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# THE USING OF MECHANODIFFUSION EFFECT IN THE PRODUCTION OF CONCENTRATED POLYEXTRACTS

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**Abstract.** In this paper, new results are presented regarding the preparation of polyextracts under the conditions of the action of the microwave field and their subsequent thickening. According to the hypothesis advanced by the authors, the features of the selective action of the microvolume field on the solvent molecules, it is possible to initiate an effect called mechanodiffusion. The effect action is particularly pronounced in the cramped conditions of capillary structures. This hypothesis is confirmed by a number of experimental studies. The created stand for the visualization of the mechanodiffusion phenomenon fixed emissions from the models of capillaries filled with liquid during the microwave field influence. The use of the endoscope shielded from the microwave field made it possible to record this effect for the first time. It is noticed that from the capillary during the microwave field influence not only liquid is thrown out, but also paint particles, that is, dry substances. For extraction processes, this effect is particularly valuable, since it allows one to initiate a rapid transition of components into the extract, including insoluble ones. It is important to keep thermolabile biologically active substances and vitamins when manufacturing phytopreparations. An experimental stand has been created, where the extraction process is carried out under vacuum. The working pressure is in the range of 20–40 kPa. Such conditions ensure the boiling of the extract already at 30–40°C, which contributes to continuous updating of the boundary layer, which greatly intensifies the process. Due to the phenomenon of barodiffusion, there is no need to use several extractants to obtain a polyextract. The necessary stage in the production of phytopreparations is the concentration of extracts. The microwave vacuum-evaporator allows you to remove moisture at low energy costs and a high rate of moisture removal.

**Key words:** microwave extraction, vacuum, mechanodiffusion, intensification, mass transfer.

# ВИКОРИСТАННЯ МЕХАНОДИФУЗІЙНОГО ЕФЕКТУ ПРИ ВИРОБНИЦТВІ КОНЦЕНТРОВАНИХ ПОЛІЕКСТРАКТІВ

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**Анотація.** У даній статті представлено результати щодо отримання поліекстрактів в умовах дії мікрохвильового поля та їхнього подальшого згущення. Згідно висунутої авторами гіпотези, завдяки особливості селективної дії мікрохвильового поля на молекули розчинника, можливо ініціювати ефект, названий механодифузією. Особливо чітко ефект проявляється в умовах обмеженого простору капілярних структур. Дана гіпотеза підтверджується рядом проведених експериментальних досліджень. На створеному стенді для візуалізації явища механодифузії зафіксовано викиди з моделей капілярів, заповнених рідиною, при впливі мікрохвильового поля. Використання цифрової камери-зонда, екранованої від мікрохвильового поля, дозволило вперше зафіксувати цей ефект. Помічено, що з капіляра при обробці в мікрохвильовому полі викидається не тільки рідина, а й частки фарби, тобто сухі речовини. Для процесів екстрагування такий ефект особливо цінний, оскільки дозволяє ініціювати швидкий перехід компонентів до екстракту, в тому числі й нерозчинних. При виробництві фітопрепаратів важливо зберігати термолабільні біологічно активні речовини і вітаміни. Створено експериментальний стенд, де процес екстрагування проводиться за умов розрідження близького до вакууму. Робочий тиск коливається в межах 20–40 кПа. Такі умови забезпечують кипіння екстракту вже за 30–40°С, що сприяє безперервному оновленню граничного шару та значно інтенсифікує процес. Завдяки явищу бародифузії відсутня необхідність у використанні декількох екстрагентів для отримання поліекстракту. Необхідним етапом виробництва фітопрепаратів є концентрування екстрактів. Мікрохвильовий вакуум-випарний апарат дозволяє видаляти вологу при низьких енерговитратах і високій швидкості вологовидалення.

**Ключові слова:** мікрохвильове екстрагування, вакуум, механодифузія, інтенсифікація, масообміну.

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## Introduction. Formulation of the problem

Forecasts of the well-known model of the Club of Rome for the present century determine the timeframe for the successive development of the energy, ecological and food crises [1]. Food technologies in industrially developed countries are characterized by two problems: high energy intensity and significant losses of target components. The first problem is due to ineffective processes of heat transfer and mass transfer during dehydration of food raw materials. The second problem is the specific structure of raw materials. As a rule, these are cellular and capillary-porous structures, and the contents of pores, capillaries and cells are the goal of food technology. Since these objects are of a nanoscale size, traditional technologies do not fully extract the contents of raw materials and rationally use energy. The processes of transport take place in extremely cramped conditions. This leads to the formation of significant thermal and diffusion resistances. Scientific and technical contradictions between the growing requirements to the quality of the food product, the energy intensity of its production and the technology of heat and mass transfer are obvious.

To solve these contradictions, it is necessary to search for new principles for the organization of heat and mass transfer processes, use of unique opportunities for combined effects on transport processes, and the formation of complex combinations of driving forces aimed at efficiently extracting target components from raw materials. Particular attention must paided to micro- and nanoscale structures of raw materials. These elements in traditional technologies are practically not considered. In the food industry and pharmaceutical technologies, the tasks of dehydration and extraction of target components are relevant. In this connection, the phenomena that arise when a liquid interacts in micro- and nanocapillaries during the electromagnetic field influence are of interest. The effectiveness of food technologies (productivity, specific energy intensity, quality of the finished product, the degree of extraction of valuable components of raw materials, etc.) is largely determined by the possibilities of direct effects on cell membranes, microorganisms, pores, capillaries, etc. The objective is to find effective principles, approaches for local actions aimed at intensive, low-energy operations with food raw materials, and even with individual nanoscale elements of this raw material. It is important to create the fundamental foundations of evolutionary nanometric phenomena and processes.

## Analysis of recent research and publications

The efforts of many scientific schools are aimed at solving the problems of energy resources providing. Scientists suggest new methods of a systematic approach to the study of energy-related problems [2-3], innovative thermal technologies [4-5], the introduction of alternative energy sources, heat pumps [2], heat recovery systems [3], etc. Experience of proposed approaches in solving problems of effective energy use is especially relevant for the food industry.

