - 1.022}, \quad (\rho c_p)_{\rm ef} = \rho_{\rm s}\,(4185u + 4.85T - 211).$$

The Darcy formula is known to disregard the convective transfer of a liquid and a gas in a porous medium for diffusion equations [4]. At the same time, on occasion it is necessary to allow for the convective component in the heat-condition equation [10]. In our case the contribution of this component is insignificant compared to that of the conductive component.

The system of equations (1)–(7) with boundary conditions (18) was solved by the finite-element method. The calculation results are presented in Fig. 1. In Fig. 1a which shows the dynamics of change in the humidity of the sample, it is seen that the redistribution of moisture in the porous material is pronounced even after 1000 sec. In the "cold" part of the sample, where T = 300 K (Fig. 1b), the moisture content grows to 0.32 kg/kg, whereas in the "hot" part, it decreases to 0.28 kg/kg. The gradients of moisture content increase still further with time. The motion of moisture to the "cold" part is caused not only by the liquid pressure as a function of the temperature according to formula (6) but also by the vapor flow. The curves for the instant of time $\tau = 2\cdot10^4$ sec correspond to the steady state, since no further variations in the parameters were observed during the numerical experiment.

Heat and Mass Transfer in the Process of Microwave Heating of Wood. *Formulation of the Problem.* The electromagnetic wave is incident onto a plate of wood of thickness L = 0.06 m perpendicularly in the direction of fibers; the vector of the electric field strength $\mathbf{E}$ = 1800 V/m with an angular frequency of ω = 15.4 GHz is in parallel to the surface.

At the initial instant of time (τ = 0), the moisture content of wood is u_0 = 0.3 kg/kg, the temperature is T_0 = 300 K, and the pore vapor pressure determined from the sorption isotherm is $p_{\rm v0}$ = 3791 Pa. For the sake of comparison the calculation parameters are the same as those in the problem from the previous section. The sample is

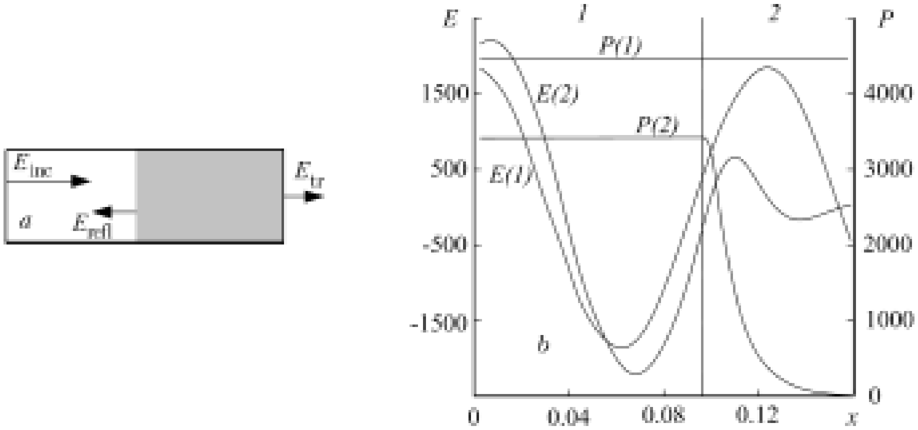

Fig. 2. Geometry of the problem (a) and results of solution of the Helmholtz equation (b). E, V/m; P, W/m^2; x, m.

placed in a chamber with a pressure of p_{ch} = 3240 Pa and a relative humidity of φ = 85%. The wood's permittivity ε which is a function of the temperature and the moisture content is determined from the formulas [4]

$$\varepsilon'' = 9.7 + 9.2u - 0.056T - 0.17u^2 + 0.0000826T^2 - 0.0183uT\,,$$

$$\varepsilon' = -\,17.2 - 48.6u + 0.1145T + 12.8u^2 - 0.00017T^2 + 0.19uT\,,$$

where $\varepsilon = \varepsilon' - i\varepsilon''$.

