Electrodynamic Technologies in the Eco-industry of Food and Pharmaceutical Production

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Abstract. The growing interest in the world for research on microwave processing technologies of raw materials is shown. It has been established that information in available sources is only about laboratory-scale equipment, and theoretical information (models, mechanisms, calculation methods) is practically absent. The aim of the work is to conduct systematic studies in the "extractor — dehydrator — plant material" scheme. To achieve the goal, these electrodynamical systems are presented with parametric, mathematical, and experimental models. The most significant result of the work is that the concept of a "hybrid" process is introduced to explain the mechanism of interaction between the electromagnetic field and the raw material. Using the first law of thermodynamics, it is shown that the "hybrid" process performs work to move the solution from the volume of the material to its surface. As a result, sluggish diffusion processes are accompanied by powerful flows, the driving force of which is the pressure difference in the capillary of the material and the environment. The importance of the work is that new effects are established: mechanodiffusional and vapordynamical. Mechanodiffusional allows obtaining polyextracts in one extractor, and vapordynamical allows the dehydration of the solid phase in the form of two parallel streams — vapor and juice. Experiments were conducted with rosehip fruits, soybeans, tomato squeezes, and sunflower meal. It is shown that electrodynamical dehydrators are characterized by stable performance indicators of vapor generation up to concentrations of 85°brix, at low levels of energy consumption. The results of chemical studies of the obtained samples in electrodynamical devices are presented.
***Keywords*:** electrodynamic apparatuses, energy technologies, extraction, evaporation, drying, mathematical and experimental modeling, food and medicinal plant raw material.

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Tehnologii electrodinamice în eco-industria alimentară şi farmaceutică

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Rezumat. Este fundamentată relevanța problemei eficienței resurselor energetice în tehnologiile alimentare și farmaceutice. Se arată creşterea interesului în lume pentru cercetarea tehnologiilor cu microunde pentru prelucrarea materiilor prime. Sunt date exemple de utilizare cu succes a extractoarelor şi evaporatoarelor cu microunde în prelucrarea materialelor vegetale medicinale și alimentare. S-a stabilit că sursele disponibile conțin informații doar despre dispozitivele la scară de laborator, în timp ce informațiile teoretice (modele, mecanisme, metode de calcul) sunt practic absente. Scopul lucrării este de a efectua cercetări sistematice în schema „extractor – deshidrator – materii prime vegetale". Pentru atingerea acestui scop, aceste sisteme electrodinamice sunt reprezentate prin modele parametrice, matematice și experimentale. Se propune o clasificare a sistemelor electrodinamice. Cel mai semnificativ rezultat al lucrării este că conceptul de proces „hibrid" este introdus pentru a explica mecanismul de interacțiune dintre câmpul electromagnetic și materiile prime. Acest proces este inițiat de un câmp electromagnetic, bazat pe specificul materialelor vegetale. Folosind prima lege a termodinamicii, se arată că procesul „hibrid" funcționează pentru a muta soluția din cea mai mare parte a materiei prime la suprafața sa. Ca urmare, procesele de difuzie lente sunt însoțite de fluxuri puternice, a căror forță motrice este diferența de presiune în capilarul materiei prime și a mediului. Semnificația lucrării este că au fost stabilite efecte noi: mecanodifuziune și parodinamică. Metoda mecanodifuziei face posibilă obținerea de poliextracte într-un singur extractor, iar metoda dinamică cu abur permite deshidratarea fazei solide sub forma a două fluxuri paralele - abur și suc. Și acestea sunt toate premisele pentru o reducere semnificativă a resurselor energetice în prelucrarea industrială a materialelor vegetale.

Cuvinte-cheie: aparate electrodinamice, tehnologii energetice, extracție, evaporare, uscare, modelare matematică şi experimentală, materie primă alimentară şi plante medicinale.

Электродинамические технологии в экоиндустрии пищевых и фармацевтических производств

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Аннотация. Обоснована актуальность проблемы ресурсо-энергоэффективности в пищевых и фармацевтических технологиях. Показан рост интереса в мире к исследованиям микроволновых технологий переработки сырья. Приведены примеры успешного применения микроволновых экстракторов и выпарных аппаратов при переработке лекарственного и пищевого растительного сырья. Установлено, что в доступных источниках есть информация только об аппаратах лабораторного масштаба, сведения теоретического характера (модели, механизмы, методы расчета) практически отсутствуют. В работе поставлена цель: провести системные исследования в схеме «экстрактор — дегидратор — растительное сырье». Для достижения поставленной цели эти электродинамические системы представлены параметрической, математической и экспериментальными моделями. Предложена классификация электродинамических систем. Наиболее существенным результатом работы является то, что для объяснения механизма взаимодействия электромагнитного поля и сырья введено понятие «гибридный» процесс. Этот процесс инициируется электромагнитным полем, базируется на специфике растительного сырья. С привлечением первого закона термодинамики показано, что «гибридный» процесс совершает работу по перемещению раствора из объема сырья на его поверхность. В результате вялые диффузионные процессы сопровождаются мощными потоками, движущей силой которых являются разность давлений в капилляре сырья и среды. Значимость работы в том, что установлены новые эффекты: механодиффузионный и пародинамический. Механодиффузионный позволяет получать в одном экстракторе полиэкстракты, а пародинамический — осуществлять дегидратацию твердой фазы в виде параллельных двух потоков — пара и сока. А это все предпосылки существенного сокращения энергетических ресурсов при промышленной переработке растительного сырья. Выдвинутые положения подтверждены экспериментом. Опыты проводились с плодами шиповника, соей, томатными выжимками и шротом подсолнечника. Показано, что электродинамические дегидраторы характеризуются стабильными показателями паропроизводительности вплоть до концентраций 85°brix, при низких уровнях энергетических затрат. Приведены результаты химических исследований, полученных в электродинамических аппаратах образцов.

Ключевые слова: электродинамические аппараты, энерготехнологии, экстрагирование, выпарка, сушка, математическое и экспериментальное моделирование, пищевое и лекарственное растительное сырье.

INTRODUCTION

During the processing of plant material, the key processes in food and pharmaceutical production are extraction, evaporation, and drying. Traditional equipment for these processes has a number of common drawbacks, such as long processing times, insufficient process intensity, use of expensive agents, damage to the final product, high energy costs, and high labor intensity. Moreover, some traditional equipment does not allow for the preservation of ecological safety of the production [1—2]. Dirty heat carriers, gasoline, and other environmentally unfriendly solvents are used as extractants. There are often cases of significant losses of the product itself, raw materials, and wasteful use of energy resources [3—6]. All of these determine the relevance of searching for new approaches to creating modern equipment.

Currently, one of the innovative ways to improve heat and mass exchange equipment in the world is considered to be the use of electromagnetically dynamic systems, which are characterized by high specific power effects on biomass placed in the reactor chamber. Thus, the power of microwaves decisively affects the drying rate, effective moisture diffusion, and drying time [7]. As the power of microwaves increases, the drying rate and effective moisture diffusion capacity increase, and the drying time is reduced. Positive results of using microwave have been obtained in the drying of oil camellia seeds [8], as well as in the drying of corn and apple slices [9]. Energy costs for microwave drying are much lower than for electric thermal drying with the same load. The issues of modeling drying lines in a periodic microwave regime have been studied in [10], and a good agreement with the experiment has been obtained.

