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Modelling of the Heat and Mass Transfer in Vegetable Materials during Combined Microwave Convective Heating

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Running title: **Combined Microwave Convective Heating and Modeling of Heat and Mass Transfer Process**

Abstract
The paper discusses the results of mathematical modeling of the interrelated processes of heat and moisture transfer specifying the influence of the operating parameters on the drying dynamics and kinetics of vegetable raw materials in the process of combined convective and impulse electromagnetic microwave action.

Practical applications
The proposed model can be used to optimize the technological parameters of combined microwave-convective drying of vegetable materials and to control the process.

Key words: heat and moisture transfer, drying, drying kinetics and dynamics, vegetable materials

Introduction

In a high-frequency electromagnetic field the heating of dielectric materials is based on the effect of different kinds of polarization (electron, ion, or dipole). The high-frequency energy expended in the polarization (charge displacement) of a dielectric transforms to heat. The entire bulk of the material is thereby heated simultaneously, comparatively rapidly and uniformly. Under convective, conductive, and infrared irradiation, when the sizes of the body are much larger than the radiation penetration depth, heat transfer from the outside to the inside of the material occurs due to the heat conduction. Unlike the above techniques, rational selection of the microwave radiation frequency and the heat treatment chamber parameters will permit obtaining a relatively uniform heat release throughout the bulk of the material. The specific feature of drying materials in the field of rf and microwave-frequency currents is rapid and comparatively uniform bulk heating creating a certain temperature gradient directed to the inside of the sample. This is due to the fact that the temperature of the surface layers of the material is lower than the temperature of its internal layers because of the heat release to the surroundings and moisture evaporation. Moreover, with decreasing moisture content of the material, the quantity of released heat decreases. As a result, the direction of moisture transfer under the action of the temperature gradient ∇T coincides with the direction of moisture transfer. As a consequence of the fast bulk heating of the material, evaporation of moisture in its internal region occurs, which causes a vapor pressure gradient ∇p_v accelerating the moisture transfer. These effects promote intensification of the drying process.

In recent years, heating of materials in a microwave-frequency field has been most widely used. The advantages of microwave heating are the practically zero thermal lag, i.e., the possibility of instantaneous turn-on and turn-off of the heat action on the material being treated, the high accuracy of regulating heating and maintaining higher temperature inside the material, the possibility of realizing selective, uniform and ultrapure heating. Selective heating is based on the dependence of the energy loss in the dielectric on the dielectric properties of in homogeneities and inclusions in it, for example, on the moisture content, and so on.

Moist materials have the properties of semiconductors in which along with the polarization phenomena, displacement of free charges – the so-called conduction current – arises.

It is known [1] that the specific loss (dissipation) of energy in the material, i.e., the quantity of heat released in its unit volume, depends on the parameters of the field: the intensity E, the frequency f as well as on the dielectrical properties of the material: ε' and $\tan\delta$. The higher the electric field frequency, the greater the heat released. As the dielectric loss angle $\tan\delta$ and the dielectric constant ε' increase, the quantity of heat released in the process of the material treatment increases. The lower dielectric losses, the greater the depth to which microwaves penetrate.

In many materials when the moisture content increases the dielectric losses (product of ε' and $\tan\delta$) increase, and when the moisture content decreases, the dielectric losses decrease. This property promotes the release of a larger quantity of heat in the first drying period and a decrease in the quantity of heat released in the second period, which retards the increase in the material temperature. Avoiding superheating of the material is very important for thermolabile materials.

The application of the microwave field in combination with other energy actions is effective. In practice, combined means of power input with the use of the microwave field (convective+microwave, vacuum or sublimation+microwave) are the most commonly used ones [1-7].

Physical Formulation of the Problem

We consider the process of drying a raw potato particle in the form of a parallelepiped in a layer stirred with a stirrer and blown with a gas at a constant temperature T_m and velocity v under the action of a microwave field of intensity E. Since the particle length is much larger than its cross-sectional sizes, a two-dimensional problem is solved. Because the material is being stirred, a uniform thermal and hydrodynamic action on the particle surface is assumed. It is assumed that the air pressure is constant, and heat transfer due to molar motion of the liquid and vapor as well as moisture thermal diffusion can be neglected.

