HEAT AND MOISTURE TRANSFER IN A STATIONARY DISPERSED LAYER OF VEGETABLE MATERIALS WITH COMBINED POWER INPUT

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The results of modeling and investigating heat and moisture transfer in a stationary dispersed layer of vegetable materials with convective and cyclic SHF-convective power input are presented. The mathematical model is made up of equations for conservation of gas-phase mass, filtration, and heat and moisture transfer in phases accounting for internal resistance to transfer of heat and moisture in particles in calculating the processes of heat and mass transfer and on the basis of deepening the evaporation zone. The conformity of the calculated results with the experimental data using the example of drying sliced potato particles and the possibility of stepping up the process of dehydration is shown.

Keywords: *heat and moisture transfer in a stationary layer, drying of vegetable materials, SHF-convective drying.*

Introduction. The processes of drying vegetable materials relating to colloid capillary-porous bodies, as a rule, require significant energy costs. This is due to the heat consumption for the moisture phase transition, the high initial moisture content of the materials, their thermolabile properties preventing the use of high temperatures for treatment, and also, in many cases, due to an inefficient power input resulting in energy losses.

More recently, due to the aggravation of the problem of energy saving and the intention to reduce the cost of production, the efforts of many investigators are focused on looking for ways to raise the efficiency of the existing technologies and developing radically new ones. Note that in this area of science and technology, the researchers′ attention is attracted by the use of combined pulse and oscillating electromagnetic-convective methods of heat and moisture treatment of materials, and also regimes of vacuum or freeze-drying impacts in combination with SHF (superhigh-frequency) and IR radiation [1–4]. This is due to the fact that such methods of power input make it possible to create soft regimes of thermal action and to raise the process efficiency. For example, in [2], it is shown that the use of IR radiation in heat treatment as an initial pulse of external action on a wet product significantly intensifies the dehydration of fruits, reduces energy expenditures by 25–35%, improves the quality of the final product, and results in a decreased loss of vitamins. Investigations into the oscillating SHF convective method of drying some vegetable materials in stationary [3] and fluidized beds [4] are indicative of a reduction in the time of dehydration and energy expenditures.

For drying and heat treatment of vegetable origin materials, wide use is made of devices with dense stationary or quasi-stationary disperse layer (bed) systems with convective heat input, for example, belt-type, conveyor, and chamber rack installations. However, in most cases, they have comparatively high heat rates and waste heat-transfer-agent-related losses.

In investigating and optimizing the drying process parameters, an important role is played by the methods of calculation. To model the processes of heat and mass transfer, wide use is made of the continuum mechanics method. In [3], a description is given of the heat and mass transfer in a dense dispersed layer for the case of convective and convective-microwave heating. Two-phase models are considered; however, no account is taken of the internal thermal and diffusion resistance in wet particles and of their sorptive properties.

There is an approach to modeling heat and mass transfer in porous multicomponent systems based on the molecular-radiation theory of transfer [5]. An expression has been obtained for specific intensity of evaporation on the basis of the Arrhenius formula. In this case, the evaporation intensity is determined by the thickness of the boundary layer in which the evaporation process occurs.
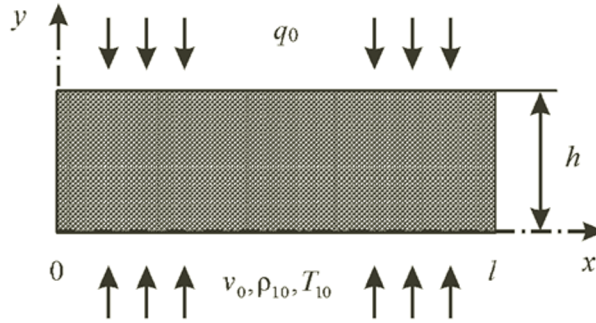
Fig. 1. Diagram of a dispersed layer and energy impact.

In [6], a mathematic model is given of an adsorption heat regenerator (a system of adsorbers with a dispersed layer) made up of the equations of physical and chemical adsorption kinetics and the equations of heat and mass transfer on the basis of the theory of two-phase filtration.

In describing heat transfer in disperse media, single-component homogeneous models are used. These models allow equating the temperatures of the phases (components), which makes it possible to reduce them to one equivalent equation [7, 8]. Their relative simplicity made it possible to obtain a number of analytical solutions. However, for unsteady-state processes with periodic variation in the parameters of the heat-transfer agent or periodic energy impact, the difference in the temperatures of the gaseous and dispersed phases can be substantial, which in turn can result in major errors.