During the drying of kivano seeds (African cucumber), the influence of microwave drying and sublimation drying methods on the chemical composition, organoleptic, textural, and antioxidant properties of kivano seeds, as well as the potential of microwave drying as an alternative to sublimation drying, was studied. For this purpose, kivano seeds were dried using a lyophilizer and a microwave dryer. The protein, ash, fat, fiber, vitamin C, beta-carotene, total phenolic content, antioxidant, textural, and organoleptic properties of the dried seeds were compared. Microwave drying increased the total phenolic content in kivano seeds and reduced the drying time. This study showed that the microwave drying could become a promising innovative alternative for the rapid production of freeze-dried fruit materials while maintaining product quality [11]. Optimization of drying conditions for the production of high-quality dried pineapples was carried out using microwave pre-treatment before the conventional hot-air drying. It was demonstrated that the microwave pre-treatment should be considered as a stage of the industrial pineapple and other products processing to reduce drying time and obtain higher quality products [12].

For the first time, the kinetics of drying and dehydration of sliced bitter melon was investigated using low-temperature microwave drying. The power density of the microwaves played a crucial role in the dehydration characteristics of the dried bitter melon during microwave drying [13]. In the study of microwave drying of green turnip, the adjustable microwave falling power was preferred for improving product quality and reducing energy consumption. A power control strategy for microwave drying of green turnip cylindrical roots was proposed by comparing continuous and intermittent microwave drying with gradually decreasing microwave power based on experimentally determined dielectric properties and changes in the electric field intensity with respect to the temporary moisture content. The experiments showed that such power regulation leads to a higher dehydration coefficient of the dried green turnip and a significant reduction in energy consumption compared to continuous and intermittent microwave drying. Additionally, this power control strategy can maintain the material temperature within specified values with small fluctuations [14]. The effect of microwave power, vacuum degree, and loading weight on the moisture content of seedless white grapes during microwave vacuum drying was studied. It was found that during microwave vacuum drying, the effective moisture diffusion coefficient of seedless white grapes varied from 1.0232×10^{-9} to 4.6354×10^{-9} m^2/s [15].

During the study of the evaporation process, cherry nectar and apple juice were concentrated using traditional thermal methods and intermittent microwave concentration under vacuum conditions (at 250 mbar). The total phenol content in the apple juice and cherry nectar samples varied within the range of 209.87—216.67 mg/L and 571—588.57 mg/L, respectively [16]. Barberry juice was concentrated using two different methods (indirect heating and microwave evaporation at pressures of 100 and 30 kPa) until reaching 60 Brix degrees. The results showed that the microwave evaporation rate was 49% higher than that of indirect heating. In addition, the use of this method can better preserve the anthocyanin content, antioxidant activity, and total phenol content in barberry juice compared to the traditional method [17]. During the concentration of orange juice using microwave vacuum evaporation (MVE) and rotary evaporation (RE), the kinetics of vitamin C degradation, total phenolic content (TPC), total carotenoid content (TCC), and color values were investigated. MVE significantly increased the evaporation rate. Results showed that the degradation rate constants of vitamin C, TPC, and TCC in orange juices concentrated using RE were significantly higher than those using MVE [18]. The use of microwaves as an alternative to traditional evaporation methods was investigated for concentrating sugar solutions. Moreover, dielectric spectroscopy can be an effective tool to help use MVE for obtaining high-quality sugars [19]. It was found that microwave heating can be used for pineapple juice concentration with minimal impact on quality characteristics [20]. Positive results were obtained from the use of microwaves in drying and extraction during processing of alfalfa. The method was optimized with regard both to drying and extraction, and modes of minimal energy consumption were recommended [21].

Thus, the key processes in the processing of plant raw materials are extraction and dehydration. Mass transfer processes are multifactorial (Fig. 1) and require priority resolution.

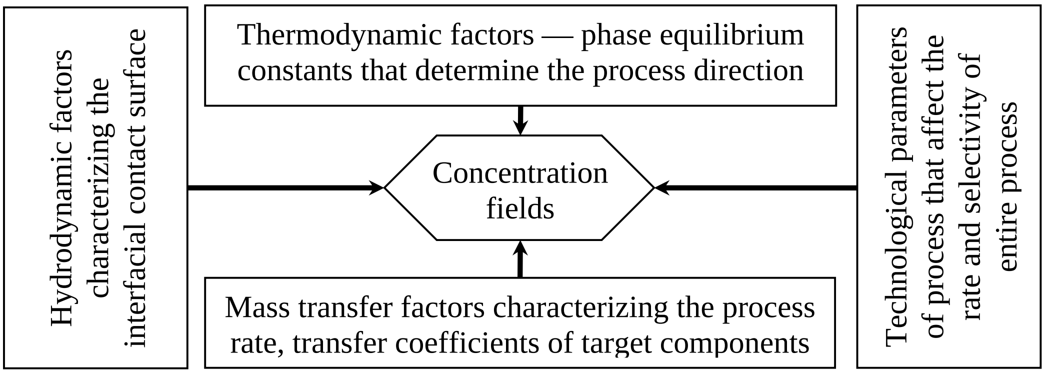


Fig. 1. Factors determining mass transfer process.

The literature review conducted allows us to draw two conclusions. The first one is that there are scientific and technical contradictions for traditional technologies of plant raw material processing (Burdo O.G. et al, *Problemele energeticii regionale*, 2018). As the temperature increases, the intensity of the mass transfer process increases, however, the rate of degradation of thermolabile elements also increases. Therefore, the level of thermal exposure should be chosen based on both physical and chemical research.

The second conclusion is that the use of microwave technologies allows for a significant increase in the efficiency of the process even at room temperatures, to increase the mass transfer characteristics of equipment, to sharply reduce energy costs, and to make some processes more environmentally friendly. However, all known studies are limited to laboratory scale.

The task of the work is to solve the formulated problems by using developed electrodynamical systems in ONUT (Odesa National University of Technology) (Burdo O.G. et al, *Problemele energeticii regionale*, 2018). The solution is based on two hypotheses.

1. "The use of substances with polar molecules as extractants and the transition to electromagnetic principles of energy supply will allow for the extraction of target components from raw materials in the form of two streams: traditional diffusion and additional hydrodynamic, with the power of the latter being able to exceed the former by orders of magnitude."
2. "The inclusion of hydrodynamic driving force in the transport process will ensure the extraction of a wider range of target components from the raw material, as it will be possible to extract not only components soluble in this extractant, which will solve the problem of polyextracts."

CLASSIFICATION AND DEVELOPMENT OF SCIENTIFIC FOUNDATIONS OF ELECTRODYNAMIC TECHNOLOGIES

Let's consider the classification of electrodynamic technologies developed at ONUT (Fig. 2).

Regarding the object of research — food and medicinal plant raw materials — let us develop the scientific basis of electrodynamic technologies at the level of static and kinetic models.

In this work, when developing static models of electrodynamic systems, two consecutive processes are considered: extraction and dehydration of the extract, for example, by evaporation (Fig. 3). By mixing the plant raw material G_r and the solvent G_{ex}, the necessary hydrodynamic modulus is achieved. The extractor outputs a stream of extract, the amount of which is G_e, and the concentration of target components is X_e. It is possible to obtain a more concentrated product in the amount of G_p and at the concentration of X_p by evaporating the solvent from the extract. The solvent vapor, in the amount of G_{ex}, is directed to the mixer or condensed.

In the process of extraction, as a rule, the characteristics of the raw material (G_R, C_R) are known. The objectives of the calculations may be: the concentration of the target components X_S and the amount of the resulting sludge G_S (Fig. 3), or the content of extractive substances in the solution. Equations of material balance.

