Проведено аналіз процесу екстрагування в технології переробки олійної сировини. Показані вихідні положення, специфіка, сучасні наукові школи і рівень подання класичного процесу екстрагування. Специфіка математичного моделювання процесу екстрагування з появою додаткової рушійної сили, яка значно впливають на кінетику екстрагування в електромагнітному полі надвисокої частоти, наведено з класичної теорії процесу.

Отримано розрахункові формули кінетики екстрагування в мікрохвильовому полі, що розвивають теорію про кінетику екстрагування в електромагнітному полі. Наведено аналіз варіантів подання математичного опису процесу екстрагування дисперсних матеріалів в електромагнітному полі надвисокої частоти. Повна модель масообмінних процесів при екстрагуванні в мікрохвильовому полі в диференційній формі дозволить сформувати умови проведення комплексних експериментальних досліджень, які в повній мірі визначають процес екстрагування олійної сировини.

Теоретично обґрунтовано процес тепломасообміну між усіма визначальними об'єктами всередині екстрактора із електромагнітним полем надвисокої частоти. На основі матеріального балансів визначено рівняння, які описують основні динамічні характеристики режиму екстрагування олієвмісного матеріалу в екстракторі. У зв'язку з тим, що точного аналітичного розв'язку представленої математичної моделі у вигляді системи диференціальних рівнянь у частинних похідних не існує, запропоноване наближене рішення. Воно дозволяє ідентифікувати розподіл концентрації екстракту в залежності від розміру фракцій сировини, наявності та величини потужності імпульсного електромагнітного поля надвисокої частоти, гідромодулю екстракту, температури, розчинників для будь-якого моменту часу.

На основі експериментальних досліджень екстрагування олієвмісного матеріалу встановлено, , що під дією мікрохвильового опромінення значення коефіцієнта масовіддачі при екстрагуванні олієвмісної сировини на порядок зростає ($\beta=1\cdot10^{-5}$), порівняно з екстрагуванням без впливу МХ поля ($\beta=1\cdot10^{-6}$). Вилучення олії під дією мікрохвильового поля збільшується до 30 %, а споживання електроенергії зменшується на 93–97 %.

Застосування мікрохвильового поля дозволить не тільки підвищити ефективність виробництва, але і на порядок знизить затрати енергії на процес

Ключові слова: екстракція, мікрохвильове поле, тепло- і масообмін, матеріальний баланс, диференційні рівняння

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CONSTRUCTION OF A MATHEMATICAL MODEL OF EXTRACTION PROCESS IN THE SYSTEM "SOLID BODY LIQUID" IN A MICROWAVE FIELD

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1. Introduction

Ukraine occupies one of the leading positions in the world for the volume of production and processing of oils and fats. Modernization of the equipment used at oil-fat producing enterprises, the employment of modern resource-saving technologies, a wide range of products, the high level of competitiveness, are the attributes that characterize a contribution of this sector to the local economy. Energy crisis and an increase in consumer demand for more high-quality products, specifically vegetable oil, stimulated more research aimed at finding effective technologies of extraction.

Extraction of valuable components from vegetable (oil) raw materials refers to the important processes that are characterized by high energy intensity. Improving the efficiency of extraction significantly affects the technical-economic indicators of processing industry in agricultural production. At the present stage of development of equipment and technology for extracting the oil raw materials, the potential of microwave technology should be recognized: the application of electromagnetic field (EMF) of ultra-high frequency (UHF). Employing the specified technology, in our opinion, will lead to the intensification and improvement of efficiency of the traditional manufacture of vegetable oils to obtain products with the new, better consumer qualities. The theoretical postulates and experimental data acquired earlier have demonstrated the effectiveness of the application of microwave technology for extraction.

Microwave technologies relate to those energy-saving because of their natural specifics. However, in order to design actual equipment, it is necessary to conduct comprehensive studies, the purpose of which is to determine the rational conditions for the process under which it would be possible to achieve the uniformity of a microwave field, failure-safe operation, as well as labor safety.

In order to deeper study the influence of UHF EMF on the processes of mass and heat transfer, it is necessary to have mathematical models that would describe the process under consideration in the simplified yet adequate form. Undertaking a theoretical research into mathematical modeling of the process of extraction will make it possible to specify experimental studies and will enable the construction of an algorithm for improving the technologies of oilseed crops processing.

The scientific literature provides many models for the extraction processes regarding the conditions for periodicity or continuity of their course at various intensification techniques (increasing pressure and temperature, imposing vibrations, mechanical agitation, etc.) [1–5]. The basic theoretical concepts that underlie the extraction processes are given in fundamental studies [4, 5]. The theoretical references, substantiation of appropriateness and effectiveness of UHF EMF application, as well as a review of existing modelling methods, are described in detail in works [3, 5]. Specifically, it was noted that in terms of the physical effect of EMF on solid materials that are extracted, the leading role in the intensifying action belongs to barodiffusion processes.

It is a relevant task to undertake a research into the further development and improvement of the mathematical apparatus that characterizes the heat-and-mass exchange processes in the specified extraction units.

2. Literature review and problem statement

One of the principal stages in the design of extraction units is mathematical modeling. A procedure for calculating extraction units is based on taking into consideration the three basic aspects of the process: equilibrium in the system, kinetic patterns at all stages of mass transfer, and the structure of phase flows in the device.

Research into the process of extraction of oil-containing crops is mostly based on conducting experimental studies into extraction kinetics. Thus, authors of [6] acquired experimental data on the extraction kinetics of soybean oil and free fatty acids (FFA) for systems containing soy and ethanol with different levels of hydration (0 and 5.98 % by weight of water) at temperatures of 40, 50 and 60 °C. The obtained experimental data reveal that an increase in the level of ethanol hydration inhibits the extraction of soybean oil but increases the extraction of FFA while the temperature promotes the solubility of both fatty compounds. The experimental data were compared to models [7, 8], which make it possible to determine coefficients of mass transfer at the stages of diffusion and estimate the coefficients of diffusion. The derived values for diffusion coefficients show that the applied models were suitable to describe the kinetics of oil extraction, as well as other compounds present in soy. A value for the diffusion coefficient for soybean oil increased with an increase in temperature and a decrease in the level of hydration in the solvent. However, the authors failed to propose any mathematical models that would describe the process of extraction in general; the calculation procedure is not given either.

Paper [9] reports results of research into kinetics of the solid-phase extraction from Fumaria officinalis, in order to derive diffusivity and explain the mass transfer. It is shown that the extraction was carried out by changing the following operating conditions: temperature, hydromodule “solid body – solvent” and the percentage of ethanol content in solvent. A simple method is described, which is based on the Fick’s laws for predicting the effective coefficient of diffusion and speed intensity from the experimental kinetics. The Bio number revealed that the diffusion inside particles is the degree of control over the process of extraction. It is shown that it is desirable to operate with a moderate weight ratio “solid substance–liquid” at the maximally possible temperature and at a moderate content of ethanol in water [9].

