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NUMERICAL MODELING OF NONISOTHERMAL MOISTURE TRANSFER IN BIOLOGICAL COLLOIDAL POROUS MATERIALS*

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The authors derive and substantiate a system of equations of heat and moisture transfer in colloidal capillary-porous undersaturated media with account for the mutual effect of the vapor and liquid pressure, determined by the contribution of surface forces, and the temperature on the rate of interphase mass transfer and the thermocapillary flows. Examples are given of the numerical calculation of evolution of the moisture content and temperature fields and the kinetic dependences in a wide moisture content range for materials of biological origin, namely, yeast, soil. A comparison is made with experimental data.

All disperse systems may be classified as free disperse (suspensions, emulsions, ash) and bound disperse systems. In the latter, one of the phases cannot move freely because it is structurally bound. Capillary-porous bodies are grouped into the latter category. The colloid state of a substance extends to a wide range of pore sizes from 10^{-7} to 10^{-2} cm, which is typical of all real bodies. The main feature of this state is the decisive role of surface phenomena. Present-day colloid chemistry deals with both coarse-disperse ($10^{-4} - 10^{-2}$ cm) and fine-disperse or purely colloid systems with pores of size from 10^{-4} to 10^{-7} cm. It is pertinent to note that a system acquires colloid properties even if only one of the three dimensions is within the indicated high-dispersity region. For instance, the surface layers at the phase boundaries in pores, foams, and living microorganisms are assigned to two-dimensionally extended colloid systems.

At present, cell membranes are of keen interest. Their properties differ from those of the bulk phases separated by the membranes. The situation becomes even more complicated when only some part of a porous space contains living cells and a gas serves as a dispersion medium, i.e., the porous medium is in an undersaturated state.

According to the classification of P. A. Rebinder characteristics of the forms of moisture-material binding are based on the origin and energy of binding of the moisture with the solid skeleton of the body. Microbiological materials are assigned in their colloid-physical properties to capillary-porous colloidal bodies [1], which manifest all the forms of moisture-material binding. The goal of the present work is to derive and substantiate a system of differential equations the heat and mass transfer in undersaturated colloidal capillary-porous media with account for the mutual effect of the vapor and liquid pressure, determined by the contribution of capillary and surface forces, and the temperature on the rate of interphase mass transfer and the thermocapillary flows. In order to choose the methods and regimes of drying of different microbiological materials, it is necessary to carry out comprehensive studies aimed at development of a rational drying technology.

In theoretical studies of transport processes in porous media no unified phenomenological approach exists [1-3]. Inconsistencies in the theories of drying, sorption, and two-phase filtration are fundamental, although these theories must describe combined heat and mass transfer in porous media involving phase changes.

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To describe the above processes it is necessary to use laws of conservation of mass and energy. The transfer equations derived from the conservation laws are not closed. To close them, one must determine the interphase mass transfer rate, the additional specific heat of sorption (or desorption), the potentials of liquid and vapor transfer, and the dependence of the liquid pressure P_{liq} on the moisture content and the temperature, elucidate the physical mechanism of thermal moisture conduction, and derive relations for its calculation.

In constructing a physical model, we will consider only rigid porous structures without structural changes. We assume that the sample shrinkage and the change in porosity upon drying are insignificant and the permeability coefficients of the vapor and the liquid are equal.

In a porous medium, the boundary of two phases is subdivided into many separate segments with different curvature. Applying the analogous Fourier number for mass transfer, we find that the local thermodynamic equilibrium (LTE) in pores of cylindrical, spherical, or flat geometry develops with the relaxation time $\tau_r \approx 2 \cdot 10^{-10} - 7.5 \cdot 10^{-10}$ sec for a pore radius $\approx 10^{-7}$ m, which as a rule, is considerably smaller than the time of the macroprocess of drying; therefore the LTE hypothesis is valid for "intense" drying processes as well. For dynamic equilibrium between the liquid and the vapor the chemical potentials of the phases must be equal:

$$\mu_{\text{liq}}(P_{\text{liq}}, T) = \mu_{\text{v}}(P_{\text{v}}, T), \tag{1}$$

and the liquid pressure is determined by the vapor pressure using the Kelvin formula [4]

$$P_{\text{liq}} = P_{\text{s}} + \frac{RT}{v'_{\text{liq}}} \ln \frac{P_{\text{v}}}{P_{\text{s}}}. \tag{2}$$

Equation (2) is verified experimentally in [4, 5], where the domains of its applicability are also shown. We do not consider the case where the thickness of the liquid film is less than 10 Å; we assuming here that the body is "dry."

