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KINETICS OF MICROWAVE DRYING OF A FREE-FLOWING ORGANIC MATERIAL

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The kinetics of drying of a dense buckwheat layer in a microwave electromagnetic field of frequency 2.45 GHz has been investigated for different amounts of the material charged into a working chamber. Analysis of the kinetics curves has shown that the drying of the material studied is divided into the periods of heating, drying with a constant rate, and drying with a decreasing rate. The influence of the power supplied as well as the mass and dimensions of a sample on the rate of its drying has been investigated and a formula for calculating this rate has been obtained. It has been established that, in the process of drying of a disperse material, the amount of microwave energy converted into heat energy depends not only on the mass of a sample, but also on the thickness and area of its surface layer. Generalized equations for calculating the moisture content in a layer of a free-flowing material and its temperature have been obtained.

The microwave drying of free-flowing materials possessing the properties of polar dielectrics, among which are agricultural products, holds considerable promise because it provides the following advantages as compared to other forms of drying of these materials: a heat energy is generated directly in the material being dried and therefore is used rationally; the drying is safe for the environment, is realized at a high rate [1], and provides a high quality of the product obtained [2]. It is known that it is not economically advantageous to completely replace convective drying by microwave drying [3]; however, microwave drying can be used to advantage at the finite stage of the process, where the conditions of heat and mass transfer become inappropriate for convective drying. It has been established that it is well to use microwave drying for materials with a moisture content changing from 0.18 to 0.13 kg/kg in the process of drying [3], which corresponds to the moisture-content range of cereals. At the same time, it is difficult to realize a drying process in a microwave field because the main mechanisms of heat and mass transfer are not clearly understood. As the investigation object, we used buckwheat because this cereal is produced in large volumes, is in popular demand in the world market, and should match the high quality requirements [4]. The aim of the present work is to investigate the kinetics of drying of a dense buckwheat layer in a microwave field in different regimes and under different geometric conditions.

Investigations were carried out with the use of a microwave apparatus including a working chamber of volume 20 dm^3 supplied with power from a magnetron with a generation frequency of 2.45 GHz and an output power of 80–400 W. The time dependences of the integral moisture content and temperature of the material studied were determined with the use of experimental cells representing cylindrical reservoirs, the side walls and bottom of which were made in the form of a net transparent to radio waves. The cells were installed at a height of 0.07 m from the base of the chamber, which allowed the vapor formed to emerge from them in all directions. We investigated buckwheat samples with an initial moisture content of 0.2–0.25 kg/kg, an initial temperature of 17–26°C, and a mass of 0.05–1.2 kg. The thickness of the buckwheat layer in a cell was 0.008–0.048 m, the diameter of this layer was 0.11–0.276 m, and the area of its open surface (from which vapor was removed) was $8\cdot10^{-3}$–$94\cdot10^{-3}$ m^2. A cell with the material studied was placed into the microwave chamber. After a certain time, varying from 30 sec to 5 min depending on the power supplied, the amount of evaporated water was determined by the gravimetric method and the moisture content of the buckwheat was calculated. The temperature of the buckwheat was measured with the use of copper-constantan thermocouples that were placed in the layer immediately after the shutdown of the magnetron.

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TABLE 1. Influence of the Mass and Dimensions of a Buckwheat Layer on the Useful Heat Flow, the Heat Losses, and the Efficiency of a Drying Chamber

Number of experiment	m, kg	$F_s \cdot 10^3$, m^2	δ, m	t, °C	Q_r, W	Q_{conv}, W	Q_{usf}, W	η_c
1	0.05	18.4	0.008	60	1.3	6.9	33.6	0.21
2	0.06	15	0.016	68	1.25	7.1	38	0.24
3	0.1	18.4	0.016	75	2.08	10.5	48.6	0.3
4	0.15	28.6	0.016	65	3.1	11.7	51.24	0.32
5	0.2	39.6	0.009	55	3.3	12.0	50.5	0.32
6	0.2	29.4	0.032	83	5.0	18.1	69.4	0.43
7	0.31	59.8	0.009	47	4.7	12.1	48.4	0.31
8	0.31	33.2	0.048	90	7.9	22.0	84.2	0.53

