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DEVELOPMENT OF WAVE TECHNOLOGIES TO INTENSIFY HEAT AND MASS TRANSFER PROCESSES

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Запропоновано технології адресної доставки енергії для інтенсифікації тепломасопереносу при переробці харчової сировини. У основі запропонованих гіпотез – хвильові технології комбінованої електромагнітної і вібраційної дії. Обгрунтовано механізми, ефекти і математичні моделі бародіффузії і дії вібраційних полів. Запропоновано числа хвильової подібності, на основі яких узагальнені бази експериментальних даних по екстрагуванню і сушінню. Наведено результати оптимізації мікрохвильового екстрактора

Ключові слова: харчові технології, адресна доставка енергії, інтенсифікація масопереносу, екстрагування, сушіння

Предложены технологии адресной доставки энергии для интенсификации тепломассопереноса при переработке пищевого сырья. В основе предложенных гипотез – волновые технологии комбинированного электромагнитного и вибрационного действия. Обоснованы механизмы, эффекты и математические модели бародиффузии и действия вибрационных полей. Предложены числа волнового подобия, на основе которых обобщены базы экспериментальных данных по экстрагированию и сушке. Приведены результаты оптимизации микроволнового экстрактора

Ключевые слова: пищевые технологии, адресная доставка энергии, микроволновые технологии интенсификация массопереноса, экстрагирование

1. Introduction

Providing mankind with energy resources is one of the key problems of the present time. This is especially true of food technologies, which are considered among the primary elements of consuming energy resources in economically developed countries [1, 2].

In the food industry, significant energy losses are observed when water is transferred to steam in drying processes. Heat treatment often causes overheating and deterioration in the quality of the product. When drying fruit and vegetable raw materials, the effect of high temperatures destroys valuable components such as vitamins, antioxidants, and aromatic substances. As a result, there happen tangible losses of a significant part of the useful properties of the product. In the extraction process, high temperatures destroy many of the components that are desirable to be preserved in the product.

Thus, traditional heat processing technologies for food raw materials cause two main problems: energy overexpenditure and product quality losses.

Therefore, it is essential to solve the problems of searching for innovative solutions aimed at reducing the thermal impact on food raw materials, lowering the specific energy consumption, and diminishing the company's environmental load.

2. Literature review and problem statement

Food technologies are predominantly based on the processes of heat treatment. Water from the raw material is removed in vacuum evaporators and in drying facilities. To a large extent, this process determines the quality, energy costs and the cost of producing the finished product [3]. It is here that scientific and technical contradictions are emerging between the growing demands for quality, the energy intensity of food production, and the technology of heat and mass transfer. Currently, the search for new approaches in the organization of food thermotechnologies is being actively pursued. The development of the industry takes place in two directions: improving the traditional equipment by optimizing the operating modes [4] or developing new equipment [5]. Vacuum evaporating units are well studied, the maximum in improving the design of this type of installation is practically reached, and a slight increase in the energy efficiency of these devices is achieved due to optimization of the regimes [6]. However, in such installations, it is impossible to avoid exposure of the product to high temperatures, which is undesirable in the production of juice concentrates and plant extracts [7]. This is especially true of juices with high antioxidant activity and a rich set of vitamin complexes [8] that belong to thermolabile substances. When concentrating the juices by freezing, all the useful components of the products are preserved [5]. Serious prospects are suggested for equipment based on nanotechnology, which is still developing [9].

3. The aim and objectives of the study

The aim of the study is to improve food thermotechnologies by modernizing traditional schemes and developing fundamentally new heat and mass transfer technologies that guarantee food safety while significantly reducing energy costs.

To achieve this aim, the following tasks were set to be solved:

– to explain the mechanisms of intensifying heat and mass transfer processes in the conditions of vibrational and electromagnetic fields;

– to determine the effect of structural and regime parameters on the efficiency of extracting moisture from the solid phase of food raw materials;

– to confirm the practical feasibility of the principles of targeted delivery of energy in various food technologies.

4. Methods of mathematical and experimental modeling of drying and extraction processes

At present, an important reserve for improving the energy efficiency of food technologies is the intensification of heat and mass transfer processes. The innovative solutions proposed by the authors of this work are based on the following hypotheses.

Hypothesis 1. The combined effect of the heat flux and the wave vibrational field helps reduce the thickness of the diffusion boundary layer. This will lead to an intensification of the process of moisture removal, reduction of drying time, and lesser energy consumption during the dehydration process.

Hypothesis 2. A targeted delivery of electromagnetic energy directly to the polar molecules of the liquid in the capillaries when extracting and dehydrating raw materials will help initiate a strong and specific hydrodynamic flow. As a result, the intensity of the mass transfer will significantly increase due to a sharp decrease in the internal diffusion resistance, energy costs, and process time.

More detailed methods of mathematical and experimental modeling of drying and extracting processes are described in [10].

5. Mechanisms as well as mathematical and experimental models of mass transfer processes in the conditions of vibrational and electromagnetic fields

Let us consider the mechanisms of action of inertial forces on the kinetics of mass transfer processes.

5. 1. Barodiffusion and its mechanisms

The mechanisms of barodiffusion, its driving forces and possible effects, which intensify the process of mass transfer, are illustrated by a thermophysical model (Fig. 1).