However, there are remaining issues, not addressed by authors in [9], related to forecasting an increase in the concentration of the substance that is extracted depending on the supplied power of the ultra-high frequency electromagnetic field.

Regular extraction methods are described using the models of derivatives from the Fick’s laws since parameters of the model include physical values that can be applied for further interpretations. For example; the Bio number (Bi) expresses the relative significance of the internal and external mass transfer resistance [10]. Theoretical kinetic models are also applicable for extending the modeling of the extraction process. On the other hand, when simulating the process of extraction “solid body–solvent”, associated with the supply of microwave energy, ultrasound, electrical charge, simplified (empirical) models from the modified Fick’s law are applicable. Empirical models, in such cases of energy supply, are the best and indicate a much more complicated process of mass transfer. Such models are more suitable for extraction processes using the ancillary methods, since they cannot be adequately described in theory [11]. However, it is probably needed to conduct a theoretical research into the process of modeling in a microwave field and compare theoretical curves to experimental data.

A model of the process of extraction kinetics should define a process duration (exposure) under a periodic mode, as well as the estimation of the mass transfer intensity.

During the process of extraction (removal of an extractive substance from solid components of vegetable raw materials) in the UHF electromagnetic field, the intensity of mass transfer is defined by: the mass conductivity, convective diffusion, as well as the effect of a microwave radiation.

When considering in detail the effect of the latter factor on the process, it was established in papers [3, 12–14] that energy of the microwave field, by concentrating in the liquid phase of capillary volume of a solid particle, induces the formation of “steam bubbles” of the extracted substance. The result of the action of electromagnetic energy is the emergence of a pressure gradient with the liquid (periodically) pushed out of the capillary into the flow of solution.

In contrast to the classical determination of a barodiffusion mass transfer, which defines the filtration motion of a steam phase under the influence of pressure gradient D, effect of barodiffusion of an electromagnetic field implies the removal of the liquid phase (its part). The intensity of barodiffusion is defined by the magnitude of pressure that grows in a capillary at an increase in the intensity of electromagnetic influence.

The mechanism of the combined process of mass transfer of the extracted substance from a capillary-porous structure into solvent is explained in accordance with [4, 15] by the electrodiffusion model representation: diffusion in a solid phase is determined from the first Fick's law:

$$I=-D\frac{\partial c_m}{\partial n}=-D\frac{dc_m}{d\delta}. \qquad (1)$$

Next, the dissolved substance moves to the outer surface (along capillaries) where concentration is determined by the diffusion resistance; the same flow is transferred by the convective diffusion to the "core" of the extractant flow because the substance does not stay at the interphase surface. Thus, it is possible to record:

$$I_1=\beta'(C_m-C_n)=\beta(C_n-\overline{\chi}), \qquad (2)$$

where C_m, C_n is the concentration at the interphase surface and in an extractant; $\overline{\chi}$ is the mean concentration of an extractant; β is the effective coefficient of mass release and a mass exchange coefficient.

In parallel to flow I_1, the flow I_2 emerges in the particles of the solid-phase in a microwave field due to an increase in pressure in capillaries (barodiffusion). The flow of mass I_2 is defined by a "specific" effective coefficient of mass release β_p and a difference in pressure in the capillary:

$$I_2=\beta_p(P_k-P_p), \qquad (3)$$

where P_k, P_p is the pressure in a capillary and solvent (extractant).

Flow I_2 must turbulize a boundary layer and increase, accordingly, the intensity of mass transfer β_p.

The total flow of mass is the sum of flows:

$$I=I_1+I_2=-Ddc_1/d\delta. \qquad (4)$$

An analysis of prospects to solve the problem on mass transfer during extraction in a microwave field analytically (models of mass transfer from a plate to a flow of liquid; diffusion at flow motion in a channel, diffusion from a point source), given in [4, 5], revealed that even under very serious simplifications of the problem it is almost impossible to derive analytical dependences for a quantitative analysis of the process in an actual device. Thus, a promising way to study the process of extraction in an UHF electromagnetic field would be to model it at the level of micro kinetics with the identification of the derived models based on experimental data. In the practice of calculating parameters and operational modes of units for the extraction of a substance from a solid body, the key issue is to devise a simple (simplified) mathematical notation of the process. A mathematical model would reliably take into consideration, while limiting and intensifying, the physical phenomena, and the assumptions accepted in this case would be neutralized by the experimentally derived values for effective coefficients. Such approaches to investigating complex phenomena of transfer have been employed in papers [1, 2].

Given the impossibility to optimally run a material extraction process in the system "solid body–liquid" with MW energy supply based on the criteria of energy efficiency and quality of the resulting product without an adequate mathematical model.

3. The aim and objectives of the study

The aim of this study is to construct a mathematical model for the extraction process, which would take into consideration the effect of UHF EMF on intensity of the transfer processes.

To accomplish the aim, the following tasks have been set:

– to substantiate the physical parameters that are included in the structure of a mathematical model for the heat-and-mass processes in the extraction of oil raw materials in an ultra-high frequency electromagnetic field, which would take into consideration all interacting objects, and to derive an approximated solution to it;

– to study experimentally the process of extraction of oil (rapeseed) raw materials in an ultra-high frequency electromagnetic field and to verify the theoretical and experimental data obtained.

4. Construction of a mathematical model for the process of extraction of oil-containing raw materials with a microwave energy supply

Under conditions of the electromagnetic field, there is the interaction between polar molecules of the system "product–extractant" and electromagnetic energy, the result of which is the formation of a steam phase in a capillary-porous structure of the raw material with the intensification of the hydrodynamic flow, which can significantly reduce the internal diffusion resistance of oilseed raw materials, intensify the mass exchange process, shorten the duration of the process, and improve the yield of extraction components. The power of such a flow is defined by the characteristics of the raw materials and parameters of the electromagnetic field. A complete model of mass transfer processes during extraction in a microwave field in the differential form would make it possible to establish the conditions for comprehensive experimental study, which would fully define the extraction process of oil raw materials.

In order to construct a mathematical notation of the extraction process (under a periodic mode) under the action of UHF EMF, it is required to formalize the physical processes (phenomena), which predetermine certain forms of a substance transfer under the action of a microwave field. In the general case, the effect of UHF EMF implies the intensive selective (in terms of volume) heating of a liquid substance contained in a solid body and produces a thermobarodiffusion effect [5, 15].