Mathematical Model

Let us write the heat and mass transfer equations for the two-dimensional case in the Cartesian coordinate system:

$$\left(c_d + c_{liq}u\right)\rho_d \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(u)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(u)\frac{\partial T}{\partial y}\right) + \varepsilon^* r \rho_d \frac{\partial u}{\partial t} + I \quad (1)$$

$$\frac{\partial u}{\partial t}=\frac{\partial}{\partial x}\left(D(u,T)\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(D(u,T)\frac{\partial u}{\partial y}\right) \quad (2)$$

The initial conditions:

$$t=0,\ T(x,y,0)=T_0,\ u(x,y,0)=u_0 \quad (3)$$

The boundary conditions:

$$\lambda(u)\left.\frac{\partial T}{\partial x}\right|_{x=\pm l/2}=\lambda(u)\left.\frac{\partial T}{\partial y}\right|_{y=\pm l/2}=$$

$$=\alpha(T_m-T_{sur})-(1-\varepsilon^*)r\beta\left[p_{v.sur}(u,T)-p_m\right]$$

$$D(u,T)\left.\frac{\partial u}{\partial x}\right|_{x=\pm l/2}=D(u,T)\left.\frac{\partial u}{\partial y}\right|_{y=\pm l/2}=$$

$$=\frac{\beta}{\rho_d}\left[p_m-p_{v.sur}(u,T)\right] \quad (4)$$

In the boundary condition (4), for the moisture transfer equation the moisture flux density is directly proportional not to the difference between the moisture contents, as it is assumed in [8], but to the difference between the partial pressures of vapor near the surface of the material and in the environment. The partial pressure of vapor near the particle surface is determined by the desorption isotherm $p_{v.sur}=F\left(u_{eq},T_{sur}\right)$. From the desorption isotherm it follows that as the free moisture evaporates, the partial vapor pressure near the surface of the material tends to the vapor saturation pressure at the surface temperature $p_{v.sur}=p_s(T_{sur})$.

The sorption (desorption) isotherm determines the dependence $u_{eq}=f\left(p_v,T\right)$. The desorption isotherm is described by the following approximation formula [9]:

$$u_{eq}=u_{0.5}(T)\left(\frac{\varphi}{1-\varphi}\right)^{1/n} \quad (5)$$

where $u_{0.5}$ (T) is the temperature dependence of the equilibrium moisture content at $\varphi=p_v/p_s=0.5$. The exponent n is a constant value for one and the same material.

The function $u_{0.5}$ (T) is defined as

$$u_{0.5}(T)=A\exp\left[-B(T-T_0)\right] \quad (6)$$

From the results of approximation of the data indicated in [10], it has been found that for the potato n=2.4, A=0.135, B=0.0087, and T_0=293.

After removal of bound moisture the sorption equation is necessary for determining the specific heat of evaporation, the source term. In the hygroscopic region of the moisture state, the vapor pressure is found from the desorption isotherm equation $p_v=F\left(u_{eq},T\right)$, and the specific heat of evaporation of moisture is found from the Clausius–Clapeyron equation

$$r=\frac{RT^2}{M_v}\frac{1}{p_v}\left(\frac{\partial p_v}{\partial T}\right)_{u_{eq}} \quad (7)$$

that takes into account the necessary expenditures of heat to overcome the moisture-material binding energy.

In view of formula (5) the expression for the specific heat of evaporation takes on the form

$$r=\frac{RT^2}{M_v}\left(\frac{1}{p_s}\frac{\partial p_s}{\partial T}-\frac{nu_{0.5}^{n-1}}{u_{0.5}^n+u_{eq}^n}\frac{\partial u_{0.5}}{\partial T}\right) \quad (8)$$

where $\partial u_{0.5}/\partial T=-Bu_{0.5}(T)$.