The temperature in the chamber is T_{ch} = 300 K, the porosity of wood is m = 0.5, its permeability along fibers is $k = 10^{-14}$ m^2, and the density of dry wood is ρ_{dr} = 470 kg/m^3. It is necessary to find the distribution of the fields of pressure of the vapor and moisture content of the sample for different instants of time.

Solution. The distribution of the electric field strength is determined by the vector Helmholtz equation

$$\nabla \mathbf{E} - \varepsilon_0\,\mu_0 \omega^2 \varepsilon \mathbf{E} = 0\,. \tag{19}$$

The source of an electromagnetic wave must transmit, without hindrance, a wave reflected from the sample, whereas a wave transmitted by the sample must not be reflected backward (Fig. 2a). We have two boundary conditions corresponding to the absence of the reflection of a wave with strength E_0

$$\nabla E + k_{\text{w}} iE = 2k_{\text{w}} iE_0 \tag{20}$$

and to absorption at exit from the sample

$$\nabla E + k_{\text{w}} iE = 0\,.$$

The reflection coefficient S is determined by the ratio of the specific reflected power (of the flux) to the power of the source

$$S = \sqrt{\frac{P_{\text{refl}}}{P_{\text{source}}}}\;,\quad P_{\text{source}} = 0.5\cdot\frac{E_0^2}{Z_H}\,,\quad P_{\text{refl}} = P_{\text{source}} = 0.5\,\text{Re}\,(E\overset{*}{H})\,,\quad H = \frac{1}{\omega\mu_0}\frac{\partial E}{\partial x}\,. \tag{21}$$

Let us consider results of solution of electrodynamic problem (19) and (20) in the system free space (region 1) — sample (region 2), as is shown in Fig. 2b. Curves $E(1)$ and $P(1)$ correspond to the field strength and the power flux in the absence of a sample (i.e., ε in region 2 is determined as $\varepsilon = 1 - i(0)$). The strength curve is sine-type; the