Problem Formulation and Mathematical Model. A layer of immobilized wet dispersed material is considered (Fig. 1). The layer of the material is blown through from bottom to top with a heat-transfer agent, viz. heated air. To intensify heat- and mass-transfer processes, the dispersed layer is exposed to SHF radiation from above, which can be assigned to be both constant and pulsing with time. It is possible to create an oscillating convective (thermal, hydrodynamic) impact. Such regimes of unsteady-state energy impact on a wet material can provide sparing conditions of thermal impact and reduce the heat rate for the process of moisture removal.

The mathematical model includes the following equations:

the gas-phase mass conservation equation

$$\frac{\partial \rho_1}{\partial \tau} + \nabla \cdot (\rho_1 \mathbf{w}) = j_{vp} ; \tag{1}$$

Darcy's equation of motion

$$\mathbf{v} = -\frac{k}{\mu} \nabla p , \tag{2}$$

where $\mathbf{v}$ is the gas velocity calculated for the corresponding cross-sectional area of the dispersed layer, i.e., the filtration velocity, $\mathbf{v} = \mathbf{w}\varepsilon$ m/s. Then

$$\frac{\partial (\overset{\circ}{\rho_1} \varepsilon)}{\partial \tau} + \nabla \cdot (\overset{\circ}{\rho_1} \mathbf{v}) = j_{vp} ; \tag{3}$$

the equation for vapor transfer in a dispersed (granular) layer

$$\frac{\partial (\overset{\circ}{\rho}_{vp} \varepsilon)}{\partial \tau} + \mathbf{v} \nabla \overset{\circ}{\rho}_{vp} = \nabla \cdot (D_{vp.eff} \nabla \overset{\circ}{\rho}_{vp}) + j_{vp} ; \tag{4}$$

the equation of heat transfer in the layer's gaseous phase

$$c_1 \overset{\circ}{\rho_1} \left(\varepsilon \frac{\partial T_1}{\partial \tau} + \mathbf{v} \nabla T_1 \right) = \nabla \cdot (\lambda_{1eff} \nabla T_1) - \alpha S_{sp} (T_1 - T_2) . \tag{5}$$

The effective coefficients of thermal conductivity of the gaseous phase and vapor diffusion as functions of the filtration velocity were taken into account using the following expressions in the direction of the corresponding axes: $\lambda_{1y.\text{eff}} = \lambda_1(\varepsilon + 0.5\text{Pe})$ $\lambda_{1x.\text{eff}} = \lambda_1(\varepsilon + 0.1\text{Pe})$, and $D_{\text{vp.eff}} = D_{\text{vp}}\varepsilon + 0.5d_{\text{pt}}\mathbf{v}$ [9, 10].

The equation of moisture transfer in the solid phase can be written as

$$(1 - \varepsilon)\frac{\partial U}{\partial \tau} = \nabla \cdot (D_{\text{eff}}\nabla U) - j_{\text{vp}} .$$ (6)

The equation of heat transfer in the solid phase of the layer is the following:

$$c_2\rho_2(1 - \varepsilon)\frac{\partial T_2}{\partial \tau} = \nabla \cdot (\lambda_{2\text{eff}}\nabla T_2) + \alpha S_{\text{sp}}(T_1 - T_2) - r_{\text{vp}}j_{\text{vp}} + (1 - \varepsilon)I .$$ (7)

The intensity of mass transfer from the solid phase to the gaseous phase is found by the following expression:

$$j_{\text{vp}} = \beta_u S_{\text{sp}}[u - u_{\text{eql}}(p_{\text{vp}}, T_1)] ,$$ (8)

where the partial pressure of water vapor in the layer p_{vp} is determined from the equation of state.

To describe a sorption (desorption) isotherm of materials, an approximation formula is used [11]:

$$u_{\text{eql}} = u_{0.5}(T)\left(\frac{p_{\text{vp}}}{p_{\text{sat}} - p_{\text{vp}}}\right)^{1/n} ,$$ (9)

where $u_{0.5}(T) = A\exp[-B(T - T_0)]$ is equilibrium moisture content as a function of temperature at $\varphi = p_{\text{vp}}/p_{\text{sat}} = 0.5$. The exponent n is constant for one and the same material. As a result of approximation of the data from [12], for potatoes the exponent is approximately equal to $n = 2.4$, and the constants are $A = 0.135$, $B = 0.0087$, and $T_0 = 293$ K.