The saturated vapor pressure, depending on the temperature, is determined by the Antoine equation

$$\lg\left(\frac{p_s}{133.3}\right)=A'-\frac{B'}{T-C'} \quad (9)$$

where $A'=8.07414$; $B'=1733$; $C'=39.31$.
Hence

$$p_s=133.3\cdot10^{A'-\frac{B'}{T-C'}} \quad (10)$$

$$\frac{\partial p_s}{\partial T}=133.3\cdot10^{A'-\frac{B'}{T-C'}}\frac{\ln(10)B'}{(T-C')^2} \quad (11)$$

The specific heat of evaporation of the free moisture is

$$r=R_vT^2\frac{B'\ln(10)}{(T-C')^2} \quad (12)$$

The specific heat power released in a unit volume of the material under the action of the electromagnetic field I (W/m^3) is equal to

$$I = 5.56 \cdot 10^{-11} \delta' E^2 f \varepsilon' \operatorname{tg}\delta \qquad (13)$$

where δ' is the impulse function that depends on time. The specific heat released inside the material is also determined by means of the Bouguer-Lambert-Beer law

$$I = kq_0\left(1-R^*\right)\left[\delta_x \exp\left(-k\left(l^*-x\right)\right)+ \right.$$
$$\left. +\delta_y \exp\left(-k\left(l^*-y\right)\right)\right] \qquad (14)$$

where δ_x, δ_y – are individual periodic functions, $\delta_x = 1$, if $\sin\left(\pi t/t^*\right) > 0$ and $\delta_x = 0$, if $\sin\left(\pi t/t^*\right) \le 0$; $\delta_y = 1$, if $\sin\left(\pi t/t^* + \pi\right) > 0$ and $\delta_x = 0$, if $\sin\left(\pi t/t^* + \pi\right) \le 0$; t^* – is exposure time of microwave radiation, which when taking into account the rate of layer stirring is specified by $t^* = 30$ s; $l^* = l/2$; $q_0 = q_0'/\left[1-\exp\left(-kl\right)\right]$.

The penetration depth of microwave action for potato is known to be about 12 mm, which is much larger than the lateral dimension of the sample (potato dimension 4×4mm).

The moisture conductivity coefficient is determined by the empirical formula [11, 12] :

$$D(u,T) = a_0 \exp(-a_1/u)\exp(-a_2/T) \qquad (15)$$

where $a_0 = 1.29 \cdot 10^{-6}$, $a_1 = 0.0725$, $a_2 = 2044$.

Equation (15) holds in the range of parameters 0.01 $< u < 5$; $333 < T < 373$.

The heat conductivity coefficient W/(m·K) of the potato sample is determined depending on the moisture content with the use of the expression [13] :

$$\lambda = 0.13 + 0.52\frac{u}{u+1} \qquad (16)$$

To determine the heat transfer coefficient, let us make use of the criteria equation for the fixed layer, since the stirring rate of particles is low [14]:

$$\mathrm{Nu_{eff}} = 0.395\,\mathrm{Re_{eff}^{0.64}}\,\mathrm{Pr}^{0.33} \qquad (17)$$

where

$\mathrm{Re_{eff}} = v_{\mathrm{eff}} d_{\mathrm{eff}}/\nu = 4v/\left(a'\nu\right) = 4v/\left[a_0'\left(1-\tilde{\varepsilon}\right)\nu\right]$ is the Reynolds number; $\mathrm{Nu_{eff}} = \alpha d_{\mathrm{eff}}/\lambda_{\mathrm{g}}$ is the Nusselt number; $\mathrm{Pr} = \nu/a$ is the Prandtl number.

Assuming that the heat and mass transfer processes are analogous, we will determine the mass transfer coefficient by a formula similar to (17).The diffusion Nusselt number $\mathrm{Nu'_{eff}} = \beta' d_{\mathrm{eff}}/D_{\mathrm{v}}$ and $\beta' = \beta R_{\mathrm{v}} T$.

The diffusion coefficient of the vapor is equal to

$$D_{\mathrm{v}} = D_0\frac{p_0}{p}\left(\frac{T}{T_0}\right)^{1.5} \qquad (18)$$

where $D_0 = 22 \cdot 10^{-6}$ m²/s; $T_0 = 273$ K; $p_0 = 101325$ Pa.