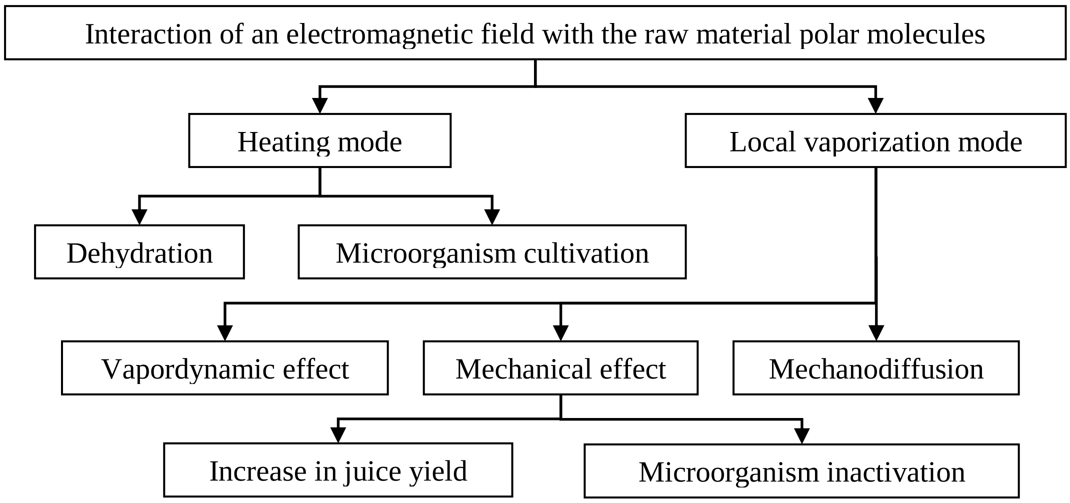


Fig. 2. Classification of specific effects in the electrodynamic systems.

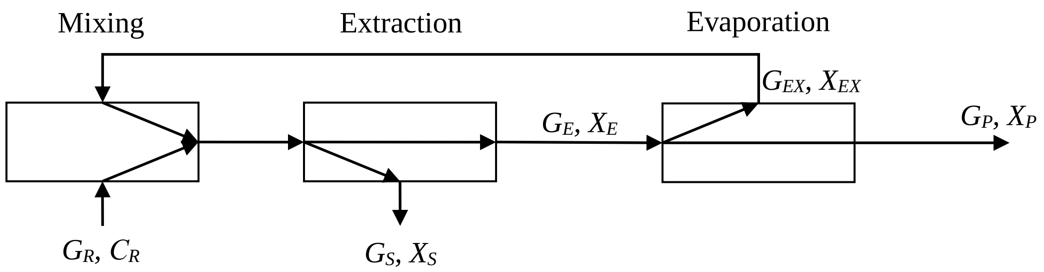


Fig. 3. Material flows scheme. [1]

$$\left.\begin{aligned} G_{EX} + G_R &= G_E + G_S \\ G_{EX} X_{EX} + G_R C_R &= G_E X_E + G_S X_S \end{aligned}\right\} \qquad (1)$$

are found from the values of:

$$X_S = X_E - \frac{G_{EX} X_{EX} + G_R C_R - G_E X_E}{G_{EX} + G_R - G_E} \qquad (2)$$

$$X_{EX} = \frac{G_E X_E - G_P C_P}{G_E - G_P} \qquad (3)$$

The analytical studies of the kinetics of the extraction process include a thermophysical model of the extraction stages, a model of a heterogeneous cell consisting of a solid phase, an extractant, and a boundary layer at the phase contact boundaries. The mathematical description is based on the idea of A.V. Lykov's drying model, P.A. Rehbinder's concepts of moisture bonding forms, and mass transfer mechanisms developed by the authors of (Burdo O.G. et al, *Problemele energeticii regionale*, 2018).

Then, the differential equation of heat and mass transfer will have the form

[1] Appendix 1

In (4): K_{ij} — are the phenomenological coefficients; P — is the pressure; t — is temperature; C — are the concentrations of target components; subscripts: $_P$ — is at the surface; $_M$ — is in the intercellular space; $_K$ — is in the cellular structure of the raw material.

The mathematical model (4) is complex in practical implementation due to an uncertainty in calculating the phenomenological coefficients.

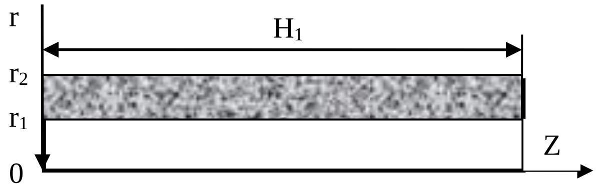
Let's simplify the task of modeling the mass transfer process. The physical scheme of the process (Fig. 4) is represented by a channel located in the solid phase of the raw material and filled with an extractant.

The following assumptions were made in formulating the modeling problem:

- all target components of the raw material are expressed as a common complex;
- following the moisture binding model of Rehbinder, the complex is considered on the surface and in the volume (in capillaries and cells);
- for each time interval (zone), the transfer coefficients are assumed to be constant;

- the solid body has a poly-capillary structure whose transfer of target components occurs by diffusion;
- the structure of the solid body remains unchanged during the mass transfer process.

$$\left.\begin{aligned}
\frac{\partial U_P}{\partial \tau} &= K_{11}\nabla^2 U_P + K_{12}\nabla^2 U_K + K_{13}\nabla^2 U_A + K_{14}\nabla^2 t + K_{15}\nabla^2 P \\
\frac{\partial U_K}{\partial \tau} &= K_{21}\nabla^2 U_P + K_{22}\nabla^2 U_M + K_{23}\nabla^2 U_K + K_{24}\nabla^2 t + K_{25}\nabla^2 P \\
\frac{\partial U_A}{\partial \tau} &= K_{31}\nabla^2 U_P + K_{32}\nabla^2 U_M + K_{33}\nabla^2 U_K + K_{34}\nabla^2 t + K_{35}\nabla^2 P \\
\frac{\partial t}{\partial \tau} &= K_{41}\nabla^2 U_P + K_{42}\nabla^2 U_M + K_{43}\nabla^2 U_K + K_{44}\nabla^2 t + K_{45}\nabla^2 P \\
\frac{\partial P}{\partial \tau} &= K_{51}\nabla^2 U_P + K_{52}\nabla^2 U_K + K_{53}\nabla^2 U_A + K_{54}\nabla^2 t + K_{55}\nabla^2 P
\end{aligned}\right\} \tag{4}$$



r_1 – internal radius of channel;
r_2 – external radius of solid phase;
H_1 – channel length

Fig. 4. Physical scheme of mass transfer process.

The mathematical model presented in the article reflects the coupled processes of hydrodynamics, heat transfer, and mass transfer, i.e. it contains the Navier—Stokes equations, continuity and energy equations with corresponding uniqueness conditions. Electromagnetic energy is volumetrically supplied, with power N and boundary conditions of the second kind $(N = const)$. The analytical model of the axisymmetric scheme is written in cylindrical coordinates (Burdo O.G. et al, *Problemele energeticii regionale*, 2018). The mathematical model for the heating stage and the stage of vapor phase formation includes energy equations, a one-dimensional Fick's equation establishing a non-stationary concentration field in the system. It is shown (Burdo O.G. et al, *Problemele energeticii regionale*, 2018) that in addition to the traditional diffusive mass transfer, Fick's equation also allows for the possibility of convective transport of the target elements. The authors attempted to use this possibility to intensify the mass transfer processes.

This is precisely the basis for the second hypothesis formulated above. In the depth of the solid phase capillary, a vapor bubble is formed using the microwaves. As a result, the pressure in the capillary sharply increases, and a hydrodynamic driving force arises, which "ejects" the contents of the capillary at a speed corresponding to the main hydrodynamic equation (Burdo O.G. et al, *Problemele energeticii regionale*, 2018).