In the processes of food production, it is often necessary to interact with the structures where the raw materials of vegetable or animal origin are processed, which has a complex capillary structure, often nanoscale. In the extraction, drying and dehydration processes, thin capillaries and cell walls significantly complicate the diffusion processes [4]. With the advent of electromagnetic energy generators, Western scientists study diffusion processes during the electromagnetic field influence [5]. The processes arising from the field action were initially considered random, but further studies confirmed the selective effect of the microwave field on water molecules [6]. The authors of [7] note that under the action of the microwave field, in addition to the usual thermal diffusion, the component of the action of the microwave field that substantially intensifies the process is attached. This is explained by the dipole shift of polar water molecules [6-7]. However, this explanation is not sufficient for drying and dehydration processes, which are also significantly intensified in the microwave field [8].

In the extraction process, the walls of plant cells are complicated by diffusion processes, preventing the extraction of target components [4-6]. However, with the use of a microwave field, the yield of extractive substances is significantly increased, as noted in the scientific papers of Western [5], Asian [4, 6-7] and domestic scientists [8-9]. According to the literature data, one extractant in traditional extraction processes can not efficiently extract all the useful substances from the raw material, therefore several different solvents are used successively, and the product is called polyextract [10-13]. Polyextracts are widely used as phytopreparations for the treatment of inflammatory diseases, immunostimulants. In addition, such extracts are used for the production of dietary and health food. In the course of studies of the processes of extracting the microwave field, a significant intensification of the processes and transition to an extract of components insoluble in traditional methods has been revealed. So, for example, during amaranth oil extracting with alcohol in a microwave extractor [9] an increased content of squalene was noted, despite the fact that alcohol does not dissolve squalene.

**Goals and objectives of the study** A hypothesis is advanced that it is expedient to search for the possibilities of controlling transport processes at the level of nanoscale elements of food raw materials by using the full use of surface phenomena and innovative methods of energy impact. The creation of the theory foundations of such technologies, the proof of their effectiveness, and the experimental verification of the proposed hypotheses are defined as the goal of the present studies. All this will contribute to an integrated solution of the key human problems of energy-resource-efficient, environmentally safe food production based on perspective principles – nanotechnologies.

In curent research, we approved that hypothesis by mathematical and experimental modeling. The visualiztions, results of yield of total soluties increasing in extracts, concentrated juices which one exceed traditional and modern technologies is the goal of that study.

## Research materials and methods

Traditional nanotechnology involves manipulating molecular elements and creating systems with new physical and chemical properties. The basis of such technologies is the most complex laboratory tools.

In the laboratory "Food Nanotechnology" of the Odessa National Academy of Food Technologies, a fundamentally new direction [14], food nanotechnologies (FNT) has been proposed and is developing. The analysis showed that the goal of most food technologies is nanoscale elements of raw materials: water molecules and cell membranes, pores and capillaries, polysaccharides and proteins. It is these objects that are aimed at the main stages of food technology (Fig. 1).

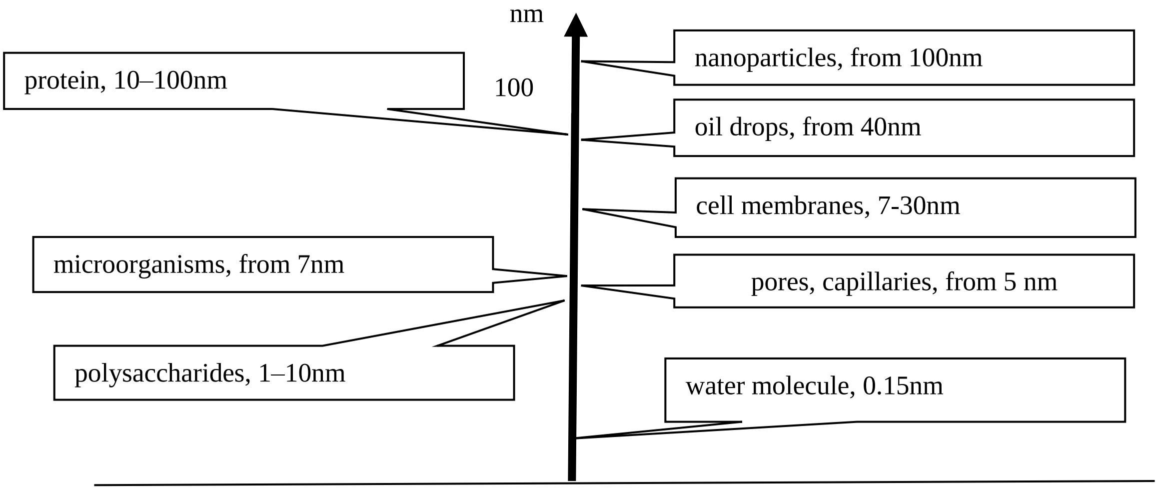

**Fig. 1. Scale scale objects of food nanotechnology.**

For the first time, mass-transfering processes were organized at the nanoscale level. Moreover, this corresponds to the definition of nanotechnology [15]. The principles that can be implemented when converting food production to nanotechnology will significantly reduce energy intensity, the level of thermal effects on raw materials and products, and obtain fundamentally new products. The paradigm and scientific foundations of food nanotechnologies being developed in ONAFT include: the hypothesis of barodiffusion transfer from nanoscale elements of raw materials, the thermodynamic scheme of a nanoprocess and the thermal mechanical model of a plant cell, the kinetic model of mass transfer [8].

From the positions of nanoscience, the facts of the change and transformation of the structure of the flavor and aromatic complexes of the product, the sterilization of microorganisms at low temperatures, and the like are explained. It is shown that the cause of these facts is general – the effect of the electromagnetic field (EMF) [8]. For the first time [ppt] the provisions of the effect of "mechanodiffusion" are formulated.

At the same time, a number of inconsistencies with the adopted regulations have been identified, it is established that a greater number of components pass into the solution than can be dissolved. This work is devoted to explaining this paradox. To explain the revealed paradoxes, the scientific and technical concept is proposed: "Under the EMF conditions, it is possible to organize the targeted delivery of energy to the polar molecules of the raw material elements and to ensure the exit from the raw material of a specific stream containing highly soluble components of the solid phase (diffusion flux) and practically insoluble components of the solid phase, the links of which are weak with it". This is a purely mechanical flow, the power of which is determined by the difference in pressure. It can be initiated, it can be controlled by the parameters of the electromagnetic field. Since this flow is determined not only by diffusion, but also by mechanical driving forces, the term "mechanodiffusion" is given to it.