Calculations were performed for the following values of the process parameters: u_0=3.07 kg/kg; T_0=293 K; c_{d} = 1465 J/(kg·K); c_{liq} = 4190 J/(kg·K); ρ_{d}=230 kg/m^3; R_{v}=461.6 J/(kg·K); R=8314.2 J/(kmole·K); $M_{\mathrm{v}} = 18.02$ kg/kmole; ε^*=0.75; α=54 W/(m^2·K); $\beta = 0.36 \cdot 10^{-6}$ kg/(m^2·Pa·s); p_{m}=3500 Pa; T_{m}=333 K; l = 4 mm; v=1.2 m/s; ε'=57; tan δ=0.26; $f = 2.45 \cdot 10^9$ Hz; E=500 V/m; $k = 83$ m^{-1}; $q_0' = 8000$ W/m^2; $R^* = 0.1$.

Discussion of the Results of Numerical Calculation and Comparison with Experimental Data

Steady-state microwave – convective action

As a result of the numerical solution of the system of differential equations (1) and (2) with the initial and boundary conditions (3) and (4) we have investigated the dynamics and kinetics of the heat and moisture transfer in drying particles of raw sliced potatoes of section 4×4 mm dried convectively with the use of microwave radiation [15]. Figure 1 shows the moisture-content and temperature fields of the sample at the end of the drying process for the instant of time t = 2700 s. Analysis of these fields, as well as of the time dependences of the moisture content at various points of the sample throughout the process, shows that the moisture content at the center of the sample is higher than in its surface layers. The fastest decrease in the moisture content occurs at the sample edges (curve 4, Fig. 2a) and the slowest decrease is observed at its center (curve 1). At the end of the process, a certain nonuniformity of the moisture content is observed in the cross-section of the sample with its highest value at the center of the sample. In the heating, the first period and at the beginning of the second one, the temperature at the sample center is lower than in its surface layers, and at the end of the second period the temperature at the sample center becomes higher than on its surface (Fig. 2b). This is due to the action of the microwave field heating the internal layers of the product. The kinetic moisture content curve shows the first drying period, when the drying rate is a constant $du/dt = \text{const}$, and the second period of the decreasing drying rate. The heating period, the period of a constant adiabatic saturation (wet thermometer) temperature and the period of increasing temperature are clearly observed on the temperature curve. When calculating the drying process the drying curve is not divided into the periods.

For the case under consideration the specific amount of the heat released inside the material due to the exposure of microwave radiation in the equation (1) was determined in two ways: as a volume source by the formula (13) and by means of the Bouguer-Lambert-Beer law using the formula (14). A slight discrepancy was revealed when comparing the local values of temperature and moisture in different points of the sample material for both types. In particular, comparison between moisture content and temperature in the center of the sample is shown in Fig. 2. This is due to the fact that the penetration depth of microwave radiation for potato is about 12 mm, which is far greater than the transverse dimensions of the sample. At the same time the characteristic time of mixing the particles in the layer (number of rev / min- 1÷3) is far less than the drying period. Further calculations were carried out using the formula (13).

Impulse and impulse-step microwave action with steady-state convective action

Electromagnetic microwave field was set in three different ways (modes): 1 – constant in time with intensity $E = 500$ V/m; 2 – impulse: in the time intervals $0 \le t \le 300$, $900 \le t \le 1200$ and $1800 \le t \le 2100$ with the field intensity $E = 500$ V/m, and in the intervals $300 \le t \le 900$, $1200 \le t \le 1800$ and $t \ge 2100$ with intensity $E = 0$; 3 – impulse-step: in the time intervals $0 \le t \le 300$ and $900 \le t \le 1200$ with the field intensity $E = 700$ V/m, $1800 \le t \le 2100$ $E = 350$ V/m, and in the intervals $300 \le t \le 900$, $1200 \le t \le 1800$ and $t \ge 2100$ with the field intensity $E = 0$. Other parameters are given in part 3.

Under impulse- microwave action in mode 3, the temperature in the centre of the sample at the end of the process is lower than at its edges (Fig. 3). However, this difference is very small, i.e., the sample is practically uniformly heated.