The task set in the work is to organize the output of the solution from the capillary channel at a speed of w. To do this, an auxiliary process is carried out, which the authors referred to as "hybrid". The concept of forming the hybrid process is based on the difference in temperature and moisture content gradients in the raw material in traditional and electromagnetically assisted technologies (Fig. 5).

Let's write the first law of thermodynamics for the schemes (Fig. 5).

For the traditional scheme, the supplied energy (Q)is spent only for an increase in the internal energy (ΔU_T),and no work is done $A_T = 0$.

$$Q = \Delta U_T + A_T \tag{5}$$

From the heat balance equation, the change in the internal energy is proportional to the product volume (V), its density (ρ) and the difference in enthalpies at the end (i_K) and beginning of the process (i_H).

$$\Delta U_T = V \times \rho \times (i_K - i_H) \tag{6}$$

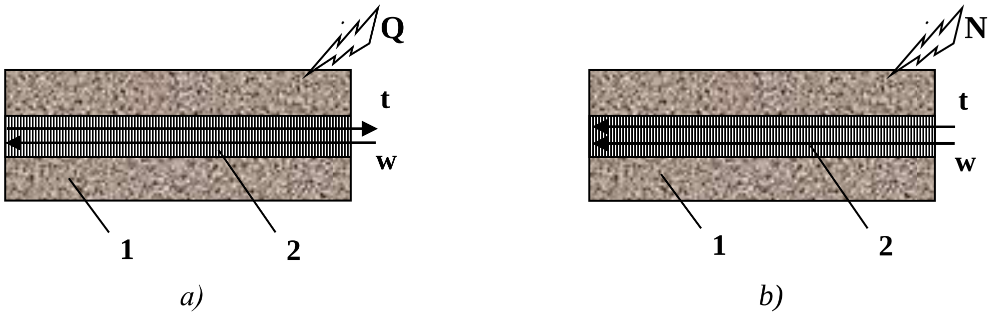


Fig. 5. Temperature (t) and moisture contents (w) gradients during traditional drying (a) and hybrid processes (b).

In the case of the innovative, hybrid process (index i)

$$Q = \Delta U_I + A_I \tag{7}$$

there are differences both in the nature of the energy source, the power of the magnetron (N_E), and its efficiency (η): $Q = \eta \times N_E$, as well as in the distribution of energy flow. Part of it goes to increase the internal energy

$$\Delta U_I = V \times \rho \times (i_K - i_H) \tag{8}$$

and part of it goes to perform the work

$$A_I = F \times L = \frac{\Delta P}{S} \times L \tag{9}$$

The value of work is proportional to the force acting on the liquid (F) and the length of its transportation (L). The force (F) is determined by the increase in the capillary pressure (ΔP), which is determined by the main hydrodynamic equation (Burdo O.G. et al, *Problemele energeticii regionale*, 2018). Thus, a portion of the liquid in the capillary, whose volume (V) is displaced to the open end of the capillary due to the work of the pressure forces (ΔP). The work of the hybrid process determines the formation of barodiffusion, mechanodiffusion, or vapordynamic flow. Moreover, the power of microwaves can easily be used to regulate the development of the hybrid process. It becomes possible to form polyextracts in a microwave extractor (Burdo O.G. et al, *Problemele energeticii regionale*, 2018).

Thus, the use of technology for targeted delivery of energy to individual phases of the raw material can radically change the hydrodynamic situation and significantly intensify the mass transfer process. In processes of combined effects on the cell, various known and unexpected effects are possible.

The hybrid process is approximately represented by a model of the functioning of a point source. The model is universal, however, like all models of this class, it is extremely difficult to be implemented in practice.

Analytical solution of the model presented is impossible, despite the serious assumptions made in setting the problem.

The complexity of the solution is associated with problems in implementing the Navier—Stokes equation and calculating the radial and axial components of velocity.

Using similarity theory methods, it is possible to significantly simplify the model and pass to the relationships that describe quasi-stationary transport processes within a limited range.

For this purpose, a parametric model of the extractor with the organization of the hybrid process and microwave dryer will be developed (Fig. 6).

In general, the effective mass transfer coefficient $\beta_э$ is influenced by the height of the raw material layer H, the density ρ and viscosity μ of the extractant, the velocity of its movement w, and the diffusion coefficient D. This group of parameters characterizes the inertial properties of the flow. The hydrodynamic situation during the formation of the boundary layer in the channel is expressed by the ratio of layer height H to the length (diameter) of layer L.

The contribution of natural convection is established by the concentration difference in the flow ΔX and the gravitational field. The action of barodiffusion due to the microwave field is determined by the pressure difference in the channel zones.

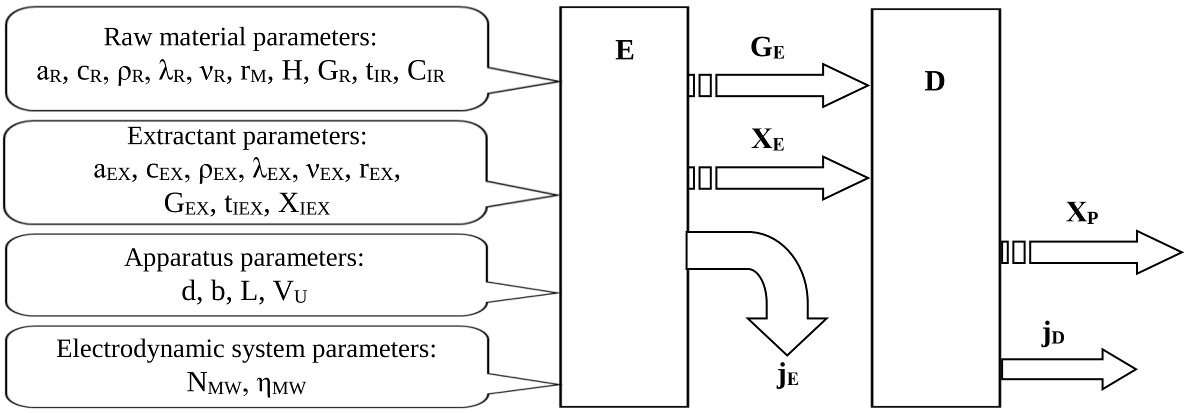


Fig. 6. Parametrical model of "Extractor — Dehydrator" system. [2]

The magnitude of this difference is proportional to the radiation energy and the energy required for vaporization. That is, to the specific heat of vaporization r and the power of the field N.

Then the initial functional dependence of the general form for the effective mass transfer coefficient will be $\beta_Э = f(H, L, r, m, w, D, r, N, k, \Delta X, g)$. Using similarity theory methods, the following criterial dependence is obtained:

$$St_m = A\times(Re)^m\times(Gr_\partial)^g\times(Sc)^n\times(Bu)^p\times(L/H)^q\times(\Pi)^k \qquad (10)$$

For the conditions of the analyzed problem, we can neglect the parameter complex Π, which is a measure of the turbulence of the hydrodynamic boundary layer in the inlet zone and is characteristic for short channels, as well as the Grashof number (Gr_∂), since the contribution of natural convection is small in the inertial flow regime. Finally, the structure of the criterial equation will be:

$$St_m = A\times(Re)^m\times(Sc)^n\times(Bu)^p\times(L/H)^q \qquad (11)$$

Similarly, for vacuum microwave extractors with a reverse refrigerator, the following is obtained:

$$Nu_m = B\times(Sc)^n\times(Bu)^p\times(L/H)^q \qquad (12)$$

The task of experimental modeling is to determine the constants *A*, *m*, *n*, *p*, and *q* in the equation (11).