Two methods are used to account for the moisture transfer in the particles of the layer material. In the first method, diffusion moisture transfer is taken into account in determining the mass-transfer coefficient. The latter is determined as a mass-transfer coefficient accounting for the resistance to mass transfer from the particles' surface and the pore-diffusion resistance to moisture transfer by the formula [13]

$$\beta_u = \frac{1}{\dfrac{1}{\beta_u'} + \dfrac{1}{\chi\beta_u''}} ,$$ (10)

where the coefficient determined by the resistance to moisture diffusion is $\beta_u'' = (\beta''/(R_{\text{vp}}T_2))(p_{\text{sat}}/u_0)$, $\beta'' = 2\pi^2 D/(3d_{\text{pt}})$.

The second method is based on a description of the evaporation zone deepening with account taken of the filtration resistance and mass-transfer resistance. The vapor flow in the dry zone from the evaporation boundary to the particle surface can be represented as

$$J_{\text{vp}} = \frac{4\pi D'R\xi}{\xi - R}(p_{\text{vp.srf}} - p_\xi) ,$$ (11)

where $D' = \rho_{\text{vp}}k_{\text{vp}}/\mu_{\text{vp}}$. Then the velocity of the evaporation boundary deepening is described by the equation

$$\frac{d\xi}{d\tau} = \frac{D'}{U_0}\frac{R}{\xi(\xi - R)}(p_{\text{vp.srf}} - p_\xi) .$$ (12)

We can write for the vapor flow on the particle surface

$$\frac{D'\xi}{R(\xi - R)}(p_{\text{vp.srf}} - p_\xi) = \beta_p(p_{\text{vp.srf}} - p_{\text{vp}}) .$$ (13)

With account of (13), Eq. (12) will assume the form

$$\frac{d\xi}{d\tau} = -\frac{\beta_p D'R^2}{U_0\xi[D'\xi - \beta_p R(\xi - R)]}(p_\xi - p_{\text{vp}}) .$$ (14)

The evaporation boundary coordinate is connected with moisture content by the relation $\xi = R\sqrt[3]{U/U_0}$. Then the intensity of mass transfer from the solid phase to the gaseous phase will be written as

$$j_{vp} = \frac{3(1 - \varepsilon)\beta_p D'}{D'R - \beta_p R^2(1 - \sqrt[3]{U_0/U})} \, (p_\xi - p_{vp}) \,. \tag{15}$$

It is assumed that the vapor partial pressure on the evaporation boundary corresponds to the saturation vapor pressure. The density of the gas mixture and the water vapor is determined by the ideal gas law

$$\rho_1^\circ = p \, \frac{M_1}{R^* T_1} \,, \quad \rho_{vp}^\circ = p_{vp} \, \frac{M_{vp}}{R^* T_1} \,. \tag{16}$$

The quantity of heat released in the material particles under the action of electromagnetic radiation is equal to

$$I = \delta(\tau) k' q (1 - R_{rfl}) \, \exp\left[-k'(h - y)\right] \,, \tag{17}$$

where $\delta(\tau)$ is a periodic (pulse) function of time, $q = q_0 / [(1 - \varepsilon)(1 - \exp(-k'h))]$, and q_0 is the density of the electromagnetic radiation flux incident on the surface of the layer, W/m^2.

The moisture conductivity coefficient is found from the empirical formula [14]

$$D(u, T) = a_0 \, \exp(-a_1/u) \, \exp(-a_2/T) \,, \tag{18}$$

where $a_0 = 1.29 \cdot 10^{-6}$, $a_1 = 0.0725$, and $a_2 = 2044$. Equation (18) is true in the range of the parameters $0.01 < u < 5$ kg/kg and $333 < T < 373$ K.

The specific heat of moisture evaporation is found from the Clausius–Clapeyron equation

$$r_{vp} = \frac{R^* T^2}{M_{vp}} \left(\frac{1}{p_{sat}} \frac{\partial p_{sat}}{\partial T} - \frac{n u_{0.5}^{n-1}}{u_{0.5}^n + u_{eql}^n} \frac{\partial u_{0.5}}{\partial T} \right) , \tag{19}$$

where $\partial u_{0.5}/\partial T = -B u_{0.5}(T)$. The pressure of saturated water vapor p_{sat} in the temperature range from 0 to 100°C is determined from an approximate Antoine equation:

$$p_{sat} = 133.3 \cdot 10^{8.074 - \frac{1733}{t + 233.84}} \,. \tag{20}$$

The coefficient of water vapor diffusion in the air is equal to

$$D_{vp} = D_0 \, \frac{p_0}{p} \left(\frac{T}{T_0} \right)^{3/2} , \tag{21}$$

where $D_0 = 22 \cdot 10^{-6}$ m^2/s, $p_0 = 101{,}325$ Pa, and $T_0 = 273$ K.

