DOI 10.1007/s10891-022-02468-0
Journal of Engineering Physics and Thermophysics, Vol. 95, No. 1, January, 2022

KINETICS OF DEHYDRATION OF VEGETABLE MATERIALS IN A DENSE BED WITH CYCLIC MICROWAVE-CONVECTIVE ENERGY SUPPLY

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Certain results are presented of experimental investigation and numerical modeling of the kinetics and heat and moisture transfer in a blown dense bed of vegetable materials with convective and cyclic microwave-convective energy supply. The kinetic dependences of the dehydration of vegetable materials are analyzed and the possibility of reducing the duration of the process is shown with the example of raw-potato and celery-root particles. A comparison is made of the calculated and experimental kinetic dependences which points to their satisfactory agreement and to the adequacy of the model.

Keywords: *heat and mass transfer in a dense bed, microwave-convective drying, drying of vegetable materials.*

Introduction. Nonstationary combined methods of energy supply in the processes of drying and heat treatment of materials are developed at present. Researchers' attention focuses, in particular, on cyclic and oscillating electromagnetic-convective actions and vacuum treatment combined with microwave or infrared irradiations [1–7]. The interest expressed in them is determined by the possibility of enhancing heat- and mass-transfer processes, ensuring comparatively soft regimes of heat treatment due to the short duration of a high-temperature action, and preserving qualitative indices of the material to be dehydrated. For example, in [8, 9], it has been shown that with cyclic microwave-convective energy supply in fixed and fluidized beds, the duration of the process of drying of vegetable materials is reduced and the expenditure of energy decreases. Study [10] gives results of the investigation of microwave-convective drying of bananas at a variable radiation power. Positive aspects of such a regime and the quality of dry products have been noted. In [11], a study has been made of the convective-condensation techniques of drying of thermolabile materials.

To describe and analyze these processes, various methods are employed, in particular, the models of heat and mass transfer in single particles with allowance for the heat-transfer-agent flow past them and the method of continuum mechanics for dispersed beds.

In the present work, an analysis is made of certain results of experimental investigation of the kinetics of dehydration of vegetable materials and of modeling of heat and mass transfer in a fixed and miscrible bed on cyclic microwave exposure. The dispersed bed is blown with heated air from the bottom upward in a filtration regime.

A mathematical model is based on the mass equations of a gas phase and its filtration through the dispersed bed, and also on the equations of transfer of heat and moisture in the phases [3, 12]. The gas motion in the bed is described by Darcy′s equation. Here, account is taken of the dependence of the effective thermal conductivities of the gas phase and diffusivities of the vapor on the velocity of filtration in the direction of coordinate axes.

The transfer of moisture in the particles of the bed′s material is taken account of by two methods. In the first method, the diffusion transfer of moisture is taken into consideration in describing the mass-transfer coefficient. The latter is defined as the mass-transmission coefficient allowing for the resistance to mass transfer from the particles′ surface and for the intradiffusion resistance to the transfer of moisture. The second method is based on description of the deepening of an evaporation zone with account of the filtration resistance of a dry zone and the mass-transfer resistance. Here, it is assumed that at the evaporation boundary, the partial vapor pressure corresponds to the saturation pressure. The thermal resistance to the transfer of heat inside the particles is allowed for in the heat-transfer coefficient which is calculated as the heat-transmission coefficient. The specific heat of evaporation of moisture is found from the Clausius–Clapeyron equation which, simultaneously with the desorption-isotherm equation, takes account of the energy of bond of moisture with the

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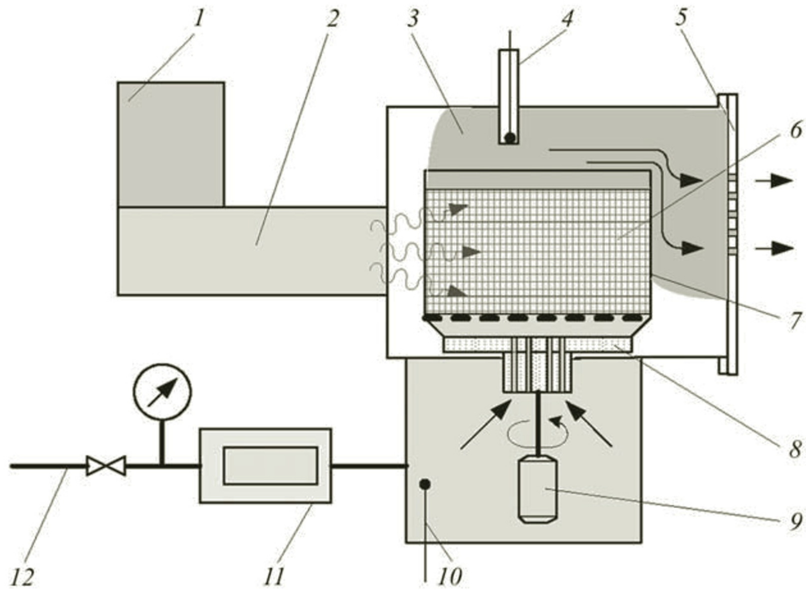