In order to formalize the phenomenon of a barodiffusion transfer of a substance's component that is extracted under the action of a microwave field, we shall employ the general theory of heat and mass transfer in a capillary-porous body [14, 16, 17]. It follows from the heat-and-mass transfer that the intensifying effect of a microwave field is largely predetermined by an intensive volumetric heating of the liquid phase in a solid skeleton of the substance. Volumetric heating decreases fluid viscosity, gives rise to vaporization, increases pressure of the steam phase and the liquid phase filtration transfer ("release" of the fluid from a capillary into the external environment). Thus, both at thermal dehydration and extraction there occur the same, mentioned above, flows of mass: diffusion, capillary, barodiffusion [14, 16, 18]. Based on the law of preservation of a substance mass, a local derivative from the volumetric concentration of the i-th component of the substance for time equals the sum of divergence from the flows of mass and the source of the substance, predetermined by the phase transition (liquid to steam) [16]:

$$\frac{\partial(U_i S)}{\partial\tau} = div\left(J_{1Dif} + J_{kap}\right) + I_B, \quad (5)$$

where J_D is the density of the diffusion flux; $J_D = -\rho_0 \lambda dradU$; $I_{kap} = \Pi \cdot \rho b\delta$ is the density of the flow of capillary moisture; Π is the porosity of the body; ρ is density, b is the saturation of pores, δ is the average linear speed of the molar motion of the i-th substance; $I_B = \varepsilon' \rho_0 \frac{\partial U}{\partial \tau}$ is the intensity of the source of the substance predetermined by the phase transition (steam formation) and by pushing the liquid phase by the pressure of steam formed under the influence of an electromagnetic field; D is the diffusion coefficient; ε is the criterion of a phase transition; $\varepsilon' = (1-æ)\varepsilon$ is the equivalent coefficient of a phase transition and thermomechanical moisture removal, æ is the coefficient of the "thermomechanical" pushing of a substance [18] (effect of the thermomechanical pushing of moisture out of the pores of a solid body when drying using a pressure drop is estimated by the magnitude $æ = 0{,}05 - 0{,}4$ ([18]).

Given that the flow of a substance is predetermined by a thermodiffusion transfer in a monocapillary structure of the body, which is defined by the uneven temperature field of the body, almost absent at volumetric heating, we shall rerecord equation (5) substituting J_D, I_B with appropriate expressions:

$$\rho_0 \frac{\partial U}{\partial \tau} = \rho_0 \lambda \nabla^2 U + \varepsilon' \frac{\partial U}{\partial \tau} \rho_0, \quad (6)$$

or, for a one-dimensional body, for the concentrations of the extracted substance:

$$\frac{\partial c}{\partial \tau} = \frac{D_{ef}}{1 - \varepsilon'(\Theta)} \frac{\partial^2 c}{\partial x^2} = D_{ef}(\Theta) \frac{\partial^2 c}{\partial x^2}, \quad (7)$$

where D_{ef} is the effective diffusion coefficient that characterizes all possible types of mass transfer of the target component in the form of a certain unified mass [1].

Thus, we have derived a differential equation that describes the non-stationary field of concentration of the component inside the capillary-porous materials. In a differential equation, the physical effects of a transfer, related to the movement of the liquid and steam-gas phase in a material, are integrally accounted for by a unified quasi-diffusion transfer with effective coefficient D_{ef}. In practical calculations, one must have a dependence (acquired from experiments) of the magnitude of a diffusion coefficient on temperature and power of internal heat release due to the influence of UHF EMF.

To solve equation (7), when implementing the process of extraction of the dispersed solid phase, the boundary conditions of third kind are applied. According to the boundary conditions of third kind, the exchange of target component between the surface of a capillary-porous body and the surrounding liquid environment can be recorded in the form of equation for an external mass release:

$$j_f = -\beta\left(c_f - c_p\right), \quad (8)$$

where j_f, c_f is the flow and concentration of the target component at the surface of solid particles; c_p is the concentration of the component in the external environment (extractant); β is the mass release coefficient.

A flow that is guided to the surface from the depth of a porous structure through effective diffusion (in the absence of a source at the interphase surface, it is equal to the flow that is guided away from the surface) because the substance at the surface does not accumulate and there is the following equality:

$$D_{ef}\left(\frac{\partial c}{\partial x}\right)_f = \beta(c_p - c_f), \quad (9)$$

which is the boundary condition; the initial condition, at $\tau=0$; $c=c_0$.

For a body (a particle) that has the shape of a one-dimensional plate of thickness $2R$, a compatible solution to equations (7), (9) is known [19] and, according to the mean-volumetric value for a change in the concentration of a component, is derived from equation:

$$\frac{\bar{c}(\tau) - c_p}{c_0 - c_p} = \sum_{n=1}^{n=\infty} B_n e^{-\mu_n^2 \frac{D_{ef}}{R^2}\tau}, \quad (10)$$

where

$$B_n = \frac{2\sin^2 \mu_n}{\mu_n\left(\mu_n + \sin\mu_n \cos\mu_n\right)},$$

where μ_n are the roots of the characteristic equation:

$$\mu = Bi_m ctg\mu; \quad Bi_m = \frac{\beta \cdot R}{D_{ef}}$$

is the mass-exchange Bio criterion.

Equation (10) describes the kinetics of extraction – the removal of a target component from the solid phase in a time function τ, at constant value for the concentration of solution c_p=const and diffusion coefficient D_{ef}.

It is known from [19, 20] that at large values for the Fourier criterion $F_o = \frac{D_{ef}}{R^2}\tau$ (practically at F_o>0.3), a series in equation (10) quickly converges and one can neglect all the terms in a series except for the first one and use the one-term approximate solution:

$$\bar{c}(r) = c_p + \left(c_0 - \overline{c_p}\right) B_1 e^{-\mu_1^2 \frac{D_{ef}}{R^2}\tau}. \quad (11)$$

Differentiate equation (11) for time:

$$\frac{d\bar{c}(\tau)}{D_{ef}} = -\Delta\bar{c}\mu_1^2 \frac{D_{ef}}{R^2} e^{-\mu_n^2 \frac{D_{ef}}{R^2}\tau} B_1, \quad (12)$$

where $\Delta c = c_0 - \overline{c_p}$.

We determine from equation (12) the magnitude $B_1 e^{-\mu_n^2 \frac{D_{ef}}{R^2}\tau} \cdot \Delta c$, substitute into equation (11); we obtain after transforms:

$$-\frac{d\overline{c}(\tau)}{d\lambda}=K_{ek}\left(\overline{c}-c_p\right)=K_e\left(\overline{c}(\tau)-c_p(\tau)\right), \tag{13}$$

where, respectively, [20]:

$$K_{ek}=\mu_1^2\frac{D_{ef}}{R^2};\ \ \mu_1^2=\frac{1}{\frac{4}{\pi^2}+\frac{1}{Bi_m}}.$$

The magnitude K_{ek} is termed an extraction coefficient (similar to the drying coefficient by O. V. Lykov); we determine it experimentally, depending on the operational parameters of the process. The magnitude c_p can accept a value for the equilibrium concentration, which is also determined experimentally.

Theoretical methods of the diffusion coefficient calculation, as known from the scientific literature [1, 2], are not applicable in real systems. The only way to obtain data on the magnitude of diffusion coefficients D and D_{ef} are the experimental measurements of process parameters in the system "solid fraction–liquid (a solvent)".