The isotherms of sorption (desorption) $W = f(\varphi, T)$, where $\varphi = P_{\text{v}}/P_{\text{s}}$ are usually known from experiments. Knowing $P_{\text{s}}(T)$, we may represent the isotherm as

$$W = f(P_{\text{v}}, T), \tag{3}$$

where P_{v} is the vapor pressure in the pores. Using (3), we may express P_{v} in terms of the inverse function as

$$P_{\text{v}} = F(W, T). \tag{4}$$

Taking into consideration (4), Eq. (3) may be written as

$$P_{\text{liq}} = P_{\text{s}}(T) + \frac{RT}{v'_{\text{liq}}} \ln \frac{F(W, T)}{P_{\text{s}}(T)}. \tag{5}$$

Thus, formula (5) yields the dependence of the liquid pressure on the moisture content and the temperature in explicit form. Unlike Kelvin formula (2), it takes into account concrete physicochemical properties of the porous sample.

The experimental temperature-dependent sorption isotherms show that with increasing T the liquid pressure increases, thus leading to the effect of thermal moisture conduction.

The upper bound of applicability of (5) is determined by difficulties encountered in experiments aimed at obtaining the isotherms at $\varphi \to 1$. These difficulties have led to the assertion that upon sorption the macropores are not occupied [1]. However, experiments [5] with special temperature-control systems show that at $\varphi \to 1$ the macropores also become filled with the liquid. Therefore Eq. (5) is valid up to complete saturation of the pores with the liquid.

Upon fulfilling the LTE hypothesis, when the phases pass through many equilibrium states in a nonequilibrium process, we have [2-5]

$$I = \rho_d \frac{\partial W}{\partial \tau} = \rho_d \left[\left(\frac{\partial W}{\partial P_v} \right)_T \frac{\partial P_v}{\partial \tau} + \left(\frac{\partial W}{\partial T} \right)_{P_v} \frac{\partial T}{\partial \tau} \right] . \tag{6}$$

Differentiating equilibrium condition (1) with respect to the temperature, we arrive at the well-known Clausius-Clapeyron relation for the specific heat of sorption

$$L_m = \frac{RT^2}{v''_{liq}} \left(\frac{\partial \ln P_v}{\partial T} \right)_W . \tag{7}$$

Using (3), (4), we may write (7) in the form

$$L_m = \frac{RT^2}{v''_{liq}} \left(\frac{\partial \ln F(W, T)}{\partial T} \right)_W . \tag{8}$$

Thus, knowledge of the sorption isotherms is necessary for determination of the mass transfer rate, the dependence of the capillary pressure of the liquid on the moisture content, and the specific heat of sorption.

To explain the abrupt change in moisture content at the boundary of contact of two porous bodies, A. V. Luikov [1] has introduced the notion of a moisture transfer potential in porous bodies.

It has been established experimentally [5] that in an equilibrium state equality of capillary pressures $P^k = P_v - P_{liq}$ holds for pores in the bulk of the entire system for all porous (including colloidal) bodies, i.e., the vapor pressure and the liquid pressure may be considered as potentials. It is pertinent to note that although at equilibrium the chemical potentials of the phases are equal, nevertheless they are independent functions since in different phases the functional relationships of the variables are different, and therefore the number of equations depends on the number of phases [3]. We write now the filtration laws for each phase in the form

$$u_v = - \frac{k f_v(\theta_v)}{\eta_v} \nabla P_v , \quad u_{liq} = - \frac{k f_{liq}(\theta_{liq})}{\eta_{liq}} \nabla P_{liq} , \tag{9}$$

where $f_v(\theta_v)$, $f_{liq}(\theta_{liq})$ are the relative phase premeabilities. Let us denote $D_{liq}(\theta_{liq}) = k f_{liq}(\theta_{liq}) / \eta_{liq}$, where $f_{liq}(\theta_{liq})$ [3] is a monotonically decreasing function of the saturation θ_{liq} of the liquid phase and $D_{liq}(\theta_{liq}) = 0$ at some limiting θ^*_{liq}. At $\theta_{liq} < \theta^*_{liq}$, the liquid passes from a capillary-bound mobile state to an immobile adsorption-bound one [3]. The quantity θ^*_{liq} may be determined by the nuclear magnetic resonance (NMR) method, which also permits determination of the self-diffusion coefficient in a porous body, which is related to $D_{liq}(\theta_{liq})$, e.g., by the Darken equation [6].

