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Electrotechnologies of Targeted Energy Delivery in the Processing of Food Raw Materials

O. G. Burdo[a, *], **V. N. Bandura**[b, **], **and Yu. O. Levtrinskaya**[a]
[a] *Odessa National Academy of Food Technologies, Odessa, 65082 Ukraine*
[b] *Vinnytsia National Agrarian University, Vinnytsia, 03680 Ukraine*
**e-mail: terma_onaft@rambler.ru*
***e-mail: bandura_3@ukr.net*

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Abstract—In this paper, we emphasize that the most important problems in human development (energy, ecology, food) are in typical of the food-production sector, and their solutions are connected with the search for fundamentally new approaches to the thermal processing of raw materials. The prospects of electrotechnologies of targeted energy delivery for single elements of food raw materials are substantiated. Hypotheses for energy-efficient processes of dehydration, extraction, and inactivation of microorganisms are formulated. A dimensionless complex (energy action number) based on the critical analysis of the literature is put forward, as is our study of the interaction of the electromagnetic field with food raw materials. This number is used to evaluate the power of mass-transfer processes and its kinetics. The results of the analytical and experimental simulation of drying and the pasteurization processes are presented. The stages of energy conversion in drying technologies.

Keywords: food raw materials, electromagnetic field, drying, pasteurization, energy capacity, energy efficiency

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INTRODUCTION

The traditional production of food in industrially developed states —consumes much energy [1–6]. In many countries, the food industry is a leader in energy consumption leader. Overall food production doubles every 15 years, and its energy consumption doubles every 12 years. This growth in the specific consumption of energy in economies is a disturbing fact for all mankind, due to reductions in organic fuel storage. The urgency of problems of energy and ecology have given impetus to scientific investigations predicting development scenarios for mankind. An interstate group of European scientists (whose base laboratory was in Rome) presented their data in the form of a global predictive model for the development of mankind [2] termed the “Club of Rome.”

The proposed model was of a scenario type. It included key parameters of the state of society. The researchers began with the formation of a database for 1970. Trends were found in the main parameters. Organic fuel storage, mortality, the birth rate, the human population, the production of goods, the volume of services, and environmental loads were considered successively. The period of exploration was 70 years. The most pessimistic scenario included the opinion that all trends established at the moment of the model development would persist. Given this presupposition, it was predicted that in 2030, mankind would develop a with an acute crisis of energy and ecology.

The authors then changed the limitations and presented a scenario in which mankind found new sources and resources of energy. They predicted a grave crisis by 2060. However, the scenarios following were created with increasing optimism. The authors supposed that, in time, environmental loads would decrease by a factor of 4–5. This time, they predicted a crisis in the provision of food by the end of the century.

ANALYSIS OF LITERATURE SOURCES AND PROBLEM FORMULATION

One can deduce from the global model of the development of mankind (the Club of Rome model) that the key problems for this century are energy, ecology, and food. This conclusion can be illustrated by qualitative dependences (Fig. 1). Each crisis has three stages: development, explosive growth, and stabilization at an attained level.

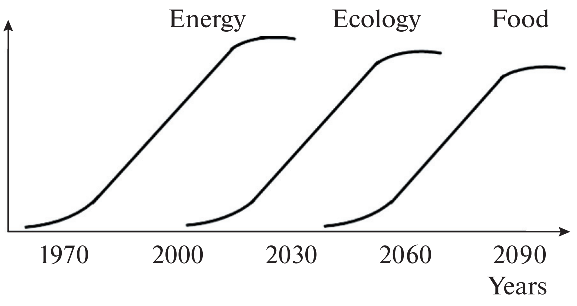


Fig. 1. Periods of crisis formation.

The authors established the limits of their models and predicted scenarios of development. However, they did not propose any methods to realize these limits. This article formulates the task of finding ways to improve food technologies.

Non-waste technologies can resolve industry's problems of environmental safety and problems of sources of reserve food . However, such problems can only be solved with revolutionary changes in food and processing industry. Fundamentally new technological approaches must be used. These are necessary to create low-energy-consuming food production with greater nutritional value, the creation of a range of new types of food, and the deep processing of food raw materials [1, 3–6].