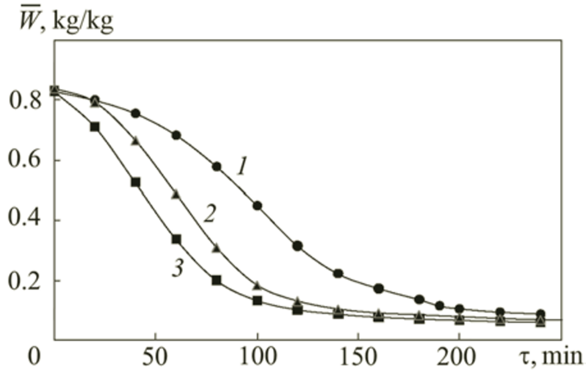
Fig. 1. Diagram of the experimental setup with microwave-convective energy supply: 1) magnetron; 2) waveguide; 3) drying chamber; 4 and 10) thermocouples; 5) removable cover of the chamber; 6) material′s sample; 7) detachable perforated-bottom vessel for the material; 8) revolving table with air ducts; 9) drive; 11) air heater; 12) compressed-air supply line.

material. The quantity of heat released in the material′s particle on exposure to electromagnetic radiation over the bed height is described by the Bouguer equation. The moisture conductivity is found from the empirical formula as a function of the moisture content and temperature. The system of equations is solved numerically for a two-dimensional nonstationary case.

Description of the Experimental Setup. A diagram of the experimental setup with combined microwave-convective energy supply is presented in Fig. 1. It incorporates a drying chamber 3, magnetron 1, and waveguide 2 supplying the radiant flux to a sample of material 6. The chamber 3 is equipped with a revolving table 8 with channels to supply the heat-transfer agent. The dispersed material 6 is arranged in a detachable vessel 7 with a perforated bottom. The rotation of the table with a vessel for the material is implemented by an electric drive 9. Use is made, as the heat-transfer agent, of compressed air which is fed, by line 12, to an air heater 11 and after heating to a required temperature, enters the material layer via holes in the revolving table and the bottom of the vessel. After filtering through the dispersed bed of material, the air saturated with moisture is removed from the chamber to the environment via holes in a removable cover 5. The air temperature is monitored, using thermocouples 4 and 10, before and after the passage through the material's bed. The air pressure under the revolving table is 20–40 kPa, which enables us to ensure an average air temperature over the cross section of the vessel with a dispersed material of 0.1–0.3 m/s.

The process of dehydration of dispersed materials is implemented in a special cylindrical vessel of diameter 110 mm with a perforated bottom, which ensured a uniform distribution of the heat-transfer agent over the cross section of the vessel (bed). To ensure a uniform microwave irradiation, the vessel was set in rotation and furthermore, a cylindrical ceramic insert of diameter 30 mm was arranged on its axis. To determine the kinetics of dehydration, the vessel with a material was periodically withdrawn from the chamber and was weighted on a laboratory balance. The material′s temperature was monitored upon the readings of the air escaping from the bed. The temperature of the heat-transfer agent was selected in the range 40–60^{o}C and was maintained at the assigned level in different periods of drying.

Experimental Investigations and Their Comparison with the Results of Numerical Modeling. On the above-described setup, we carried out experimental investigations of the process of dehydration of vegetable materials: raw potatoes and celery root. The dispersed material represented predominantly cubes with dimensions 7 × 7 × 7 mm. The exposure of a moist material to microwave radiation was cyclic depending on its moisture content. The duration of irradiation τ_{irr} in each cycle was determined experimentally and varied in the range of 0.5 to 3 min. The duration of pauses τ_p between the exposures was 1–2 min and made it possible to cool down material particles, thus preventing their superheating and degradation.