Extraction experiments were conducted using rosehip fruits in the pressure range of 0.01—0.1 MPa, temperatures up to 50°C, and hydraulic ratios of 1:1—1:4.

Four different extraction methods were investigated on four stands. Stand #1 contained a thermostat with traditional extraction methods being investigated on it. Stand #2 was assembled based on a microwave chamber. The raw material layer was located in the extractant volume. Stand #3 (ONUT design) consisted of a microwave extractor, a refrigeration unit, and a circulation pump for pumping the extractant through the raw material layer. Stand #4 was developed based on a vacuum microwave extractor and a reverse refrigerator.

During the experiments, the following parameters were periodically measured: temperatures (using a FLIR TG165 thermal imager and thermocouples) — t; extractant flow rate (by weight method) — V_{EX}; microwave field duration — τ_{MW}; magnetron power (N_{MW}); optical density of the solution (using Spekol) — $Д$; extract concentration X (using the digital refractometer HI 96801); registration time of the parameters — τ. The initial parameters of the experiments are calculated: extract concentration (X_E) (based on calibration dependence); hydro module (Γ); microwave energy flow rate (E_{MW}).

The obtained data allowed us to calculate the mass of substances transferred into the solution

[2] Appendix 1

(13) and the concentrations of target components in the fruits (14).

$$m = X_E \times V_E \times \rho_E \tag{13}$$

$$C_i = C_{in} - X_E / \Gamma \tag{14}$$

where C_{in} is the initial content of target components in the fruits.

The following relationship was used to calculate the mass transfer coefficient:

$$\beta = V_E / (C_{in} - C_i) \times F \tag{15}$$

The independent effects of the type of energy, processing time, and temperature on the intensity of mass transfer were sequentially studied. The type of energy input had the greatest impact (Fig. 7).

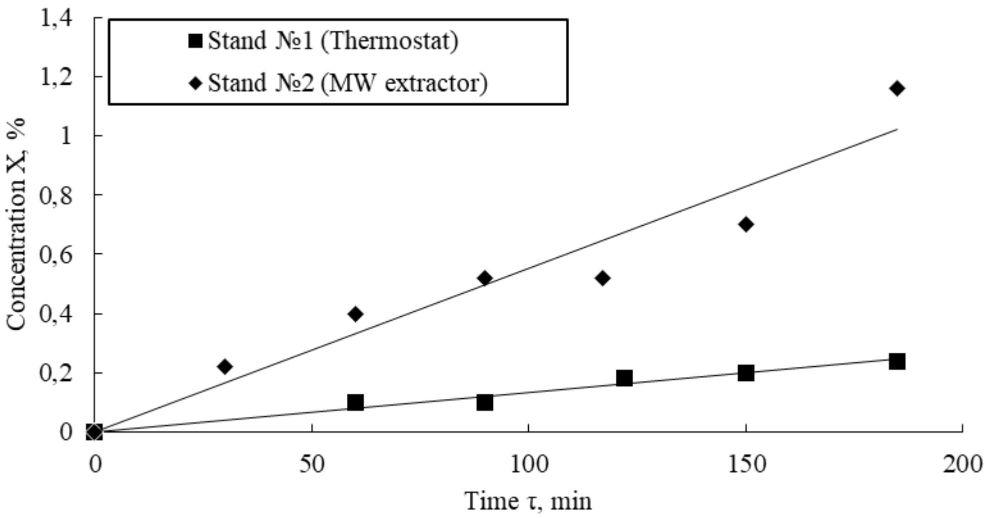


Fig. 7. Extraction kinetics in a fixed bed.

It can be seen (Fig. 7) that when processed in a microwave field, the yield of extractive substances was 5 times higher than that in thermal extraction. The influence of the degree of grinding of the fruits was determined (Fig. 8).

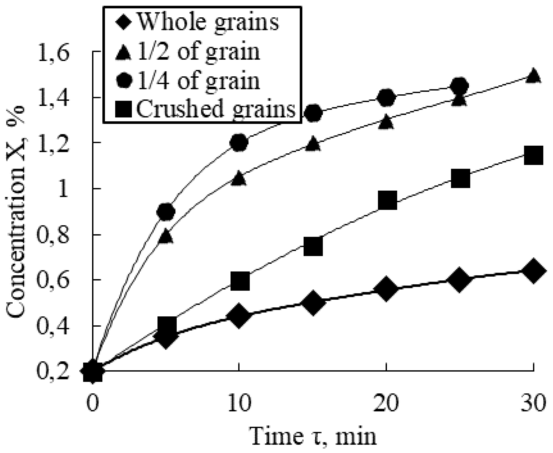


Fig. 8. Effect of grinding degree.

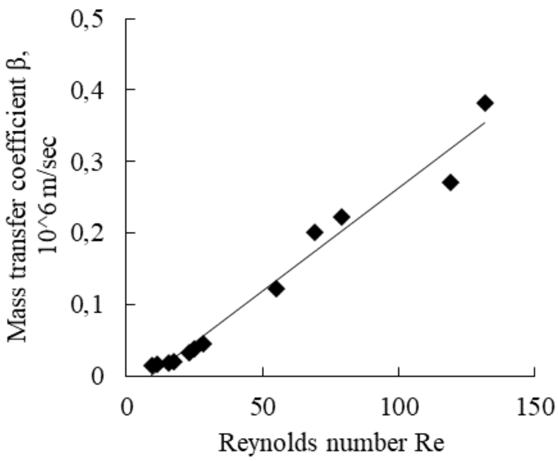


Fig. 9. Effect of extractant flow.

In terms of technological factors, preference should be given to berry halves. Therefore, further research was carried out specifically with berry halves. The second stage of the study is dedicated to working on stand #3. The main task was to establish the effect of extractant flow rate (Fig. 8). It was found that with a fivefold increase in flow rate, the intensity of extraction increases by 10 times. Processing the experimental results established the dependence of the mass transfer coefficient on the Reynolds number (Fig. 9).

The third stage of experimental research was carried out on stand #4. In the microwave chamber 1 (Fig. 10), a reactor 2 made of radio-transparent material was placed. The reactor was filled with raw materials and extractant 3. The vapor outlet from 2 was directed to the reverse refrigerator 4. The stability of pressure and temperature was achieved by matching the microwave power with the vacuum system 6 and the flow rate of cold water from the refrigeration machine 5. A special attention was paid to the reliability of sealing the "reactor—reverse refrigerator" nodes. Therefore, the vacuum pump was usually turned on only when the stand was started.

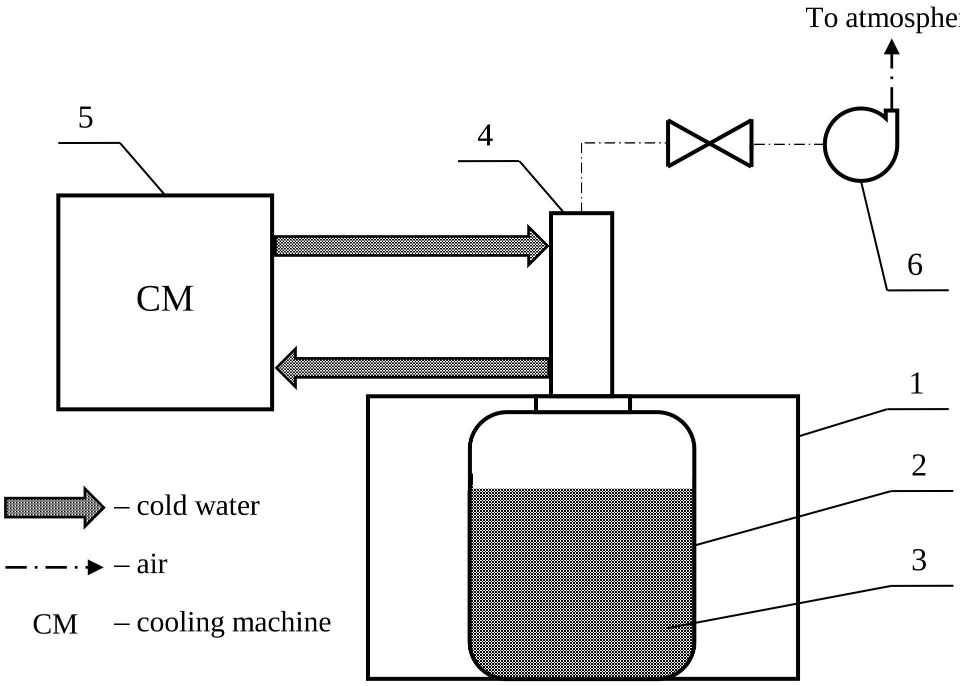


Fig. 5. Stand (№4) with microwave vacuum plant.