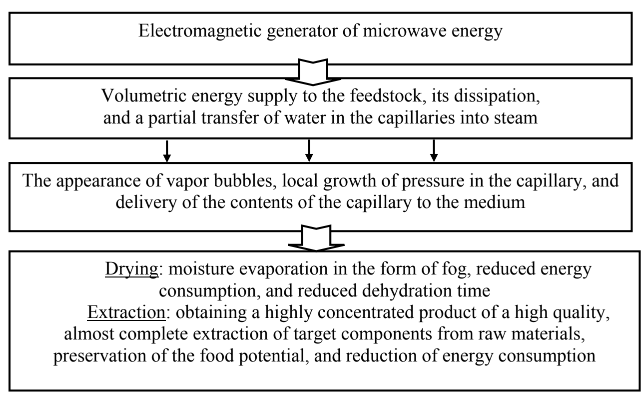


Fig. 1. The thermophysical model of the mechanism and effect of barodiffusion

Under the action of the microwave (MW) field (Fig. 2), diffusion in the solid phase is determined by the Fick equation, and the mass flow J_D in this case depends on the diffusion coefficient D and the concentration gradient in the solid: $J_D = -D \cdot gradC_T$. Due to convective diffusion, soluble substances move from the liquid phase X_G to the center of the flow, where the concentration of water-soluble substances is equal to X_E. The intensity of convective diffusion is determined by the mass transfer coefficient β: $J_K = \beta \cdot (X_G - X_E)$. The greatest diffusion resistance will be for nano- and microcapillaries of raw materials, where there are the most constrained conditions.

In the system of beans (1), capillary (2), and extractant (3), under the influence of the MW field (Fig. 2), a vapor bubble (4) appears and initiates another J_B flow parallel to the motion of the mass flows J_D and J_K.

The frequency of emissions and the number of functioning capillaries increase in proportion to the electrophysical effect. The flow that occurs under the influence of an electromagnetic field, turbulizes the boundary layer; the resistance can be an order of magnitude lower than in traditional mass transfer schemes.

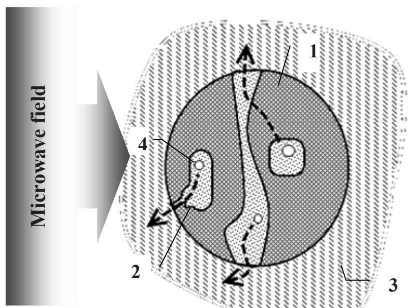


Fig. 2. The mechanism of barodiffusion

The mass flow J_B (Fig. 3) depends on the difference in pressures in the capillary P_K and in the extractant stream P_E, as well as on the mass transfer coefficient β′, which can differ significantly from β: $J_B=\beta'\cdot(P_K-P_E)$. The pressure that ensures the “start” of barodiffusion is $P_{BD}=P_E+P_K$.

$$P_{Ki}=\frac{\rho\cdot w^2}{2}\left[\frac{\lambda\cdot l_i}{d_i}+\sum\xi\right]+\rho\cdot g\cdot l_i+\frac{\sigma}{d_i}. \quad (1)$$

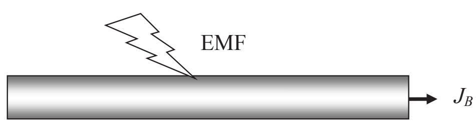


Fig. 3. The hydraulic model of barodiffusion in conditions of an electromagnetic field

In correlation 1, d_i is the diameter; l_i is the length of the capillary; w is the velocity of the liquid in the capillary; ρ is the density of the liquid; ξ is the local resistance; σ is the surface tension force, λ is the coefficient of hydraulic friction, and g is the acceleration due to gravity.

The final distribution of the concentrations of extractive substances in the system is determined by the principle of superposition of the action of motive forces of various physical types.

When modeling mass transfer from the surface of a solid phase, a known solution [11] of the boundary value problem is used:

$$c(\tau,x,y)=\frac{1}{(1-D\tau)^2}\Big\{\exp\big[(w_X+w_Y)\tau-(|x|+|y|\big]+$$
$$+D\tau\exp\frac{1}{\sqrt{D\tau}}\big[(w_X+w_Y)\tau-(|x|+|y|)-$$
$$-\sqrt{D\tau}\left\{\exp\left[\left(w_X+\frac{w_Y}{\sqrt{D\tau}}\right)\tau-\left(|x|+\frac{|y|}{\sqrt{D\tau}}\right)\right]+\right.$$
$$\left.+\exp\left[(w_Y+\frac{w_X}{\sqrt{D\tau}})\tau-(|y|+\frac{|x|}{\sqrt{D\tau}})\right]\right\}\Big\}. \quad (2)$$

Solution (2) also assumes that the value of the diffusion coefficient D and the corresponding velocity components are known. Thus, even the approximate solution of problem (2) depends on the solution of the Navier-Stokes equation.

The diffusion model in the cramped conditions of a capillary of a porous body is compiled according to classical principles. After recording the diffusion equation in cylindrical coordinates with the corresponding boundary conditions, the formulation of the assumptions, and the introduction of Bessel functions of the first type I_0 and I_1, with the parabolic velocity profile, the concentration field has the form:

$$\frac{X_P''-X_P'}{X_E-X_P'}=1-\sum_{n=1}^{n}a_n\exp\left[-b_n\left(\frac{D}{w_{C.P}0{,}25d^2}\right)Z\right]. \quad (3)$$

To simulate the barodiffusion flow J_B, the problem of diffusion from a point source to the flow is involved [11].