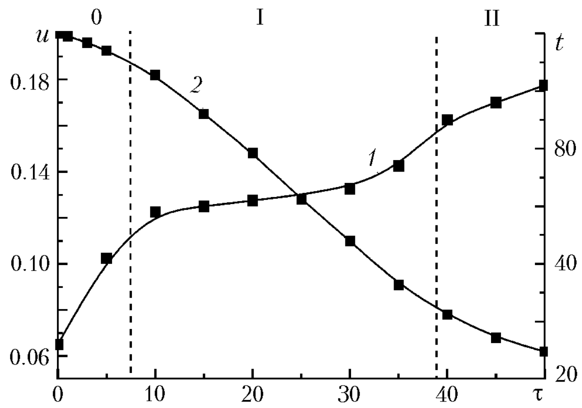

Fig. 1. Curves of the integral temperature (1) and moisture content (2) of a buckwheat layer dried in a microwave field (N_{out} = 80 W, m = 0.1 kg, δ = 0.016 m, D = 0.108 m): 0, I, II are periods of heating in the process of drying with constant and decreasing rates. The dashed lines denote the conditional boundaries of periods. τ, min.

The electric energy consumed from the supply line in the process of drying is partially converted into the magnetron output energy, a part of which is absorbed by the material. The absorbed energy is expended for heating of the material and evaporation of moisture (useful heat flow) and is lost in the process of radiative and convective heat exchange between the material and the chamber walls and the air. Under the experimental conditions, the heat energy absorbed was smaller than the output power of the magnetron.

The data on heat flows calculated for samples of different masses and dimensions at an output magnetron-power of 160 W are presented in Table 1. As the mass of the material studied increased, the amount of absorbed energy and the efficiency of the drying chamber, determined as the ratio between the useful heat energy and the output power of the magnetron, increased (experiments 1–4, 5, 8). Comparison of the results of paired experiments 5, 6 and 7, 8 has shown that an increase in the thickness of a buckwheat layer on condition that its mass remains unchanged leads to an increase in the heat energy absorbed. The losses of heat in cells increase with increase in the mass of the material and in its area penetrable to the vapor formed.

The time dependences of the integral moisture content and the temperature of the material studied indicate that the drying process considered is divided into periods, characteristic of other methods of drying of analogous materials, during which the material is heated (0) and is dried at a constant (I) and a decreasing (II) rate (Fig. 1). This allows the conclusion that the type of binding of the moisture in the material and not the method of heat supply has a determining influence on the process considered. This effect was observed in all experiments. The rate of drying of the material was calculated by the near-linear time dependences of its moisture content in the first period. Its value at different conditions was then used for determining the factors influencing the intensity of the drying.

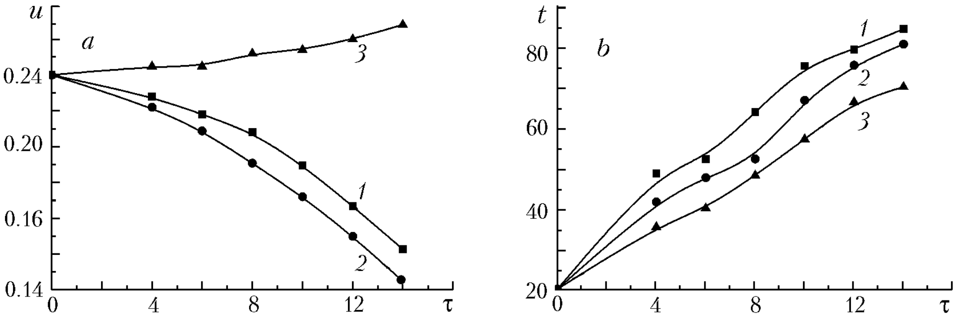

Fig. 2. Curves of the moisture content (a) and the temperature (b) of the upper (1), middle (2), and lower (3) layers. N_{out} = 240 W. τ, min.