At the first stage, a comparison was made of the efficiency of extraction in a flow without a microwave field, with a microwave field, and with a vacuum microwave extractor. Experiments were carried out with halves of rosehip fruits under the same temperature conditions. The results are shown in Fig. 11.

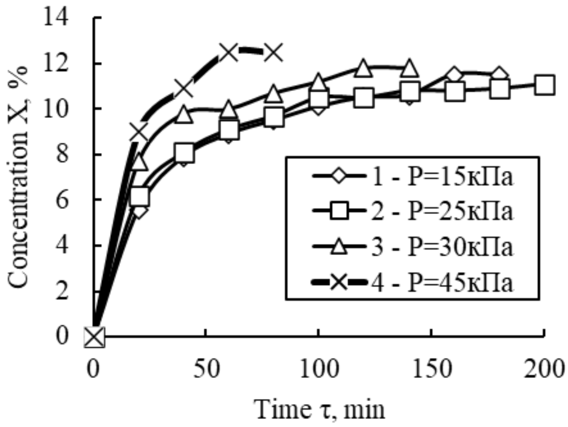


Fig. 11. Extraction kinetics for plants №3 and №4.

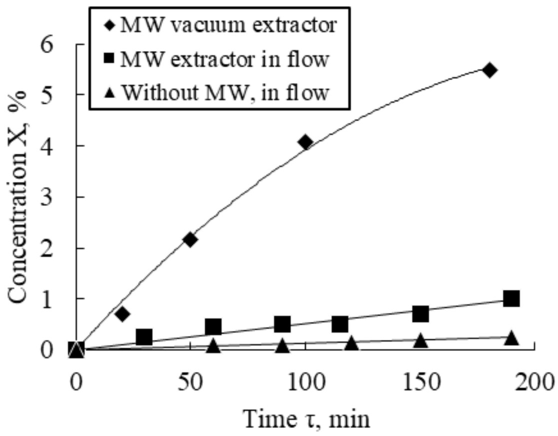
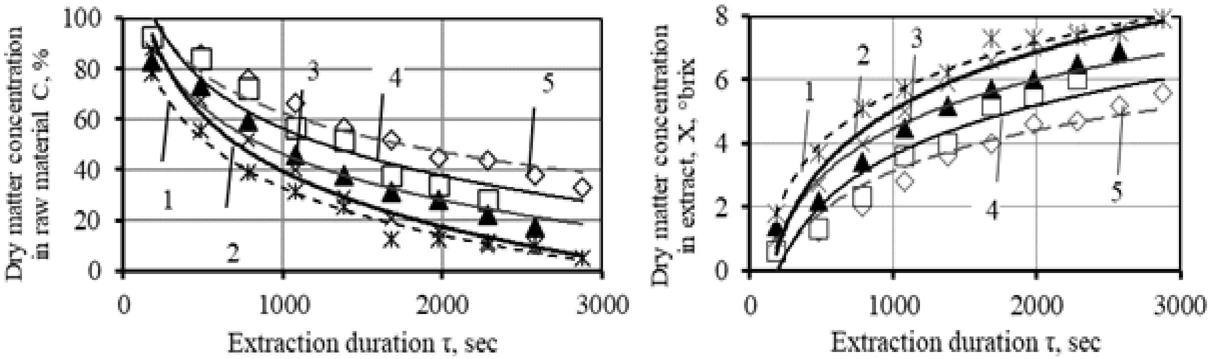


Fig. 12. Pressure effect on extraction kinetics.

As seen in Fig. 11, the effect of vacuum is apparent. The influence of pressure in the chamber on the intensity of extraction was determined (Fig. 12). With an increase in pressure from 15 kPa to 45 kPa, the extract concentration increased by 25%. However, at the same time, the extraction temperature also increased, which could have a negative impact on the content of ascorbic acid.

Thus, the contradiction between the intensity of extraction and the preservation of vitamin C should be resolved based on chemical analysis of the extract samples. The determining factor that affects the kinetics of extraction is the power of the microwave field (Fig. 13).



(1 — 1024 W, 2 — 682 W, 3 — 512 W, 4 — 273 W, 5 — 136 W)

Fig. 13. Radiation power effect on extraction kinetics.

With increasing power, the intensity of mass transfer increased, but so did the temperature of the process. The experimental data was processed, and a dependence of the mass transfer coefficient on the main parameter — the radiation power — was obtained (Fig. 14).

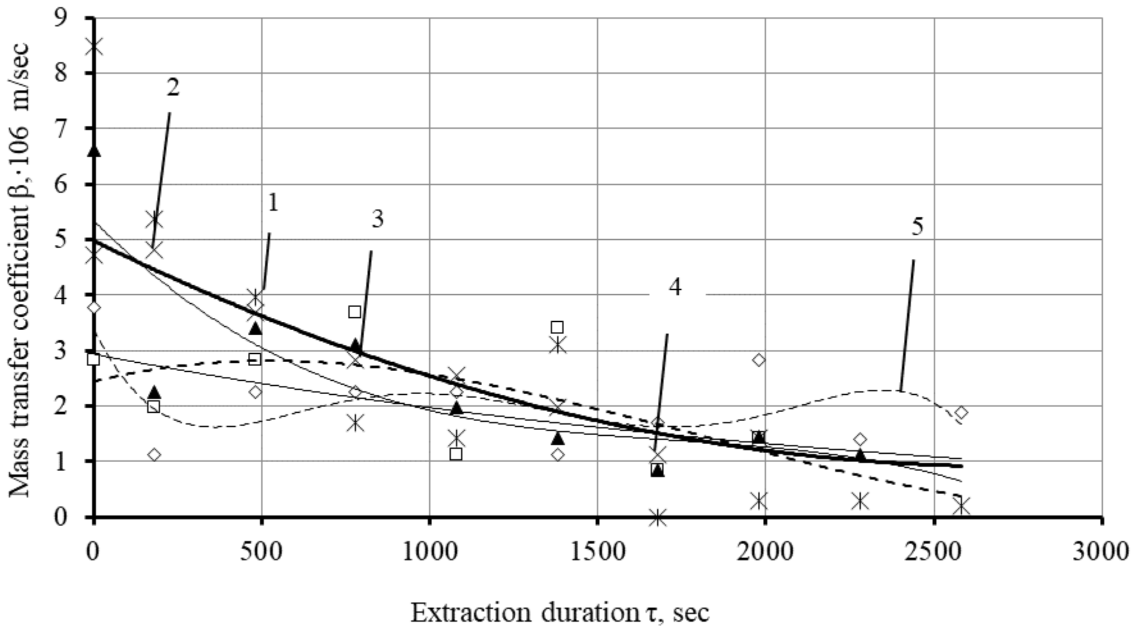


Fig. 14. Coefficient β values.