In order to verify experimental data on the kinetics of extraction using equation (13), it is necessary to determine the constants of the process: D, B, B_i, D_{ef}, K_e. The simplest experimental procedure for determining the specified magnitudes is the periodic process of extraction [2]. During experiments, one measures the quantity (concentration) of a target component transferred from the solid phase to the liquid phase at certain points of time in the non-stationary process.

To solve equation (13), it is necessary to establish relations between the systems (solid and liquid), essential magnitudes in the extracted material and an external solution. Such relation can be obtained from the equation of material balance in the differential form:

$$-V_m\frac{dc}{d\tau}=V_p\frac{dc_p}{d\tau}, \tag{14}$$

where V_m, V_p are the volumes of interacting phases.

The ratio of magnitudes of the mass of a solid particle to the mass of a solvent is used as a parameter of the process: $m_m=V_m\rho_m$; $m_p=V_p\rho_p$, where ρ_m, ρ_p is the density of the solid phase and solution.

$$\frac{dc_p}{d\tau}=-R\frac{\rho_p}{\rho_m}\frac{dc}{d\tau}, \tag{15}$$

where $R=\frac{m_m}{m_p}$ is the hydromodule.

The kinetics of a mass transfer, a change in the concentration of solution over time, is determined from equation:

$$\frac{\overline{c}_p}{d\lambda}=\beta\cdot F_V\left(\overline{c}-c_p\right), \tag{16}$$

where $\overline{c}$, c_p are the mean-volumetric values for concentrations; F_v is the specific volumetric interphase surface; β is the mass exchange coefficient.

Thus, the kinetics of extraction is described by a system of three differential equations (13), (14) and (16). In the specified differential equations the effect of a microwave field is accounted for through coefficients K_e and β (since the release of a substance from surface under the action of steam pressure, predetermined by the influence of UHF EMF, turbulizes the surface layer of solution).

For the parametric identification of the structured mathematical model (differential equations (13), (14), (16)), we must have an analytical dependence of solvent concentration (extractant) on the process duration, that is, a description of the kinetic curve.

Deduce equation (16) from equation (13):

$$\frac{d\overline{c}_T}{d\tau}-\frac{dc_p}{d\tau}=-\left(K_e+\beta F_V\right)\left(\overline{c}-\overline{c}_p\right). \tag{17}$$

Upon division of variables, we obtain:

$$\frac{d\left(\overline{c}-c_p\right)}{c-c_p}=-Kd\tau, \tag{18}$$

where $K=K_e+\beta F_v$.

The solution to equation (18) under initial conditions: $\tau=0$; $c=c_0$; $c_p=c_{po}$ will be written in the following form:

$$c(\tau)-c_p(\tau)=\left(c_0-c_{p_0}\right)e^{(-K\tau)}, \tag{19}$$

Hence, we obtain:

$$c(\tau)=c_p(\tau)+\Delta c_0e^{-K\tau}, \tag{20}$$

$$c_p(\tau)=c(\tau)-\Delta c_0e^{-K\tau}, \tag{21}$$

where $\Delta c_0=c_0-c_{po}$.

Substituting the value of $c(\tau)$ from (19) into equation (16), and the value of $c_p(\tau)$ from (21) into equation (13), upon transforms, we obtain:

$$\frac{c_p(\tau)}{d\tau}=\beta F_V\Delta c_0e^{-K\tau}, \tag{22}$$

$$\frac{dc(\tau)}{d\tau}=-K_e\Delta c_0e^{-K\tau}. \tag{23}$$

By integrating equations (22) and (23) under the predefined initial conditions, we obtain:

$$c_p(\tau)=c_{p_0}+\frac{\beta F_V}{K}\Delta c_0\left(1-e^{-K\tau}\right), \tag{24}$$

$$c(\tau)=c_0-\frac{K_e}{K}\Delta c_0\left(1-e^{-K\tau}\right). \tag{25}$$

By integrating equation (14), we obtain

$$c_p(\tau)=\overline{c}-\frac{V_m}{V_p}c(\tau), \tag{26}$$

where

$$\overline{c}=c_{p_0}+\frac{V_m}{V_p}c_0.$$

By substituting values of $c(\tau)$ from (25) into equation (26), we obtain the equation of extraction kinetics for the liquid phase.

A change in the concentration of an extractant over time:

$$c_p(\tau)=\frac{K_e V_m \Delta c_p}{(K_e+\beta F_V)V_p}\left(1-e^{-K\tau}\right)+c_{p_0}. \qquad (27)$$

Equation (27) includes three unknowns K_e, βF_v, Δc_p, which can ve derived from the experimental curve of change in the solution concentration over time, obtained for different magnitudes of power of the source of UHF EMF.

To account for the impact of UHF EMF on the extraction process in the mathematical notation in an imaginary form, we shall consider the thermal balance of a material's particle. The heat that is released in the particle (by the absorption of electromagnetic waves) $Pd\tau$ is spent on heating the material (a solid body plus a liquid) $mcd\Theta$ and a partial conversion of a liquid substance into steam $rm_0\varepsilon' dU$ (m_0 is the mass of a completely dry material), that is:

$$P=mc\frac{d\Theta}{d\lambda}+m_0 r\varepsilon'\frac{dU}{d\tau}. \qquad (28)$$

Using the definition for the Kosovich criterion:

$$K_o=\frac{rdU\varepsilon'}{cd\Theta}$$

(the ratio of heat on evaporation to the heat on heating a material) we write:

$$\frac{rdU}{d\tau}=\frac{K_0 cd\theta}{d\tau}. \qquad (29)$$

Substituting the value of $c\dfrac{d\theta}{d\tau}$ into equation (6), taking into consideration $U=\dfrac{c}{\rho_0}$, following the transforms, we obtain:

$$\frac{dU}{d\tau}=\frac{P}{\left(\dfrac{m}{K_0}+m_0\varepsilon'\right)r},$$

$$\frac{\partial c}{\partial\tau}=D\frac{\partial^2 c}{\partial x^2}+\varepsilon'\frac{P\cdot S_0}{r\left(\dfrac{m}{K_0}+m_0\varepsilon'\right)}. \qquad (30)$$

The second term in the right part of equality (30) has the dimensionality of kg/m^{3}s and describes the intensity of the internal source of a substance released under the action of a source of microwave radiation of power $P=N\eta$ (N is the power of the generator; η is its efficiency).