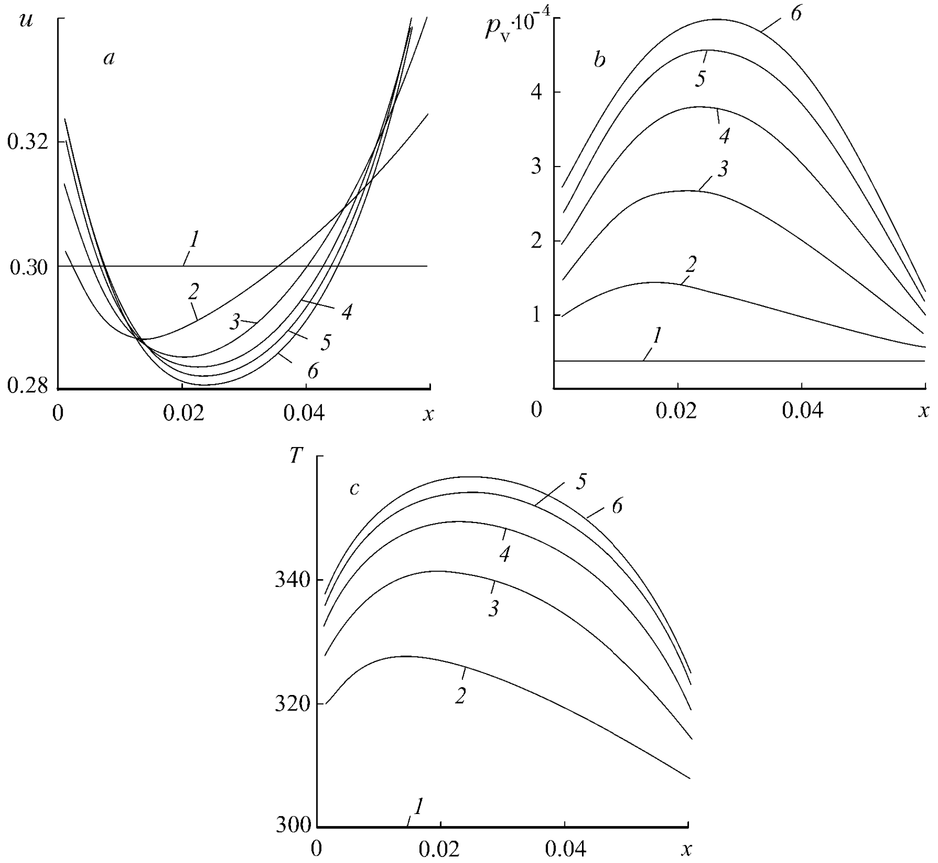

Fig. 3. Profiles of the moisture content of wood u (a), vapor pressure p_v (b), and temperature T (c) in the sample for different instants of time: 1) 0, 2) 1000, 3) 2000, 4) 3000, 5) 4000, and 6) 5000 sec. u, kg/kg; p_v, Pa; T, K; x, m.

strength at the maxima corresponds to the prescribed strength of the source E_0 = 1800 V/m, and the wavelength corresponds to the frequency ω = 15.4 GHz. As is seen in Fig. 2b, the source strength is equal to P_{source} = 4400 W/m^2, which corresponds to formula (21).

Curves $E(2)$ and $P(2)$ correspond to the field strength and the power flux in the presence of a sample with a permittivity of $\varepsilon = 4 - 4i$. Propagating (x = 0), the wave is reflected from the boundary of the sample (x = 0.1 m) and, interfering with the incident wave, forms a standing wave $E(2)$. The transmitted wave, oscillating, decays. Since $P(2)$ is a result of the difference of the incident wave and the reflected wave, it is easy to calculate the reflection coefficient S. With account for relation (20), the quantity S for the sample with $\varepsilon = 4 - 4i$ is equal to 0.47.

For this geometry of the problem, we can also determine the reflection coefficient without calculations of power fluxes, using the relations for the field strength at the interference maximum and minimum of the standing wave $E(2)$, more precisely, the absolute value of the complex quantity $E(2)$. According to the procedure indicated above, we have S = 0.46.

To solve the problem we use the system of heat- and mass-transfer equations (1)–(14) with an additional term Q determining the internal heat sources due to the action of microwaves:

$$Q = 0.5\omega\varepsilon_0\varepsilon'' E^2 .$$

Let us consider two cases:

1. Heat and Mass Transfer in Microwave Heating of a Sample with Insulated Boundaries. The sample is placed in a moisture- and vapor-tight shell. The boundary conditions are the same as above but without a microwave source. The sole exception is the chamber temperature, which is the same — $T_{\text{ch}} = 330$ K — on all sides of the sample. The calculation results are presented in Fig. 3.

The microwave heating results in a nonsymmetric heating of the sample with a temperature maximum at a depth of ~2–3 cm (fig. 3c); the pore vapor pressure significantly increases: from $1 \cdot 10^4$ to $5 \cdot 10^5$ Pa (Fig. 3b). The moisture content of the sample decreases for the same value of the coordinate and moisture moves to the cold parts of the sample. The $u(x)$ curves to the left and to the right of the maximum zone of heating intersect approximately in the same cross sections: to the left of the heating zone at the depth $x \approx 1$ cm and to the right of it at $x \approx 4.5$–5 cm; the location of the point of intersection remains virtually constant with time (Fig. 3a). We note that, according to the classical theory of A. V. Luikov, it is necessary to prescribe the thermal and moisture conductivity and the criterion of phase transition (equal to $|\mathbf{q}_{\text{v}}|/(|\mathbf{q}_{\text{v}}| + |\mathbf{q}_{\text{liq}}|)$ and unknown in the case of microwave heating) for modeling of the problems indicated. The use of the classical theory of two-phase filtration [1–5] without allowance for the thermodynamics of surface phenomena makes it impossible, too, to model heat- and moisture-conduction phenomena in porous materials in the presence of microwave heating.