For the one-dimensional case in a spherical coordinate system the equations for vapor and liquid motion are

$$m \frac{\partial (\rho_v \theta_v)}{\partial \tau} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{k \rho_v f_v(\theta_v)}{\eta_v} \frac{\partial P_v}{\partial r} \right) + I , \tag{10}$$

$$m \frac{\partial (\rho_{liq} \theta_{liq})}{\partial \tau} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{k \rho_{liq} f_{liq}(\theta_{liq})}{\eta_{liq}} \frac{\partial P_{liq}}{\partial r} \right) - I . \tag{11}$$

To close the system of equations (10), (11) in filtration theory use is made of the universal function of instantaneous saturation [3]

$$P_v - P_{liq} = \sigma \cos \vartheta \, (m/k) \, J(\theta_{liq}) , \tag{12}$$

where ϑ is the wetting angle. Formula (12) was first proposed in [7], $J(\theta_{liq})$ is the Leverett function. The surface tension σ and the wetting angle ϑ are complex functions of temperature and for real media are unknown; therefore such problems as capillary impregnation in a temperature field are, as a rule, not considered. To close Eqs. (10), (11), we will use relation (5), based on the Kelvin formula and sorption isotherms.

In investigations of slow flows, the terms describing the changes in the pressure, the specific volume of the gas, and the convective energy transfer may be ignored. As a result, the energy equation is substantially simplified and in the one-dimensional case in a spherical coordinate system it reads

$$[(1-m)\,c_{\mathrm{d}}\rho_{\mathrm{d}} + m\,(\theta_{\mathrm{v}}\rho_{\mathrm{v}}c_{\mathrm{v}} + \theta_{\mathrm{liq}}\rho_{\mathrm{liq}}c_{\mathrm{liq}})]\frac{\partial T}{\partial \tau} = \frac{1}{r^{2}}\frac{\partial}{\partial r}\left(r^{2}\lambda\frac{\partial T}{\partial r}\right) + L_{\mathrm{m}}I\,. \tag{13}$$

Expression (13) differs from the equations obtained in [1-3] since, first of all, it is closed. Indeed, to calculate the specific heat of a phase transition Eq. (8) may be used, while to determine the mass transfer rate relation (6) may be employed.

The system of equations (10), (11), (13) and closing relations (1)-(8) is applicable to problems of drying, sorption, and filtration with incomplete saturation not only in capillary-porous but also in biological colloidal capillary-porous media since formulas (1), (5), (6), (8) stem from equality of the chemical potentials of the phases but not from the forms of moisture-material binding, provided the LTE hypothesis is fulfilled. It is noted in [8] that the LTE hypothesis is used, in fact, in the Luikov theory of drying [1] for determination of mass transfer potentials, in sorption theory [2] for determination of interphase mass transfer rates, and in two-phase filtration theory for determination of the Leverett function [3]. In [8], use of formulas (1), (5), (6), (8) is substantiated for porous media partially filled not only with water but also with electrolyte solutions.

We now consider the drying process for a biological collloidal capillary-porous material, namely, baker's yeast. To calculate closing relations (5), (6), (8), it is necessary to know the family of desorption isotherms of yeast for the whole temperature range in the drying process.

For a description of the sorption-desorption isotherms of baker's yeast we shall use the approximate formula [5]

$$W_{\mathrm{liq}} = W_{0.5}(T)\left(\frac{P_{\mathrm{v}}}{P_{\mathrm{s}} - P_{\mathrm{v}}}\right)^{1/n}, \tag{14}$$

in which $W_{0.5}(T)$ is the moisture content as a function of temperature at $\varphi = P_{\mathrm{v}}/P_{\mathrm{s}} = 0.5$ or any other reference point; when $\varphi = 0.5$, the index n is constant for the same material. The most numerous group is comprised of materials with $n = 2$. Of the 500 isotherms considered in [9], approximately 350 isotherms have $n = 2$. This group includes almost all building materials, coals, peat, filter paper, etc. In the author's opinion [9], the index n reflects the "degree" of the colloid state of a material. When $n > 2$, it may be said that the material is colloidal and highly dispersed. In the given case, for baker's yeast $n = 3$. For baker's yeast $W_{0.5}(T)$ in formula (14) is of the form

$$W_{0.5}(T) = \begin{cases} 0.1\exp\left(-1.65\cdot 10^{-2}\,(T - T_0)\right), & T \le 30\,^{\circ}\mathrm{C}\,; \\ 0.08\,, & T > 30\,^{\circ}\mathrm{C}\,. \end{cases} \tag{15}$$

