RESEARCH OF HEAT AND MASS TRANSFER DURING CONVECTIVE DRYING OF COLLOID CAPILLARY-POROUS MATERIALS

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Abstract. The article presents a reasonable analysis and relevance of the study of the drying process of vegetable raw materials (colloidal capillary-porous materials). Drying is an energy-intensive industrial process that is defined from a technological point of view: on the one hand by heat and moisture exchange between the body surface and the environment, on the other hand by heating the body and transferring moisture inside it due to the form of moisture. One of the most effective ways to increase the shelf life of food is to dry it to equilibrium humidity. Very important are the technological parameters of the drying regimes, which, when used rationally, are able to preserve the biochemical properties and nutrients of the raw material at a high level in the obtained dry product. The study of dehydration of vegetable raw materials is widely practiced around the world, especially in countries such as Germany, France, USA, Argentina, Hungary, Brazil, Poland, Korea, China, Malaysia. However, the obtained processed products lose their biologically active components and nutrients, and the processing process is energy consuming. Therefore, the problem is relevant and needs an effective solution. In this paper, the kinetics of the drying process, thermogravimetric studies and a mathematical model for colloidal capillary-porous materials of plant origin were analyzed. According to the results of the highlighted research, the process of convective drying of colloidal capillary-porous materials was intensified above 21% due to the use of innovative step regimes. The developed beet-rhubarb composition is a colloidal capillary-porous material that stabilizes and protects at the

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biochemical level betanin of the beet from the effects of temperature during convective drying, has in comparison with the components of the composition lower heat of dehydration and increased thermal-stability. Prolonged high-temperature exposure causes instant complete destruction of sugars, proteins and other nutrients components. Derivatographic studies have confirmed that the use of the temperature range of $100\,°C$ in a stepwise mode of $100/60\,°C$ for the developed soybean-spinach composition is safe for biologically active substances and it is justified by experimental temperature curves. Numerical modeling of heat and mass transfer during convective drying of crushed beets and crushed soybeans using the known model by A.V. Lykov satisfactorily describes the process and can be used to model the convection drying of colloidal capillary-porous materials.

1. Introduction

Outdated technologies lead to irrational use and high energy consumption, increase energy consumption and import. This brings the issue of energy saving and energy efficiency to one of the most important tasks to be solved.

In modern conditions, these issues are an integral part of the problem of ecology. Ukraine, having a unique environment for Europe, being fully supplied with natural resources, is at the same time one of the countries in the region where energy resources are used the least efficiently and there are many environmental problems.

The polluted environment directly affects the physical condition of the population. Poor nutrition, constant stress, ecology – a complex that interacts daily with the human immune system. Nutrition is a key moment in the life of every living organism. Food occupies a leading place in everyone's life. The Ministry of Health of Ukraine reports: "The highest mortality rate in the world is caused by malnutrition. This Figure is higher than due to smoking, high blood pressure and other risk factors».

Therefore, food must have functional properties, and their processing should ensure maximum preservation of biologically active substances contained in them while reducing energy consumption for processing.

2. Relevance and existing research

Nowadays, the international status of Ukraine depends on the effective realization of its advantages of resource potential in the world labor

market and in competitiveness. In the agricultural sector of Ukraine, its development strategy should be aimed at creating an environmentally safe, efficient, socially oriented, resource-saving, scientific sector of the state economy that can ensure the position of world food market leader in agricultural products and meet domestic needs. Therefore, the development of energy-efficient heat technologies in the food industry is an important stage. Drying refers to energy efficient processes. From the technological point of view, the drying process is determined on the one hand by heat and moisture exchange between the body surface and the environment, on the other hand – by heating the body and transferring moisture inside it due to the form of moisture. The problem of processing, drying and use of vegetable raw materials with full preservation of its functionality is very relevant due to the wide range of its use in the food and pharmaceutical industries. When drying, the weight of the product is significantly reduced, which reduces the cost of transportation, packaging and reduces the need for storage space.

Investigation of the process of drying of plant material involved are carried out in countries such as Germany, France, USA, Argentina, Hungary, Brazil, Poland, Korea, China, Malaysia and others [1–5].

Given all this, there is a need to develop and improve thermal technologies for drying vegetable raw materials, which will process products with minimal energy consumption, long shelf life and preservation of biologically active substances.