Conventional technological processes of food include the use of huge flows of energy delivered to a whole volume of raw materials. Beyond the fact that the energy is not efficiently used, thermal actions result in degradation of the qualitative parameters of an ultimate product. We created the task of finding methods of direct action of energy on the separate particles of a dispersed material made of raw materials (moisture, microorganisms, cell membranes, pores, capillaries, and so on). As a result a substantial increase is expected in the efficiency of food technologies: a decrease in specific energy capacity, an improvement in ultimate product quality, a growth in the degree of the extraction of the components of the target raw materials, performance improvement, and so on. The aim was to find effective approaches to intensive low energy-consumption operations with food raw materials and even with separate nanodimensional elements of these raw materials.

The main process of most food technologies is thermal treatment. This process determines the quality of ultimate products, energy consumption, and production costs. There are evident scientific and technical contradictions between the demanding requirements for the quality of food products, the energy capacity of the means of production, and procedure for the transfer of heat and mass transfer. A number of central food technologies paradoxically solve the problems of energy resources (Table 1).

Table 1. Energotechnological possibilities for solving food production tasks

No.	Task	Traditional solutions	Hypotheses
1	Inactivation of microorganisms	Energy is delivered to the whole product volume, and it is pasteurized as a hot product	Possibilities of targeted energy delivery directly to a microorganism
2	Drying of raw materials	Energy is delivered to intermediate flow which transfers moisture into vapor	Possibilities of targeted energy delivery directly to moisture in product bulk
3	Drying of raw materials	All moisture removed from the product is transformed into vapor	Possibilities of moisture removal in the form of a two-phase flow
4	Extraction of target components	Component dissolution with extraction agent and diffusion of it into extract	Possibilities of additional transport from intracellular space and from cells of insoluble components
5	Rectification	Energy of dephlegmation and distillation is not used	Possibility of transformation of dephlegmation and distillation energy with heat pump
6	Vacuum evaporation	No efficient methods to utilize secondary steam energy	Possibility of transformation of secondary steam energy with heat pump
7	Pasteurization	Product is heated by steam generator, it is cooled by refrigerating machine	Possibility of substituting steam generator and refrigerating machine with heat pump

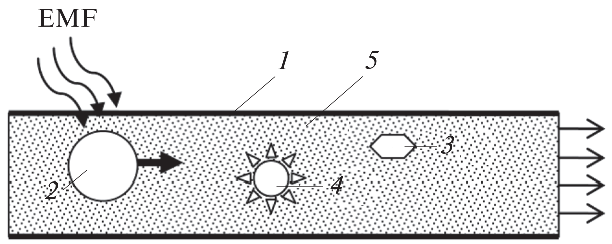


Fig. 2. Physical diagram of interaction between food system and electromagnetic field: (*1*) capillary wall, (*2*) vapor bubble, (*3*) liquid-insoluble components, (*4*) slightly soluble components, and (*5*) diffusion boundary layer.

These formulated problems can be effectively solved using modern energy action principles that consider different properties of the separate structures of raw materials with the involvement of advanced means of heat transfer and thermal transformation. Here, these problems are solved on the basis of electromagnetic technologies [7–15].

The hypothesis has been put forward that these contradictions are to be solved in the search for new principles of heat and mass transfer, using the unique possibilities of combined effects on transfer processes, forming complex combinations of moving forces focused on an effective extraction of the target components from raw materials.

METHODS FOR ANALYSIS OF ENERGY EFFICIENCY

It appears that the principles for evaluation of the energy efficiency of food production equipment must be seriously reconsidered. Heat efficiency, which is often used, is not always effective. For instance, the heat efficiency of the pasteurizer is considered to be a relation between the energy delivered to the product and the energy of the steam used. In practice, the expenses are considered to be convection and radiation losses. In the course of this approach the efficiency of the pasteurizer is 95–97%. However, not all of the energy delivered to the product is useful. It is logical to assume that only that the energy consumed directly by the microorganisms is useful for the inactivation process. According to this approach, the energy efficiency of the pasteurization apparatus is extremely low (0.004%). More than 99.9% is consumed in food spoilage [16].