The distributions of the moisture content and the temperature over the thickness of a buckwheat layer were investigated using an experimental cell consisting of three layers divided by nets transparent to radio waves. Each layer had a mass of 0.1 kg, a thickness of 0.01 m, and a diameter of 0.135 m. The side surfaces of the cell and its base were closed by an aluminum foil that served as a screen for microwaves. Thus, a microwave energy penetrated into the material and vapor was removed from it only through the open surface.

The kinetics curves obtained for a three-layer sample (Fig. 2) indicate that the temperature of all the layers increases continuously with time and drops at the interface between the upper and lower layers. The moisture content in the upper and middle layers decreases with time and the temperature of the lower layer increases and reaches 0.215 kg/kg at the end of the experiment at an initial moisture content of 0.20 kg/kg. Thus, the liquid removed from the grains in the upper layers of the material is filtrated down. The movement of water to the lower layer can be due to the action of the gravitational forces or due to the thermal-diffusion effect. To determine the main mechanism of this phenomenon, we conducted additional experiments with the use of isothermal and nonisothermal buckwheat layers with an initial moisture content of 0.25 kg/kg. Comparison of the results obtained has shown that the thermal diffusion is mainly responsible for the effect considered. For example, the moisture content in the lower layer of the isothermal buckwheat samples increased over 5 min by 0.007 kg/kg, and in the experiments with nonisothermal samples (where heat was supplied to the upper layer) the moisture content was increased by 0.08 kg/kg.

The data presented in Fig. 2 indicate that the temperature and moisture content are distributed very inhomogeneously over the layers. Such an inhomogeneity was absent in the netted three-layer cell, from which vapor was removed through the upper, lower, and side surfaces. In this case, the temperatures of the layers differed by no more than 4°C and their moisture contents differed by 0.007 kg/kg. Comparison of the data on the kinetics of drying of buckwheat, obtained with the use of cells with a solid bottom and a netted bottom transparent to radio waves, has supported the assumption that it is important to rationally organize the heat removal. For example, if, in the first case, the average moisture content in a sample was decreased from 0.2 to 0.17 kg/kg over 14 min, in the second case it was decreased by this value over 7.5 min.

Consequently, there is no sense in using a moisture-proof conveyer belt or a bottom plate in the drier. All the surfaces confining a dried object should be permeable to vapor and microwave energy.

Our investigations have shown that there is no univalent dependence of the temperature of a material on its mass. This is explained by the fact that the mean temperature of the material depends not only on its mass but also on its thickness and the area of the surface permeable to the vapor formed F_{s}. The temperature of a sample with a constant surface area increases with increase in its thickness and in the output power of a magnetron, and the temperature of a sample with a constant thickness decreases with increase in its area. At $560 \leq Q_{\text{usf}}/F_{\text{s}}$, the temperature averaged over the thickness of a layer is calculated in the period of drying with a constant rate by the formula

$$\bar{t}_{\text{I}} = 66.42 \left(\frac{Q_{\text{usf}}}{F_{\text{s}}} \right)^{0.122} \delta^{0.217} . \tag{1}$$

The mean-square error of dependence (1) is equal to 4.7%.

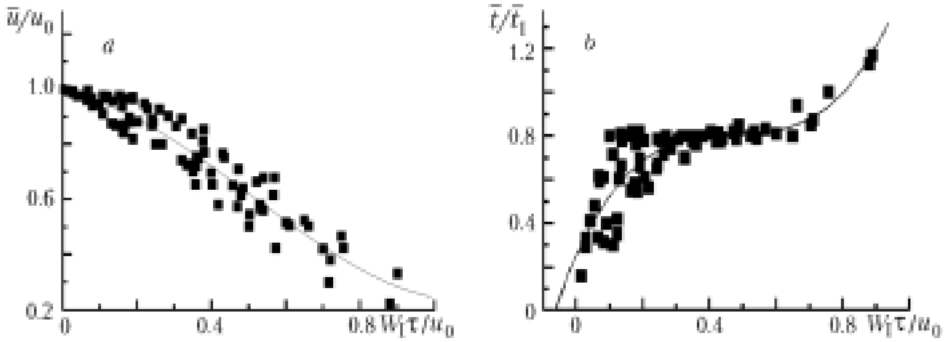

Fig. 3. Generalized curves of the moisture content (a) and temperature (b).