A high initial moisture of the biomass, when $\varphi \to 1$ and the properties of the moisture in the micropores do not differ, in fact, from the properties of free water, creates difficulties in using the proposed system of equations in the entire moisture content range since at $P_{\mathrm{v}} \to P_{\mathrm{s}}$, as follows from formula (14), the moisture content tends to infinity. Therefore in numerical modeling of the biomass drying process calculations must be made in two steps, namely, for "moist" and "hygroscopic" states of the material. At $P_{\mathrm{v}} \to P_{\mathrm{s}}$, the pores are almost completely filled with moisture whose properties in the pores differ only slightly from those of free water. Therefore, we may assume that run-off of mass, i.e., evaporation, proceeds only from the body surface, and the pore vapor pressure is determined only by the temperature-dependent pressure of the saturated vapor. In the calculations, the latter has been determined using the approximate formula

$$P_s(T) = 10^5 \left(\frac{T}{373} \right)^{15} , \tag{16}$$

which gives an approximation error of no more than 12% against the tabular value for the considered temperature range 20-80°C. Here it is assumed that the moisture is uniformly distributed with respect to the sample thickness and the interstitial moisture transfer determines, in fact, the mean moisture content. We made these assumptions for the first stage of calculations, when the material was "moist" and the heat of moisture evaporation almost did not differ from that of free water evaporation. In the second stage of calculations, when the mean moisture content of the material corresponded to $W_{cr} = 0.6$ kg/kg, we solved the complete system of equations (10), (11), (13). In so doing, we included volume sinks of heat and mass, which were determined using formula (6). As the initial values T_0, W_0, P_{v0}, we took the results obtained for the moist zone in the first stage of calculations .

We considered a single spherical granule located in an ideally mixed isothermal fluidized bed with the effective heat transfer coefficient α independent of the moisture content of the particle. The medium temperature T_m was assumed equal to the gas temperature at the bed outlet. The heat-transfer coefficient was calculated usinf the formula $\mathrm{Nu} = 1.6 \cdot 10^{-2} (\mathrm{Re}/\varepsilon)^{1.3} \mathrm{Pr}^{1/3}$ [10].

In the calculations we used the following constant parameters: $W_0 = 2.33$ kg/kg, $T_0 = 293$ K, $P_m = 3 \cdot 10^3$ Pa, $m = 0.5$, $L = 2.2 \times 10^6$ J/kg; $D_{v0} = 1 \cdot 10^{-10}$, $D_{liq0} = 1 \cdot 10^{-15}$; $R = 1.25$ mm; $c_{liq} = 4180$ J/(kg·K), $R/\nu'_{liq} = 4.6 \cdot 10^5$ J/(m^3·K), $R/\nu''_{liq} = 462$ J/(kg·K) [11]. The heat capacity coefficient of dry yeast was determined from the dependence $c_d(T) = 189 + 3.82T$ [11]. It was assumed that the granule surface was exposed to a heat flux uniformly distributed over a spherical surface. The structure and the porosity of the material were assumed constant. It was necessary to calculate the nonstationary moisture content and temperature fields and to find the kinetic regularities of the drying process.

The thermal conductivity was determined using the formula [11]

$$\lambda = \begin{cases} 0.04 + 0.5\, W , & W < 0.3 ; \\ -\,0.015 + 0.12\, W + 0.0007\, T , & 0.3 \le W \le 1{,}2 ; \\ 0.0345 + 0.078\, W + 0.0007\, T , & 1.2 < W \le 3 . \end{cases} \tag{17}$$

According to (7) and with account for (14) the specific heat of the phase transition of moisture is

$$L_m = \frac{RT^2}{\nu''_{liq}} \left(\frac{15}{T} - \frac{(n-1)\,(W_{0.5}(T))^{n-1}}{W^n + W_{0.5}^n} \frac{\partial W_{0.5}}{\partial T} \right) , \tag{18}$$

where

$$\frac{\partial W_{0.5}}{\partial T} = \begin{cases} -\,1.65 \cdot 10^{-3} \exp\left(-\,1.65 \cdot 10^{-2} (T - T_0) \right) , & T \le 30\,^\circ\mathrm{C} ; \\ 0 , & T > 30\,^\circ\mathrm{C} . \end{cases}$$

With account for (14) the derivatives in expression (6) are as follows

$$\left(\frac{\partial W}{\partial T} \right)_{P_v} = -\,\frac{15\, W P_s}{n\,(P_s - P_v)\, T} - 0.0165\, W , \tag{19}$$

$$\left(\frac{\partial W}{\partial P_v} \right)_T = \frac{W P_s}{n\, P_v\,(P_s - P_v)} . \tag{20}$$

The anisotropic liquid pressure is determined using expression (5). The boundary conditions are

$$\tau = 0 , \quad T(r,\, 0) = T_0 ; \quad P_v(r,\, 0) = P_{v0} ; \quad P_{liq}(r,\, 0) = P_{liq0} , \tag{21}$$