**The proposed scheme for the production of concentrated polyextracts.**Use in the processes of extraction, evaporation and drying of modern EMF systems will make it possible to create devices for an integrated, low-waste technology for processing food and medicinal raw materials with obtaining a wide range of high-quality biologically active medicines for medical, food and fodder use, while minimizing energy costs and environmental purity of production.

Recently, there has been growing interest in the production of polyextracts. A serious drawback of this principle is the cumbersome technological line, high energy consumption and long process duration. The authors set the task of creating a technology for the production of polyextracts using only one extractant.

In the first stage, the required value of the hydromodule is provided by mixing the fruits Gc and the solvent Gp. The mixture enters the extractor where the mass transfer of the target components from the fruits takes place under the action of EMF, an extract stream is formed, the amount of which is Ge, and the concentration of dry substances is Xe. If necessary, by evaporation, the solvent is distilled from the extract, a more concentrated product is obtained, the amount of which is Gn and the concentration of Xn. The solvent vapor, the amount of which is Gp, either is directed to the mixer, or condenses. At the same time, the amount of distillate is also Gp.

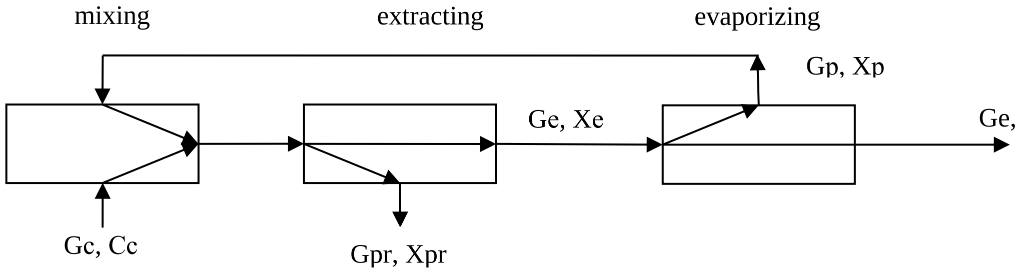

**Fig.2. Scheme of material flows.**

The characteristic of the raw material is known: Gc, Cc. Virtually easily measured parameters: Gp, Xp, Ge, Xe, Gn, Xn. For a certain amount of sludge Gm (Fig. 3), the concentration of the target components Xm is determined in it.

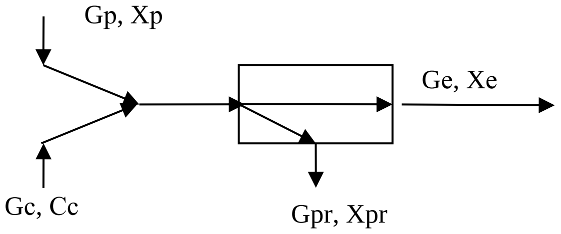

**Fig.3. Technological operator of the extractor.**

From balancing model (1) based on the principles of directional energy impact and the effect of "mechano-diffusion". The basic operator diagram of the key elements of the circuit is shown in Fig.2.

$$\left.\begin{aligned} G_p + G_c &= G_e + G_s \\ G_pX_p + G_cC_c &= G_eX_e + G_sX_s \end{aligned}\right\} \qquad (1)$$

It found that:

$$X_s = X_e - \frac{G_pX_p + G_cC_c - G_eX_e}{G_p + G_c - G_e} \qquad (2)$$

Models for evaporizing are simmilar:

$$\left.\begin{aligned} G_n + G_p &= G_e \\ G_eX_e &= G_pX_p + G_nX_n \end{aligned}\right\} \qquad (3)$$

$$X_p = \frac{G_eX_e - G_nX_n}{G_e - G_n} \qquad (4)$$

The next stage is to study the effect of "mechanodiffusion".

**Mechanism of mehanodiffusion.**The task is to prove the effectiveness of the phenomenon of mechanodiffusion in the processes of obtaining polyextracts and to give a visual confirmation of this phenomenon.

The liquid in the raw capillaries is a multicomponent system. It seems that in general, we are dealing with a new phenomenon, a new effect, the name of which can be given the "mechanodiffusion effect in the gradientless wave supply of electromagnetic energy to polar molecules". As a result of the generation of vapor bubbles, the pressure in the depth of the microcapillary increases, a hydraulic flow arises that carries with it an extract from the boundary layer, insoluble and slightly soluble components.

Thus, from the capillary, a diffusion flow of the solution emerges, which is supplemented by the flow of a whole complex of components that are not characteristic in general for classical diffusion processes (Fig. 4).

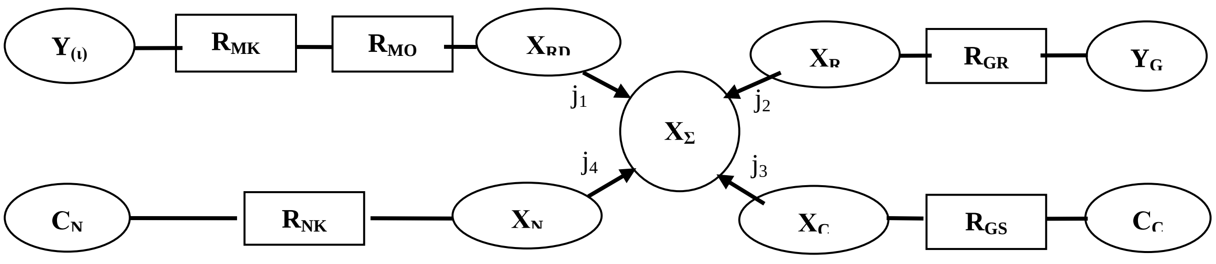

**Fig. 4. Equivalent electrodiffusion scheme of conjugate processes.**

Here, $Y_{(\text{т})}$ and $Y_G$ – respectively, flowing in the solid phase and the boundary value of the concentration of soluble components; $X_\Sigma$ – the total value of all components transferred to the extract; $C_C$ and $C_N$, respectively, concentrations in the solid phase of the poorly soluble and insoluble in the extractant components; $X_C$ and $X_N$ – the same, but in the extract.

$$J = j_1 + j_2 + j_3 + j_4 \qquad (5)$$

The intensity of the transfer of individual components is determined by the balance of the corresponding forces that are formed in the capillary of the intercellular space [14]. The resultant of these forces will determine the flow rate of a particular component. The flow of solution from the capillaries turbulizes the boundary layer, the resistance to mass transfer by barodiffusion ($R_{MK}$ and $R_{MO}$) (Fig. 4) can be several orders of magnitude lower than in traditional mass-transfer schemes.