2. Heat and Mass Transfer in the Processes of Drying in Microwave Heating of Wood. A wood sample of thickness $L = 0.06$ m is placed in a chamber with a certain fixed relative humidity φ and accordingly with a fixed partial vapor pressure ($\varphi = 85\%$ and $p_{\text{v}} = 3240$ Pa). The electromagnetic field with characteristics indicated above acts on the sample's surface; the temperature in the chamber is $T_{\text{ch}} = 300$ K. In this case the boundary conditions for the sample can be written as

$$u\big|_{x=0,x=L} = u_{\text{m}}(p_{\text{m}}, T)\,, \quad p_{\text{v}}\big|_{x=0,x=L} = p_{\text{m}} = \varphi p_{\text{s}}(T)\,, \quad \lambda \frac{\partial T}{\partial x}\bigg|_{x=0,x=L} = \alpha\,(T_{\text{ch}} - T)\,. \tag{22}$$

The character of change in the humidity, the partial vapor pressure, and the temperature is the same, on the whole, as that for heat and mass transfer with insulated boundaries (Fig. 3). The calculations show that the average moisture content of the sample decreases linearly at the beginning of the process, i.e., there is a period of constant drying rate, which is consistent with a large amount of experimental data.

Among the features of microwave drying is the fact that, unlike, e.g., the convective removal of moisture, the period of constant drying rate does not correspond to the period of constant sample temperature. No overdrying of the surface layer of the sample is observed. As a result of the decrease in the formation of microcracks, the material dried is of higher grade and more homogeneous.

Periodic Regime of Heating. Let us investigate the process of drying in discrete superhigh-frequency heating of a plane sample of thickness 0.06 m whose thermophysical and dielectric properties have been determined above. The strength of the incident superhigh-frequency field is $E_0 = 3000$ V/m. The kinetics of drying is calculated for three regimes of heating: with a continuous source of superhigh-frequency radiation and a periodic switching on and switching off of the source with periods of $\tau_{\text{on}} = \tau_{\text{off}} = 200$ and 500 sec (Fig. 4). As is seen from the plots, in the initial step of the continuous regime of superhigh-frequency heating, the moisture content in the surface layer increases but then sharply decreases with heating of the sample. However, at the end of the drying, it is somewhat higher in surface layers than in those internal because of condensation. The peak value of the vapor pressure for internal reference points of the sample is 70–75 kPa. Once the sample has been heated to 360 K, the temperature remains constant throughout the period of drying. However, beginning from $\tau = 3000$ sec, it sharply grows with the vapor pressure and moisture content decreasing with a constant rate.

The oscillating regime is characterized by the lower rates of heating and drying than those in the continuous regime. The moisture content in the surface layer has its maximum and minimum in both cases of a periodic regime of heating, which is due to the constant recondensation of moisture. Unlike the continuous regime, the average values of the temperature and the vapor pressure at reference points are lower, and the heating is slower. Thus, when the superhigh-frequency source is switched on, we have the heating of the sample, the increase in the vapor pressure, the movement of free moisture to the cold zones, and the condensation of bound moisture. In the case of superhigh-frequency de-energizing, the process of temperature relaxation (by heat conduction) and vapor-pressure relaxation (due to the permeability of the material) occurs. We emphasize that, unlike the convective heating where heat transfer is from the surface to the internal material layers and the resulting pressure gradient directed to the center keeps moisture from