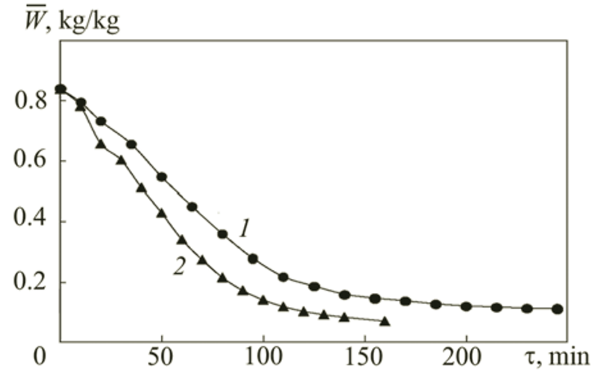


Fig. 2. Kinetic dependences of the dehydration of raw-potato (Skarb variety) particles in the shape of 7 × 7 × 7 mm cubes in a blown fixed bed at $t_1 = 70^{o}C$, a bed height of 50 mm, and different gas velocities 1) $v = 0.3$, 2) 0.55, and 3) 1.2 m/s.

Fig. 3. Kinetic dependences of the convective drying of raw-potato (Vektor variety) particles in a blown dense bed at different particle sizes and shapes: 1) particles in the form of parallelepipeds of cross section 7 × 7 mm and length 40–60 mm and 2) 7 × 7 × 7 mm cubes; $t_1 = 70^{o}C$; $v \approx 2$ m/s; the bed height is 40 mm.

First, we analyze the kinetics of convective dehydration of potato particles in the blown bed. The rate of the process of evaporation of moisture largely depends on the velocity of filtration of the gas as clearly demonstrated by the plots in Fig. 2. Here, it should be noted that ensuring a comparatively high velocity of filtration of the gas through the material of the bed increases the bed′s resistance and accordingly causes the expenditure of energy to grow. Furthermore, a high flow rate of the gas results in the great loss with a spent heat-transfer agent. This makes it necessary to create the recycling of the heat-transfer agent and the regeneration or recovery of heat, which also requires additional capital investments and energy costs.

The intensity of the removal of moisture is significantly affected by the particle size and shape. It is common knowledge that the specific surface of the material and the rate of removal of moisture grow as the particle size decreases. As can be seen in Fig. 3, the duration of dehydration of particles cut in the form of parallelepipeds of cross section 7 × 7 mm and length 40–60 mm is longer than that of the particles having the shape of 7 × 7 × 7 cubes, all other things being the same.

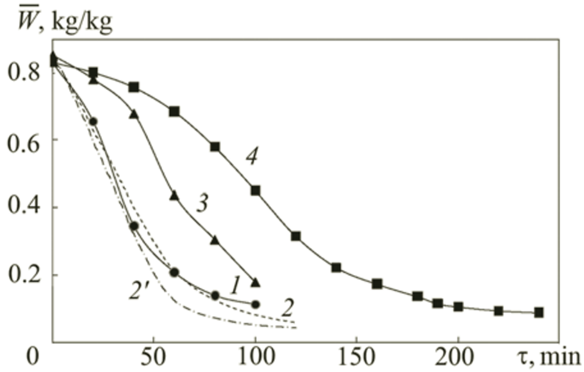
Next, we analyze the influence of convective and cyclic microwave-convective energy supply on the kinetics of the process. In Fig. 4, it can be seen that the cyclic supply of heat by microwave radiation, even in blowing the bed with cold air at a temperature of $17^{o}C$, leads to a marked growth in the rate of evaporation of moisture compared to a purely convective technique of supply of heat at an air temperature of $70^{o}C$ and an identical velocity of about 0.3 m/s. Raising the severity or, in other words, the intensity of the cyclic microwave-convective regime (curve 2), we can increase the rate of the process still further and reduce its duration.

A comparison of the results of calculating from the model given in [7] (curve 2) with the experimental data (curve 1) demonstrates their satisfactory agreement and the adequacy of the model. Mixing of the bed, i.e., increase in the effective diffusivity within the framework of the diffusion model, is seen to lead to a growth in the dehydration rate (curve 2′, Fig. 4).