3. Materials and methods of researches

In this paper, the kinetics of the drying process, thermogravimetric studies and calculated a mathematical model of drying for colloidal capillary-porous materials of plant origin were analyzed.

Our research has shown that each plant raw material requires appropriate technological modes of preparation and drying [6].

From the comparative analysis of the latest researches and publications there is a necessity of research of influence of technological parameters of processes of pre-treatment preparation and dehydration of vegetable raw materials on energy consumption at manufacturing of functional powders on the basis of objects of research. The objects of the study were colloidal capillary-porous materials, representatives of 2 functional subgroups,

namely phytoestrogenic mixture (1:1) – soy-spinach; antioxidant mixture (2:1) – rhubarb-beet.

For this purpose, was experimental studies of the drying process of prepared raw materials at a step temperature of 100/60 °C on a convective drying stand with continuous automatic collection and processing of information about changes in mass, sample temperature using the developed application program «Sooshka», which allows calculations with construction drying curves [7].

The prepared mono-raw material and compositions were poured on a mesh tray measuring 100x50 mm, which was placed on a weighing rod in the drying chamber. Thermocouples were inserted inside the material to measure the temperature change of the material during drying. Studies of the drying process were carried out to the final moisture content of the material $W_c^c = 4\%$, because, as is known, drying materials to a moisture content below 5% can significantly increase their shelf life in powder form. To determine the current humidity of the material, the samples were dried after the experiment to absolutely dry weight at 100…105 °C (GOST 28561-90 «Determination of humidity by the method of drying to constant weight»).

Studies to determine the heat of dehydration and thermal stability were performed using a derivatographic method that combines thermogravimetry (TG) with classical differential thermal analysis (DTA). This method allowed to study the state of mono-substances and compositions under programmable heating [8]. Qualitative and quantitative analysis of the processes that took place during the heating of the samples at a constant rate is realized with derivatograms – a set of curves of change: temperature of the sample (T), its mass (TG), mass change rate (DTG) and DTA curve (difference of thermoelectromotive forces of thermocouples of the sample) due to which it is possible to identify thermal processes.

The studies were performed on a Q-1000 derivatograph of the Paulik-Paulik-Erdey system (IOM, Hungary) [9] in the range of 25… 250 °C at a heating rate of 3.6 K/min. Atmosphere – still air. The inert substance in the reference crucible was alumina. The temperature scale was corrected by the melting point of benzoic acid (122.4 °C) [10]. The temperature deviation did not exceed ± 0.5K. Using the Derivatograph computer application created in the Delphi programming environment, the obtained data were collected

and processed. Samples before the study were ground in a meat grinder and crushed in a mortar to a single fractional state of particles. Samples were placed in an open conical platinum crucible from a set of derivatographs.

Calculations of the mathematical model of the theoretical study of heat and mass transfer on the basis of the existing and known theory of Lykov A.V., were carried out by means of DELPHI programming.

4. Research results

Based on the known previous studies of the authors presented in [7; 11], the preliminary preparation of raw materials [12–13] and the use of a step temperature of 100/60 °C for convective drying of colloidal capillary-porous materials of plant origin is proposed. The principle of studying the effect of gradual change of heat-coolant temperature on the drying process of colloidal capillary-porous materials is as follows: the coolant temperature is reduced from the initial 100 to 60 ºC, when the temperature in the material layer approached the allowable (60 ºC).

Drying curves of phytoestrogenic mixtures have a characteristic appearance for colloidal capillary-porous materials. As the heat-coolant temperature increases, the intensity of the drying process of the mixtures increases.

Drying curves using the developed step regime 100/60 ºC for phytoestrogenic soy-spinach mixture, spinach – thermolabile material, are presented in Figure 1 [7]. It is established: the use of step (100/60 ºC) change of heat-coolant temperature during drying of phytoestrogenic raw materials allows to reduce drying time in comparison with the monotemperature mode of 60 ºC, there is an intensification of process by 21%, the average speed of process is increased. Additional studies of qualitative characteristics confirmed the lack of negative impact on the biochemical components of raw materials [14].

Due to the fact that when drying plant materials, the increase in energy costs is due to the complicated permeability of cell membranes to water and the complexity of the water removal process (due to interaction with soluble components of cell juice and skeletal molecules) and due to lack of data in the literature , it is important to investigate the effect of creating functional compositions of vegetable raw materials on the value of heat consumption for dehydration of mixtures and their thermal-stability.