It is concluded from the results on steady-state and impulse microwave action (Fig. 1 and Fig. 3) that impulse microwave action modes allow first of all to reduce the thermal action on the material being treated: to reduce the temperature of the material in the second drying period, to provide short-term action of high temperature during the thermal pulse. However, impulse mode can result in decreasing dehydration rate (Fig. 4 a, curves 1, 2). To prevent it and avoid overheating of the material impulse-step modes of microwave action which provides strong impulses in the first and at the beginning of the second period as well as the reduction of impulse intensity in the second period can be applied. This is clearly seen in Fig. 4 (curve 3).

Comparison of the calculation results obtained under steady-state microwave action and constant dielectric loss factor ε''=const (mode 1) with values for the same mode, but with alternating dielectric loss factor as a linear function of moisture content $\varepsilon'' = 3,4u + 4,6$ shows that in the first case, the process rate is slightly higher, and the final moisture content is lower. It should be noted that a constant value of the dielectric loss factor was $\varepsilon'' = \varepsilon' \operatorname{tg}\delta = 14,82$ and represented maximum value at the initial time, i.e. at the beginning of the drying process. Therefore, with decreasing moisture content at the sample at dielectric loss variable factor, the amount of the heat released in the sample from the microwave field decreases and the sample temperature becomes lower than at the mode when $\varepsilon'' = 14,82 = \text{const}$ (Fig. 5). Similar situation is also observed at the impulse modes of microwave action.

Conclusions

A two-dimensional model of the heat and moisture transfer in the process of combined micro-wave-convective drying of vegetable materials has been developed. The dependences of the kinetics and dynamics of the process on its operating parameters under steady-state, impulse and impulse-step microwave radiation have been established. It has been shown that the temperature at the center of the sample increases in the second drying period and its dehydration time shortens under additional microwave irradiation. Impulse and impulse-step microwave modes of microwave irradiation have been found out to make it possible to reduce thermal action on the material being treated.

NOTATION

A and B, constants in the sorption isotherm;

A', B' and C', constants in the equation for saturated vapor;
a'_0, specific surface of the particle, ratio of the outer surface of the particle to its volume, m^2/m^3; $a' = a'_0(1-\tilde{\varepsilon})$;
c, heat capacity, J/(kg·K);
D, moisture conductivity coefficient, m^2/s;
E, electromagnetic field intensity, V/m;
f, frequency, Hz;
I, source term, J/(m^3·s);
k, absorption index (extinction), 1/m;
l, linear size of the body, m;
M, molecular mass, kg/kmole;
p, pressure, Pa;
q'_0 – radiant flux surface density, W/m^2;
R, universal gas constant, J/(kmole·K);
R^* – reflection coefficient;
r, specific heat of moisture evaporation, J/kg;
t, time, s;
T, temperature, K;
u, moisture content, kg of moisture/kg of dry material;
v, gas velocity calculated for the total cross-section of the apparatus with a granular layer, $v_{\text{eff}} = v/\tilde{\varepsilon}$, m/s;
x and y, current coordinates, m;
α, heat transfer coefficient, W/(m^2·K);
β and β′, mass transfer coefficients, kg/(m^2·Pa·s), m/s;
ε^*, phase transformation coefficient;
ε′, permittivity of the material (with respect to vacuum), $\varepsilon' = \varepsilon/\varepsilon_0$ or $\varepsilon = \varepsilon'\varepsilon_0$;
ε, absolute permittivity of the material, F/m;
ε_0, absolute permittivity of vacuum;
$\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m;
$\tilde{\varepsilon}$, layer porosity;
λ, heat conductivity coefficient, W/(m·K);
ν, coefficient of kinematic viscosity, m^2/s;
ρ, density, kg/m^3;
φ, relative moisture of the gas, $\varphi = p_v/p_s$;
tan δ, dielectric loss angle.
Subscripts:
0, initial state parameters;
d, absolutely dry material;
liq, liquid (moisture);
s, saturated state;
eq, equilibrium state;
v, vapor;
eff, effective parameters;
m, medium.