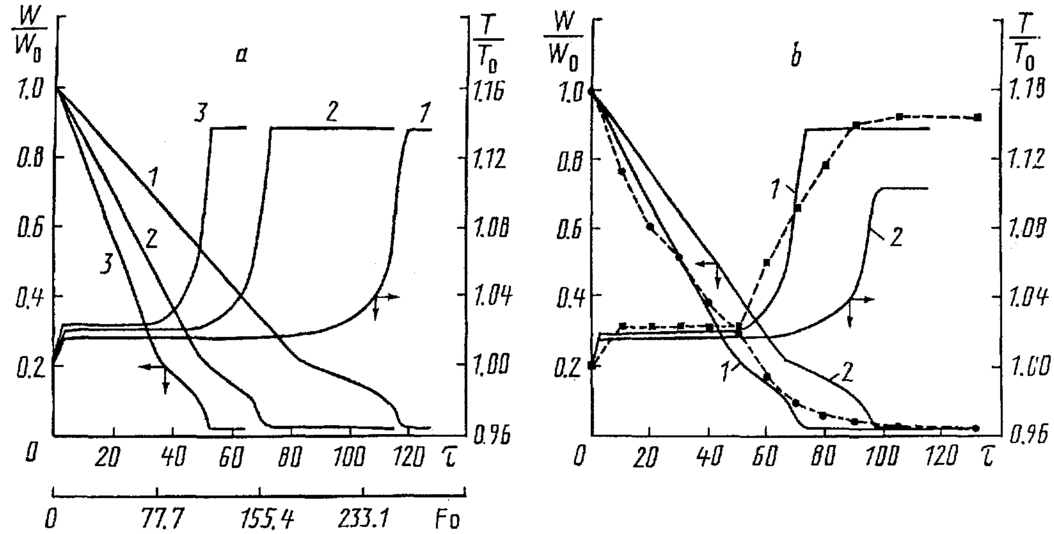


Fig. 1. Kinetic and temperature dependences: a) T_m = 333 K; $\beta = 4 \cdot 10^{-5}$ kg/m^2·sec·Pa: 1) α = 20 W/(m^2·K), 2) 35; 3) 50; b) α = 35 W/(m^2·K): 1) T_m = 333 K; 2) 323. Solid lines, calculation; dot-and-dash lines, experiment [13]. τ, min.

$$r = 0 , \quad \frac{\partial P_v}{\partial r}\bigg|_{r=0} = 0 ; \quad \frac{\partial P_{liq}}{\partial r}\bigg|_{r=0} = 0 ; \quad \frac{\partial T}{\partial r}\bigg|_{r=0} = 0 . \tag{22}$$

The "moist" state of the material is described by

$$r = 1 , \quad \lambda \frac{\partial T}{\partial r}\bigg|_{r=1} = \alpha \left(T_m - T_v\right) - L q_v , \tag{23}$$

$$q_v = D_v \frac{\partial P_v}{\partial r}\bigg|_{r=1} = \beta \left(P_m - P_v\right) , \tag{24}$$

$$D_{liq} \frac{\partial P_{liq}}{\partial r}\bigg|_{r=1} = 0 . \tag{25}$$

The "hygroscopic" state of the material is

$$r = 1 , \quad \lambda \frac{\partial T}{\partial r}\bigg|_{r=1} = \alpha \left(T_m - T_v\right) . \tag{26}$$

The volume heat and mass sinks are included using formula (6); therefore condition (23) turns into ordinary relation (26). In the calculations, we also took into account the dependence of the generalized permeability coefficients of the vapor $D_v = k f_v(\theta_v)/\eta_v$ and the liquid $D_{liq} = k f_{liq}(\theta_{liq})/\eta_{liq}$ on the moisture content [8]:

$$D_v = D_{v0} \left(1 - 0.3 \left(\frac{W}{W_{max}} \right)^2 \right) , \tag{27}$$

$$D_{liq} = D_{liq0} \left(\frac{W - 0.5\, W_{cr}}{W_{max} - 0.5\, W_{cr}} \right)^4 , \quad W_{max} = 1.2\, W_{cr} . \tag{28}$$