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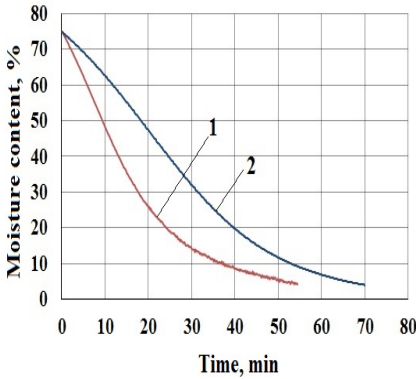
Figure 1. Change in moisture content of soybean-spinach mixture under the influence of heat-coolant temperature 60ºC and 100/60ºC. Mode parameters: δ = 15 mm, Wᶜκ = 4 %; v = 2,5 m/sec, d = 10 g/kg dry air: 1–100/60ºC, 2 – 60ºC

It is known from the literature that there is a significant difference between the actual values of specific heat consumption for their dehydration from the heat of evaporation of pure water [10]. The increase in energy consumption for the drying process of materials of plant origin is associated with the removal of water associated with molecules and ions of cell sap, as well as biopolymers of the skeleton of the material [6; 10; 15].

The objective of the study was to determine whether the effect on heat dehydration and thermal stability of the table beet reduction of pH by creating a composite mixture of beet-rhubarb (the ratio of table beet to the rhubarb into the mix was the 2:1) and formation of a composite mixture of soybeans-spinach (ratio of soybeans to spinach in the mixture was as 1:1).

In Figure 2-4 presents the obtained derivatograms. The derivatives show that the change in the mass of the samples (TG curves) with simultaneous heat absorption (DTA curves) starts at 25.0 °C and indicates the removal of water. With increasing temperature, the rate of dehydration (DTG curves) increases, reaching its maximum at a certain temperature (Table 1). At maximum points, samples of table beets, rhubarb and mixtures acquire a relative humidity W, respectively, 30.37, 21.36 and 32.94%. For table beets by differential scanning calorimetry, it was shown [16] that the maximum moisture content, after which only bound water remains in the tissues, corresponds to a relative humidity of 26.0% (Figure 2). That is, the temperature of the maximum rate of dehydration (DTG) or heat absorption (DTA) does not divide water into free and bound, as suggested in some studies.
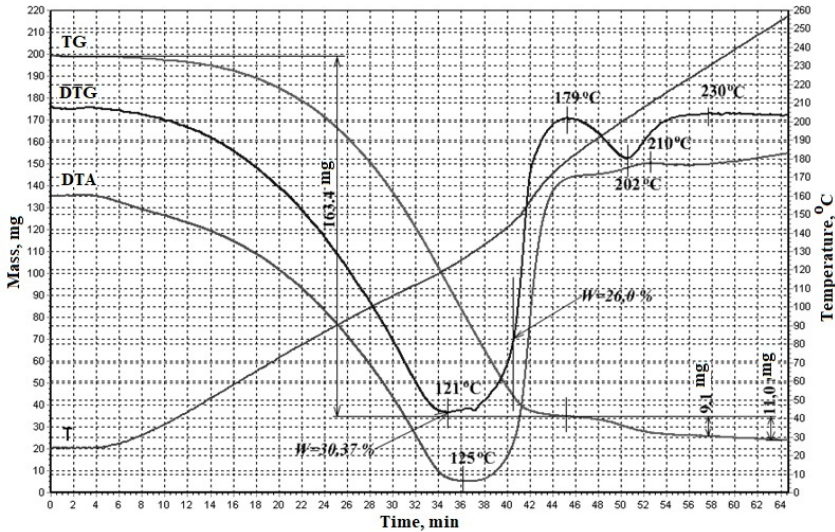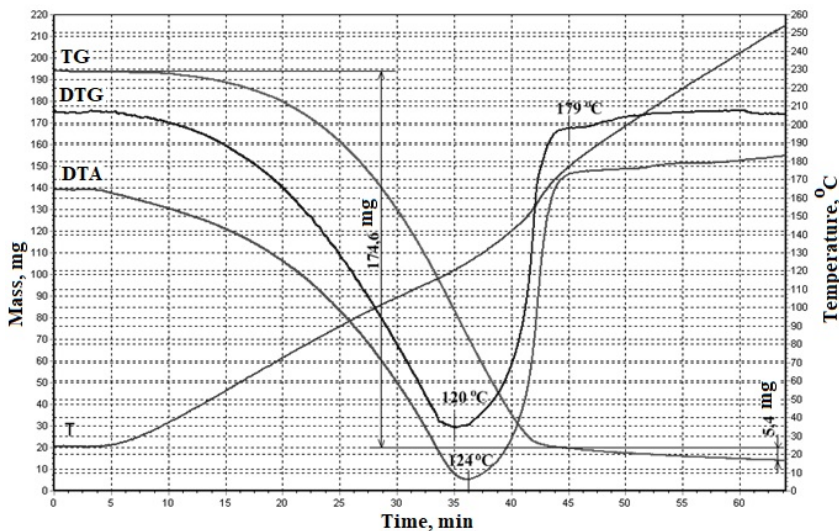
Figure 2. Derivatogram of of table beets. Sample weight 198.2 mg