The flow of extractive components A, discharged into the extractant stream that moves in the z direction at a constant speed w_0, is determined by the equation $w_0(\partial X/\partial Z)D\nabla^2X$ and the following boundary conditions: $X|_{l=\infty}=0$; $4\pi l^2D(\partial X/\partial r)=w_A$ at $l\to0$; $l^2=x^2+y^2+z^2$ (where l is the distance from the source, z is the distance from the source along the stream, and w_A is the rate at which the extractive components A enter the stream).

If the flow rate is constant (w_O), and the mode is stabilized, then:

$$X=\frac{w_A}{4\pi\cdot Dl}\exp\left[-\left(\frac{w_O}{lD}\right)(l-z)^2\right]. \quad (4)$$

Since $J_B=X\cdot w_A\cdot\rho$, the flow of the matter from the point source takes form (5), and for the one-dimensional problem ($l=z$), it will be simplified to (6):

$$J_B=\frac{\rho\cdot w_A^2}{4\pi Dl}\exp\left[-\left(\frac{w_O}{lD}\right)(l-z)^2\right], \quad (5)$$

$$J_B=\frac{\rho\cdot w_A^2}{4\pi D\cdot z}. \quad (6)$$

When the extractive components enter the flow in a laminar regime, the rate of the entry into the flow w_A and the flow amount are determined as follows:

$$w_A=\frac{\Delta P\cdot d^2}{32\cdot\mu\cdot z},\quad J_B=\frac{\rho\cdot\Delta P^2\cdot d^4}{4096\cdot\mu^2\cdot z^3\pi\cdot D}, \quad (7)$$

where μ is the kinetic coefficient of viscosity of the medium, m²/s; d is the diameter of the capillary, m; $\Delta P=P_{BD}-P_E$ is the pressure difference inside an open pore (capillary) and in the extractant stream, Pa.

The barodiffusion flow leads to difficulties in separating the J_D, J_K and J_B fluxes, since the phenomenon of barodiffusion introduces perturbations into all of the indicated components of the mass transfer process of the target component in the “raw material and extractant” system. Therefore, we write the total mass flux in the form $J_M=\beta_E\cdot(C_i-C_P)$, where β_E is the effective mass transfer coefficient taking into account internal, external and barodiffusion processes.

Obviously, even with such serious simplifications of the tasks that are made in its formulation, joint solutions (2)–(7) are very difficult. The hydrodynamic situation in the flow is determined by the turbulent flow of the extractant, complicated by vortex diffusion from the feed channels. Therefore, it is expedient to apply experimental simulation and to use the "dimensional analysis" method.

5. 2. Vibrational fields

Communication between inertial acceleration particles facilitates the release of the vapor phase from the raw material, with an alternating change in particle velocity relative to the air flow. Together with the electromagnetic method of energy supply, simultaneous intensification of both external diffusion and internal diffusion processes of mass transfer occurs (Fig. 4).

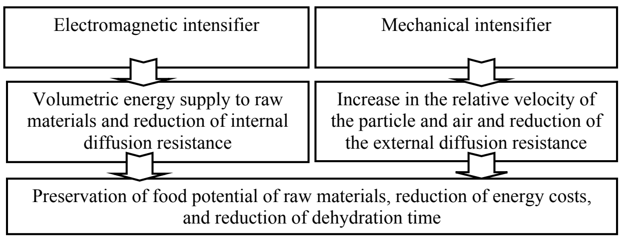


Fig. 4. The thermophysical model of the vibration mechanism

If the device uses a traditional source of energy supply, then the influence on the internal processes of mass transfer will be absent (Fig. 5) and the result will be more determined by the particle size.

5. 3. Wave simulation numbers

The specificity of the tasks posed is related to the fact that it is necessary to take into account the influence of the force effects on the elements of raw materials under combined actions of forces that differ in physical nature. It seems that it is logical to determine separately the influence of the specific nature of the energy action and the mechanical one.

To take into account the influence of the electromagnetic field during drying of the raw materials, the author of [11] proposed the value of the energy action (Burdo number). This number is expressed by the ratio of the energy expended on the organization of the process (Q_I)) to the physically necessary. The theoretical energy is considered to be the energy required to convert all the moisture removed from the raw material (Q_T) to steam.

From the thermal balance, the theoretical energy expenditure is proportional to the mass flow of the moisture removed (M) and the specific heat of the phase transition. This number is true for both traditional dryers and innovative installations. For installations with the EMF, the number of the energy action will have the form

$$Bu=(Q_I-Q_T)=N(Mr)^{-1}. \tag{8}$$

Correlation (8) determines both the energy efficiency of the equipment and the mass transfer regime. Up to certain values of the Bu number, laminar regimes of fluid motion occur in the capillary channels of the solid phase. The value of Bu can show the conditions of transition to a more intensive mass transfer, which is called the turbulent barodiffusion regime [12].

The Bu number can be used in other problems of mass transfer with gradient energy supply (Table 1).

In the correlations, it is assumed that N is the radiation power; V is the volumetric flow rate of the moisture to be removed; r is the latent heat of phase transition; d is the determining dimension; ρ is the density.