As a result of the numerical modeling, we obtained the temperature distributions of the dispersed and gas phases in fixed and miscible beds during the dehydration of potato particles. The basic parameters at which the calculations were performed, were as follows: $k = 1 \cdot 10^{-8}$ m^2, $\mu_1 = 20 \cdot 10^{-6}$ Pa·s, $c_1 = 1.006$ kJ/(kg·K), $\lambda_1 = 0.026$ W/(m·K), $\lambda_{2ef} = 0.1$ W/(m·K), $R^* = 8314.2$ J/(kmole·K); $M_v = 18.02$ kg/kmole, $\rho_{dr} = 175$ kg/m^3, $u_0 = 5.2$ kg/kg, $h = 0.05$ m, $R_{refl} = 0.05$, $k' = 83$, $u_{e.shr} = 0.03$ kg/kg, $l_0 = 0.007$ m, $l_1 = -0.043$, and $\varepsilon = 0.5$.

In the process of dehydration, the shrinkage of the particles was allowed for on the basis of experimental data on the exponential dependence on the particles′ moisture content $l = l_0 \exp [l_1(u_0 - u)]$, where $u_{e.shr} \le u \le u_0$, l is the linear dimension of a particle, m, and l_0 and l_1 are the constants.

In Fig. 5, it can be seen that the temperature of particles in the bed is oscillating in character and on switching off the microwave radiation, decreases rapidly because of the developed contact surface of the phases up to the gas temperature at entry into the bed. The upper region of the bed, onto which the radiant flux is incident, experiences the greatest heating and



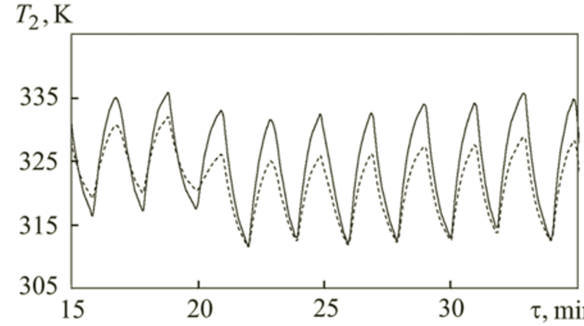


Fig. 4. Kinetic dependences of the convective and microwave-convective dehydration of potato particles (7 × 7 × 7 mm cubes) in a blown dense bed: 1) cyclic microwave-convective heat supply: time ~0–20 min, $(\tau_{rad} + \tau_v)$·number of cycles: (3 + 1)·3, (2 + 1)·1, and (1 + 1)·1, $t_1 = 60^oC$, ~20–40 min: (2 + 1)·1, (1 + 1)·2, (1.5 + 1)·2, and (1 + 1)·1, $t_1 = 40^oC$ and further is constant; 40–60 min: (1 + 1)·2, (0.5 + 1)·7, and (0.5 + 0.75)·2; 60–80 min: (0.5 + 0.5)·20; 80–100 min: (0.5 + 0.5)·5 and (0.5 + 1)·10 (superhigh frequencies, 43 min; 2 and 2′) calculated curves at $D_{ef} = 5 \cdot 10^{-12}$ m²/s and $D_{ef} = 1 \cdot 10^{-6}$ m²/s respectively; 3) cyclic microwave exposure of 2 min with a 2 min break (superhigh frequencies, 50 min), the bed is continuously blown with cold air ($t_1 = 17^oC$); 4) convective heat supply: $v = 0.3$ m/s; $t_1 = 70^oC$; the bed height is 50 mm.

Fig. 5. Temperature of particles in the dispersed bed vs. time at $D_{ef} = 1 \cdot 10^{-6}$ m²/s and $\lambda_{2ef} = 10$ W/(m·K): 1) $y = 0$; 2) $y = 0.05$ m and $x = 0.125$ m.

temperature fluctuations. Therefore, with the fixed bed of particles in the process of dehydration, it is the particle temperature on its surface that must be monitored. To avoid the superheating of the particles on the bed′s surface, the bed can be stirred, which will also contribute to the equalization of the moisture content over the bed′s height and to the enhancement of the process. Increase in the effective thermal conductivity of the bed leads to a marked decrease in the difference between the temperatures in the lower and upper regions of the bed [12]. Change in the gas temperature in the material′s bed and at exit from it is also of the oscillatory character which is similar to the particle temperature. Experimental dependences of the temperature in the heat-transfer agent at entry into and exit from the bed of raw-potato particles with cyclic microwave energy supply are presented in Fig. 6. The air temperature in the initial period of warming up was assigned at 50–60°C, and thereafter was reduced to 40°C to avoid the superheating of the material. The exposure to microwave radiation was cyclic.