After reaching the maximum, the rate of dehydration drops to zero, which corresponds to complete dehydration of the samples. The temperature of complete dehydration for the studied raw materials is practically the same and is at the level of 178–179 °C (table 1). However, the rate of dehydration depends on the nature of the material. Beetroot has the lowest speed and rhubarb has the highest speed. A mixture of beets with rhubarb has a higher rate of dehydration than beets. This fact is most likely due to the difference in humidity of the samples. The higher the initial humidity, the higher the average rate of dehydration (table 1).

In the gravimetric study of table beets after complete dehydration in the range of 179–230 °C, the loss of mass (TG) of the sample with the maximum peak velocity (DTG) at 202 °C is registered (Figure 2). Moreover, this change in mass occurs with the release of heat, the maximum of which is at 210 °C (DTA). According to the characteristic features, this process refers to thermal decomposition, but from this study it is not possible to establish a degrading substance. On the derivatograms of rhubarb and a mixture of beets with rhubarb in the studied temperature range of thermal

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**Figure 3. Derivatogram of a mixture of table beet
with rhubarb in a ratio of 2:1. Sample weight 194.0 mg**

decomposition processes with a sharp change in mass was not detected
(Figure 3). However, after complete dehydration, there is a slow decrease
in sample weight (TG). The table shows that the rate of thermal destruction
is highest in beets, and lowest – in the mixture.

The difference in the values of the temperatures of the maxima ΔT of
the dehydration rate and thermal decomposition recorded on the DTG and
DTA curves is related to the influence of the thermal conductivity of the
samples on the electromotive force of the measuring thermocouple. The
lower the thermal conductivity, the greater the temperature difference. For
wet samples $\Delta T = 2$–$4\,°C$ (Figure 2–4) for dry material $\Delta T = 8\,°C$.

Using the method described in [16], the heat expended on dehydration
during the derivatographic study was estimated (Table 1). From the table
we see that most of the heat is expended during dehydration of table
beets, as raw materials with a high content of bound water [10]. The heat
consumption for rhubarb dehydration is slightly lower. However, the
specific heat consumption during dehydration of a mixture of table beets
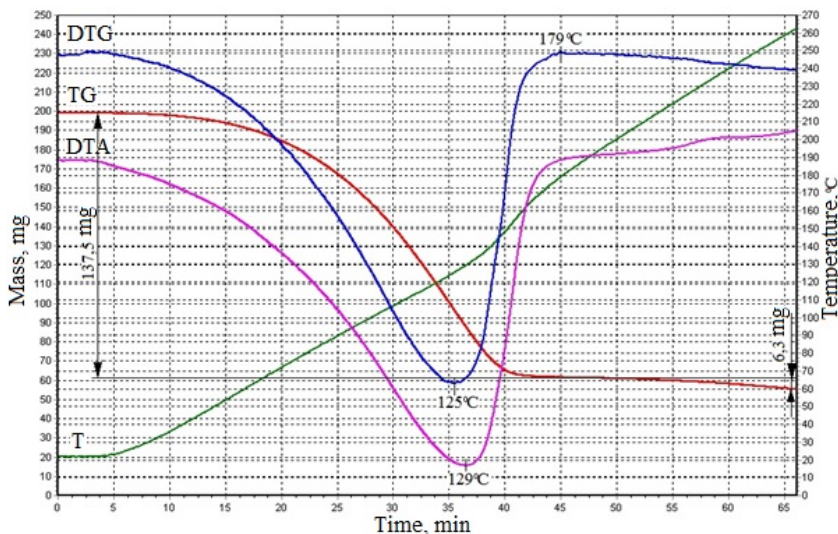
Figure 4. Derivatogram of soy-spinach mixture (1:1).
Sample weight 199 mg

with rhubarb is much smaller than the cost of dehydration of individual components of the mixture. The most likely reason for this decrease in heat consumption is a significant reduction in the content of bound water in the mixture, which may be due to changes in the structure and composition of the components of the mixture under conditions of low pH.