The structure of the flow from the capillary is explained by an equivalent electrical circuit (Fig. 5).

Based on the classical thermophysical mass transfer scheme [14], the diffusion transport mechanism from the fibrous structure to the flow corresponds only to the part of the circuit (Figs 3, 4). The successive chain of diffusion resistances consists of the sum: $R_{NK}$ (nanocapillaries), $R_{MK}$ (microcapillaries) and $R_{MO}$ (mass transfer). The total flow of all components in the integral form is determined:

The flow $j_1$ is the result of convective diffusion mass transfer through the surface of the phase contact F. The driving force of the process is the difference in the concentrations $Y – X_{RD}$

$$\dot{j}_1 = \frac{dM_{P1}}{F d\tau} = \frac{Y - X_{RD}}{R_D} \qquad (6)$$

The flow $j_2$ is the result of the mechanical transfer of soluble components from the boundary layer of the capillary through its cross section S. The driving force of the process is the pressure difference Pk-Po

$$\dot{j}_2 = \frac{dM_{P2}}{\rho S d\tau} = \frac{P_K - P_0}{R_{GR}} \qquad (7)$$

The flow $j_3$ is the result of the mechanical transfer of poorly soluble components from the capillary through its cross section S. The driving force of the process is the pressure difference $P_K$-$P_O$

$$\dot{j}_3 \frac{dM_C}{\rho S d\tau} = \frac{P_K - P_0}{R_{GS}} \qquad (8)$$

The flow $j_4$ is the result of the mechanical transfer of insoluble components from the capillary through its cross section S. The driving force of the process is the pressure difference $P_K$-$P_O$

$$\dot{j}_4 \frac{dM_H}{\rho S d\tau} = \frac{P_K - P_0}{R_{GN}} \qquad (9)$$

The results of the experiments indirectly confirm the formulated hypothesis. However, approvement more convincing by analusing visual studies [8].

**The mechanism of the transfer process from the cell.** Consider the reaction of the cell membrane under a sequential energy and mechanical action. At the heart of the analysis is a continuously heterogeneous model of the system [2].

At the first stage, the change in the volume of the cell $V_k$, the temperature $T_k$, the pressure $P_k$, and the concentration of the soluble components $C_k$ in it are as follows.

$$\tau_0 < \tau < \tau_n ; \quad P_0 < P_a \le P_n ; \quad T_0 < Y_a \le T_n$$

$$\frac{dV_\kappa}{d\tau} = K \cdot \varepsilon \cdot F_K \frac{\rho_e}{\rho_\kappa} \left[ C_e(\tau) - C_k(\tau) \right] + F_K \cdot \varepsilon w + \frac{1 - \varepsilon}{r \cdot \rho_{\ n}} \cdot \int q_u \cdot dF \qquad (10)$$

In the ratio (10), the first term takes into account the mass transfer effect, the second is the volume change due to infiltration, and the third is the volume change due to partial evaporation.

In (10) the following designations are accepted: $K$ is the mass transfer coefficient; $F_K$ is the surface area of the cell membrane; ε is the fraction of channels in the shell; $\rho_e$, $\rho_\kappa$, $\rho_n$ – the density, respectively, of the liquid in the intercellular volume, in the cell and the vapor formed in the cell; $q$ is the heat flux density; $w$ is the flow rate; $C$ is the fraction of dry matter.

At the second stage, exposure is necessary to complete the mass transfer processes. In the third stage, a sudden release of pressure occurs, which leads to an intensive release of the contents through the pores of the cell membrane. Under certain conditions, a partial or complete rupture of the shell is possible.

The above material is the scientific basis of mechanodiffusion processes in conditions of directional action of electromagnetic energy sources.Consider the physical model of a separate capillary (Fig. 5), which is filled with a liquid and is in the EM field.

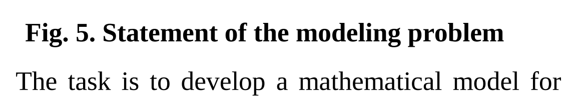

**Fig. 5. Statement of the modeling problem**

The task is to develop a mathematical model for the interaction of a microwave electromagnetic field with a liquid in a capillary 1 (Fig. 5). The energy supply N is volume at the PG of the second kind.

The modeling is based on the first law of thermodynamics and the Fourier-Kirchhoff equations, which reflect the thermal interactions between the elements of the system under consideration.

Since the work done by the body, in accordance with the problem posed, is zero, the first law of thermodynamics for this case will be written in the form:

$$Q_{st} + Q_V = \Delta U\,, \tag{11}$$

where $Q_{st}$ is the amount of heat received (or given) by the body through the surface of the capillary (S); $Q_V$ is the amount of heat that is absorbed by the solution from electromagnetic energy sources; $\Delta U$ – change of internal energy.

The amount of heat $Q_{st}$, $Q_V$ and the change in the internal energy of the body can be calculated by the formulas 12.

where $q_v$ is the specific power of internal sources (sinks) of heat, W/m$^3$.

Taking into account (12), the Fourier equation, the first law of thermodynamics in a cylindrical coordinate system takes the form (13).

Substituting further (3) in (1), we have (14).

If all the characteristics in (14) are continuous functions of coordinates and time, then the integral vanishes when the integrand is zero. Consequently has the form (15).

Equation (15) establishes the relationship between the temporal and spatial variation of temperature at any point of the body. For constant thermal conductivity, equation (5) is simplified and reduced to a linear partial differential equation of the second parabolic type.

For the task (fig. 5) is known: the volume of the product V$_1$; energy consumed by the product Nητ; temperature – t$_1$. The process takes place in the pressure ranges Ra ≤ P ≤ Pu.

The analysis can be performed separately for stage 1 (heating the product from the initial temperature $t_1=t_n$ to the evaporation temperature $t_1= t_{\text{и}}$) and for the 2 stage (actual evaporation).

At the first stage, the steam output is absent (W = 0), and energy is consumed only to increase the product temperature.