The values of β were used to calculate the corresponding Nusselt numbers. Constants in the dimensionless model (12) were determined by the methods of similarity theory. The power—law exponents for the Schmidt numbers (Sc) and the dimensionless parameter (L/H) were accepted as traditional.

The information in Fig. 14 was processed as a dependence of the mass transfer rate on the current extract concentration:

$$Nu_m = 0{,}17 \times (Sc)^{0{,}33} \times (Bu)^{1{,}6} \times (L/H)^{0{,}8} \quad (16)$$

In equation (16), the energy action number is calculated as $Bu = \left(rwd^2\rho\right)^{-1}$. This relationship is a key to the algorithm for calculating the vacuum microwave extractor.

Samples of extracts and their concentrates obtained by the proposed technology underwent sensory and chemical studies. The concentrates were obtained both in a microwave vacuum evaporator and in a block-type cryo-concentrator developed at ONTU. The results of chemical analysis are presented in Table 1.

Table 1.

Extracts and concentrates characteristics.

Sample	Dry matter concentration %	Vitamin C content, mg/100 sm^3	Vitamin C content relative to dry matter %
Extract	4,2	430…550	10,2…13
Concentrate №1	24	3640…4050	9,2…10,2
Cryoconcentrate №2	14	2120…2310	11,2…12,5

The obtained samples had a saturated, characteristic aroma of rosehip, a bright reddish-orange color, a taste without any hints of cooking, with a pronounced sour aftertaste, and a homogeneous consistency. The cryo-concentrate (No. 2) had a better aroma, color, and taste.

MICROWAVE EVAPORATION

Experiments were carried out at the installation described in (Burdo O.G. et al, *Problemele energeticii regionale*, 2018). New results on the dehydration of extracts over a wide range were obtained (Table 2).

Table 2.

The studies range during extracts evaporation.

№	Solid phase	Extractant	Pressures, MPa	Tempera-tures °C	Concentra-tions, %	Power, W	Vapor flow, g/min
1	Rosehip	Water	0,01—0,12	30—50	10—54	136	1,08
2	Rosehip	Water	0,01—0,12	30—50	17—80	512	4,64
3	Rosehip	Water	0,01—0,12	30—50	4,5—50	682	5,4
4	Sunflower oil cake	Ethanol	0,02—0,03	25—50	3—44	512	16,7— 14
5	Tomato pomace	Water	0,02—0,03	60—70	10—68	1024	11,7
6	Soybeans	Water	0,02—0,06	60—85	0,8—59	512	4,2

The information was processed as a dependence of the moisture removal rate on the current extract concentration (Fig. 15).

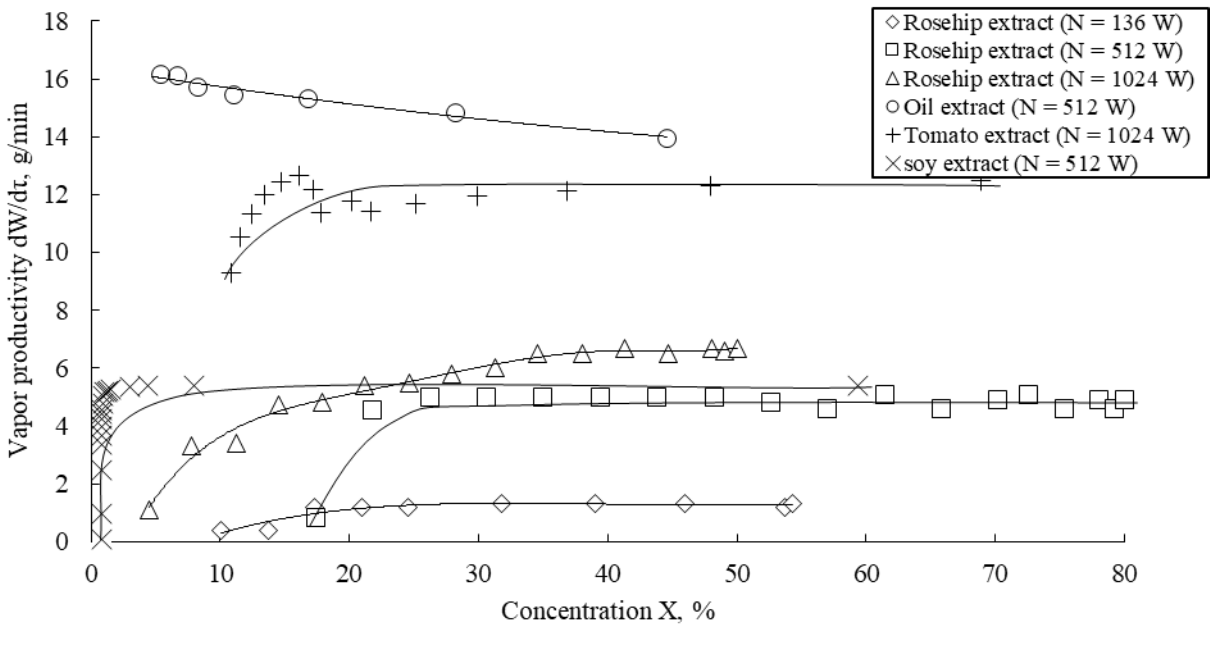


Fig. 15. Dependence of vapor productivity on the current concentration of extract.

The main conclusion based on the experimental results is that the amount of removed vapor depends on the solvent type and is closely correlated with the applied microwave power.

ENERGY OF HYBRID PROCESSES

A feature of hybrid processes initiated by electromechanical systems is that their energy is weakly dependent on the solution concentration (Fig. 16).

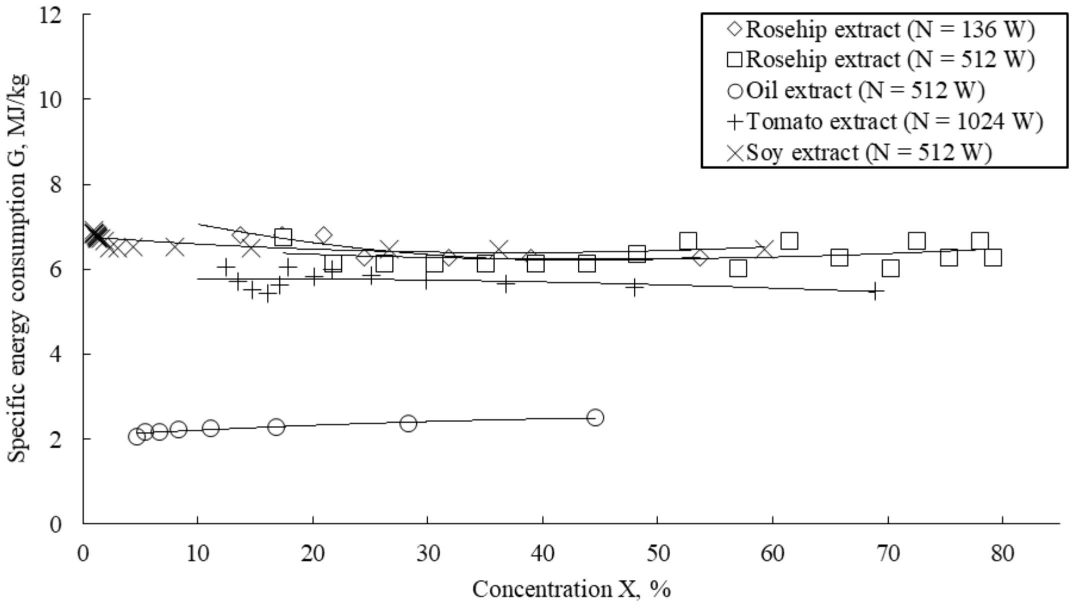


Fig. 16. Dependence of energy consumption on the concentration during various extracts evaporation.