Table 1

The calculation models

Process	Bu number	Process model
Inactivation of microorganisms	$Bu=N(\zeta VC_p\Delta t\rho)^{-1}$	$F_0=A\cdot\mathrm{Re}^n\,\mathrm{Pr}^m\,Bu^k$
Extraction	$Bu=N(rVd^2)^{-1}$	$Sh=A\cdot\mathrm{Re}^n\,Sc^m Bu^k$
Drying	$Bu=N(rV\rho)^{-1}$	$Sh=A\cdot\mathrm{Re}^n\,Sc^m Pe^p Bu^k$

For problems of combined interaction between the external fields and the product in chamber vibration dryers, corresponding numbers of similarity are proposed. In the dryer container due to vibration, a vibroboiling layer is arranged. We consider that the general hydrodynamic situation in the apparatus (particle motion) can be characterized by the total average flow velocity, and the Reynolds number (Re) corresponds to this. However, the classical number Re should be modified and tied to the parameters characteristic for drying in a vibrational field.

Taking the diameter of the particles being treated as the characteristic size of the system and the frequency of vibration as the characteristic velocity, the modified wave (vibrational) Reynolds number will take the form:

$$Re_B=\frac{\rho d^2 f}{\mu}. \tag{9}$$

The correlation between convective and molecular processes of heat transfer is characterized by the Péclet wave number:

$$Pe_B=Re_B\cdot Sc;\quad Pe_B=\frac{\rho d^2 f}{\mu}\cdot\frac{\nu}{D};\quad Pe_B=\frac{\rho d^2}{D} \tag{10}$$

and the modified vibrational mass exchange Stanton number is determined as

$$St=\frac{\beta}{df}. \tag{11}$$

In correlations (9)–(11), $Sc=\dfrac{\nu}{D}$ is the Schmidt number; d is the particle diameter; f is the frequency of vibration; μ is the dynamic coefficient of viscosity; D is the diffusion coefficient; ν is the kinematic viscosity coefficient; and β is the mass transfer coefficient.

The required equation for the Stanton wave number in the generalized variables takes the form of

$$St_B=A\cdot Re^n\Pi^m\mathrm{T}^k, \tag{12}$$

where $\Pi=\dfrac{V_Z}{V_\Pi}$ is the dimensionless parametric complex of the container loading; V_Z is the volume of loading; V_Π is the volume of the container; $T=\dfrac{T_Z}{T_\Pi}$ is the dimensionless temperature; T_Z is the current bean temperature during drying; and T_Π is the initial temperature of the grains.

For the tasks of belt dryers, equation (12) should be transformed so as to take into account the action of the electromagnetic energy sources and the vibrational mechanical intensifiers. The effect of the mechanical intensifiers is suggested to be taken into account with the help of the dimensionless Ba complex, which reflects the ratio of inertial forces that receive particles from the mechanical vibrations and inertial forces that are caused by the motion of the belt:

$$Ba = \frac{A\omega}{v}. \quad (13)$$

Taking into account the Ba number, the criterion equation (12) takes the form

$$St = B \cdot Pe^{n} Bu^{m} Ba^{k}. \quad (14)$$

The proposed equation (14) is a mechanical-diffusion model. The model allows calculating the design characteristics of the device. It makes it possible to find combinations of the operating parameters for electromagnetic drying of the bean product in a moving layer during mechanical intensification of the process.

For problems of gradient energy supply, the effective mass transfer coefficient β_{ef} is affected by the particle size d, the flux density ρ, the viscosity μ, the diffusion coefficient D, the concentration difference ΔC, and gravitational field g. The effect of barodiffusion is determined by the power of the microwave intensifier N and the specific heat of vaporization r. The consumption of the product (G_{pr}) and the extractant (G_{ex}) should be taken into account.

The composing of the matrix of the dimensions resulted in complexes that are traditionally used in mass exchange problems (Sherwood, Schmidt and Grasgof numbers). The influence of the microwave field is accounted for by the number $Bu=N/(rG_P)$.

The closer the number Bu to 1, the bigger the vapor phase is formed, the greater the pressure gradient, the more intense the emissions of the saturated extract from the capillaries, and the greater the turbulence of the boundary layer. Therefore, the number Bu can characterize not only the degree of energy impact but also the corresponding hydraulic situation in the cassette.

Barodiffusion neutralizes the contribution of natural convection, and the Grashof number can be excluded from the criterial equation:

$$Sh = A(Sc)^{n}(Bu)^{m}\left(\frac{G_{\Pi}}{G_{P}}\right)^{k}. \quad (15)$$

Similarly, the structure of the criterial equation for the continuous extraction process in the MW field is established:

$$St_{m} = A \cdot \mathrm{Re}^{m} Sc^{n} Bu^{p} \Pi^{k}. \quad (16)$$

The complex $\Pi = \frac{k}{H^{2}}$ is a dimensionless parametric permeability that takes into account the geometry of the packing of the particles of the solid material.

In equations (11) and (14)–(16), the constants A, B, n, m, and k are determined on the basis of the experimental data base.

5. 4. Experimental studying of the extraction process in the microwave field

The extraction process was studied in testing units: No. 1 (an MW chamber, with a fixed layer of raw materials) and No. 2 (a counterflow MW extractor) in a wide range of changing parameters (Table 2).