After analyzing the obtained graphs for derivatographic on a mixture of soybeans and spinach (Figure 4), we can state that the removal of water, as evidenced by the change in mass of objects (TG curves), with simultaneous heat absorption (DTA curves) begins with 22-24.0 °C (table 1). After passing the maximum points, the tested samples of mono-raw materials and mixtures reach their values of the maximum moisture content, at this stage only bound water remains. It is known that the temperature of the maximum rate of water removal (DTG) or heat absorption (DTA) in the range of 22-196 °C does not separate water into free and bound [16]. The rate of water removal after the peak peaks to zero and this means – complete dehydration of the samples. Depending on the structure of the material and

its chemical composition will be the appropriate rate of removal of water from it. From previous studies [15] it is known that the highest value in spinach, the lowest – pre-hydrothermally treated soybeans.

Table 1

The results of the analysis of derivatographic curves of antioxidant and phytoestrogenic raw materials

Material	Humidity, %	Water removal				Thermal destruction		
		Interval, °C	Maximum speed, °C	Average speed, %/c	Warmth, J/g	Interval, °C	Maximum speed, °C	Average speed, %/c
beet-rhubarb mixture	90,00	25-179	120	0,033	2276	179-254	-	0,025
soybean – spinach mixture	69,09	22-179	125	0,027	2545,4	179-240	-	0,026

After dehydration, there is a moderate decrease in sample weight (TG). After overcoming the temperature barrier of 100-105 °C in the soy-spinach mixture, there is an instant complete destruction of sugars, proteins and nutrients contained in protein-containing phytoestrogenic mixtures. The difference in the values of ΔT temperatures of the maximums of water removal rate and thermal destruction (combustion), showing the curves of DTG and DTA, is associated with the influence of thermal conductivity of vegetable raw materials (samples) on the EMF of the measuring thermocouple [10; 15].

According to the method described in [17], the heat expended on dehydration of the samples was estimated (Table 1). The specific heat consumption during dehydration of mixtures of carotene-containing components with soybeans is much lower than the cost of dehydration of mono-components of the mixture [15].

It should be noted that the specific heat of dehydration is determined in non-isothermal conditions and its values should be considered as the average obtained in the temperature range 25–179 °C.

The ratio of the specific heat of dehydration of beets, rhubarb and their mixtures; soybeans, spinach and their mixtures correlate with the results

obtained by studying the specific heat of evaporation of water from these materials in a differential microcalorimeter of evaporation [17].

In addition to experimental studies of colloidal capillary-porous materials, numerical modeling of the heat and mass transfer process during the drying of phytoestrogenic raw materials was performed [15; 18]. Numerical modeling of the process of convection drying of colloidal capillary-porous material (vegetable raw materials) is performed on the basis of the finite-difference solution of the system of heat and mass transfer equations, which consists of:

– mass transfer equation: $\dfrac{\partial u}{\partial \tau} = K_{11}\nabla^2 u + K_{12}\nabla^2 T$ (4)

– heat transfer equation: $\dfrac{\partial T}{\partial \tau} = K_{21}\nabla^2 u + K_{22}\nabla^2 T$ (5)

where u, kg/m^3 – specific moisture content of the material; T, K – temperature; τ, sec – time, ∇^2 – Laplace operator.

The coefficients included in the given system of equations have the form:

$$K_{11} = a_m;\ K_{12} = a_m^T;\ K_{21} = \frac{r\varepsilon a_m}{C_p\rho};\ K_{22} = \frac{\lambda}{C_p\rho} + \frac{r\varepsilon a_m^T}{C_p\rho},$$

where a_m, m^2/sec – moisture diffusion coefficient in colloidal capillary-porous material; a_m^T, kg/(m·K·sec) – moisture thermal diffusion coefficient; ρ, kg/m^3 – effective material density; λ – effective thermal conductivity of the material;

C_p, J/(kg K) – effective heat capacity of the material; r, J/kg – specific heat of moisture evaporation; ε ($0<\varepsilon<1$) – phase transformation coefficient, which determines the proportion of water vapor flow relative to the total flow of liquid and vapor moisture.