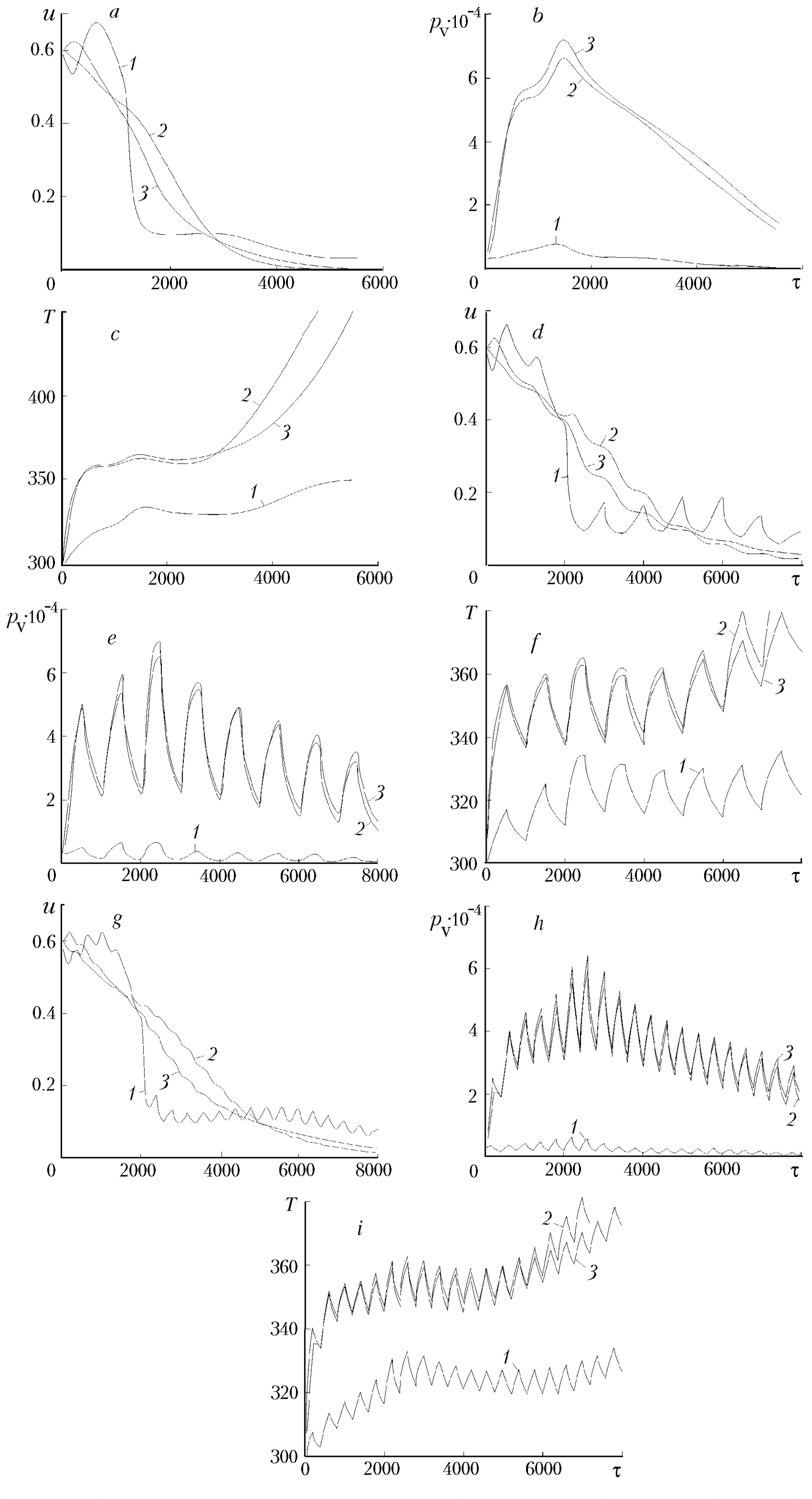

Fig. 4. Moisture content, vapor pressure, and temperature in the surface region $x = 0.001$ (a) at a distance of $x = 0.02$ m (2) and $x = 0.03$ m (3) from the sample's surface in the continuous regime of heating (a, b, and c) and in the discrete regimes $\tau_{\text{on}} = \tau_{\text{off}} = 200$ sec (d, e, and f) and 500 sec (g, h, and i). u, kg/kg; p_{v}, Pa; T, K; τ, sec.

moving to the surface and slows down drying, the superhigh-frequency heating is characterized by a considerable gradient of internal vapor pressure, directed to the surface, which accelerates the transfer of moisture to surface layers. In a discrete supply of superhigh-frequency energy, we observe lower gradients of temperature, vapor pressure, and moisture content.