Equation (30) is similar to the equation of thermal conductivity of a plate (infinite) with an internal source of heat, the solution to which is known [19], hence, by analogy [19], we write down the solution to equation (30) under boundary conditions (9) for a mean-volumetric concentration of the substance:

$$\frac{\bar{c}(\tau)-c_p}{c_0-c_p}=\frac{P_{0m}}{3}\left(1+\frac{3}{B_{im}}\right)-\sum_{n=1}^{\infty}\left(1+\frac{P_{0m}}{\mu_n^2}\right)B_n e^{-\mu_n^2\frac{D}{R^2}\tau}, \qquad (31)$$

where

$$P_{0m}=\frac{q_m R^2}{D(c_0-c_p)}$$

is the mass-transfer equivalent of the Pomerantsev criterion; q_m is the intensity of the internal source:

$$q_m=\frac{\varepsilon' P\rho_0}{r\left(\dfrac{m}{k_0}+m_0\varepsilon\right)}.$$

Confined to the first term in the series in equation (31):

$$\bar{c}(\tau)=c_p(\tau)+\Delta c\frac{P_{0m}}{3}\left(1+\frac{3}{B_{im}}\right)-\Delta c\left(1+\frac{P_{0m}}{\mu_1^2}\right)B_1 e^{-\mu_1^2\frac{D}{R^2}\tau}, \qquad (32)$$

(where $\Delta c=c_0-c_p$) and by differentiating for time, we obtain:

$$\frac{d\bar{c}(\tau)}{d\lambda}=\mu_1^2\cdot\frac{D}{R^2}\left(1+\frac{P_{0m}}{\mu_1^2}\right)B_1\Delta c e^{-\mu_1^2\frac{D}{R^2}\tau}. \qquad (33)$$

By determining from equation (33) the magnitude:

$$\Delta c\left(1+\frac{P_{0m}}{\mu_1^2}\right)B\exp\left(-\mu_1^2\cdot\frac{D}{R^2}\tau\right)$$

and by substituting it into equation (32) after the disclosure of value for criterion P_{0m} and the respective transforms:

$$\bar{c}(\tau)-c_p(\tau)-(c_0-c_p)\frac{q_m R^2}{(c_0-c_p)D}\left(1+\frac{3}{B_{im}}\right)=$$

$$=-\frac{R^2}{\mu_1^2 D}\frac{d\bar{c}(\tau)}{d\tau}, \qquad (34)$$

where

$$\mu_1^2=\left(\frac{4}{\pi^2}+\frac{1}{B_{im}}\right)^{-1}.$$

The solution to equation (30) under boundary conditions (9) we shall record in the final form:

$$\frac{d\bar{c}(\tau)}{d\tau}=K_m\left(\bar{c}(\tau)-c_p(\tau)\right)+Q_m, \qquad (35)$$

$$K_m=\mu_1^2\cdot\frac{R^2}{D}=\frac{R^2}{\left(\dfrac{4}{\pi^2}+\dfrac{1}{B_{im}}\right)D};\quad Q_m=q_m\frac{(B_{im}+3)\pi^2}{4B_{im}+\pi^2}.$$

In order to determine the kinetic dependences of change in the concentration of solid phase $\bar{c}(\tau)$ and solution $\bar{c}_p(\tau)$ equation (22):

$$\begin{cases}\dfrac{dc(\tau)}{d\tau}=K_m\left(\bar{c}(\tau)-c_p(\tau)\right)+Q_m,\\ \dfrac{dc_p(\tau)}{d\tau}=\beta F_V\left(\bar{c}(\tau)-c_p(\tau)\right),\\ V_m\left(\bar{c_0}-\bar{c}(\tau)\right)=V_p\left(\bar{c_p}(\tau)-\bar{c_0}\right).\end{cases} \qquad (36)$$

A solution to the system of equations (36) will be derived similarly to the previous variant of the mathematical notation.

Subtracting the second equation from the first equation in system (36), we obtain:

$$\frac{d\left(\bar{c}-\bar{c}_p\right)}{d\tau}=-\left(K_m+BF_V\right)\left(\bar{c}-\bar{c}_p\right)+Q_m\ , \qquad (37)$$

under initial conditions:

$$\tau=0,\ \bar{c}=\bar{c}_o,\ \bar{c}_p=\bar{c}_{po},\ \Delta c_0=c_0-c_{po}.$$

The solution to equation (37) relative to variables $c(\tau)$ and $c_p(\tau)$ will be written down in the form:

$$c(\tau)=c_p(\tau)+\frac{Q_m}{K}-\left(\frac{Q_m}{K}+\Delta c_0\right)e^{-k\tau}, \qquad (38)$$

$$c_p(\tau)=c(\tau)-\frac{Q_m}{K}-\left(\frac{Q_m}{K}+\Delta c_0\right)e^{-k\tau}, \qquad (39)$$

where $K=K_m+\beta F_v$; $\Delta c_0=c_0-c_{po}$.

By substituting the derived values for variables ($c(\tau)$ and $c_p(\tau)$ in the first and second equation of system (36), we obtain:

$$-\frac{dc(\tau)}{d\lambda}=\frac{K_m}{K}Q_m+K_m\left(\frac{Q_m}{K}-\Delta c_0\right)e^{-kt}, \qquad (40)$$

$$\frac{dc_p(\tau)}{d\lambda}=\frac{\beta F_V}{K}Q_m-\beta F_V\left(\frac{Q_m}{K}-\Delta c_0\right)e^{-kt}. \qquad (41)$$

By integrating equations (40) and (41) under initial conditions: $\tau=0$; $c=c_0$; $c_p=c_{po,}$ we obtain dependences of concentration of the target component on extraction duration:

$$c(\tau)=c_0-\frac{K_m}{K}Q_m\tau-\frac{K_m}{K}\left(\frac{Q_m}{K}-\Delta c_0\right)e^{-kt}, \qquad (42)$$

$$c_p(\tau)=c_{p_0}+\frac{\beta F_V}{K}Q_m\tau+\frac{\beta F_V}{K}\left(\frac{Q_m}{K}-\Delta c_0\right)e^{-kt}. \qquad (43)$$

Substituting values ($c_0-c(\tau)$) from equation (42) in the third equation in system (36), we obtain:

$$c_p(\tau)=c_{p_0}+\frac{\rho_p m_m K_m}{\rho_m m_p K}\left[Q_m\tau-(\frac{Q_{m,}}{K}-\Delta c_0)(1-e^{-kt})\right]. \qquad (44)$$

The resulting equation (44) describes the kinetics of extraction – a change in the concentration of solution over time under the influence of UHF electromagnetic field.

Equation (44) contains three unknown constants K, K_m, Q_m, which can be calculated from equation (44) if one has data on measurement of concentration $c_p(\tau_i)$ for various time intervals τ_i of process duration. And, by deriving these values based on ratios:

$$K_m=\frac{R^2}{D_m}\left(\frac{4}{\pi^2}+\frac{1}{B_{im}}\right)^{-1},$$

$$K=K_m+\beta F_V,$$

$$Q_m=q_m\frac{B_i+3}{\pi^2+4B_i}\pi^2.$$

It is possible to calculate the kinetic coefficients of the original equations.

The considered model representations of the kinetics of extraction of vegetable raw materials do not explicitly take into consideration the influence of a temperature regime of interaction between a solid and liquid phase, therefore, we shall consider a possibility of taking into consideration the effect of temperature (of the solid phase and environment).