For numerical modeling of the convection drying process, a sample of rectangular soybean raw material with a thickness of δ, placed in the drying chamber. The surfaces of the sample are washed with a coolant, ie dry heated air having a temperature T_∞ and the relative concentration of water vapor $\rho_{v,B,\ \infty}$ (Figure 5). The air flow rate in the drying chamber moving in the longitudinal direction has a value v_∞. The relative concentration of water vapor is defined as the ratio of the partial density of water vapor to the density of the vapor-air mixture.

The physical model of the drying process involves the transfer of heat by convection from the heated air stream to the surface of the layer of material to be dried. The water vapor formed as a result of drying the material is removed into the coolant stream. The main transfer of heat and moisture occurs in the direction perpendicular to the surface of the material.
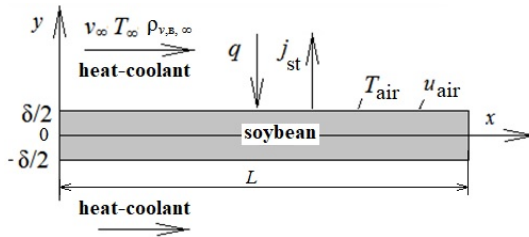
**Figure 5. Scheme to the physical model
of the convection drying process**

In the case of a small sample thickness δ heat and mass flows in the longitudinal direction can be neglected. In this case, the problem of heat and mass transfer is considered in an approximate one-dimensional formulation. If the temperature gradients in the thickness of the material are relatively low, you can also ignore the transfer of moisture by thermal diffusion. In this case $K_{12} = 0$; $K_{22} = \dfrac{\lambda}{C_p\rho}$. Under these conditions, equations (4) and (5) are simplified and take the form:

$$\frac{\partial u}{\partial \tau} = a_m \frac{\partial^2 u}{\partial y^2}; \tag{6}$$

$$\frac{\partial T}{\partial \tau} = a_T \frac{\partial^2 T}{\partial y^2} + \frac{r\varepsilon}{C_p\rho}\frac{\partial u}{\partial \tau} \tag{7}$$

where $a_T = K_{22} = \dfrac{\lambda}{C_p\rho}$ – effective coefficient of thermal conductivity of colloidal capillary-porous material.

The initial conditions for nonstationary equations (6) and (7) are temperature distributions T and specific moisture content u on the thickness of the material at τ=0. Speed is also a known quantity, temperature T_∞ and the relative humidity of the heat-coolant φ_∞. To formulate the boundary

conditions, it is assumed that the heat and mass transfer process proceeds symmetrically about the axis 0X. In this case, the system of equations (6), (7) is considered only in the domain $0 \leq y \leq \delta/2$ (Figure 6), and at $y=0$ the conditions of symmetry in the form are set:

$$\frac{\partial u}{\partial y}\bigg|_{y=0} = 0 \, ; \quad \frac{\partial T}{\partial y}\bigg|_{y=0} = 0 \, .$$

On the surface of the sample to be dried, the boundary conditions must determine the balance of moisture removed from the material and entering the coolant, as well as the balance of heat coming from the coolant to the material and spent on heating the material and evaporating moisture from the surface. The total flow of liquid and vapor moisture coming from the middle of the material to its surface is defined as $j_{\theta_\theta} = -a_m \dfrac{\partial u}{\partial y}\bigg|_{y='/2}$. From the surface of the material to the coolant, moisture is transferred in the form of vapor by diffusion. The density of this flow is calculated by expression $j_\theta = -D_{va}\rho_a \dfrac{\partial \rho_{v,2}}{\partial y}\bigg|_{y=\delta/2}$, where D_{va} – water vapor diffusion coefficient in air. Therefore, the boundary condition to equation (6) on the heat and mass transfer surface has the form:

$$-a_m \frac{\partial u}{\partial y}\bigg|_{y=\delta/2} = -D_{va}\rho_a \frac{\partial \rho_{v,2}}{\partial y}\bigg|_{y=\delta/2} \qquad (8)$$

The heat flux flowing to the surface of the material from the coolant is equal to $q_a = -\lambda_a \dfrac{\partial T}{\partial y}\bigg|_{y=\delta/2}$, where λ_a – coefficient of thermal conductivity of air. The heat flux density transferred from the heat and mass transfer surface into the material is calculated as $q_m = -\lambda \dfrac{\partial T}{\partial y}\bigg|_{y=\delta/2}$. The heat flux density expended on the evaporation of moisture from the surface is proportional to the flux density of the liquid moisture, ie, $q_{ev} = -r\left(1-\varepsilon_{air}\right)a_m \dfrac{du}{dy}\big|y=\delta/2$.