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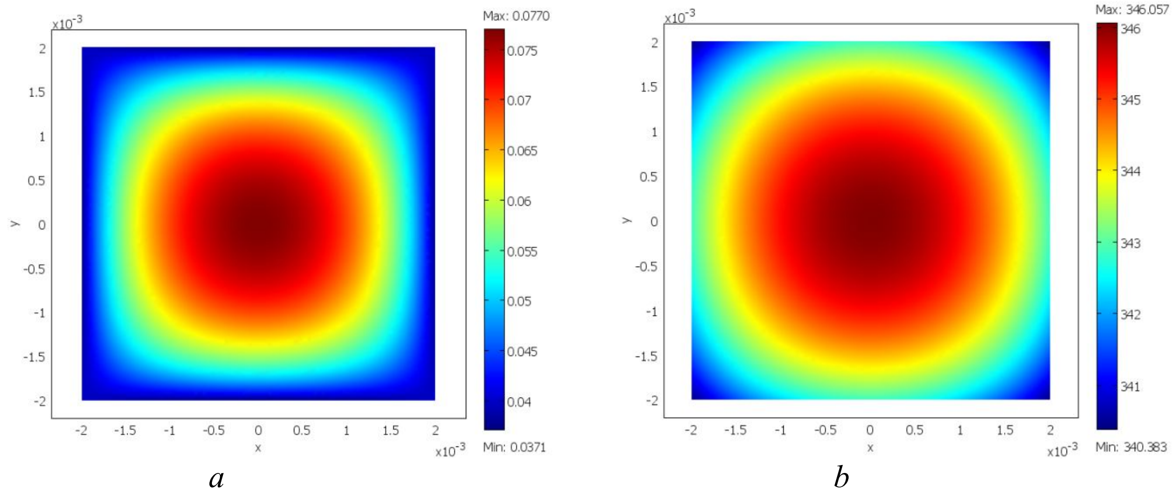
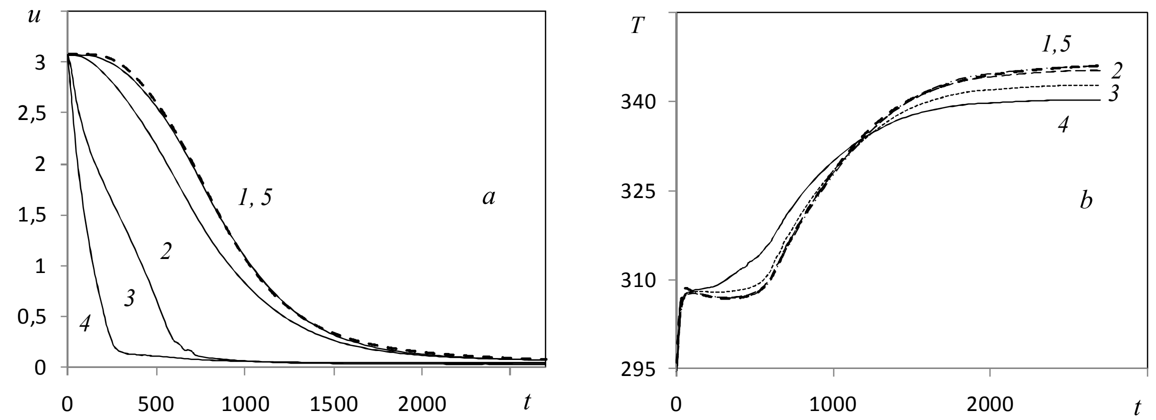
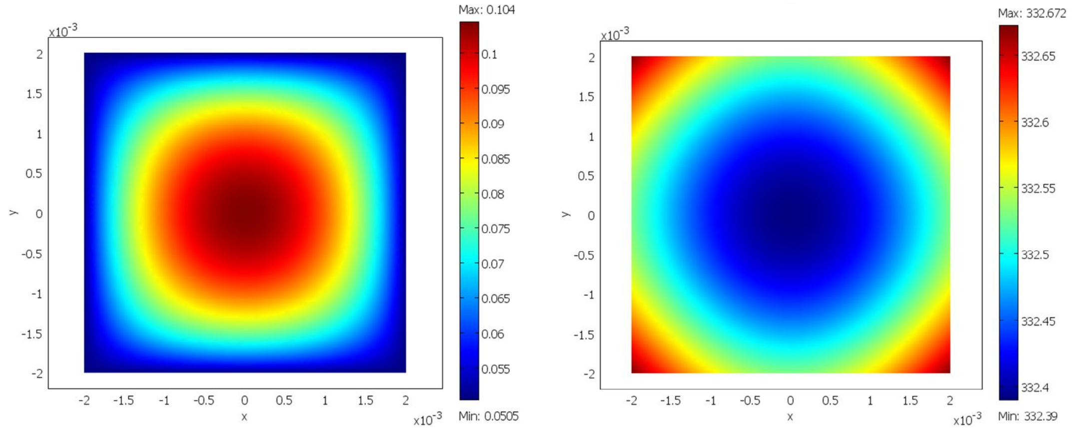