Table 2

The range of the experimental modeling

No.	Raw material	Particle size $d\cdot10^{3}$, mm	Temperature of the extract t, °C	MW force N, W/kg	Re	$P\cdot10^{2}$	$Bu\cdot10^{8}$
1	Coffee beans	0.63–3	11–90	90–900	2.7–77.1	99–468	5.2–27.9
2	Coffee beans	0.8–3	11–90	630–900	2.7–77.1	99–468	5.2–27.9
3	Coffee sludge	0.5–1.5	30–70	270–900	35.7–41.5	93.3–1,062.5	3.8–15.2
4	Coffee sludge	0.5–1.5	30-70	270–900	35.7–41.5	93.3–1,062.5	3.8–15.2

Experiments No. 1 and No. 3 were carried out in testing unit No. 1, but experiments No. 2 and No. 4 were produced in testing unit No. 2. At the first stage, the concentrations of water-soluble substances in the raw materials were determined (Fig. 5) by testing the hydraulic characteristics of the mass exchange cassettes in the longitudinal passage of water through the layers of beans and sludge.

For all values of the sludge layer – 27 mm, 20 mm, and 14 mm, – the obtained dependences are convex curves, while the classical dependence has a concave shape. In the experiments with the coffee beans (Fig. 6), the hydraulic lines are similar to the classical ones for whole beans (line 7) as well as for fractions of 2.5...3 mm (line 6) and 1/4 of beans (line 5). However, for fractions of 2...2.5 mm (line 4), bean halves (line 3), fractions of 1...2 mm (line 2), and fractions of less than 0.8 mm (line 1), these dependences become convex.

This "paradox" is explained by the fact that horizontal flows communicate energy to particles of the coffee raw material, so the thickness and porosity of the layer grow. As a result, the hydraulic resistance of the layer is reduced. This indicates a favorable phenomenon for the extraction processes: the hydrodynamic situation with such fluidization of the layer will certainly contribute to the intensification of the transfer processes.

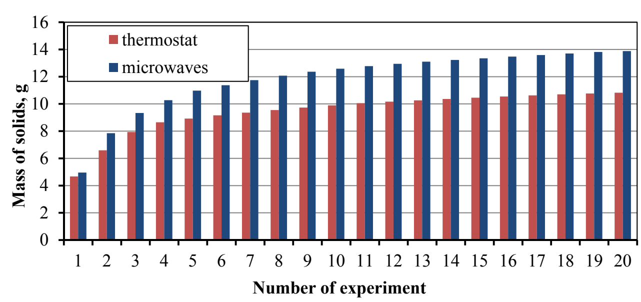


Fig. 5. The content of extractive substances in the coffee beans

The height of the product layer in the cassette was measured by immersing the measuring device directly into the cassette. For coffee particles of various sizes, different hydraulic characteristics were obtained.

It was found that to ensure thin-layered currents in the product and to increase the surface of the phase contact, it is expedient to work in the flow ranges of $1.4\cdot10^{-6}...4.2\cdot10^{-6}$ m^3/s and with the thickness of the layer of the coffee raw material of $1\cdot10^{-2}...3\cdot10^{-2}$ m.

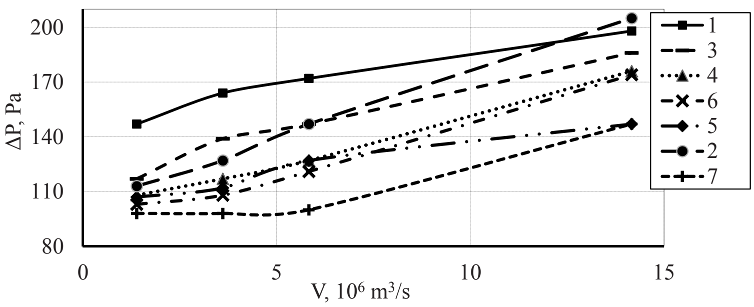


Fig. 6. The hydraulic characteristics of the cassettes of the microwave extractor: 1 – less than 0.8 mm; 2 – 1...2 mm; 3 – 1/2 of coffee beans; 4 – 2...2.5 mm; 5 – 1/4 of coffee beans; 6 – 2.5...3 mm; and 7 – whole coffee beans

For particles with a dispersion of less than 1.5 mm, the hydraulic characteristics take the form that is characteristic of fluidization processes. The bases of the experimental data (Fig. 6) are summarized by the model:

$$Eu = 6{,}836 \cdot \mathrm{Re}^{-1.06} D^{1.2}. \qquad (17)$$

At the second stage, the kinetics of the mass transfer in the system "coffee raw materials and water" was investigated (Fig. 7).