Expression $\left(1-\varepsilon_{air}\right)$ determines the proportion of the flow of liquid moisture from the total flow of moisture coming on the heat and mass transfer surface has the form:

$$-\lambda \left.\frac{\partial T}{\partial y}\right|_{x=\delta/2} = -r(1-\varepsilon_{air})a_m \left.\frac{\partial u}{\partial y}\right|_{x=\delta/2} = -\lambda_a \left.\frac{\partial T}{\partial y}\right|_{x=\delta/2}, \qquad (9)$$

To calculate the heat flux density and water vapor flux density on the surface of the material from the coolant, the expressions are used:

$$-D_{va}\rho_a \left.\frac{\partial \rho_{v,2}}{\partial y}\right|_{y=\delta/2} = \beta\left(\rho_{v,2,air} - \rho_{v,2,\infty}\right) \qquad (10)$$

$$-\lambda_a \left.\frac{\partial T}{\partial y}\right|_{x=\delta/2} = \alpha\left(T_{air} - T_\infty\right), \qquad (11)$$

where α, W/(m^{2}K) – heat transfer coefficient; β, kg/(m^{2}sec) – mass transfer coefficient, T_{air} – surface temperature of heat and mass transfer, $\rho_{v,2,air}$ – the relative concentration of water vapor in the coolant near the surface of the material.

A rectangular sample of CCPM in length is considered L_1=100 mm; width L_2=50 mm and thickness δ =15 mm. The temperature of the heat-coolant (heated air) at the entrance to the drying chamber is t_∞ = 60 °C, and its relative humidity φ_∞=7%. Under these conditions $\rho_{v,в,\infty}$=0,00858. Air flow rate in the drying chamber u_∞ =2,5 m/sec. The initial mass of the sample is m_n=33,78 g. Mass of dry material (after complete removal of moisture) m_c=12,79 g. The initial temperature of the soybean layer varies linearly from 37,1 °C in the middle of the sample (y=0) to 46,7 °C on its surface (y=δ/2). The initial specific moisture content is u_0=280,0 kg/м^3. Sorption-desorption curves for determining the equilibrium moisture content of crushed soybeans depending on the relative humidity and thermophysical properties of crushed soybeans are taken from scientific publications.

The results of numerical simulation of the temperature regime of the drying process were compared with experimental data. Figure 7 shows the change in temperature over time in the middle of this soybean sample. Curve (1) corresponds to the results of numerical simulation, and curve (2) – the results of the experiment. As can be seen from Figure 6 in the middle of the sample, the temperature varies rapidly for 120 minutes from the beginning of the drying process.

An important integral characteristic of the drying process is the time dependence of the mass of the sample to be dried. In Figure 7 (curve 1)
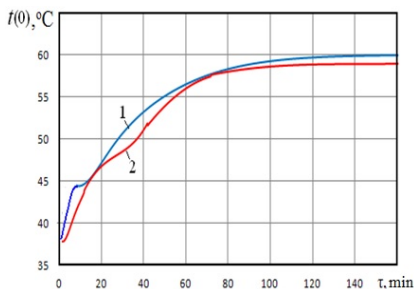
Figure 6. Time change of temperature inside of the soybean layer during its drying: 1 – results of numerical simulation; 2 – experimental data
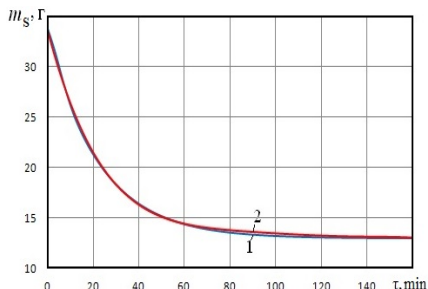
Figure 7. Time change of the mass of the soybean layer during its drying: 1 – results of numerical simulation; 2 – experimental data

shows the results of calculating the change in time of the mass of the soybean sample during its drying.