As was shown above, the intensive steam formation under the action of a microwave field (boiling liquid in the microvolumes of a product [4, 5, 15]) creates excess pressure in the solid phase, which, according to experiments [2], changes little in terms of volume. The excess pressure is determined by the intensity of the phase transformation of liquid-vapor, which is quantitatively determined from equation [16]:

$$\frac{\partial P}{\partial\tau}=-\frac{\varepsilon'}{c_B}\frac{\partial u}{\partial\tau}, \qquad (45)$$

where $c_B=\Pi M_B/\rho_0 RT$ is the specific capacity of the fluid's steam (a capillary body capacity relative to the moist air), M_B is the molecular weight of the substance (formed by steam), ρ_0 is the density of a dry solid body, R is the universal gas constant, T is the absolute temperature, Π is porosity.

The magnitude of pressure of steam depends on its concentration and temperature according to ratio:

$$P=\rho_n R_n(\Theta+273), \qquad (46)$$

we shall obtain by differentiating it:

$$\frac{\partial P}{\partial\tau}=\rho_n R_n\frac{\partial\theta}{\partial\tau}. \qquad (47)$$

We obtain the following equation from equations (45) and (47):

$$\frac{\partial P}{\partial\tau}+\varepsilon'\frac{\partial u}{\partial\tau}=c_B\rho_n R_n\frac{\partial\theta}{\partial\tau}. \qquad (48)$$

Substituting values of $\varepsilon'\frac{\partial u}{\partial\tau}$ (48) in equation (6) and passing over to the volumetric concentration, we shall write equation (7) in the form:

$$\frac{\partial c}{\partial\tau}=D_e\frac{\partial^2 c}{\partial x^2}+c_B\rho_n R_n\frac{\partial\theta}{\partial\tau}. \qquad (49)$$

In equation (49), the last term accounts for the flow of a substance under the influence of an increase in temperature predetermined by UHF heating.

The kinetics of heating a solid phase in a microwave field can be derived from the solution to the equation of thermal conductivity of an infinite plate with an internal source of heat:

$$\frac{\partial\theta(x_1\tau)}{\partial\tau}=a\frac{\partial^2\theta(x_1\tau)}{\partial x^2}+\frac{q_V}{c\rho_0}, \qquad (50)$$

under boundary conditions of third kind:

$$-\frac{\partial\theta(R_1\tau)}{\partial x}+\frac{\alpha}{\lambda}\left(t_p-\theta(R_1\tau)\right)=0, \qquad (51)$$

for a mean-volumetric temperature (at small size of particles), it takes the form [19].

$$\frac{\theta(\tau)-\theta_0}{t_p-\theta_0}=1+P_0\left(\frac{1}{3}+\frac{1}{B_i}\right)-\sum_{n=1}^{\infty}\left(1+\frac{P_0}{\mu_n^2}\right)B_n\cdot e^{-\mu_n^2 F_0}, \qquad (52)$$

where t_p is the temperature of solution;

$$P_0=\frac{q_V R^2}{\lambda\left(t_p-\theta_0\right)}$$

is the Pomerantsev criterion;

$$F_0=\frac{D}{R^2}\tau$$

is the Fourier criterion; $2R$ is the thickness of the plate; λ, a are the coefficients of thermal conductivity and thermal diffusivity; μ_n are the roots of the characteristic equation.

Equation (52) is similar to equation (31), therefore, leaving the intermediate transforms (employed above), we write the final equation of the kinetics of heating.

$$\frac{d\bar{\theta}(\tau)}{d\tau}=K_m\left(t_p-\theta(\tau)\right)+Q_m, \tag{53}$$

where

$$K_m=\frac{R^2}{\left(\frac{4}{\pi^2}+\frac{1}{B_i}\right)a};$$

$$B_i=\frac{\alpha R}{\lambda}.$$

$$Q_m=\frac{q_V R^2}{\lambda}\left(\frac{1}{3}+\frac{1}{B_i}\right). \tag{54}$$

At a preliminary heating of the solution to boiling point temperature $t_p=t_k$, equation (53) can be integrated:

$$\theta(\tau)=\left(t_к+Q_m\right)-\left[\left(t_к+Q_m\right)-\theta_0\right]e^{-k_m\tau}, \tag{55}$$

where θ_0 is the initial temperature of the material; t_k is the boiling temperature of solution.

Relation between the temperature of solution and the power of heat release in its volume under the action of UHF magnetic field and the temperature of the solid phase is determined from the equation of thermal balance for a solution:

$$Q_2=\alpha F_p\left(\theta-t\ \ \right)=kf_{oc}\left(t-t\ \ \right), \tag{56}$$

where $Q_2=P_2/V_p$ is the specific heat of heat release in solution under the influence of UHF EMF; $P_2=N\eta$ is the power of a solution heating source in UHF field; F is the interphase surface; t is the surface of the container with a solution (external); a, k are the coefficients of heat exchange between a solid-phase and solution and heat transfer from the solution into the environment; t_{oc} is the ambient temperature.

We obtain from equation (54):

$$t_p=a+b\theta, \tag{57}$$

where

$$a=\frac{P_2+kft_{oc}}{kf+\alpha F};\ \ b=\frac{\alpha F}{kf+\alpha F}.$$

By substituting values for t_p into equation (56):

$$T_m=\frac{\bar{d}\theta(\tau)}{d\tau}=A-B\theta(\tau), \tag{58}$$

where

$$A=\frac{P_2+kft_{oc}}{\alpha F+kf}+Q_m;\ \ B=\frac{kf}{\alpha F+ef}.$$

We shall obtain a solution to equation (58) under initial conditions: $\tau=0$, $\theta=\theta_0$ in the following form:

$$\bar{\theta}(\tau)=\frac{A}{B}-\left(\frac{A}{B}-\theta_0\right)e^{-k_m\tau}, \tag{59}$$

where $k_m=\frac{1}{T_m}$.

The resulting equation defines the kinetics of warming (heating) of a material in solution under the influence of UHF EMF. Temperature of the solution is determined from equation (58) by substituting $\theta(\tau)$ from equation (59), that is:

$$t_p(\tau)=a+b\theta(\tau). \tag{60}$$

By differentiating equation (59) for time:

$$\frac{d\bar{\theta}}{d\tau}=K_m\left(\frac{A}{B}-\theta_0\right)e^{-k_m\tau}, \tag{61}$$

and by substituting the derived value in equation (49):

$$\frac{\partial c}{\partial\tau}=D_e\frac{\partial^2 c}{\partial x^2}+\omega_0 e^{-k_m\tau}, \tag{62}$$

where

$$\omega_0=c_B\rho_n R_n K_m\left(\frac{A}{B}-\theta_0\right)$$

is the equivalent value of the maximum intensity of the component flow that is released under the action of UHF EMF.