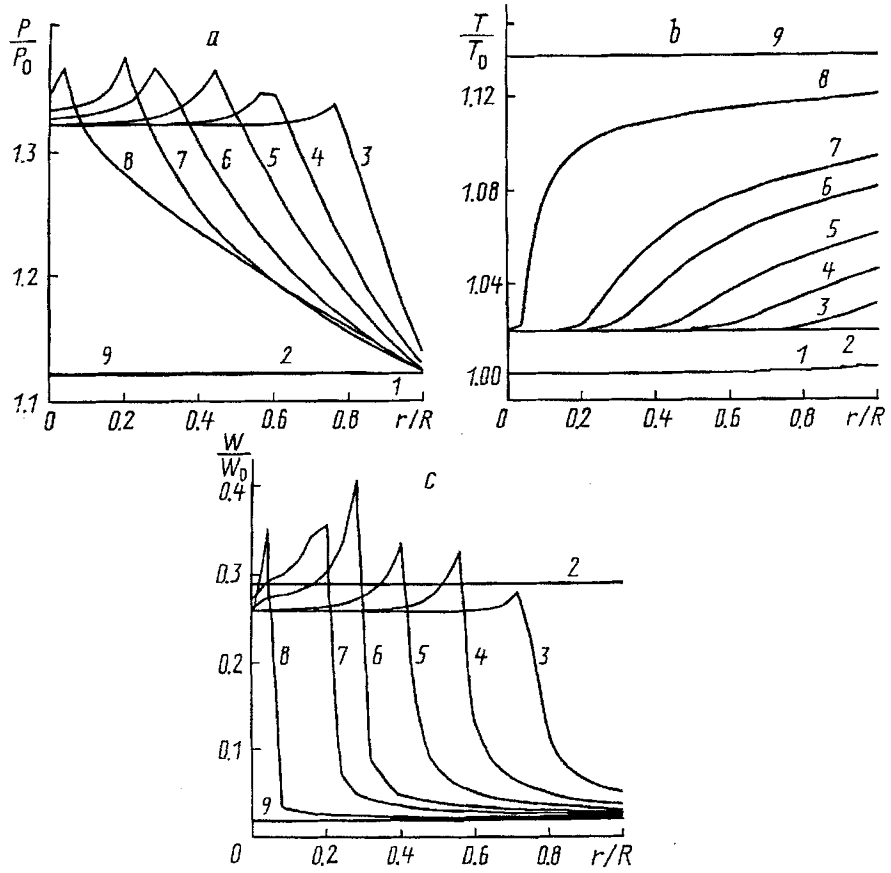
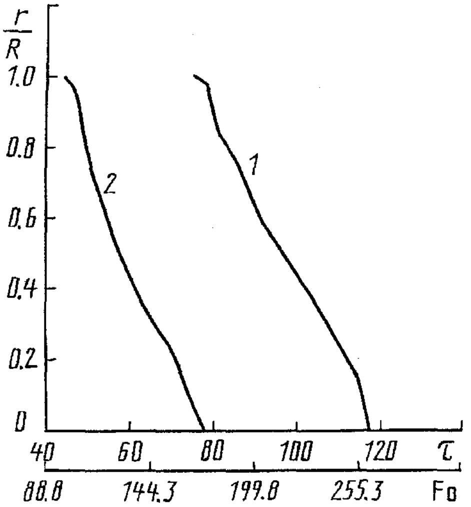


Fig. 2. Fields of vapor pressure (a), temperature (b), moisture content (c): 1) Fo = 0.0577; 2) 98.35; 3) 109.9; 4) 121.4; 5) 133; 6) 144.5; 7) 150.3; 8) 156.1; 9) 167.6 (curve 1 in Fig. 2c is not depicted).

To solve the system of equations, we used a package of applied programs of nonlinear parabolic equations [12]. Calculations were performed with the number of nodes over the radius equal to 51 and 101 and the time step $\Delta\tau = 1.25$ sec, with the minimum permissible time step being $\Delta\tau = 10^{-4}$.

The kinetic and temperature curves in Fig. 1, given for different convective drying conditions, indicate that in the first drying period, characterized by removal of the extracellular moisture (from $W = 2.3$ to 1.1 kg/kg) and some portion of the free intracellular moisture (from $W = 1.1$ to 0.2 kg/kg), the drying rate is constant. At the beginning of the process, when the material is heated, its temperature increases quickly up to the temperature of the freely evaporating water and then remains unchanged. In this period, mass transfer is most vigorous and all the heat transferred to the material is spent for moisture evaporation. Next, when some portion of the bound intracellular moisture is removed, the drying rate decreases, whereas the mean temperature of a granule increases and becomes equal to the gas temperature. With increasing heat transfer coefficient, with all other conditions being equal, the drying and heating rates increase substantially. For instance, with an increase in α from 20 to 50 $\mathrm{W/(m^2 \cdot K)}$, the drying time is cut in half (Fig. 1a). As has been noted earlier, in the period of the "moist" state of the material, temperature and pressure gradients of the vapor are absent. Consequently, the vapor temperature and pressure distributions are uniform over the granule radius (curves 1, Fig. 2). The moisture distribution over the granule radius is also considered to be uniform. In the hygroscopic region, as a result of volume evaporation and an increased resistance to diffusional transfer the vapor is brought into wave motion (curves 3-8, Fig. 2a), with the maximum pressure front being displaced to the granule center. Figure 2b shows the temperature fields, which indicate heating zone motion, as the moisture content decreases, from the granule surface to its center, whose temperature corresponds to the wet-bulb thermometer reading. The moisture content distribution with respect to the granule radius for different moments of time shows that the drying process is accompanied by deepening of