Conclusions. We have formulated the interrelated system of heat- and mass transfer and electrodynamic equations for modeling of the superhigh-frequency drying of capillary-porous materials. This makes it possible to describe the processes of drying, sorption, and filtration of a liquid in a sample in its incomplete saturation with allowance for the superhigh-frequency heating from a unified standpoint. We have shown the dynamics of change in the humidity, temperature, partial vapor pressure, average humidity, and other parameters with variation of boundary conditions, including the case of pulsed microwave heating.

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NOTATION

a, mass of the liquid sorbed in a unit volume, kg/m^3; c_{dr}, heat capacity of the dry sample, J/(kg·K); c_p, $c_{p\mathrm{v}}$, and $c_{p\mathrm{liq}}$, specific heat of the sample, the vapor, and the liquid at constant pressure, J/(kg·K); E, electric field strength, V/m; $\mathbf{E}$, vector of electric field strength, V/m; F, function inverse of f; H, magnetic field strength, A/m; $\overset{*}{H}$, complex conjugate value of the magnetic field; i, imaginary unit; I, mass sink, kg/(m^3·sec); k, permeability of the sample along fibers, m^2; k_{v} and k_{liq}, relative phase permeability of the vapor and the liquid; k_{w}, wave number in free space; L, sample thickness, m; m, sample porosity; P_{refl} and P_{source}, powers of the reflected signal and the source, W/m^2; P_{s}, saturated-vapor pressure, Pa; p_{v} and p_{liq}, vapor and liquid pressures in the sample, Pa; p_{m}, vapor pressure in the ambient medium, Pa; Q, heat sink, J/(m^3·sec); $\mathbf{q}_{\mathrm{v}}$ and $\mathbf{q}_{\mathrm{liq}}$, mass fluxes of the vapor and the liquid, J/(m^3·sec); R, universal gas constant, J/(mole·K); r, specific heat of phase transition, J/kg; Re, Reynolds number; S coefficient of reflection of the electromagnetic wave; T, T_{ch}, and T_0, temperature in the sample and the chamber and at the initial instant of time, K; T_{m} temperature of the medium, K; u, moisture content of the sample, kg/kg; u_{m}, moisture content on the sample's surface; x, coordinate, m; Z_H, characteristic impedance resistance; α, coefficient of heat exchange with the ambient medium, W/(m^2·K); ε, permittivity, F/m; ε' and ε'', real and imaginary parts of permittivity; $\varepsilon_0 = 8.85 \cdot 10^{-12}$, electric constant, F/m; η_{liq} and η_{v}, coefficients of dynamic viscosity of the liquid and the vapor, Pa·sec; θ_{v} and θ_{liq}, vapor and liquid saturations in a porous body; λ, thermal conductivity of the sample, W/(m·K); $\mu_0 = 4\pi \cdot 10^{-7}$, magnetic constant, H/m; ∇, differential operator; ν', molar volume, m^3/mole; ν'', molar mass, kg/mole; ρ, sample density, kg/m^3; ρ_{dr}, ρ_{s}, ρ_{v}, and ρ_{liq}, densities of the dry and saturated wood, the vapor, and the liquid, kg/m^3; τ, time, sec; φ_{air}, relative humidity of air, %; φ, relative humidity of the sample, %; ω, angular frequency, GHz. Subscripts: w, wave; on, switching on; off, switching off; e, equilibrium; liq, liquid; source, source; ch, chamber; refl, reflected; v, vapor; inc, incident; tr, transmitted; dr, dry; m, medium; ef, effective value; s, saturated; 0, initial; max, maximum; min, minimum.

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