For the length 0 ≤ Z ≤ Z1; radii 0 ≤ r ≤ r1:

Initial conditions (τ = 0): $t_1 = t_{\text{н}}$; $V_1 = V_{\text{Н}}$.(16).

$$Q_{st} = \int_S \int_0^{\tau} dQ d\tau,\ Q_V = \int_V \int_0^{\tau} q_V dV d\tau,\ \Delta U = \int_V \int_0^{\tau} c_V \rho \frac{\partial t}{\partial \tau} dV d\tau. \tag{12}$$

$$\int \int_{SO}^{\tau} dQ d\tau == \int \int_{VO}^{\tau} \left[ \frac{\partial}{\partial r}\left(\lambda \frac{\partial t}{\partial r}\right) + \frac{\lambda}{r} \cdot \frac{\partial t}{\partial r} + \frac{1}{r^2} \cdot \frac{\partial}{\partial \varphi}\left(\lambda \frac{\partial t}{\partial \varphi}\right) + \frac{\partial}{\partial Z}\left(\lambda \frac{\partial t}{\partial Z}\right)\right] dV d\tau \tag{13}$$

$$\int_V \int_0^{\tau} \left[ c_V \rho \frac{\partial t}{\partial \tau} - \frac{\partial}{\partial r}\left(\lambda \frac{\partial t}{\partial r}\right) - \frac{\lambda}{r} \frac{\partial t}{\partial r} - \frac{1}{r^2} \frac{\partial}{\partial \varphi}\left(\lambda \frac{\partial t}{\partial \varphi}\right) - \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right) - q_V \right] dV d\tau = 0. \tag{14}$$

$$c_V \rho \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial r}\left(\lambda \frac{\partial t}{\partial r}\right) + \frac{\lambda}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial}{\partial \varphi}\left(\lambda \frac{\partial t}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right) + q_V\ . \tag{15}$$

$$\frac{\partial t_1}{\partial \tau} = a_1 \left( \frac{\partial^2 t_1}{\partial r^2} + \frac{1}{r} \frac{\partial t_1}{\partial r} + \frac{1}{r^2} \frac{\partial^2 t_1}{\partial \varphi^2} + \frac{\partial^2 t_1}{\partial z^2} \right) + \frac{N\eta}{V_1 c_{1V} \rho_1}\,, \tag{16}$$

For the second stage, directly evaporation, the process is characterized by the constancy of the phase transition temperature (tu=const), and the energy supplied (Nητ) is expended on increasing the internal energy upon changing the heat capacity, transferring the water to steam. The result is an increase in the concentration of the solution, or an increase in the pressure in the capillary. The energy equation takes the form:

$$N\eta\tau = V_u t_u (c_1\rho_1 - c_2\rho_2) \tag{17}$$

During evaporation, the pressure in the capillary increases

$$P(t) = Pa + \Delta P \tag{18}$$

and the volume of liquid decreases

$$V_1(\tau) = V_n - V_u(\tau) \tag{19}$$

Moreover, a decrease in volume may be a consequence of the ejection of a part of the liquid from the capillary.

In the relations (12) – (19): *c* - specific heat; *λ* – the coefficient of thermal conductivity; *a* –the coefficient of thermal diffusivity; *N* – power of the electromagnetic generator; *η* – the efficiency of the magnetron; *τ* – time of work; *z*, *r*, and *φ* are coordinates.

Thus, the system of relations (12) – (19) determines the nonstationary temperature field, the material and energy balances of processes. However, the practical implementation of the model is complicated. To obtain the engineering method, we will use methods of the theory of similarity.

The total consumption of evaporated moisture is determined by the power of the electromagnetic generators (*N*); the volume occupied by the raw material ($V_c$), and the volume of moisture in it ($V_c$); thermophysical properties of the solvent, the main of which is the energy necessary for the phase transition, i.e. Specific heat of evaporation (*r*). It is (*r*), most likely, is a complex characteristic of the properties of the solvent.

When a process of traditional mass transfer is combined with the action of a pulsed electromagnetic field, a flow of liquid from the capillaries is initiated. The frequency of emissions and the number of functioning capillaries increase with increasing N-radiation power. The influence of the electromagnetic field is proposed [14] to take into account the number of energy actions, the number of Burdo (Bu). The number Bu determines the ratio between the energy of radiation and the energy required for similar processes in traditional technologies, determines both the energy efficiency of the equipment and the mass transfer regime. Up to certain values V of the Bu number, laminar flow regimes exist in the capillary channels of the solid phase. The number Bu can show the conditions of transition to a more intensive mass transfer, which it is logical to call the regime turbulent barodiffusion.

Then the ratio of energy required for evaporation in the basic technology ($Q_u$), and energy ($N$), expended on the process according to the scheme (Fig. 2), will be determined:

$$Q_u = W_0 r \quad \text{and} \quad Bu = \frac{N}{W_0 r} \qquad (20)$$

Since the specific heat of evaporation (r) is a function of pressure, the number (Bu) must take into account the effect of the pressure at which the evaporation process passes.

The intensity of evaporation should depend on the ratio of volumes of raw materials and moisture in it. It is proposed to introduce for this purpose a parametric complex - a dimensionless volumetric moisture content (V):

$$V = \frac{V_B}{V_C} \qquad (21)$$

Since the influence of (V) starts at some critical value ($V_K$), the calculation procedure should include an estimate of the current values (V), a comparison with the critical value ($V_K$) and determine the time (τ) when the correction for (V) should be taken into account.

The current performance of the device is proposed to be calculated by the criterial model:

$$W = \frac{W_u}{W_0} = A \cdot Bu^n V^m \qquad (22)$$

Dimensionless performance (W) makes sense of the ratio of current performance (W) to the base (it is assumed, $W_0$=1g / sec). Calculated for individual time intervals (τ).

The liquid in the raw capillaries is a multicomponent system. It seems that in general, we are dealing with a new phenomenon, a new effect, the name of which can be given the "mechanodiffusion effect in the gradientless wave supply of electromagnetic energy to polar molecules". Thus, from the capillary (1), a diffusion flow of the solution emerges, which is supplemented by the flow of a whole complex of components that are not characteristic in general for classical diffusion processes (fig. 3).

It is likely that the process is similar in the capillaries of food raw materials.

The energy supply N is volume at the PG of the second kind.

When stating the problem of mathematical modeling, the following assumptions are accepted:

- all target components of raw materials are expressed in the form of a common complex;
- for each interval of time (zone), the transport coefficients (thermal conductivity, thermal diffusivity and diffusion are assumed to be constant);
- a solid body has a polycapillary structure in which the transfer of the target components occurs by diffusion and mechanodiffusion;
- in the process of mass transfer the structure of a solid remains unchanged.