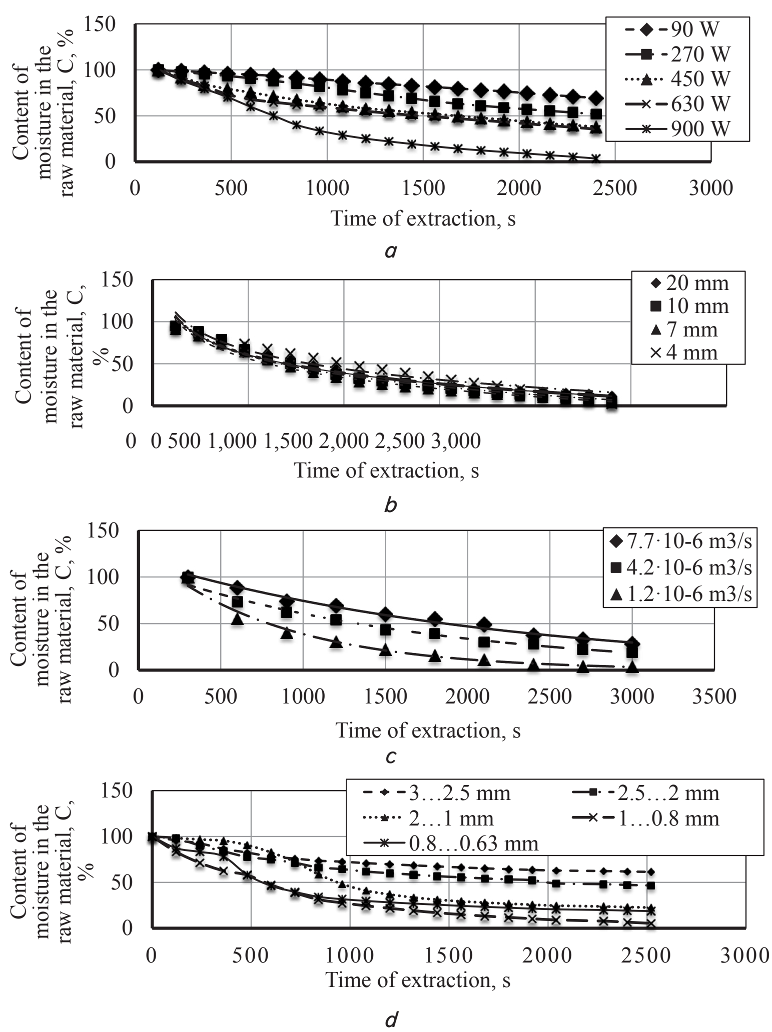


Fig. 7. The kinetics of mass transfer of water-soluble substances in the MW field: *a* – the influence of the MW field force; *b* – the thickness of the layer; *c* – the consumption of the extractant; and *d* – the size of the fractions

The effect of the regime parameters on the kinetics of mass transfer during extraction in the MW field was investigated (Fig. 7). It has been found that when the volume flow of the extractant is increased 3 times, the yield of the extractives from the coffee raw material is increased by 35 % and the extraction time is reduced twice. This is explained by a significant reduction in the external diffusion resistance. When the flow rate is increased 2.5...3.5 times, the effective mass transfer coefficient increases 2.7...5 times, respectively. It is recommended to calculate the intensity of the mass transfer during extraction from coffee raw materials under the action of a microwave field by the following correlation:

$$St_m = 0.004 \cdot (\mathrm{Re})^{-0.5} (Sc)^{0.3} (\Pi)^{0.6} (Bu)^{0.33}. \qquad (18)$$

Equation (18) is the key in the calculation and optimization of the microwave coffee extractors.

5. 5. Experimental studying of the drying processes in the vibrational and microwave fields

The drying process was studied in testing units: No. 3 (a chamber with a fixed layer of raw materials) and No. 4 (a belt installation with IR and MW intensifiers) in a wide range of changing parameters (Table 3).

In the experiments on the vibratory dryer, the influence of the regime factors on the intensity of mass transfer was studied successively. The initial moisture content was W=11.7; 14; 16 %; the container loading indicators were Π=0.67; 0.5 and 0.33 (Fig. 8 a); and the vibration frequency was f=80; 10; 120 s^{-1} (Fig. 8, *b*). The air flow velocity was 1.2 m/s. The typical dependences of the influence of the key parameters on the nature of the drying lines are shown in Fig. 8.

When choosing the vibration parameters of the working container, the following tasks were set and solved:

– to ensure maximum drying intensity;

– to arrange a layer of raw material to be evenly dried and intensively mixed;

– to avoid overheating of the particles;

– to maintain the existence of the fluidized layer.

The generalization of the obtained experimental database has helped establish the sought criterial equation:

$$St_B = 97.4 Re_B^{0.76} \Pi^{0.91} \mathrm{T}^{3.1}. \qquad (19)$$

The experiments with the coffee sludge have determined that if the amount of energy supplied is increased three times, the rate of moisture removal increases by 30 %. On average, the drying speed is 1.3...1.7 %/min. The capacity of the unit in the loading mode of 3 kg/m^2 at a belt speed of 0.33 cm/s was 1.5 kg/h of dry sludge with a moisture content of 10 %. The experiments were carried out at the specific load values of 1.2...3.3 kg/m^2. There was a decrease in the rate of moisture removal at loading greater than 2.5 kg/m^2.

Table 3

The range of the experimental modeling

No.	Raw material/testing unit	t, °C	kW/m²	kg/m²	W_i, %	W_r, %	J, MJ/kg·sp.hum
1	sunflower/No. 3	28...44	7.33...27.51	1.8...3.6	16.7	2	3.67...3.80
2	soy/No. 4	36...49	7.33...27.51	2.8...5.6	24.3	3	3.84...4.36