The resulting equation in terms of its structure is similar to the equation of thermal conductivity of a plate with an internal source of heat release, whose power decreases in line with the exponential law over time. A solution to equation (62) under boundary conditions of third kind, by analogy to [19], is recorded in the following form:

$$\frac{c(x,\tau)-c_p(\tau)}{c_o-c_p(\tau)}=$$

$$=\frac{Po_m}{Pd}\left[1-\frac{\cos\sqrt{Pd}\,\frac{x}{R}}{\cos\sqrt{Pd}-\frac{1}{Bi_m}\sqrt{Pd}\sin\sqrt{Pd}}\right]\exp(-PdFo)-$$

$$-\sum_{n=1}^{n}\left(1-\frac{Po_m}{Pd-\mu_n^2}\right)A_n\cos\mu_n\frac{x}{R}\exp(-\mu_n^2 Fo), \tag{63}$$

where $F_0=\frac{D_e}{R^2}\tau$ is the Fourier criterion; $Pd=\frac{k}{a}R^2$ is the Predvoditelev criterion.

A change in time of the mean-volumetric value for the concentration of a target component $\bar{c}(\tau)$ will be derived from the explicit formula:

$$\bar{c}(\tau)=\frac{1}{R}\int_0^R c(x,\tau)\mathrm{d}x;$$

$$\frac{\bar{c}(\tau)-c_p(\tau)}{c_0-c_p(\tau)}=$$
$$=\frac{Po_m}{2\cdot Pd}\left[2-\frac{A_1\exp\left(-Fo\cdot\mu_1^2\right)\left(Po_m-Pd+\mu_1^2\right)\cos\mu_1}{\mu_1^2-Pd}-\frac{Bi_m\cos\sqrt{Pd}\cdot\exp(-Pd\cdot Fo)}{Bi_m\cos Pd-\sqrt{Pd}\sin Pd}\right], \quad (64)$$

where

$$\mu_1=\sqrt{\left(\frac{4}{\pi^2}+\frac{1}{Bi_m}\right)^{-1}}.$$

Equation (64) was obtained when taking into consideration only the first term in the series in equation (63). We obtain from equation (64):

$$\bar{c}(\tau)=c_p(\tau)+\frac{\left(c_0-c_p(\tau)\right)Po_m}{2\cdot Pd}\times$$
$$\times\left[2-\frac{A_1\exp\left(-\mu_1^2\frac{D_e}{R^2}\tau\right)\left(Po_m-Pd+\mu_1^2\right)\cos\mu_1}{\mu_1^2-Pd}-\frac{Bi_m\cos\sqrt{Pd}\cdot\exp\left(-Pd\cdot\frac{D_e}{R^2}\tau\right)}{Bi_m\cos Pd-\sqrt{Pd}\sin Pd}\right]. \quad (65)$$

By differentiating equation (65) for time, we obtain:

$$\frac{d\bar{c}(\tau)}{d\tau}=\frac{D_ePo\cdot\left(c_0-c_p(\tau)\right)}{2Pd\cdot R^2}\times$$
$$\times\left[\frac{A_1\mu_1^2\left(Po_m-Pd+\mu_1^2\right)\cos\mu_1\exp\left(-\mu_1^2\frac{D_e}{R^2}\tau\right)}{\mu_1^2-Pd}+\frac{Bi_m\cos\sqrt{Pd}\cdot\exp\left(-Pd\cdot\frac{D_e}{R^2}\tau\right)}{Bi_m\cos Pd-\sqrt{Pd}\sin Pd}\right]+c_p'(\tau)\times$$
$$\times\left[1-\frac{Po_m}{2Pd}\left(2-\frac{A_1\exp\left(-\mu_1^2\frac{D_e}{R^2}\tau\right)\left(Po_m-Pd+\mu_1^2\right)\cos\mu_1}{\mu_1^2-Pd}-\frac{Bi_m\cos\sqrt{Pd}\cdot\exp\left(-Pd\cdot\frac{D_e}{R^2}\tau\right)}{Bi_m\cos Pd-\sqrt{Pd}\sin Pd}\right)\right]. \quad (66)$$

The equation of material balance for a solid phase and solution will be applied in a differential form (14). Substituting the value for derivative (66) in equation (14), we obtain:

$$\frac{dc_p(\tau)}{d\tau}=-\frac{V_TD_ePo\cdot\left(c_0-c_p(\tau)\right)}{2V_pPd\cdot R^2}\times$$
$$\times\left[\frac{A_1\mu_1^2\left(Po_m-Pd+\mu_1^2\right)\cos\mu_1\exp\left(-\mu_1^2\frac{D_e}{R^2}\tau\right)}{\mu_1^2-Pd}+\frac{Bi_m\cos\sqrt{Pd}\cdot\exp\left(-Pd\cdot\frac{D_e}{R^2}\tau\right)}{Bi_m\cos Pd-\sqrt{Pd}\sin Pd}\right]-\frac{V_T}{V_p}c_p'(\tau)\times$$
$$\times\left[1+\frac{Po_m}{2Pd}\left(2-\frac{A_1\exp\left(-\mu_1^2\frac{D_e}{R^2}\tau\right)\left(Po_m-Pd+\mu_1^2\right)\cos\mu_1}{\mu_1^2-Pd}-\frac{Bi_m\cos\sqrt{Pd}\cdot\exp\left(-Pd\cdot\frac{D_e}{R^2}\tau\right)}{Bi_m\cos Pd-\sqrt{Pd}\sin Pd}\right)\right]. \quad (67)$$

Solution of equation (67) under initial conditions: $\tau=0$, $c_p=c_{p0}$

$$c_p(\tau)=\frac{\left[\begin{array}{l}c_0\cdot\left(A_{11}\exp\left(Pd\frac{D_e}{R^2}\tau\right)+B_{11}\exp\left(\mu_1^2\frac{D_e}{R^2}\tau\right)\right)+\\+Po_mV_T+\exp\left(\frac{D_e\left(Pd+\mu_1^2\right)}{R^2}\tau\right)\times\\\times\left(\begin{array}{l}2\cdot c_{p0}PdV_p-\left(A_{11}+B_{11}\right)c_{p0}Po_mV_T+\\+c_{p0}\left(2\cdot Pd+\left(A_{11}+B_{11}-2\right)Po_m\right)V_T\end{array}\right)\end{array}\right]}{\left[\begin{array}{l}A_{11}\exp\left(Pd\frac{D_e}{R^2}\tau\right)Po_mV_T+B_{11}\exp\left(\mu_1^2\frac{D_e}{R^2}\tau\right)Po_mV_T+\\+2\cdot\exp\left(\frac{D_e\left(Pd+\mu_1^2\right)}{R^2}\tau\right)\left(Pd\left(V_p+V_T\right)-Po_mV_T\right)\end{array}\right]}, \quad (68)$$

where

$$A_{11}=\frac{A_1\left(Po_m-Pd+\mu_1^2\right)\cos\mu_1}{\mu_1^2-Pd};$$

$$B_{11}=\frac{Bi_m\cos\sqrt{Pd}}{Bi_m\cos Pd-\sqrt{Pd}\sin Pd}.$$

According to equation (68), the concentration of the extracted raw material depends on the criteria by Pomarantsev, Predvoditelev, Bio, the coefficient of diffusion, and a hydromodule. Respective parameters largely depend on the characteristics of the substance extracted, the solvent, and the conditions for the course of the process. Therefore, the verification of mathematical models for the extraction process necessitates conducting an experimental research.