The mathematical model should reflect the conjugate processes of hydrodynamics, heat transfer and mass transfer, i.e. contain the Navier-Stokes equations, continuity and energy with the corresponding uniqueness conditions [14].

For stationary mode $\frac{dw}{d\tau} = 0$ and the Navier-Stokes equation will have the form:

$$\rho w \; grad \; w = \rho g - grad \; P + \mu \nabla^2 w \qquad (23)$$

For incompressible liquids (ρ = const), the continuity equation is simplified.

$$div \; w = 0 \qquad (24)$$

For the mass transfer process, the mass concentration of the component C is substituted in the mass conservation equation [8] instead of the density.

$$\frac{\partial C}{\partial \tau} + w_r \frac{\partial C}{\partial r} + w_z \frac{\partial C}{\partial z} + C\left(\frac{\partial w_r}{\partial r} + \frac{\partial w_z}{\partial z}\right) = 0 \qquad (25)$$

Equation (13) takes into account that the concentration of the component varies in space and in time.

The modeling is based on the first law of thermodynamics and the Fourier-Kirchhoff equations, which reflect the thermal interactions between the elements of the system under consideration. For the evaporation processes in EMF, such an analysis performed in article [8]. Based on the model obtained in [8], we study the process of extracting food raw materials from the solid phase. A more complex structure of raw materials predetermines the specific, specific effects of the process.

The analysis can be carried out separately for stage 1 (heating the product from the initial temperature $t_1 = t_n$ to the start temperature of steam formation $t_1 = t_u$) and for the 2 stage (actual vaporization).

At the first stage, energy is consumed only to increase the temperature of the product.

For the length $0 \le Z \le Z1$; radii $0 \le r \le r1$:

Initial conditions ($\tau = 0$): $t_1$ = tн; $V_1 = V_H$. The nonstationary temperature field with allowance for the action of EMF is determined in the form.

$$\frac{\partial t_1}{\partial \tau} = a_1\left(\frac{\partial^2 t_1}{\partial r^2} + \frac{1}{r}\frac{\partial t_1}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t_1}{\partial \varphi^2} + \frac{\partial^2 t_1}{\partial z^2}\right) + \frac{N\eta}{V_1 c_{1V}\rho_1} \quad (26)$$

In the ratio (14): c is the specific heat; λ is the coefficient of thermal conductivity; a is the coefficient of thermal diffusivity; N – power of the electromagnetic generator; η is the efficiency of the magnetron; τ - time of work; z, r, φ- coordinates.

The influence of the EMF is expressed in (14) as the action of an internal energy source with a power N and with an efficiency η.

The second stage is the formation of the vapor phase. The process is characterized by the constancy of the temperature of the phase transition (tu = const), and the supplied energy (Nητ) is expended on increasing the internal energy with a change in the heat capacity, transferring water to steam. The result is an increase in pressure in the capillary. Moreover, this increase in pressure can be explosive because of the small volume of liquid in the capillary and the concentration of energy

$$P(\tau) = Pa + \Delta P \quad (27)$$

In this case, significant changes will occur in the formation of the concentration field of the target components in the system. In accordance with the Fick equation, the nonstationary concentration field has the form:

$$\frac{\partial c}{\partial \tau} = D\frac{\partial^2 c}{\partial z^2} + \frac{\partial c}{\partial z} w_Z \quad (28)$$

The first term in (3) characterizes a purely diffusion transfer, the process is traditionally sluggish. The proposed concept is based on the potential possibilities of the second term in (15). This change in the concentration field due to the exit of the concentrated solution from the capillary with a velocity w, the value of which depends on the value of the pressure jump ΔP from (2). The relationship between these parameters is expressed by the hydraulics of the capillary system with the length of the channels (l), their diameter (d), the coefficient of friction (λ), and the sum of the local hydraulic resistances (ζ) at the coefficient of surface tension (σ):

$$\Delta P = \frac{\rho w^2}{2}\left[\frac{\lambda l}{d} + \Sigma\zeta\right] + \rho g l + \frac{\sigma}{d} \quad (29)$$

As a result, the volume of liquid in the capillary decreases and its current value is determined by the equation of material balance

$$V_1(\tau) = V_H - (V_\Pi - V_\Psi)(\tau) \quad (30)$$

Moreover, the volume decrease can be a consequence of the release of the vapor volume ($V_\Pi$) and the part of the liquid ($V_\Psi$) from the capillary.

Thus, the system of relations (24)–(30) determines the nonstationary temperature and concentration field, the material and energy balances of processes.

## Results of the research and their discussion

Experimental modeling of extraction processes. Experimental studies were carried out on the stand, the main components of which are: a vacuum microwave chamber filled with a solid phase and an extractant. Before the experiments, the chamber was evacuated. During the experiment, the pressure in the chamber was stabilized by matching the power of the supplied electromagnetic energy and the operation of the energy removal system from the chamber. For this, a reflux condenser is provided, the temperature regime of which is regulated by the water cooling system. The set of the water cooler included a refrigerating machine, a circulation pump and a thermostat (Fig. 6).