In Fig. 6, it can be seen that during the microwave exposure, the temperature of the heat-transfer agent at exit from the bed grows rapidly, and thereafter, on switching off the radiation, is reduced. The durations of microwave exposure and of cooling periods were selected depending on the temperature of the heat-transfer agent at exit from the bed, the temperature of particles in the bed, and other parameters of the process. At the beginning of the process, the periods of exposure to superhigh-frequency radiation are longer, and on removal of bound moisture at the end of the process, shorter. The parameters of the regime must ensure, on the one hand, high intensity of the evaporation of moisture and the economic efficiency of the process, and on the other, preserve the high quality of the product.

By the method of numerical modeling, we have investigated the moisture-content distribution of particles over the bed height (Fig. 7). With a fixed dense bed, the moisture content of the particles varies noticeably with height and its deviations peak at the end of the first period and at the beginning of the second period of drying, and thereafter, on removal of bound moisture, the particles′ moisture content is equalized and tends to an equilibrium value. Here, the moisture distribution along the vertical coordinate at the beginning of the process acquires a parabolic form, and then becomes equalized with time. In Fig. 7, it can clearly be seen that the mixing of the bed and increase in the effective diffusivity lead to a noticeable equalization of the moisture content of the particles over its height.

We have obtained the concentration distributions of moisture in the dispersed bed at different instants of time. As a result, the dynamics of evolution of the concentration (moisture-content) field of the dispersed phase has been investigated.

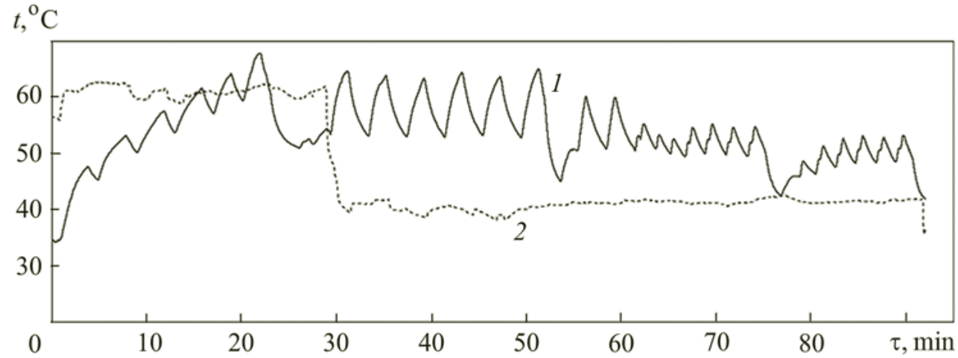


Fig. 6. Temperature curves during the cyclic microwave-convective energy action on the bed of material (the particles are 7 × 7 × 7 mm cubes and the bed height is 50 mm) and at $v = 0.3$ m/s: 1) readings of the thermocouple above the bed at a height of 20 mm; 2) air temperature at entry into the bed; the time is ~0–20 min, $(\tau_{rad} + \tau_v)$·number of cycles: (3 + 1)·4 and (2 + 1)·2, $t_1 = 60^{o}$C; ~20–40 min: (2 + 2)·5, $t_1 = 40^{o}$C and further is constant; ~40–60 min: (1 + 2)·3, (0.5 + 1)·2, and (1 + 1)·4; ~60–80 min: (1 + 1)·10; 80–100 min: (0.5 + 1)·14 (superhigh frequencies, 51 min).