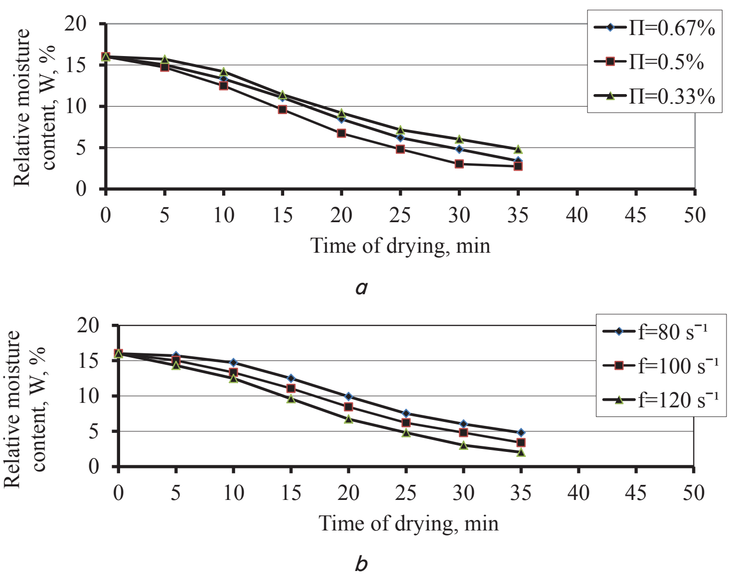


Fig. 8. The kinetics of the drying process of sunflower in the vibrodryer under the following changes: *a* – the container loading; *b* – the vibration frequencies

An increase in the number of IR modules from 1 to 3 increases the drying speed 1.5 times. The experiments with cooked peas were carried out on an IR belt dryer. The studying of the drying process of the cooked peas determined the influence of the specific load on the belt and the specific power of the heaters on the main factor – the rate of drying (Fig. 9).

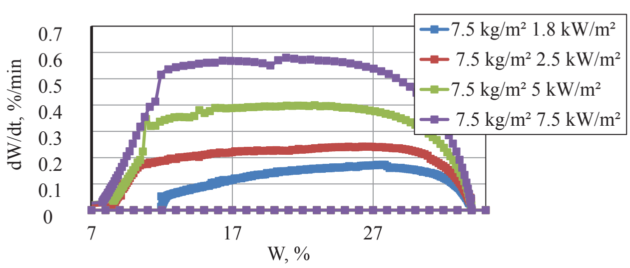


Fig. 9. The influence of the power input energy

The results of studying the process of drying sunflower seeds are given below (Fig. 10, 11).

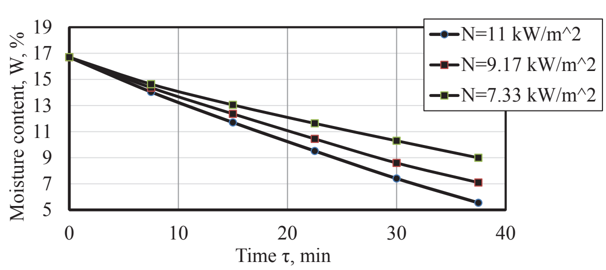


Fig. 10. The drying lines for sunflower seeds on an IR belt dryer

The experiments were carried out in one module, with cassettes filled with sunflower seeds moving on the belt. After passing through the module, each cassette was weighed. By the loss of mass, the kinetic dependencies were constructed.

With increasing the density of the heat flow, the rate of drying proportionally increased (Fig. 11).

The type of energy supplied also matters significantly. If for the known installations [13, 14] the achieved drying rates were 0.32 %/min, for the vibrating dryer the obtained rate was 0.4 %/min (Fig. 8), and on the IR belt dryer this parameter was 0.75 %/min when drying peas (Fig. 10) and 1.75 %/min when drying sludge and seeds of sunflower (Fig. 12).

It is concluded that the number of modules, the distance between them, the speed of the belt, the power of the IR emitters and the specific loading of the belt with the product are the elements of a complex multiparametric optimization problem that has an independent solution for each type of product. At the same time, the information presented in the section makes it possible to carry out design works for the construction of an IR dryer and to modernize traditional belt dryers with the transfer to partial or full use of IR heaters.

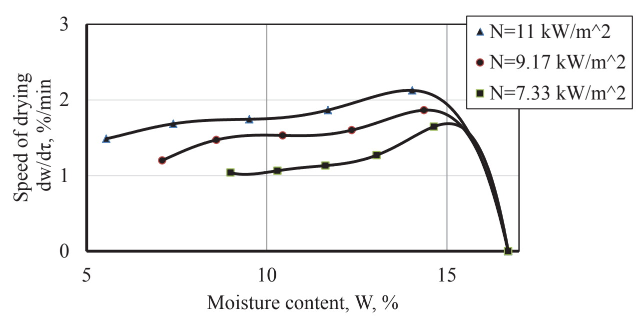


Fig. 11. Lines of the speed of drying sunflower seeds

6. Discussion of the results and optimization of the innovative equipment

A methodology for calculating and optimizing a continuous countercurrent extractor system "coffee raw materials and water" has been developed. A computer experiment showed that the specific energy consumption was 220...370 kJ per 1 kg of extracted solids. The greatest influence on the extraction process under the influence of the MW field is exerted by the output power of the magnetrons, the productivity of the raw material and the extractant, and the height of the layer of raw materials in the mass exchange module.

Taking into account the structure of the developed mathematical model of the extractor, a method of optimizing the parameters of the installation was used in the study. The method is based on specifying the parameter spaces R_n by uniformly filling these spaces with the points x_j, j=l, 2, ..., N over the whole space.

In each x_j, the value of the objective function Z is calculated. The information obtained is used in the procedure for improving the problem and optimizing the solution [15].

From an economic point of view, it is advisable to take into account the annual electricity consumption, the capital costs of the installation and the cost of production in the optimization criteria. To simplify the task, it makes sense to take into account only the variable component in the criterion:

$$Z = \max(Pr \cdot Y - K_C - C_{EC} \cdot \Pi_{EC}), \qquad (20)$$

where Π_{EC} is the annual energy consumption, kW·h; C_{EC} is the cost of energy unit, UAH/kW·h; K_C is the cost of the installation, UAH; Pr is the price of the finished product; and Y is the performance of the installation. The optimization of the installation consisted in the search for the maximum value of the objective function Z.