The solvent and its phase transition heat play a decisive role in determining the specific energy consumption in microwave evaporation devices. Therefore, aqueous extracts require three times more energy than alcohol extracts (Fig. 16). It is noteworthy that stable energy consumption is maintained even at high concentrations, where traditional evaporation devices are not effective, in the area of energy-intensive drying technologies.

Gas chromatographic analysis was used to determine the fatty acid composition of tomato pomace oil obtained using a microwave evaporation apparatus (Fig. 17).

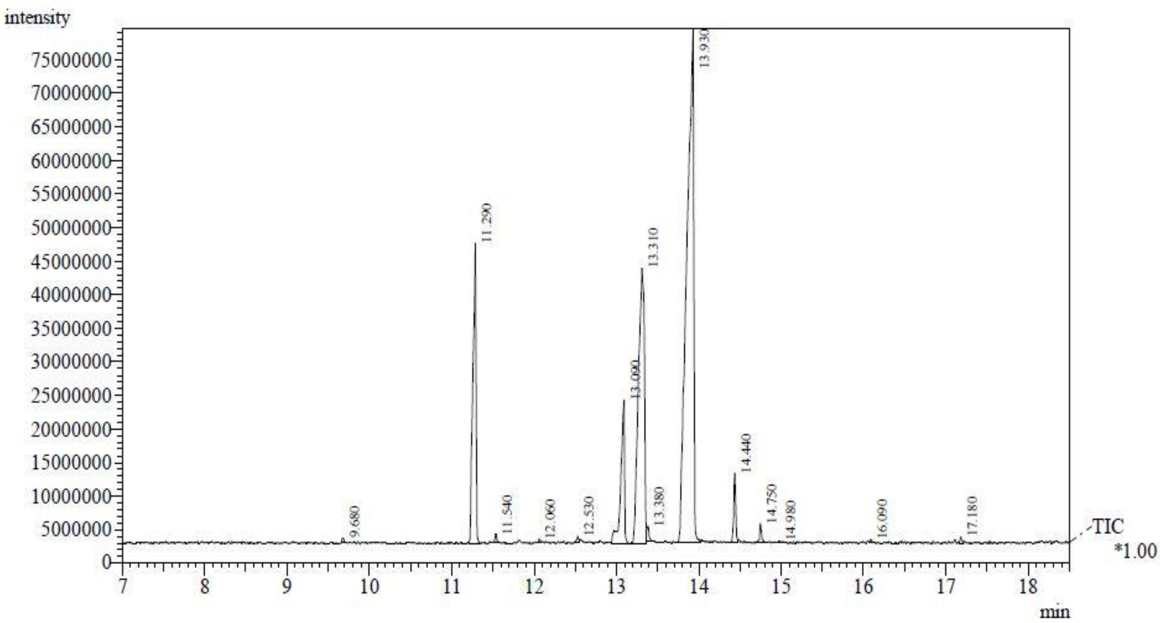


Fig. 17. Chromatogram of tomato pomace oil.

Table 3.

The content of fatty acids in tomato pomace oil.

№	Name of acid	Content, %
1	Myristic	0,14
2	Palmitic	13,70
3	Palmitolinic	0,20
4	Heptadecanoic	0,09
5	Heptadecenoic	0,18
6	Stearic	7,49
7	Oleic	24,04
8	Vacecenoic	0,53
9	Linoleic	50,74
10	Linolenic	2,06
11	Arachidic	0,53
12	Eicosadiene	0,05
13	Behenic	0,06
14	Lignoceric	0,19

As can be seen from the obtained data (Table 3), the oil from tomato extracts obtained using a microwave vacuum evaporation apparatus belongs to the linoleic type (with a linoleic acid content of 50.74%), similar to most traditional vegetable oils (sunflower, soybean). However, it should be noted that the oil from tomato extracts has a significantly higher biological value due to its much higher content of alpha-linolenic acid (2.06%) compared to sunflower oil, in which this indicator is up to 0.4%. Alpha-linolenic acid belongs to ω-3 fatty acids, which play an important role in maintaining healthy human body function, and the search for sources of supply in the diet is a relevant problem. The oil from tomato extracts also contains a higher percent of palmitic acid (13.7%), which promotes better absorption. The high biological value of oil from tomato extracts is also due to the presence of lycopene, which is a powerful antioxidant and a unique natural agent for the prevention of cardiovascular and oncological diseases.

CONCLUSIONS

The hypothesis that the use of substances with polar molecules as extractants and the transition to electromagnetic principles of energy supply would allow the output of target components from plant materials in the form of two streams, the traditional diffusion and additional hydrodynamic, with the power of the latter being orders of magnitude higher than diffusion, has been formulated and proven in this work.

Experimental setups and corresponding methodologies have been developed to compare traditional and proposed extraction principles in an electromagnetic field. Traditional modes were simulated in a thermostat. Microwave-assisted extraction was performed on stationary layer setups, in the mode of extractant circulation, and under vacuum conditions with a reverse refrigerator.

Comprehensive experimental studies of the kinetics of extraction in an electromagnetic field have established that the use of a microwave generator intensifies the mass transfer process several times over. Using the methods of similarity theory, the obtained database of experimental data was generalized as a dimensional model, which was used as a key element in the developed engineering methodology for the calculation of microwave extractors.

The extractor is distinguished by the ability to transfer target components from the raw material at temperatures of up to 40°C with high intensity. The operating time of the apparatus is by 5—8 times less than the traditional methods, while the values of the final concentration of the product are correspondingly higher. The vapor productivity and specific energy costs of the evaporator remain practically unchanged over the entire range of working concentrations (from 0.5 to 85°Brix).

APPENDIX 1

[1]**Fig. 3.** Material flows scheme. (G_R — raw material mass, C_R — concentration of target components in raw material, G_S — sludge mass, X_S — concentration of target components in sludge, G_E — extract mass, X_E — extract concentration, G_{EX} — extractant mass, X_{EX} — extractant concentration, G_P — product mass, X_P — product concentration).

[1]**Fig. 6.** Parametrical model of "Extractor — Dehydrator" system. (a_R — thermal diffusivity coefficient of raw material, c_R — heat capacity of raw material, ρ_R — density of raw material, λ_R — thermal conductivity of raw material, ν_R — kinematic viscosity of raw material, r_M — phase transition heat of moisture, H — raw material layer height, t_{IR} — initial temperature of raw material, C_{IR} — initial concentration of target components in raw material, a_{EX} — thermal diffusivity coefficient

of extractant, c_{EX} — heat capacity of extractant, ρ_{EX} — density of extractant, λ_{EX} — thermal conductivity of extractant, ν_{EX} — kinematic viscosity of extractant, r_{EX} — phase transition heat of moisture, t_{IEX} — initial temperature of raw material, X_{IEX} — initial concentration of target components in raw material, d, b, L — height, width and length of apparatus, V_U — useful volume of apparatus, N_{MW} — magnetron power, η_{MW} — magnetron efficiency, E — extractor, j_E — extractor specific energy consumption, D — dehydrator, j_D — dehydrator specific energy consumption).

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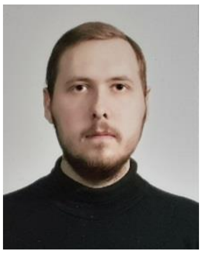

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