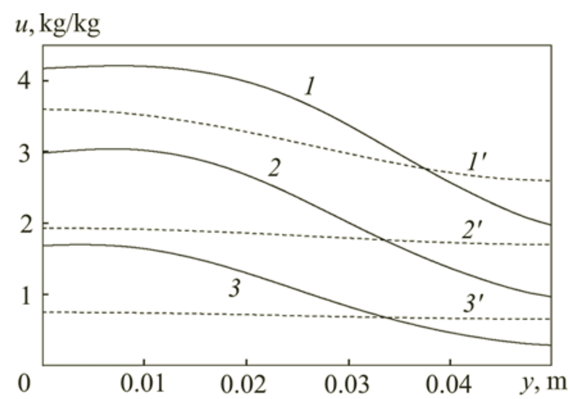


Fig. 7. Distribution of the moisture content of particles in the bed along the vertical coordinate: 1 and 1′) $\tau = 500$, 2 and 2′) 1000, and 3 and 3′) 2000 s. Unprimed figures correspond to $D_{ef} = 5\cdot10^{-12}$ m^2/s and primed ones, to $D_{ef} = 1\cdot10^{-6}$ m^2/s; $0 \le \tau \le 12$, $\tau_{rad} = 3$ min and $\tau_v = 1$ min; $12 < \tau \le 40$, $\tau_{rad} = 1$ and $\tau_v = 1$; $40 < \tau \le 60$, $\tau_{rad} = 0.5$ and $\tau_v = 0.5$; $\tau > 60$, $\tau_{rad} = 0.5$ and $\tau_v = 1$. At $0 \le \tau \le 20$, $t_{10} = 60^{o}$C and at $\tau > 20$, $t_{10} = 40^{o}$C: $q_0 = 7\cdot10^4$ W/m^2; $v = 0.3$ m/s; $h = 0.05$ m.

The results of the moisture-content distribution of dispersed particles for two instants of time are given in Fig. 8. Clearly, in the dense immiscible bed, the evaporation of moisture is the fastest in the upper part of the bed, with the moisture-concentration front shifting to the bed′s lower part with time.

The density (concentration) of the steam in the bed grows rapidly in the period of warming up of the bed, peaks, and thereafter decreases throughout the process. Here, the time dependences of the steam density are oscillatory in character with decrease in the oscillation amplitude (Fig. 9). This is due to the decrease in the intensity of evaporation of moisture from the particles.

We have obtained the dependences of the specific heat of evaporation upon the reduction in the moisture content of the particles. To calculate them, use was made of the moisture-desorption isotherm and the Clausius–Clapeyron equation. With increase in the moisture content of the particles, the value of the specific heat of evaporation markedly grows, which is due to the growth in the energy of bond of moisture with the material. Here, the curves for different cross sections of the bed are wavy in character with a relatively small amplitude of oscillations and differ little, in practice, since the moisture

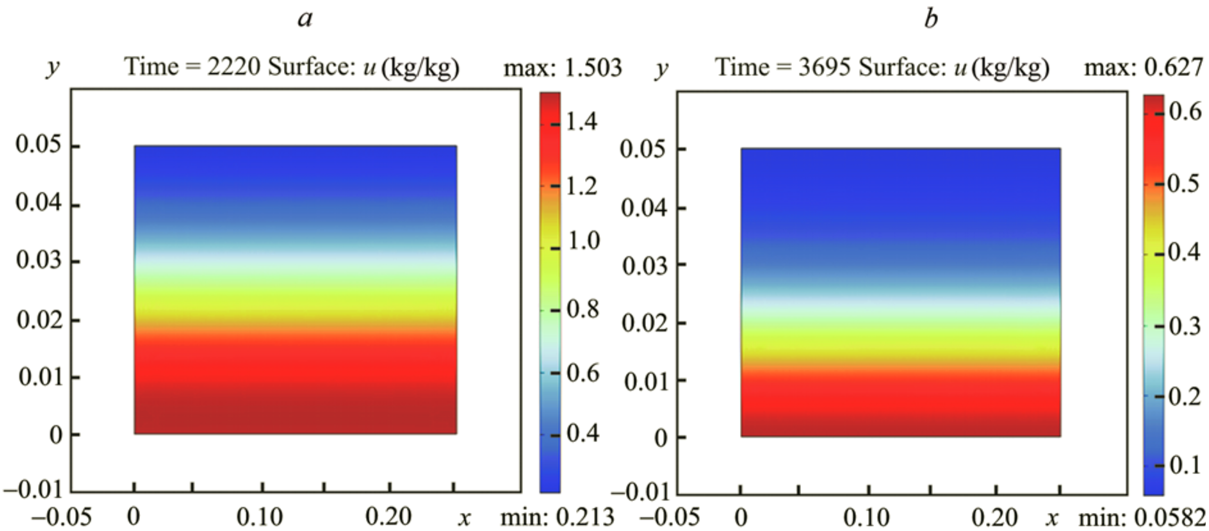
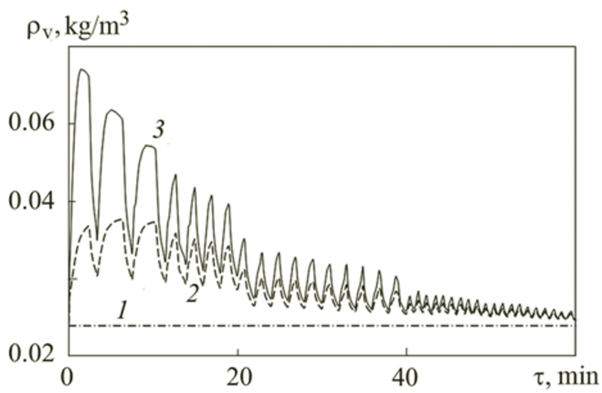