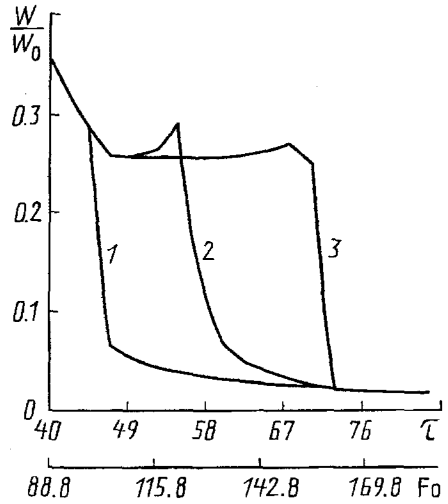


Fig. 3. Deepening of the evaporation zone: $T = 333$ K, 1) $\alpha = 20$ W/(m^2·K); 2) 35.

Fig. 4. Moisture content as a function of time at different points of the granule: 1) $r/R = 1$; 2) 0.52; 3) 0.

the evaporation zone (Fig. 2c). Here, numerical modeling shows that the evaporation zone becomes more distinct. In this zone, an increase in the moisture content is observed, which is due to the effect of heat and moisture conduction and vapor condensation, as a consequence of the increased pressure, since the front of the maximum moisture content and that of the vapor pressure coincide. Curve 1 in Fig. 2c is not depicted since it displays the uniform moisture distribution at the beginning of the drying process. From the relations for deepening of the evaporation zone it is seen that enhancement of heat transfer causes shortening of the first period and, consequently, a faster deepening of the evaporation zone (Fig. 3). The deepening rate of the evaporation zone depends weakly on the amount of heat supplied to the granule surface, which is likely due to the prevailing effect of diffusional resistance to vapor transfer. The plot of moisture content versus Fo in the hygroscopic region at three sites illustrates displacement of the moisture evaporation zone from the surface inward during convective drying (Fig. 4). A comparison of the numerical results and the experimental data [13] for the given parameters (Fig. 1b) shows their satisfactory agreement. Obviously, a decrease in the gas temperature prolongs the drying process and decreases the final temperature of the material. Therefore, it is reasonable to dry baker's yeast and other thermolabile materials by employing multistage convective drying with a gradual decrease in the gas temperature as well as an oscillating temperature regime of drying.

In order to elucidate the influence of the sorption properties of a material on the effects of moisture and heat conduction and to make a comparative analysis, we consider, for instance, an aggregated high-loam soil with an isotherm of the form

$$W = A \exp(-\kappa T) P_{\mathrm{v}} - B \exp(\omega T), \tag{29}$$

where $A = 10^5$, $B = 3 \cdot 10^5$, $\kappa = 4$, $\omega = 5$.

Thermophysical characteristics of the soil are given in [14]. We consider an infinite cylinder located in the soil, with its surface maintained at some constant temperature T_{m}. It is required to find the time variation of the moisture content and temperature fields. For the system of equations (10)-(13) boundary the conditions are

$$\tau = 0, \quad T(r, 0) = T_0, \quad P_{\mathrm{v}}(r, 0) = P_{\mathrm{v}0}, \quad P_{\mathrm{liq}}(r, 0) = P_{\mathrm{liq}0}; \tag{30}$$

$$r = 0, \quad \frac{\partial T}{\partial r}\bigg|_{r=0} = 0, \quad \frac{\partial P_{\mathrm{v}}}{\partial r}\bigg|_{r=0} = 0, \quad \frac{\partial P_{\mathrm{liq}}}{\partial r}\bigg|_{r=0} = 0; \tag{31}$$