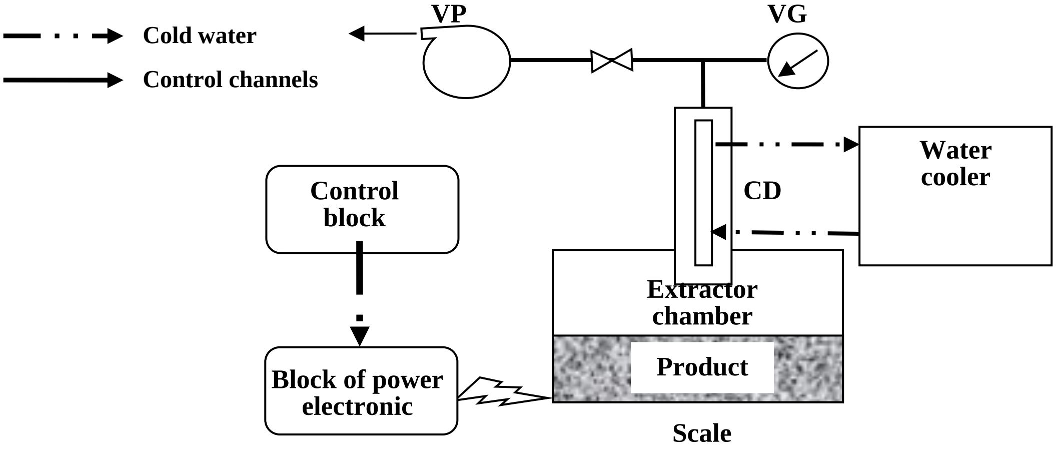

**Fig.6. The scheme of the experimental stand.**

Experimental studies were carried out whith coffee of arabica and dogrose variety. Extracting from coffee with a hydromodule 1:4 we obtain 32% of dry soluties from the total mass of grains passed into the extract. Compared with 18% in the classical technology is a significant progress. Even in counter-flow microwave exyractor the better result was a 28% from the total mass of grains. Temerature during extraction fluctuated from 30 to 40°C. Experimental studies whith applying dogrose berries shown ewen better results. During the extraction process the temperature wasn't higer than 50°C. The concentration of soluties in extract reached 7 % for 100 g of gogrose dried berries to 400 ml of solvent (distilated water). There 21 % of total dogrose berries mass pass to extract. The better result in classical tecnologies is 10–0% depending of plant variety. Low pressure in extracting chamber provides intensive boiling of extract. Under such conditions the boundary layer permanently updating, which allows increasing of mass-transfer efficiency.

**Experimental modeling of concentration processes.** Experimental studies were carried out at the stand (Fig. 7), the main units of which are: evaporator chamber, chamber body, product, vacuum pump condenser (CD), refrigerating machine (RM), a condensate collector (CC), and a scale. Steam volumes of the evaporator and condenser are connected by a steam pipe, vacuum control in the system is carried out by a model vacuum gauge (VG). The electromagnetic energy supply is carried out by the power electronics unit according to the commands of the control unit, which contains a timer and a power regulator. The water cooler consists of a steam compressor refrigeration machine, a container with cooled water, a water temperature regulator and a circulating pump that supplies cold water to the condenser.

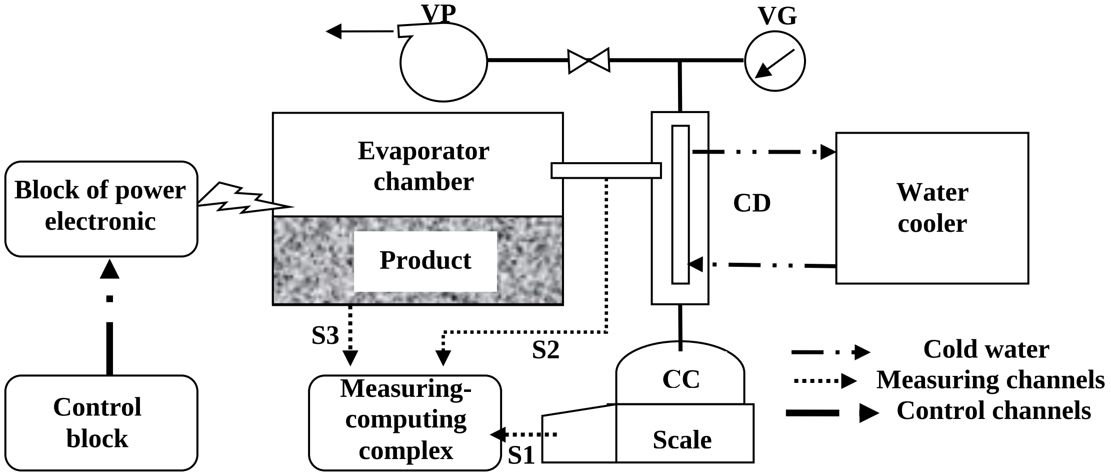

**Fig. 7. Scheme of the experimental stand**

The stand is computerized, current information from electronic scales, the temperature meter of the emerging steam and the product in the evaporator chamber through the interface is fed, registered and processed by the processor. In the stand we used electronic scales of the type TBE-0,21-0,01 and temperature sensors (S2, S3) of the Dallas DS 18b20 type. Information was collected on a laptop or a tablet CHUWI CW1506. The developed program provided for display of thermograms on the display screen, moisture loss from the camera and instantaneous rates of moisture removal (% per minute). To study the effect of the microwave field on food raw materials, products with various properties, including thermolabile ones, were chosen (Table 1).

**Table 1 – Objects of experimental research.**

| Product | Type | Structure |
|---|---|---|
| Echinacea juice | MPRM (medicinal plant raw material) | Liquid homogeneous system |
| Coffee slurry | Alcohol system | Disperse heterogeneous composition |
| Extract of coffee oil | Alcohol solution | Liquid heterogeneous composition |
| Seafood | Mussels | Solid fractions and water |
| Tomato paste | Food product | Liquid heterogeneous structure |
| Pomegranate juice | Food product | Liquid homogeneous system |

In the experiments, the following were recorded: power consumption, vacuum, product temperature and steam output. The current values of W were determined from the indications of electronic scales (by the mass of the condensate in the collection). Thus, the yield of steam was determined with high accuracy. Operating temperatures did not exceed 50°C. Typical dependencies for 4 product types are shown in Fig. 8. The experimental results allowed to determine the evaporation rate, the change of which is shown in Fig. 9.