Fig. 8. Distribution of the concentration of moisture (moisture content) in the dispersed bed for different instants of time at $D_{ef} = 5{\cdot}10^{-12}$ m^2/s: a) τ = 2220 and b) τ = 3695 s.



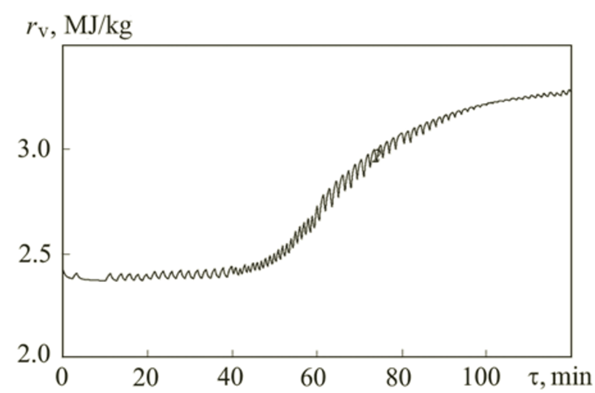


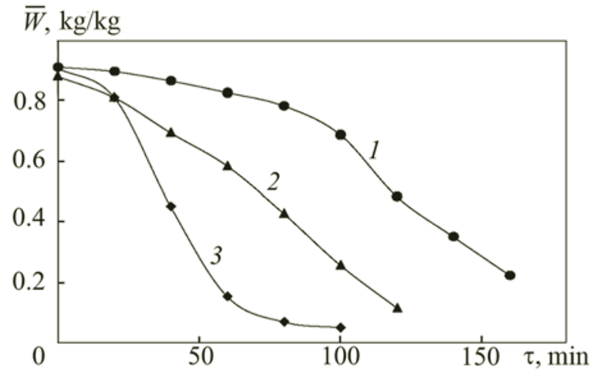
Fig. 9. Density (concentration) of the vapor in the bed vs. time at $D_{ef} = 5{\cdot}10^{-12}$ m^2/s: 1) $y = 0$; 2) $y = 0.025$ m; 3) $y = 0.05$ m.

Fig. 10. Dependence of the specific heat of vaporization of moisture on reduction in the moisture content of particles in the bed at $D_{ef} = 1{\cdot}10^{-6}$ m^2/s and $y = 0.05$ m.

content of the particles at the end of the process differs insignificantly. The dependence of the bed-average specific heat of evaporation of moisture is given in Fig. 10.

Next, we analyze the results of investigation of the kinetics of dehydration of celery root cut into cubes with dimensions 7 × 7 × 7 mm in a blown fixed bed with convective and combined microwave-convective energy supply. In Fig. 11, it can clearly be seen that at an identical velocity of filtration of the gas through the bed of 0.3 m/s and even at its lower temperature, cyclic microwave radiation makes it possible to substantially enhance mass transfer and to reduce the duration of the process. Here, increase in the duration of exposure to microwave radiation at the initial stage and throughout this process (curve 3, Fig. 11) leads to a much higher intensity of mass transfer compared to the irradiation regime (curve 2) only at the initial stage on removal of free moisture. We note a substantial influence of the velocity of filtration of the gas on the rate of a purely convective process of dehydration. However, even at a filtration velocity of 1.2 m/s, the dehydration rate with combined energy supply is higher.