The heat-transfer coefficient in a stationary granular bed is determined from the expression [15]:

$$Nu_{eqv} = 0.395 \, Re_{eqv}^{0.64} \, Pr^{0.33}, \tag{22}$$

where $Re_{eqv} = v d_{eqv}/\nu = 4v/(S_{sp}\nu)$.

The heat-transfer coefficient is calculated with account for the thermal resistance to the particles' heat conduction from the formula [13]:

$$\alpha = \frac{1}{\dfrac{d_{eqv}}{\lambda_1 Nu_{eqv}} + \dfrac{3}{2} \dfrac{d_{pt}}{\pi^2 \lambda_{pt}}} \,. \tag{23}$$

If we assume analogy of the processes of heat and mass transfer, the coefficient of mass transfer is determined from a formula similar to formula (22).

The system of equations was solved with the following boundary conditions (Fig. 1). For the gas-phase mass conservation equation (3): $-\mathbf{n}\cdot\mathbf{v}|_{x=0;x=l} = 0$, $-\mathbf{n}\cdot\mathbf{v}|_{y=0} = v_0$, and $p|_{y=h} = p_0$. For the vapor-transfer equation (4): $\mathbf{n}\cdot(-D_{vp.eff}\nabla\rho_{vp}^{\circ} + \rho_{vp}^{\circ}\mathbf{v})\big|_{x=0;\,x=l} = 0$ is the impermeability condition; $\rho_{vp}^{\circ}\big|_{y=0} = \rho_{vp0}^{\circ}$; $\mathbf{n}\cdot(-D_{vp.eff}\nabla\rho_{vp}^{\circ} + \rho_{vp}^{\circ}\mathbf{v})\big|_{y=h} = 0$. For the gas-phase heat-transfer equation (5): $-\mathbf{n}\cdot(-\lambda_{1eff}\nabla T_1)\big|_{x=0;\,x=l} = 0$, the boundaries are heat-insulated; $T_1|_{y=0} = T_{10}$ and $\mathbf{n}\cdot(-\lambda_{1eff}\nabla T_1)\big|_{y=h} = 0$. For the solid-phase moisture transfer equation (6): $\mathbf{n}\cdot(-D_{eff}\nabla U)\big|_{\substack{x=0;\,x=l;\\ y=0;\,y=h}} = 0$. For the solid-phase heat-transfer equation (7): $-\mathbf{n}\cdot(-\lambda_{2eff}\nabla T_2)\big|_{x=0;\,x=l} = 0$ and $\mathbf{n}\cdot(-\lambda_{2eff}\nabla T_2)\big|_{y=0;\,y=h} = 0$.

The change in the height of the bed due to shrinkage in drying was not taken into account, and allowance was made for the addition of particles with the same properties to the layer, since this occurs, e.g., in drying in belt-type installations when the material is transferred from one belt to another.

Discussion of Calculation Results and Their Comparison with Experimental Data. Heat and mass transfer was investigated in a stationary layer of "Vector"-variety potato particles. The layer was blown through with heated air from bottom to top. The initial height of the layer was 40 mm. The particles were cubes with dimensions of $7 \times 7 \times 7$ mm and parallelepipeds with a cross section of 7×7 mm and a length of 40–60 mm. The air velocity calculated for the layer cross section was on average about 2 m/s, and its temperature at the layer inlet was 70°C. The mass of the layer was determined at assigned intervals of time. As a result, drying kinetics curves were obtained. For analogous conditions, a numerical solution of the above-mentioned system of equations for unsteady-state two-dimensional heat and mass transfer in a layer with convective heat input was obtained. Furthermore, certain data were obtained for the case of exposure to electromagnetic SHF radiation directed at the layer from top to bottom.