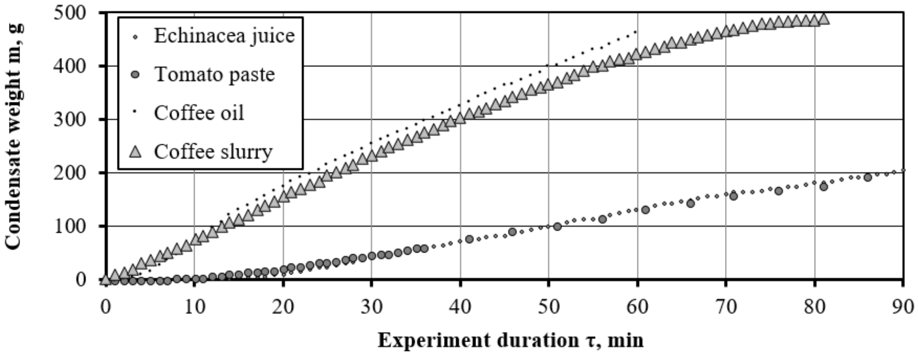

**Fig. 8. Change in condensate mass at the output of their MWA**

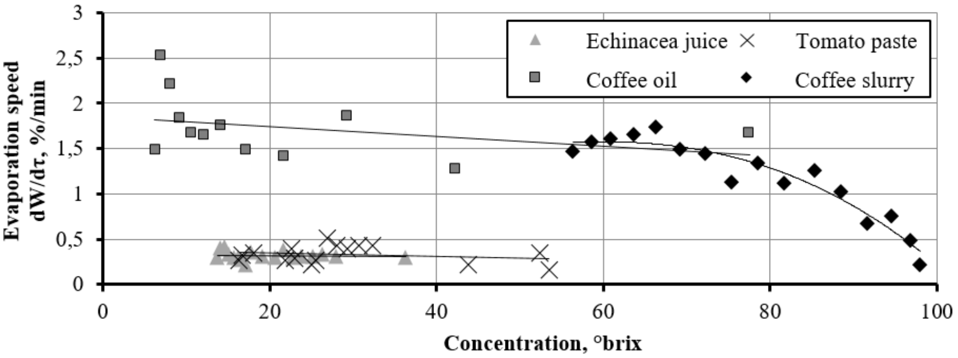

**Fig. 9. Lines of vaporization rate in MW**

Based on the results of the analysis of the correspondence between the rate of evaporation and the concentration of the product, a relationship is constructed in the apparatus (Fig. 10), from which it can be seen that the rate of evaporation in a vacuum MW apparatus is practically constant. Insignificant fluctuations can be explained by the error of the experiment.

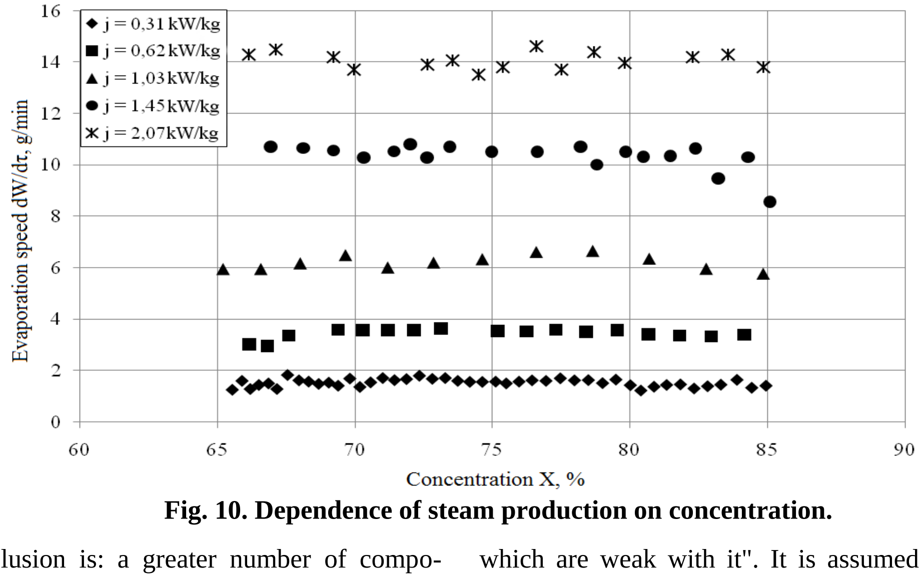

**Fig. 10. Dependence of steam production on concentration.**

The conclusion is: a greater number of components pass into the solution than can be dissolved. These facts are explained on the basis of the hypothesis: "Under the conditions of EMF, a specific flow can be organized that contains highly soluble components of the solid phase (diffusion flux), and practically insoluble components of the solid phase, the bonds of which are weak with it". It is assumed that this is a purely mechanical flow, the power of which is determined by the difference in pressure. It can be initiated, it can be controlled by EMF parameters. The proposed hypothesis requires a physical, mathematical justification and a visual fixation of a new phenomenon.

Analysis of the results of the experiments leads to the following conclusions: the evaporation rate in MVA is practically constant (minor fluctuations can be explained by the error of the experiment); high values Vof product concentrations (up to 80 °brix) are achieved; the coffee slurry at the outlet practically did not contain a liquid phase; the effect of the volume of liquid in the product is noticed after concentrations of more than 80 °brix; alcohol-containing systems are characterized by the rate of evaporation at times higher than water-containing ones.

As a result of processing the experiments, the criterial equation is obtained:

$$W = \frac{W_u}{W_o} = 0.76 \cdot Bu^{1.13} \qquad (31)$$

The ratio (31) allows, with an error of no more than 20%, to calculate the capacity of the microwave vacuum evaporator in the range of the energy action numbers $0.4 \geq \text{Bu} \geq 0.04$ (W and - the current productivity of the apparatus, $\text{W}_0$ - the basic capacity of the apparatus (1 kg/sec)).

Scientific hypotheses are confirmed in practice. Under the conditions of cognac production, the electromagnetic extractor provided an intensification of mass transfer thousands of times. In coffee technology, the degree of extraction of components from grains increased by 15%, and energy costs were reduced by 50%. Experimental samples of 60% of coffee concentrate have high taste characteristics. Tests of the microwave vacuum evaporator showed the possibility of obtaining high-quality products with a concentration of up to 90 °brix.

## Conclusion

Local action on nanoscale elements of food raw materials will allow to give fundamentally new approaches to the organization of processes in the agroindustrial complex. A new scientific direction is developing in food nanotechnologies – control of transfer processes at the boundary of the phases of nanometric food structures. An instrument of such management may be the energy impact. In EMF conditions, a specific flux may arise from the intercellular space of the components insoluble by the extractant. This effect was discovered for the first time and was given the name "mechanodiffusion effect". In the dehydration of capillary-porous structures, with certain combinations of raw material parameters and MW field, the liquid from the capillary volume can be removed as a two-phase system. The mechanism of this phenomenon is as follows. The concentration of energy in the depth of the capillary, overheating of the liquid, the partial transition of liquid into vapor, the growth of pressure in the capillary and the mechanical release of the contents of the capillary. The process is determined not by diffusion moving forces, but by hydrodynamic forces, whose potential can be orders of magnitude higher.

To initiate mechanodiffusion, the structural characteristics of the raw materials, the characteristics of the liquid phase and the parameters of the EMF must be closely coordinated. The result of the organization of such processes can be an increase in the yield of the target components, the transition to a solution of valuable components that have not been extracted by traditional methods (aromatic complexes, taste components, etc.), improving energy efficiency.

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