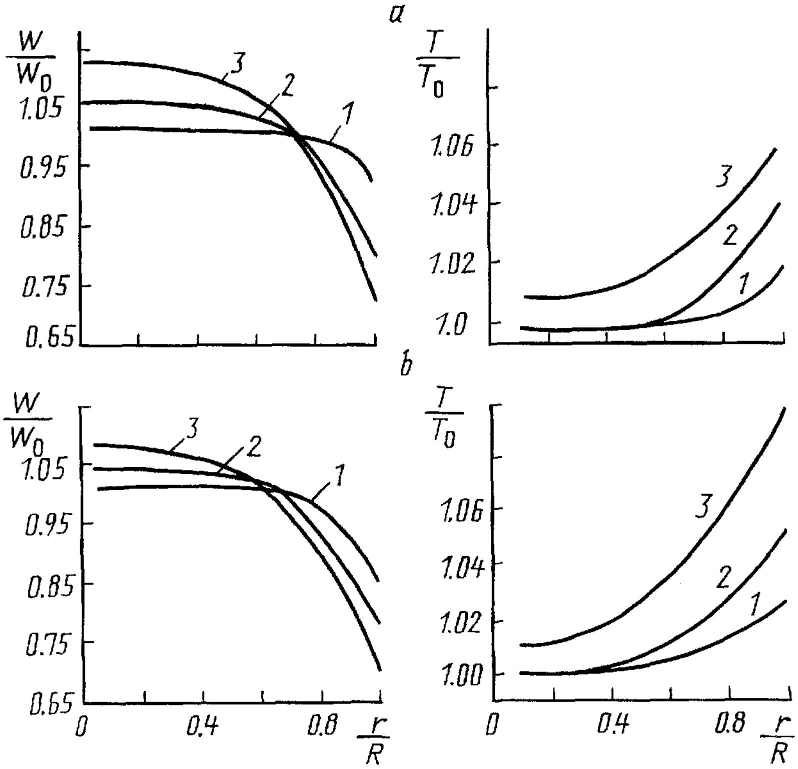


Fig. 5. Moisture content and temperature fields for the soil: a) $\tau = 1.5$ h (1); 4.5 (2); 13.5 (3): b) $\tau = 3$ h (1); 9 (2); 27 (3).

$$r = R\,, \quad T(R\,,\,\tau) = T_{\text{m}}\,, \quad D_{\text{liq}}\frac{\partial P_{\text{liq}}}{\partial r}\bigg|_{r=R} = D_{\text{v}}\frac{\partial P_{\text{v}}}{\partial r}\bigg|_{r=R}\,. \tag{32}$$

Figure 5 shows moisture content and temperature distributions calculated for soils with various transfer coefficients in the liquid and vapor phases. For the first variant (Fig. 5a) $D_{\text{liq}} = 0.5\cdot 10^{-5}$, $D_{\text{v}} = 0.5\cdot 10^{-9}$ and for the second variant (Fig. 5b) $D_{\text{liq}} = 0.1\cdot 10^{-16}$, $D_{\text{v}} = 0.5\cdot 10^{-7}$ are adopted.

Owing to the occurrence of heat and moisture conduction the moisture content increases at "colder" points of the soil. Calculations showed that the intensity of heat and moisture conduction substantially depends on the temperature, the radius of the heat source, the initial moisture content, and the thermophysical properties of the soil. The results obtained are quite consistent with experimental data [14].

A comparison of the evolution of the moisture content fields for the yeast (Fig. 2c) and the soil (Fig. 5) shows that deepening of the evaporation zone is less pronounced for the soil and that the moisture content gradients over the sample radius are not as high for the soil as for the yeast. The heat and moisture conduction effect in the soil is lower. Living cells are thermolabile materials, and their response to temperature effects is much stronger, which should be taken into consideration when choosing a rational technology for their dewatering to keep the cells viable.

NOTATION

D, generalized permeability coefficient; c, heat capacity, J/(kg·K); f, relative phase permeability; k, permeability coefficient, m^2; L, specific heat of evaporation of water, J/kg; L_{m}, heat of desorption, J/kg; m, porosity of the material; P, pressure, Pa; R, universal gas constant, J/(kmole·K); r, radial coordinate, m; T, temperature, K; u, velocity, m/sec; ν'_{liq}, molar volume of the liquid, kmole/m^3; ν''_{liq}, molar mass of the liquid, kmole/kg; W, moisture content of the material, kg/kg; α, heat transfer coefficient, W/(m^2·K); β, mass transfer coefficient, kg/m^2·sec·Pa; ε, voidage of the fluidized bed; η, dynamic coefficient of viscosity, Pa·sec; θ, saturation of the porous medium; λ, thermal conductivity, W/(m·K); ρ, density, kg/m^3; τ, time, sec; φ, relative moisture content; Nu, Re, Pr, Fo, Nusselt, Reynolds, Prandtl, Fourier numbers. Subscripts: v, vapor; m, medium; d, dry material; liq, liquid; s, saturated state; 0, initial value.

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