The main parameters used for calculations were $k = 1\cdot10^{-8}$ m^2, $\mu_1 = 20\cdot10^{-6}$ Pa·s, $c_1 = 1.006$ kJ/(kg·K), $\lambda_1 = 0.029$ W/(m·K), $D_{eff} = 5\cdot10^{-12}$ m^2/s, $\lambda_{2eff} = 0.1$ W/(m·K), $R^* = 8314.2$ J/(kmole·K), $M_{vp} = 18.02$ kg/kmole, $\rho_{dr} = 175$ kg/m^3, $u_0 = 5.2$ kg/kg, $U_0 = 910$ kg/m^3 of the solid phase, $S_{sp} = 428.6$ m^2/m^3, $v_0 = 2$ m/s, $h = 0.04$ m, $T_{10} = 343$ K, $d_{eqv} = 0.00467$ m, $q_0 = 1.6\cdot10^4$ W/m^2, $d_{pt} = 2R = 0.00869$ m, $R_{rfl} = 0.05$, $k_{vp} = 5\cdot10^{-15}$ m^2, $k' = 83$, $\varepsilon = 0.5$, and $a_0' = S_{pt}/V_{pt} = 857.1$ 1/m.

A comparison of the calculated data under a model accounting for moisture-diffusion resistance inside the particles in the mass-transfer coefficient with the experimental data is indicative of their satisfactory agreement (Fig. 2). Furthermore, using the model to calculate the evaporation zone also yields agreement with the experimental data. The drying curve has an approximately exponential form with a long duration of the period of decreasing velocity. Hence, there is a predominantly intradiffusion moisture transfer which does determine the time of dehydration. The drying kinetics is influenced by the particles′ shape. It is seen from the experimental data that the velocity of drying a layer of particles in the form of cubes with dimensions of $7 \times 7 \times 7$ mm is higher than in the case of a layer made up by particles having the shape of parallelepipeds with a cross section of 7×7 mm and a length of 40–60 mm. The average temperature of the layer of particles demonstrates the fastest rise of the beginning of the process and tends asymptotically to the gas temperature.

The rate change in the particles′ temperature depends on a number of factors; in particular, it is significantly influenced by the gas-flow velocity whose increase results in a marked rise of the particles′ temperature (Fig. 2b).

The water-vapor concentration rises rapidly in the initial period of the process and becomes higher in the upper cross sections of the layer. With the passage of time, it decreases monotonically and tends to the value at the layer inlet (Fig. 3a). Wet particles have a higher moisture content in the upper layer cross sections, which is due to the rise in the water-vapor concentrations and the drop in the driving force of the process. In the process of dehydration, the particles′ moisture content tends to an equilibrium value (Fig. 3b).

The temperature of the gaseous phase at the layer inlet was maintained constant and equal to 70°C. The layer had the initial temperature of 30°C. The gas temperature of the layer at the initial instant of time is equal to the temperature of the particles, and then, with the passage of time, it rises to values close to the temperature at the inlet (Fig. 4a). The upper layers have a lower temperature, and only at the end of the drying process does their temperature approach the gas temperature. As the gas velocity rises, the temperature equalization in the layer occurs much faster.