Figure 1. Moisture content (a) and temperature (b) fields at the instant of time $t = 2700$ s



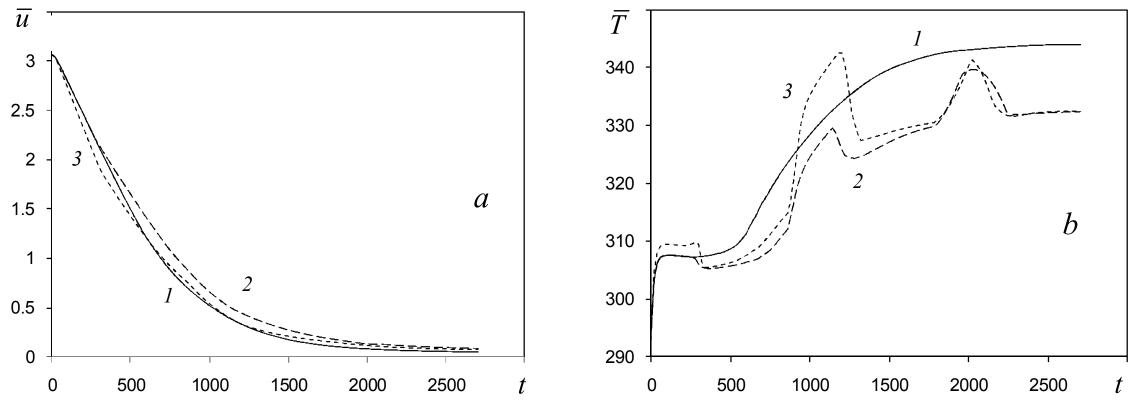
1 – $x = 0$, $y = 0$; *2* – 0.001, 0; *3* – 0.002, 0; *4* – 0.002, 0.002; *5* – parameters correspond to the curve *1*, source term is calculated by means of the formula (14)

Figure 2. Dependences of moisture content (*a*) and temperature (*b*) on time at different points of the sample at $E = 500$ V/m



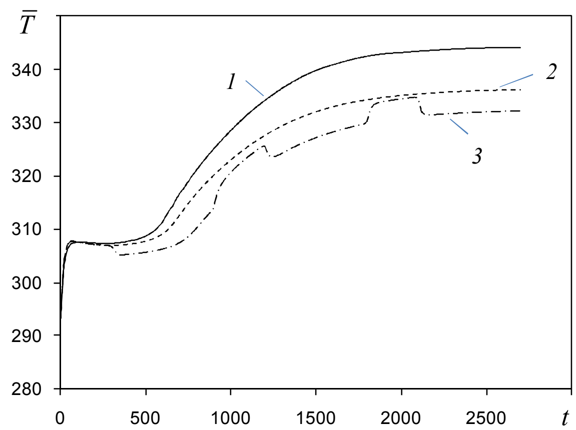
a *b*

Figure. 3. Moisture content (a) and temperature (b) fields at the end of the process at $t = 2700$ s and mode 3 with impulse microwave field intensity



1 – mode 1with constant microwave field intensity; *2* – mode 2 with impulse microwave action; *3* –mode 3 with impulse-step microwave action

Figure. 4. Kinematic curves of the moisture content (a) and temperature (b)



1 – mode 1 with constant microwave field intensity and $\varepsilon'' = \text{const}$; *2* – mode 1 with constant microwave field intensity and $\varepsilon'' = 3,4u + 4,6$; *3* – mode 2 with impulse microwave action and $\varepsilon'' = 3,4u + 4,6$

Figure. 5. Time dependences of average temperature of the sample