For the function Z (20), the optimized parameters are the layer height in the cassette δ, the heating temperature of the extractant t, the hydromodule q, the mass exchange module dimensions (L, B, h), and the number of modules in the height of the installation n. To solve the problem, the Gauss-Seidel method of coordinate-wise descent is chosen, which is a classical iterative method. The method reduces the problem of finding the largest value of the function of several variables to a multiple solution of one-dimensional optimization problems. The program EXTRACTOR.2 was written in the Pascal programming language, in the Borland Delphi 7.0 environment.

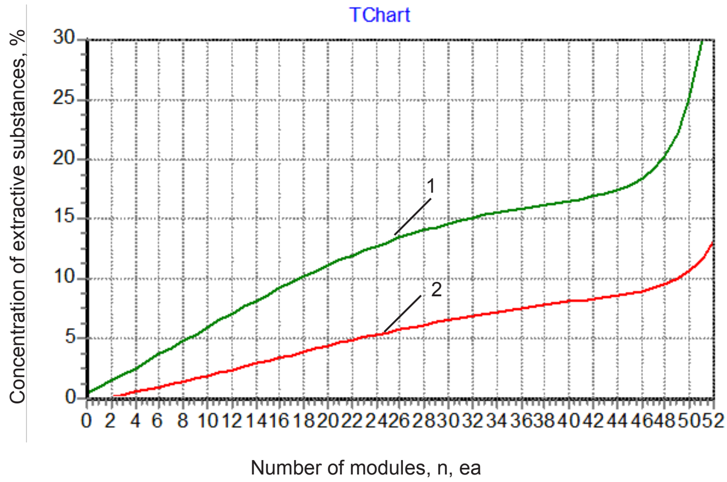
The implementation of the coordinate descent algorithm was carried out for each coordinate of the local optimum. The concentration fields in the extractor were determined (Fig. 12). Here, the number n of mass exchange modules is plotted along the ordinate axis; along the abscissa axis, the data reflect the following: (1) the change in the concentration of the liquid phase (extractant) and (2) the solid phase along the height of the extractor H.

A computer experiment was conducted to analyze the effect of the design parameters such as the length of the mass exchange module L, the width of the mass exchange module B, the height of the mass exchange module h, and the number of mass exchange modules n for the technical and economic indicators.

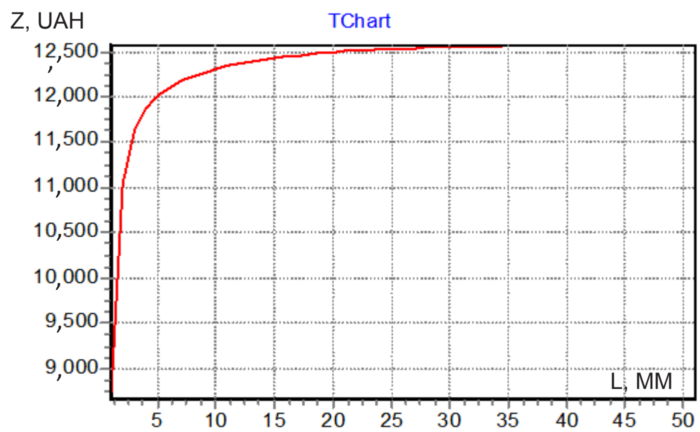
It turned out that the maximum economic efficiency of the functional was achieved when the length of the mass exchange module was 937 mm.

In the future, for devices with a module length of 0.9 m, functional calculations for different module widths have been performed. Analogously, an analysis is made of the effect of all variable parameters on each coordinate of the local optimum. With an increase in the capacity of the installation, the functional Z grows due to more rational use of energy. With an increase in power by a factor of 4.5, Z increases by a factor of 8.

Based on the results of the optimization, a standard range of microwave extractors of continuous action was developed.



a



b

Fig. 12. The computer modeling: *a* – the distribution of the concentration of extractive substances according to the modules corresponding to the local maximum of Z

7. Conclusions

1. Local effect on nanoscale elements of food raw materials can help develop fundamentally new approaches to the organization of food technologies. In fact, this new scientific direction is food nanotechnology. A powerful means of initiating the appearance of nanokinetics is the pulsed electromagnetic field. The combined effect of the vibrational and electromagnetic fields can significantly intensify the processes of heat and mass transfer.

2. The efficiency of moisture extraction from the solid phase depends on the matching of the duration and power of the wave influences. If the duration is short, the flow of moisture from nano- and microcapillaries cannot be formed. With a long duration and high power, unwanted superheating of the solid phase is possible. With a finer organization of the power supply, it is advisable to change the parameters of the EMF in time in accordance with the instantaneous values of the dielectric characteristics of the solid phase (presence and quantity in the moisture channels). The force of the electrophysical effect should also be coordinated with the

channel diameters; in smaller channels, a greater pressure drop is required for the occurrence of a barodiffusion flow.

3. The scientific hypotheses are confirmed in practice. In coffee technology, the degree of extraction of components from beans increased by 15 %, and energy costs were reduced by 50 %. The experimental samples of 60 % of coffee concentrate have proved to have high taste characteristics.

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