As can be seen from Figure 7, for the first 80 minutes from the beginning of the drying process, the mass of the soybean sample due to moisture evaporation decreases from the initial value of 33.78 g to 13.5 g. Then the process of removing moisture is significantly slowed down.
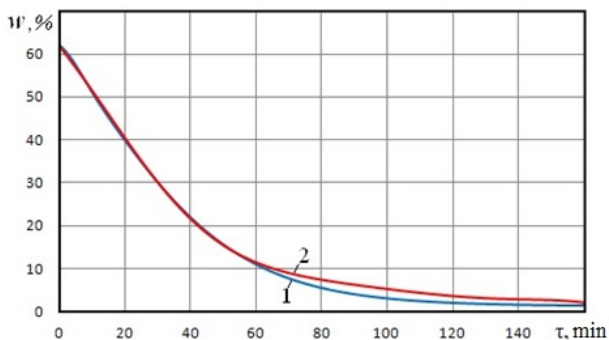
Comparison of the results of numerical simulations with the calculation data indicates their satisfactory agreement.

Another important integral characteristic of the drying process is the change over time in the relative concentration of moisture in the material $w(\tau)$. This value is calculated by the formula:

$$w = \frac{m_{з} - m_{c}}{m_{з}} \cdot 100\% \tag{12}$$

Its dependence on time is shown in Figure 8. The nature of the change in this value is generally similar to the change in the $m_{з}$ value. For the first 60 minutes from the beginning of drying the value $w(\tau)$ varies quite intensively: from 62% to 11%. In the future, its change in time slows down. This value is also determined from the experiment.

As can be seen from Figure 8, on the time interval $0<\tau<60$ min. the calculated results and experimental data agree quite well. Then, at the stage of drying, there is a slight discrepancy.

**Figure 8. Dependence on time of relative concentration
of moisture in a layer of soy in the course of its drying:
1 – results of numerical modeling; 2 – experimental data**

From the analysis of numerical simulation data, as well as the results of comparing the calculated data with experimental data, we can conclude that the proposed numerical model satisfactorily describes the process of convection drying of crushed soybeans and can be used to calculate the mode parameters of this process. Comparing the results of the previously performed and presented in [18; 19; 20] numerical modeling of convection drying of crushed beets with the results for crushed soybeans [15; 20], we conclude that the proposed model satisfactorily describes the process of convection drying of colloidal capillary-porous materials.

5. Conclusions
The generalized analysis of the obtained data confirmed that the use of stepwise drying mode 100/60 °C intensifies the drying process of phytoestrogenic mixtures (21%), and also does not lead to deterioration of the quality characteristics of the final product.

Thus, the universality of this step mode makes it possible to reduce energy costs for convective drying and can be used in mass production of functional powders, which are an available source of natural vitamins and minerals to strengthen human immunity during epidemics and exacerbations of viral diseases.

Based on the results of derivatographic studies of antioxidant raw tissues (table beets, rhubarb and a mixture of table beets with rhubarb 2:

1), it can be stated that the dehydration of the mixture occurs at a rate 10% higher than the average rate of dehydration of table beet tissues; the average specific heat of dehydration of the mixture is 13.5% lower than the heat of dehydration of table beets and almost 9% less than the heat of dehydration of rhubarb; the thermal stability of the mixture exceeds the thermal stability of table beets. Therefore, the developed beet-rhubarb composition for stabilization and protection of betanin from the effects of temperature during drying has in comparison with the components of the composition lower heat of dehydration and increased thermal stability.

According to derivatographic studies of phytoestrogenic raw materials based on soybeans, it was found that the average specific heat of dehydration of soybean-spinach mixture is 2.5% lower than the average specific heat of dehydration of spinach, but 1.6% higher than the average specific heat of dehydration of hydrothermally treated soybeans.

It is determined that the average rate of dehydration of the mixture is 10% higher than the average rate of dehydration of the components. Prolonged high-temperature exposure causes instant complete destruction of sugars, proteins and other nutrients components.

Therefore, taking into account the temperature ranges and physicochemical properties of the studied antioxidant and phytoestrogenic raw materials, long-term high temperature exposure is not recommended. The development of pre-treatment of antioxidant and phytoestrogenic mixtures allows to reduce energy consumption for the dehydration process and save the maximum amount of biologically active substances.

From the analysis of numerical simulation data, as well as the results of comparing the calculated data with experimental data, we can conclude that the proposed numerical model satisfactorily describes the process of convection drying of crushed soybeans and can be used to calculate the regime parameters of this process.

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