The rate of drying of the material studied increased with increase in the output power of the magnetron. An increase in the mass of a layer led, independently of its dimensions, to a decrease in the rate of its drying because the amount of the absorbed heat increased more slowly than the mass of the layer (see Table 1). The influence of a change in the mass of a layer, caused by a change in its thickness and in the area of its surface, on the rate of drying was investigated at N_n = idem. The rate of drying decreased more slowly in the case where the thickness of the layer increased and its diameter remained unchanged than in the case where the diameter of the layer increased at δ = idem. For example, in the case where the thickness of the layer changed from 0.008 to 0.048 m and its mass changed from 0.05 to 0.31 kg at $D = 0.11$ m = idem, the rate of drying decreased from $2.9 \cdot 10^{-4}$ to $1.2 \cdot 10^{-4}$ sec^{-1}, i.e., by 2.4 times (see Table 1, experiments 1 and 8). In the case where the mass of the layer increased in the same range with increase in its diameter from 0.11 to 0.276 m at $\delta = 0.008$ m = idem, the rate of drying decreased from $2.9 \cdot 10^{-4}$ to $4.5 \cdot 10^{-5}$ sec^{-1}, i.e., by 6.5 times (see Table 1, experiments 1 and 7). Consequently, it makes sense to increase the mass of a layer at the cost of an increase in its thickness, the limiting value of which should not exceed the double depth of penetration of electromagnetic energy into the layer [1]. The rate of microwave drying changed from $5.9 \cdot 10^{-5}$ to $62.8 \cdot 10^{-5}$ sec^{-1}, which is much higher than the rate of other drying processes. This is explained by the fact that, in the case considered, the heat release is homogeneous throughout the volume of a layer, which makes it possible to supply the layer with a large amount of heat in a unit time without its overheating. For example, the temperature of a buckwheat layer did not exceed 80°C at a heat-flow volume density $Q_{\text{usf}}/V_m = 667{,}520$ W/m^3.

On the basis of the experimental data on the temperature and moisture-content distribution in three- and four-layer samples, we calculated the coefficient of microwave-energy attenuation in a buckwheat layer: $\alpha = 30.1$ m^{-1}. Thus, the thickness of a layer, which decreases a microwave energy by e times, is equal to approximately 0.033 m. The numerical values of these quantities depend on the electrophysical characteristics of the material being dried and are true for a buckwheat with an average moisture content of 0.18 kg/kg and a density of 840 kg/m^3. The changes in the initial temperature and the moisture content of a material within the above-indicated ranges do not influence the rate of its drying.

On the basis of the experimental data obtained, we have derived an equation that which allows one to calculate, with an error of 6.3%, the rate of drying of a material in the first period of the process (Fig. 1):

$$W_{\text{I}} = 2.34 \cdot 10^{-5} \left(\frac{Q_{\text{usf}}}{m} \right)^{1.03} . \tag{2}$$

Dependence (2) is true for the above-indicated experimental conditions at $139 \leq Q_{\text{usf}}/m \leq 1250$ W/kg.

On the basis of experimental data on the integral moisture content and temperature of the material studied, we constructed generalized modified kinetics curves of its drying and heating — the dependences of the dimensionless current moisture content $\bar{u}/u_0$ and temperature $\bar{t}/t_1$ on the dimensionless quantity $W_{\text{I}}\tau/u_0$ — which fairly completely account for the conditions of the interrelated heat and moisture transfer in the process of drying [5]. The quantity $W_{\text{I}}\tau/u_0$ has a definite physical meaning: it defines the relative decrease in the moisture content for the time interval 0–τ, which would happen in the case where the drying rate averaged over this time interval is equal to the rate of drying in the first period of the process.