An investigation was made into the influence of the effective coefficients of thermal conductivity of the gas λ_{1eff} and diffusion of the vapor $D_{vp.eff}$ as functions of filtration velocity on the parameters of heat and moisture transfer in the layer. The calculations were conducted with account of the dependence of these coefficients on filtration velocity and at their constant values corresponding to a filtration velocity equal to zero. It is seen from Fig. 2b and 4a that the average temperature of the layer particles (curve 1′) and the local gas temperature in the layer (curve 3′) are somewhat lower at constant effective coefficients; however, the deviation is insignificant even at a filtration velocity of 2 m/s. With decrease in the filtration velocity, this deviation is even smaller. The water vapor density or concentration (Fig. 3a) and the moisture content of the layer particles (Fig. 3b) are somewhat higher at constant coefficients, but this difference for the investigated parameters of the process is not large either.
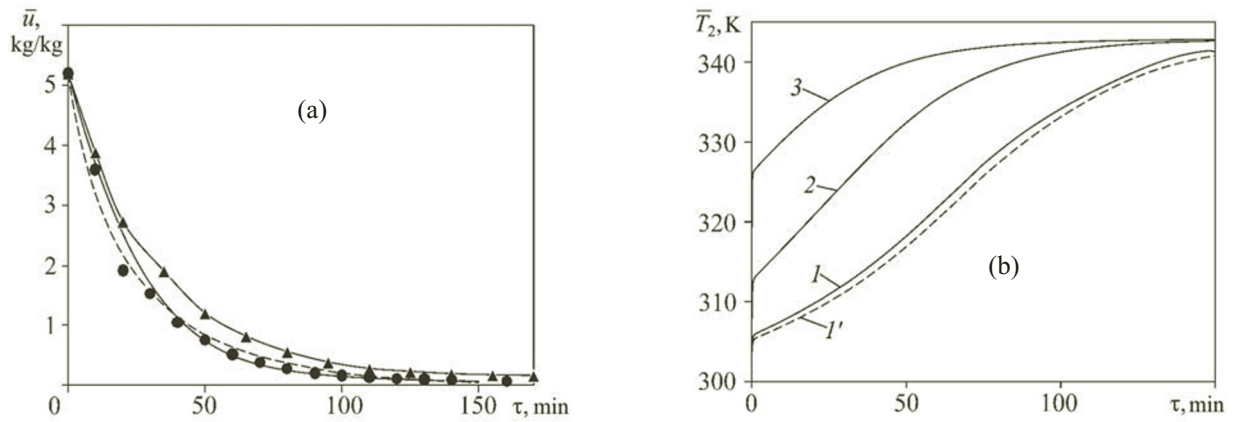
Fig. 2. Average moisture content (a) and temperature (b) of the particles versus time with convective heat input: a) the solid line is the calculation under the mass transfer model, the dots are the experiment (• is the cubes with dimensions of $7 \times 7 \times 7$), the solid line with ▲ dots is the experiment with particles in the form of parallelepipeds with a cross section of 7×7 and a length of 40–60 mm, the dashed line is the calculation under the model of the evaporation zone deepening ($v_0 = 2$ m/s); b) 1, $v_0 = 0.2$; 2, 0.5; and 3, 2 m/s; $1'$ is the calculation at constant effective thermal conductivity coefficients of the gas and constant effective coefficients of diffusion of the vapor.
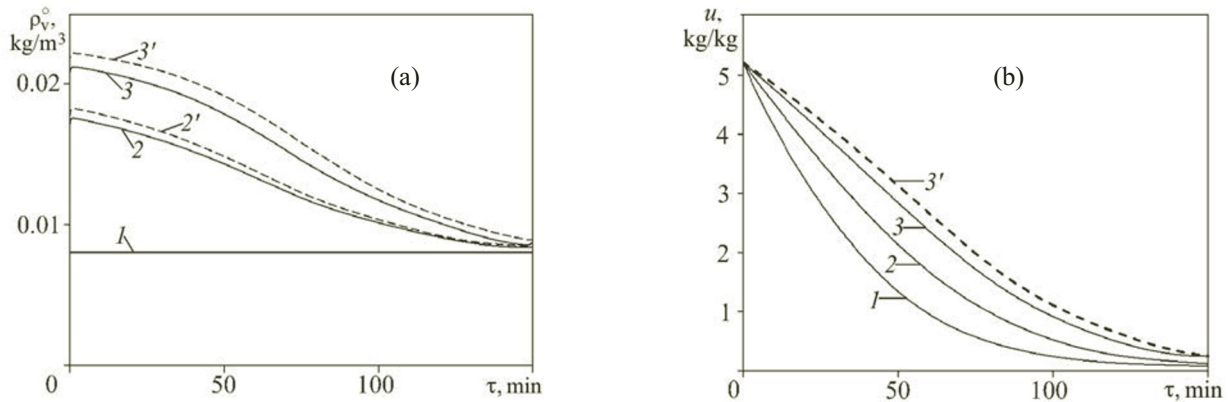

Fig. 3. Dependences of the vapor concentration (a) and moisture content of the particles in different cross sections of the layer at $v_0 = 0.2$ m/s and $x = 0.125$ m: 1) $y = 0$, 2) 0.2, and 3) 0.4 m; $2'$ and $3'$, calculation at constant effective coefficients of thermal conductivity of the gas and diffusion of the vapor.

The specific heat of evaporation of bound moisture varies with time significantly (Fig. 4b). At the beginning of the process, it somewhat drops, which is due to the rise in the particles′ temperature. Further on, due to the reduction in the moisture content and upon the removal of bound moisture, the specific heat of evaporation rises significantly, which is due to the moisture–material bond energy. Since the particles have a higher moisture content in the upper layer, the specific heat of evaporation for them is lower.