A similar situation is observed in the evaluation of the heat efficiency of drying installations. Here, calculations are carried out as a relation of energy that is physically necessary for transformation of the moisture in the product into steam to the energy consumed by the drying agent. In modern dryers the principles of moisture removal from raw materials are developed not only in the form of the vapor phase but also in the form of liquid drops. These are, say, the processes of filtration drying [7]. In this case, that approach is senseless. The thermal efficiency of the evaporating apparatus is 85%. However, should the energy losses with secondary vapor not be taken into account? These losses are considerable even in multiple-vacuum evaporators.

A wide application of the approaches used in energy management [7] where the energy input per unit product is taken into account (MJ/kg or MJ/l, etc.) is proposed to compare energy efficiencies. If apparatus with different power sources are compared, one can calculate the energy efficiency expressed through the presented material expenses. The efficiency of dryers is known to be determined by the parameter MJ per 1 kg of evaporated moisture. However, in cases when moisture is removed from the bulk of the product in the form of fog [7], this efficiency is not correct.

MECHANISM OF THE INTERACTION OF ELECTROMAGNETIC FIELDS AND RAW MATERIALS

When raw materials, usually saturated with water, interact with an electromagnetic field (EMF), a peculiar phenomenon appears [9–15, 17–19] that can be called a mechanodiffusive effect at the gradientless wave input of electromagnetic energy to polar molecules. As can be seen from Fig. 2, the generation of vapor bubbles (*2*) deep in the microcapillary (*1*) causes a growth in pressure and the onset of a hydraulic flow that entrains the solution from the boundary layer (*5*), in insoluble (*3*) and slightly soluble (*4*) components.

Thus, from the capillary (*1*), a solution-diffusion flow comes, which is complemented with a flow of some components that are usually not typical of classical diffusion processes. The frequency of emissions and the number of functional capillaries grow with growth in N (emission power). Mass flow j_2 is determined by the effective mass-transfer coefficient β_P and the pressure difference in the capillary P_{k} and flow P_{e}.

Flow j_2 is created by a strong hydrodynamic moving force. It creates turbulence in the boundary layer and can be some orders of magnitude greater than classical diffusion flow j_1. It is necessary to include the influence of this flow on classical mass–transfer equations. Based on the principles of similarity theory, a new dimensionless complex is proposed (the energy action number) [7, 17], which accounts for the influence of the EMF (the Bu number). This is a relation between the power of emission and the energy necessary for similar processes in conventional technologies. The

Table 2. Calculated models

Process	Bu number	Process model
Activation and inactivation of microorganisms	$\mathrm{Bu} = N(\xi V C_p \Delta t \rho)^{-1}$	$F_0 = A\,\mathrm{Re}^n\,\mathrm{Pr}^m\,\mathrm{Bu}^k$
Extraction	$\mathrm{Bu} = N(rwd^2\rho)^{-1}$	$\mathrm{Sh} = A\,\mathrm{Re}^n\,\mathrm{Sc}^m\mathrm{Bu}^k$
Drying	$\mathrm{Bu} = N(rV\rho)^{-1}$	$\mathrm{Sh} = A\,\mathrm{Re}^n\,\mathrm{Sc}^m\mathrm{Pe}^p\mathrm{Bu}^k$

Bu number defines both the energy efficiency of the equipment and the mode of mass transfer. Up to particular values of the Bu number there are laminar flow conditions in solid phase capillary channels. The Bu number can show the conditions for a transition to more intensive mass transfer, which can logically be called a turbulent barodiffusion mode [7]. In general terms, the energy action number characterizes the relationship of the energy consumption of the innovation technology (Q) and the base case (traditional technology):

$$\mathrm{Bu} = Q/Q_0.$$

For the processes under examination, the methods of similarity theory were used to determine the structures of models in the generalized variables and the relationships to calculate the Bu number (Table 2).

In the relationships, the following designations are accepted: F_0, Sh, Re, Pr, and Sc are the Furrier, Sherwood, Reynolds, Prandtl, and Schmidt numbers, respectively; N is the emission power; V is the volume rate of the removed moisture; r is the latent heat of transition; d is the characteristic dimension; and ρ is the density.

The resistance to barodiffusion mass transfer may be several orders of magnitude less than conventional modes of mass transfer [14].

The mechanisms considered here can substantially enhance the processes of activation of raw materials and of the activation and inactivation of microorganisms [11, 14–16].