Figure 3 presents generalized modified curves of the moisture content and temperature of buckwheat layers with different initial moisture contents, useful heat flows, masses, and dimensions (thickness and diameter of a layer and area of the surface from which heat is removed). The periods of drying are defined by the equations

$$\frac{\bar{u}}{u_0} = 1 - 0.22\,\frac{W_{\rm I}\tau}{u_0} - 1.55\left(\frac{W_{\rm I}\tau}{u_0}\right)^2 + 1.02\left(\frac{W_{\rm I}\tau}{u_0}\right)^3 , \tag{3}$$

$$\frac{\bar{t}}{\bar{t}_1} = 0.46 + 3.34\left(\frac{W_{\rm I}\tau}{u_0}\right) - 6.91\left(\frac{W_{\rm I}\tau}{u_0}\right)^2 + 4.86\left(\frac{W_{\rm I}\tau}{u_0}\right)^3 . \tag{4}$$

Formulas (3) and (4) are true with a mean-square error of 11.9 and 13.7% respectively. The value of $\bar{t}_{\rm I}$ is determined from Eq. (1) and $W_{\rm I}$ is determined from (2).

To the critical moisture contents determining the boundaries between periods I and II (see Fig. 1) corresponds the critical values of the quantity $W_{\rm I}\tau/u_0$:

$$(W_{\rm I}\tau/u_0)_{\rm crI} = 0.2\,,\quad (W_{\rm I}\tau/u_0)_{\rm crII} = 0.8\,,\quad u_{\rm crI} = 0.9u_0\,,\quad u_{\rm crII} = 0.35u_0\,. \tag{5}$$

By these values we can determine the regions corresponding to the periods of heating at constant and decreasing rates of drying of a material. The above relations make it possible to determine the period of the process at a definite instant of time and the duration of each period.

The useful heat flow necessary for calculating the rate of drying of a material and its temperature by dependences (2) and (1) can be determined by the energy consumed from the supply line with account for the efficiency of the magnetron and the drying chamber:

$$Q_{\rm usf} = N_{\rm n}\eta_{\rm m}\eta_{\rm c}\,. \tag{6}$$

When the mass of a buckwheat layer changed from 0.05 to 1.2 kg and its relative volume $V_{\rm mat}/V_{\rm c}$ changed from 0.003 to 0.07, the efficiency of the drying changed from 0.25 to 0.56. For a layer of thickness no less than 0.016 m, it can be determined, with an error of 6.2%, by the formula

$$\eta_{\rm c} = 0.56\left(1 - \frac{4.63}{5.87 + \exp\,(182V_{\rm mat}/V_{\rm c})}\right). \tag{7}$$

When the mass and volume of the material charged into the microwave chamber increased at a constant energy consumed from the supply line ($N_{\rm n}$ = idem), the useful heat flow increased because of an increase in the efficiency of the drying chamber. However, in this case, the rate of drying and the efficiency of the drier decreased, and the duration of the process and the electric-energy consumption increased. The expediency of increasing the mass of a material can be estimated on the basis of comparison of the specific energies expended for these effects. In the range of change in the moisture content of the material studied, 0.2–0.14 kg/kg, the specific energy expended was equal to $1.15\cdot10^6$ J/kg for a sample of mass 0.05 kg, $0.8\cdot10^6$ J/kg for a sample of mass 0.2 kg, and $0.65\cdot10^6$ J/kg for a sample of mass 0.31 kg. Thus, it makes sense, from an economical standpoint, to increase the mass of the material charged into the drying chamber and simultaneously increase, for increasing the efficiency of the apparatus, the power of the magnetron to a value at which the temperature of the material will be lower than the critical one.

NOTATION

D, diameter of a layer, m; e, base of a natural logarithm; F, area of a surface, m^2; m, mass of a material, kg; N, power, W; Q, heat flow, W; t, temperature, $^{\rm o}$C; u, moisture content of a material, kg/kg; V, volume, m^3; W, rate of drying, sec^{-1}; α, attenuation coefficient, m^{-1}; δ, thickness of a layer, m; η, efficiency; τ, time, sec. Subscripts: out, output; c, chamber; con, convective; cr, critical; r, radiant; mat, material; m, magnetron; s, surface open for vapor release; usf, useful; n, net; 0, initial value; I and II, periods of drying with a constant and a decreasing rate; overscribed bar, average value of a quantity.

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