Investigations of the shrinkage of the bed of material in the process of thermal dehydration of raw-potato and celery-root particles have shown a considerable decrease in the bed′s height as moisture evaporates, particularly in the



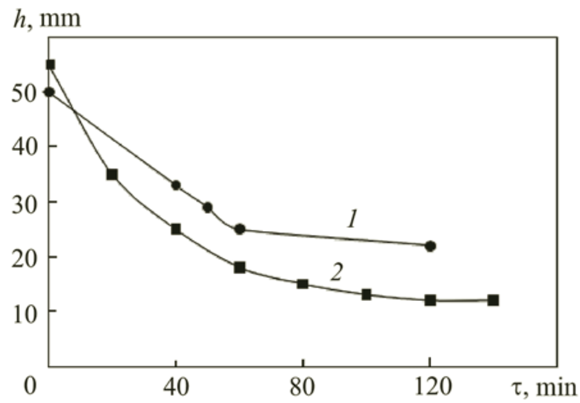


Fig. 11. Kinetic dependences of the convective (curve 1) and cyclic microwave-convective (curves 2 and 3) dehydration of celery-root particles in a blown dense bed: 1) $v = 0.3$ m/s and $t_1 = 70^oC$; 2) $t_1 = 60^oC$; the time is ~0–20 min $(\tau_{rad} + \tau_v)$·number of cycles: (3 + 2)·1 and (0.5 + 2)·8; hereafter the superhigh-frequency radiation is switched off: 3) the time time is ~0–20 min: (3 + 2)·1, (2 + 2)·3, (1.5 + 2)·1, and (1 + 2)·1 and $t_1 = 60^oC$; 20–40 min: (2 + 1)·1, (1.5 + 2)·1, and (1 + 2)·5 and $t_1 = 40^oC$; 40–60 min: (1 + 1.5)·2 and (0.5 + 1)·11 and $t_1 = 40^oC$; 60–80 min and further: (1 + 1)·1 and (0.5 + 1)·12 and $t_1 = 40^oC$; $v = 0.3$ m/s; particle size, 7 × 7 × 7 mm cubes and the bed height is 55 mm.

Fig. 12. Shrinkages of the bed vs. time in microwave-convective drying: 1) potato cubes; 2) celery-root cubes.

period of removal of free and loosely bound moisture approximately during the first hour of drying. The height of the celery-root bed decreases approximately 4.5 times, and the shrinkage of the bed of potato particles is somewhat lower (Fig. 12).

Conclusions. The results of the carried-out investigations demonstrate the possibility of enhancing the process of dehydration of vegetable materials in the blown dense bed, and also its considerable reduction on cyclic microwave-convective exposure. Here, the superheating of a material can be prevented and its qualitative indices be ensured by selecting correctly the duration of the periods of irradiation or reducing its power as the material is dehydrated. In the process of dehydration, a nonuniformity of the moisture-content distribution of particles over the height of the dense bed is observed. This nonuniformity can be increased through the mixing of the bed and its cyclic irradiation on both sides or by changing periodically the direction of filtration of the gas through the bed. A comparison of the calculation results with the experimental data points to their satisfactory agreement and to the adequacy of the mathematical model. We emphasize that vegetable materials are usually of high initial moisture content and are energy-consuming as far as the process of dehydration is concerned. Therefore, the consumption of electric power and the power of microwave oscillators can be reduced by combined microwave-convective supply of energy.

NOTATION

c, specific heat, J/(kg·K); D_{ef}, effective moisture conductivity of a dispersed bed, m^2/s; h, bed height, m; k, permeability coefficient of a dispersed bed, m^2; k', index of absorption of radiation; M, molecular mass, kg/kmole; R^*, universal gas constant, J/(kmole·K); R_{refl}, reflection coefficient; r_v, specific heat of vaporization, J/kg; T and t, temperatures, K and ^oC; u, moisture content of particles, kg/kg; $u_{e.shr}$, moisture content corresponding to the end of the process of shrinkage, kg/kg; v, gas velocity calculated for the cross-sectional area of the bed, m/s; W, moisture content of particles (for the total mass) $W = u/(1 + u)$, kg/kg; x and y, horizontal and vertical coordinates, m; ε, porosity of the bed; λ, thermal conductivity, W/(m·K); μ, dynamic coefficient of viscosity, Pa·s; ρ, density of the gas phase (dry air and steam), kg/m^3; τ, time, min. Subscripts: 0, initial state; 1 and 2, gas and solid phases; v, vapor; dr, dry material; ef, effective; –, average sign.

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