EFFECT OF APPLICATION OF ELECTROMAGNETIC ENERGY INPUT

In the modern developed electromagnetic heat technologies of drying, the following hypothesis is used: the application of targeted energy delivery for dehydration directly to moisture within the bulk of the product will allow the initiation of a powerful hydrodynamic flow that appears at the interaction between the EMF and the polar molecules of moisture in the capillaries (CM). This will lead to the removal of water both as vapor phase and fog, which will greatly increase the rate of heat and mass transfer due to a sharp decrease in resistance to internal diffusion and a reduction in energy consumption and the time for the dehydration process.

This hypothesis is associated with new and novel methods of dehydration involving the nanotechnology principles to develop barodiffusion processes [7, 18, 19].

Recent years have been characterized by the rapid development of drying apparatus with electromagnetic energy sources (EES) [8–9, 11–15]. In addition, designs are improving, due to increased confidence in engineering. The interaction processes of products and electromagnetic waves are much less understood than electrophysical phenomena in electromagnetic radiation generators. The technique of electromagnetic generators is ahead of the theory of heat and mass transfer during the drying process with the electromagnetic input of energy. Considering that there are no recognized engineering methods of design for even conventional drying, the peculiarities of drying with the electromagnetic input of energy have scarcely been studied. However, successful simulation of drying with EES can provide a powerful impetus for the widespread implementation of advanced engineering in food technologies.

It is characteristic that in these technologies, the lines of drying also differ. If in traditional patterns of drying periods of constant and drooping rates are expressed, then in modern dryers the microwave (MW) energy provides a constant addition of moisture to the surface of the product, due to laminar barodiffusion (Fig. 3a). If the turbulent barodiffusion mode is realized, then moisture in the form of a fog is directly thrown out into the air flow (Fig. 3b). Paradoxically, dehydration proceeds at an increasing rate. These patterns are obtained experimentally [7, 19]. The lowest values for the drying rate during the initial period of work are explained by the fact that surface moisture (SM) blocks the barodiffusion process that begins to develop along with the removal of part of the SM.

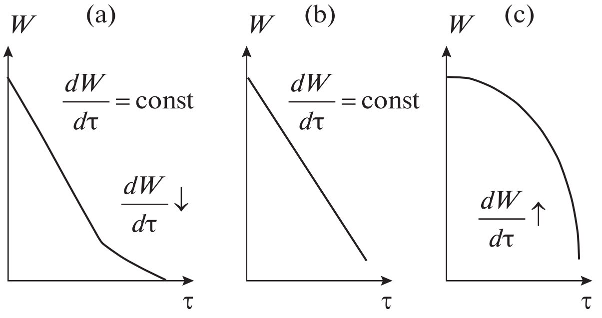


Fig. 3. Line of moisture removal: (a) traditional drying, (b) laminar barodiffusion, and (c) turbulent barodiffusion.

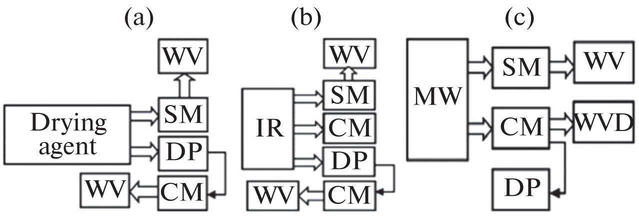


Fig. 4. Schematic diagrams of drying: (a) traditional convective drying, (b) infrared drying, and (c) microwave drying.

An important role (Fig. 4) is also played by the type of energy: conventional convective (CV), infrared (IR), and MW energy.

In the CV mode, the drying agent initially gives up energy to the SM and then to the dried part (DP) of the product, which transfers energy to the CM. This is convectional convective drying (Fig. 4a), which results in wet vapor flow (WV). in IR drying (Fig. 4b), capillary moisture is partially removed directly by the electromagnetic energy and partially as at the convective drying.

In the case of MW drying (Fig. 4c) from the capillaries due to the barodiffusion there can be observed a flow of a mixture of WV and water drop (WVD). This mixture composition also characterizes specific dehydration power. The more the drop fraction, the greater the power consumption.

In a convective dryer, energy conversion is as follows. Energy conversion in the fuel and steam mode takes part at an efficiency of 50% and a drying efficiency of 40%; the amount of useful energy is 8 MJ. This is equivalent to removal of 3 kg of moisture from the product. In the proposed dryer with an electromagnetic energy input, the result (normalized to the initial resource, fuel) is twice as high (Table 3), and the technically feasible level is 50 kg of moisture.