Calculations were performed for heat and mass transfer in a dispersed layer at a combined SHF-convective energy impact. In this case, SHF radiation was supplied either only at the beginning of the process (at $\tau < 900$ s, in steps) or in a step-pulsed mode, i.e., at first, use was made of exposure to SHF radiation with a constant flux density, then pulsewise with time ($900 \leq \tau \leq 3600$ s), and further on ($\tau < 3600$ s), heat input was only by convection from the gas flow (Fig. 5).

The exposure to SHF radiation leads to a rise in the velocity of the drying process and a reduction in its duration due to additional heat input to wet particles. The rate of heating the particles in the initial period rises markedly and, in the step mode, becomes higher than for the convective heat input. When the radiation-flux density is high, there is a danger of
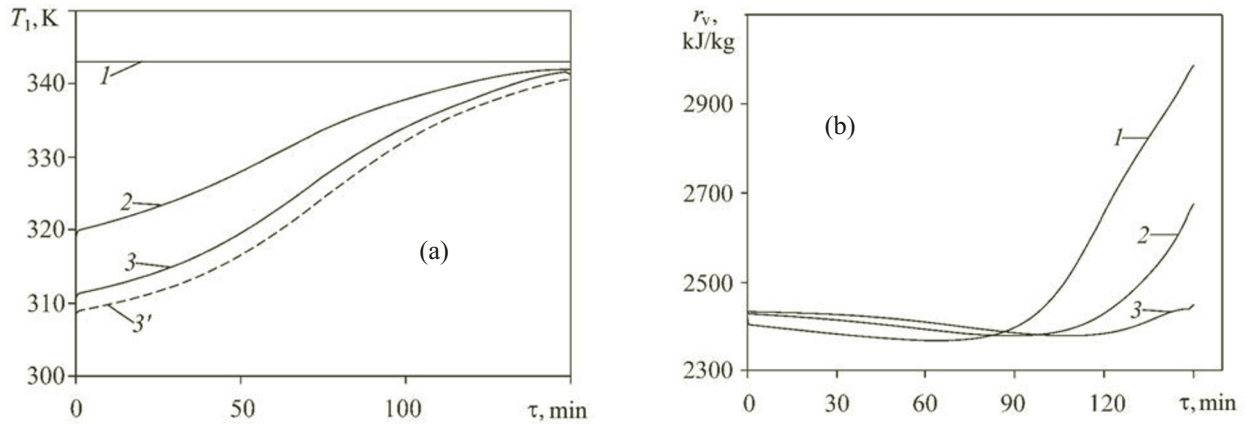
Fig. 4. Dependences of the gas temperature (a) and specific heat of vaporization (b) in different cross sections of the layer at $v_0 = 0.2$ m/s, and $x = 0.125$ m: 1) $y = 0$, 2) 0.2, and 3) 0.4 m; 3′, calculation at constant effective coefficients of thermal conductivity of the gas and diffusion of the vapor.
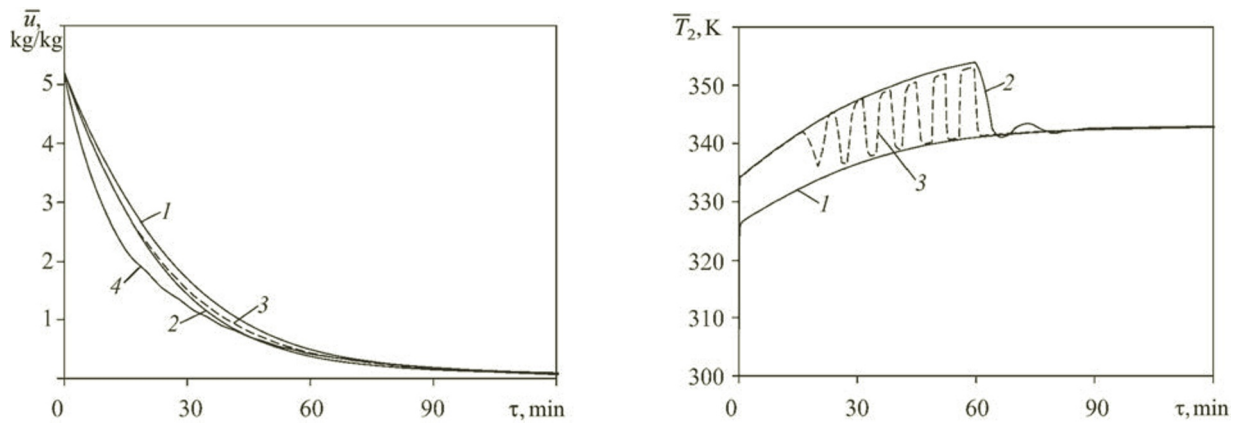