5. Results of experimental research

The main elements of the experimental microwave bench (Fig. 1) was a chamber in which, by using a magnetron, a microwave field was induced, as well as a container, which actually hosted the process of extraction of the examined objects: soybean of the varieties “Vinnychanka” and the winter rapeseed variety “Champion”.

Fig. 1. Experimental microwave bench

Operating principle of the experimental bench is as follows: the process of extraction occurs in the container with a product under the action of a microwave field in chamber 1. The power mode is set using regulator 3. Steam from the extractant enters inverse refrigerator 2, where it is condensed and drained back into the reaction container with the studied sample and a solvent. A micelle is taken by a syringe for the further examination of the concentration of oil.

The main factors that affect the process of extraction: a size fraction of raw materials, the existence and magnitude of power of the pulsed microwave field, a hydromodule of the extract, temperature, time of extraction, solvents, ethyl alcohol C_2H_5OH, hexane C_6H_{14}.

Classic technologies for extraction of oil employ the non-polar aliphatic hydrocarbons due to their greatest effectiveness among solvents. Given the use of the action of a microwave field as an intensifying factor, we conducted research involving a polar ethyl alcohol, the intensity of whose removal under MW irradiation grew to match the efficiency of hexane (Fig. 2). When studying the process of extraction without exposure to a microwave field, only under the action of temperature, the solvent hexane proves significantly more effective than ethyl alcohol (Fig. 3).

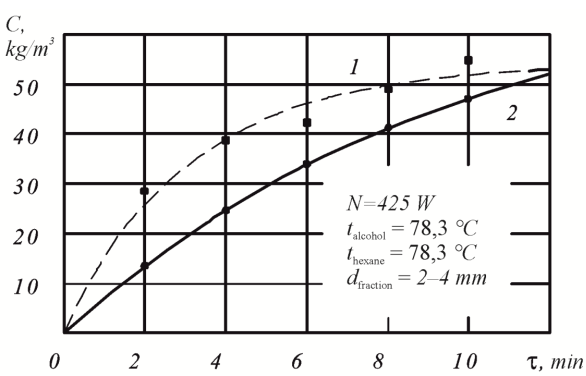

Fig. 2. Dependence of oil concentration on duration of extraction of rapeseed by hexane (1) and alcohol (2)

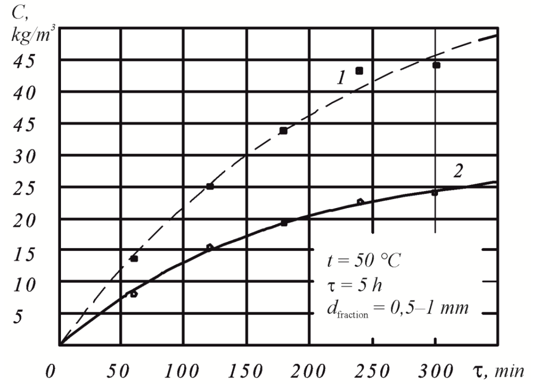

Fig. 3. Dependence of oil concentration on time during extraction of rapeseed by hexane (1) and alcohol (2)

6. Discussion of results of the mathematical modelling of the process of extraction of oil raw materials

Verification of the constructed mathematical model (68) can be based on data from experiments, by comparing the analytical and the experimentally obtained dependences. To be determined are the resulting parameters of the solution concentration under the influence of temperature, size of fraction, solvent, and the influence of a microwave field. The experimental data were approximated by second-order polynomials; graphical interpretation of the experimental data and the calculated curves for dependences of change in the concentration in the process of extraction are shown in Fig. 2, 3.

By employing the methods of analytical modeling based on equations of energy and material balances, we have constructed a mathematical model of the heat and mass transfer processes during extraction of oil raw materials in an electromagnetic field of ultra-high frequency. A special feature and the significance of the proposed model are in the fact that it establishes patterns in the heat and material interaction between all objects engaged in the heat- and mass exchange inside an extraction unit. This means that the obtained scientific result in the form of the developed mathematical model for the processes of heat and mass exchange during extraction of oil raw materials in an electromagnetic field of ultra-high frequency, the equations of material balance for a solid phase and solution, as well as energy balance, is interesting from a theoretical point of view.

The given approximated analytical solution to the presented model makes it possible to:

– to approximately determine the concentration of an extracted material over time;

– to determine and refine the parametric complexes of the model based on the empirical dependences of the kinetics of extraction of a plant-derived raw material (oil);

– to further use a given model for the synthesis of the system of optimal control over the process.

Based on the constructed empirical mathematical model (68) of the kinetics of extraction in a microwave field, we parametrically identified the approximate solutions to the analytical mathematical model. The research results reported here could prove useful for the improvement of installations and technologies for extraction in UHF EMF.

The approximate solution to the system, presented in the framework of this study, makes it possible to predict an increase in the concentration of an extracted substance depending on the supplied power of an electromagnetic field of ultra-high frequency in order to calculate energy efficiency of the extraction process and to synthesize a system for optimal control over the process. Therefore, the applied aspect of the application of the obtained result is the possibility of using it to identify the parameters of a mathematical model after conducting experimental research into the kinetics of extraction of oil raw materials. That creates prerequisites for the transfer of the obtained solutions when constructing a parametric series of the extraction unit designs.

7. Conclusions

1. Analytical research into a mathematical model of the process of raw materials extraction during application of the addressed delivery of UHF electromagnetic energy directly to the polar molecules will initiate a powerful, specific hydrodynamic flow. A given flow occurs in the interaction between the electromagnetic field and the polar molecules of fluid inside the capillaries. This would, in our opinion, significantly improve the intensity of mass transfer due to a sharp decrease in the internal diffusion resistance, reduce energy costs and duration of the process.

2. The reported approximated solution to the system makes it possible to predict an increase in the concentration of an extracted substance depending on the supplied power of an electromagnetic field of ultra-high frequency.

3. The experimental study that we conducted established that under the action of microwave irradiation a value for the coefficient of mass release during extraction of oil-containing raw materials grows by an order of magnitude ($\beta=1\cdot10^{-5}$), compared to extraction without an effect of a MW field ($\beta=1\cdot10^{-6}$). Extracting the oil under the action of a microwave field increases to 30 %, while electricity consumption decreases by 93–97 %.

4. The constructed mathematical model is employed for engineering calculation for determining the main structural elements of a device with the predefined productivity at the recommended operational parameters. Structural parameters include the geometrical dimensions of the unit and location of MW emitters. Operating parameters include a hydromodule and power of the emitter.

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