Fig. 5. Average moisture content (a) and average temperature of the particles (b) in the layer vs. time with combined convective-SHF power input: 1) convective heat input; 2) heat input by convection and stepped SHF radiation; 3) by convection and step-pulsed SHF radiation; 4) calculation under the evaporation-zone-deepening model.

overheating the particles and reducing their quality. In connection with this, it is expedient to use pulsed radiation which reduces the duration of the high-temperature action. When the SHF radiation is switched off, the particles′ temperature decreases rapidly and tends to the gas temperature. However, the pulsed-step mode leads to a certain deceleration of the process (curve 3, Fig. 5a). The calculations were performed under two models (curves 2 and 4) whose analysis indicates that the model with the evaporation zone deepening leads to a higher rate of the process in the first period of drying.

Conclusions. The kinetics and dynamics of the drying process have been studied on the basis of modeling and conducting experimental investigations into the heat and moisture transfer in a stationary layer of vegetable materials using the example of sliced potato particles in convective and combined energy impact. Agreement between the calculated results and experimental data and also the possibility of intensifying the process have been shown.

NOTATION

c, specific heat, J/(kg·K); d_{pt} and d_{eqv}, equivalent diameter of particles and channels, m; h, layer height, m; k and k_{vp}, permeability coefficients of the layer and the particle dry zone, m^2; $k′$, absorption coefficient; M, molecular mass, kg/kmole;

$\text{Nu}_{\text{eqv}} = \alpha' d_{\text{eqv}}/\lambda_1$ and $\text{Nu}'_{\text{eqv}} = \beta d_{\text{eqv}}/D_{\text{vp}}$, thermal and diffusion Nusselt numbers; $\text{Pr} = \nu/\alpha$, Prandtl number; $p_{\text{vp.srf}}$, p_ξ, and p_{vp}, vapor pressure on the particle surface, the evaporation boundary, and the layer pores respectively, Pa; Re_{eqv}, Reynolds number; r_{vp}, specific heat of vaporization, J/kg; R, particle radius, m, $R = d_{\text{pt}}/2$; R^*, universal gas constant, J/(kmole·K); R_{rfl}, reflection coefficient; R_{vp}, gas constant for the water vapor, J/(kg·K); S_{sp}, specific surface area of the layer, m^2/m^3; T, temperature, K; u, moisture content of the particles, kg/kg, $u = U/\rho_{\text{dr}}$; U, volumetric moisture content, kg/m^3 of the particle; U_0, volumetric moisture content of the particle corresponding to the beginning of the deepening of the evaporation zone, kg/m^3; $\mathbf{w}$, vapor velocity in the gaps between the layer particles, m/s; $\mathbf{v}$, gas velocity calculated per cross-sectional area of the layer, $\mathbf{v} = \mathbf{w}\varepsilon$ m/s; α, heat-transfer coefficient, W/(m^2·K); β'_u, $\beta_p \Delta p_{\text{vp}}/\Delta u$, mass transfer coefficient referred to the difference of moisture contents, kg/(m^2·s·kg/kg); $\beta_p = \beta/(R_{\text{vp}}\overline{T})$, mass-transfer coefficient referred to the difference of partial vapor pressures, kg/(m^2·s·Pa); β, mass-transfer coefficient referred to the difference of concentrations, kg/(m^2·s·kg/m^3); ε, layer porosity; $\chi = \rho_{\text{lq}}/\rho_{\text{vp}}$, equilibrium solubility; λ, thermal-conductivity coefficient, W/(m·K); μ_{vp}, vapor dynamic-viscosity coefficient, Pa·s; ν, kinematic viscosity; ρ_1° and ρ_1, true and reduced densities of the gaseous phase (dry air and water vapor), kg/m^3, $\rho_1 = \varepsilon\rho_1^\circ$; ρ_2 and ρ_{vp}, densities of wet and dry particles, kg/m^3. Subscripts: 0, initial state; 1 and 2, gaseous and solid phases; sat, saturated state; rfl, reflection; vp, vapor; srf, surface; eql, equilibrium state; sp, specific; pt, particle; eqv, equivalent; eff, effective; ξ, evaporation boundary; –, averaging sign.

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