The fuel energy conversion in the components of drying apparatus is explained in detail by the modes in Fig. 5. A comparison is made between the conventional and MW modes.

Electrodiffusion models of drying technologies [19] are presented in Table 4.

In the conventional pattern (Table 4, No. 1) the flow must overcome the pore-diffusion resistance (R_k) and convection resistance (R_c) from the surface of the product into the environment. The resultant diffusion flow is J_d. In pattern with the electromagnetic energy generators, an intense barodiffusion flow (J_b) appears, which overcomes hydrodynamic resistance (R_b). In the case of laminar barodiffusion (Table 4, No. 2) the flow brings the components to the surface of the product, ensuring a steady mass transfer from the surface (J_c). Here, $J_c > J_d$. In the case of turbulent barodiffusion (Table 4, No. 3) the flow (J_b) can bring the components directly into the medium, in parallel to the conventional flow J_d. Here, $J_b \gg J_d$.

The following factors are key for the functioning of the barodiffusion flow:

—the presence of liquid with polar molecules within the product bulk;

—the correspondence of the parameters of the EMF to the mass-transfer problem in hand; and

—the conformity of the structural characteristics of the product with the parameters of electromagnetic energy.

The technology of targeted energy delivery in the drying of raw materials allows a substantial augmentation of the process [18]. Two-phase flow in the form of vapor and finely dispersed water drops comes out from

Table 3. Power engineering for drying processes

Mode	Energy of 1 kg fuel	Useful energy	Removed moisture amount
Traditional	40 MJ	8 MJ	3 kg
Microwave	40 MJ	12–16 MJ	6 kg

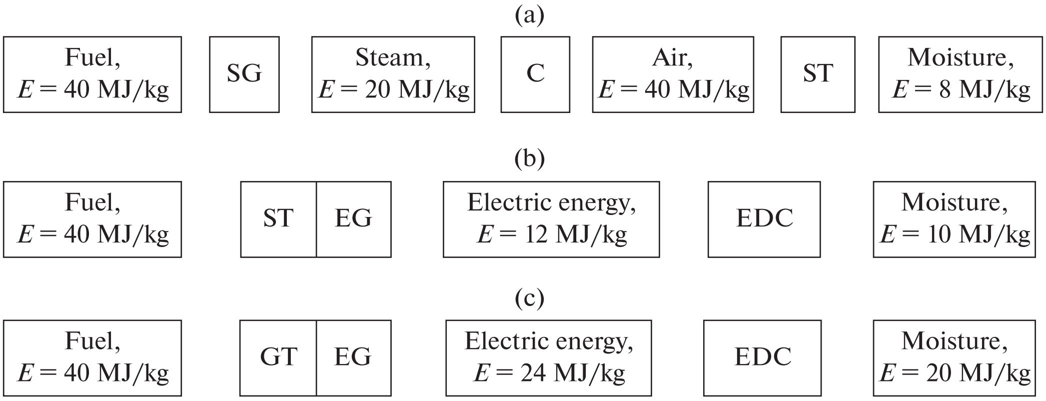
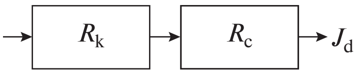
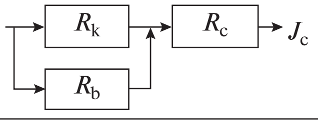
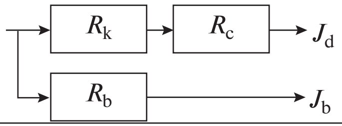


Fig. 5. Energy conversion in drying technologies (all parameters are for 1 kg fuel): (a) traditional convective technologies, (b) microwave drying in the circuit with steam turbine, and (c) microwave drying in the circuit with gas turbine. Conventional symbols: (SG) steam generator, (C) steam calorifer, (CC) convective drying chamber, (ST) steam turbine, (EG) electric generator, (GT) gas turbine, and (EDC) electromagnetic drying chamber.

the bulk of raw materials. As traditional heat efficiency only takes account of vapor, a method has been proposed to account for energy efficiency based on the Bu number (Table 2). Different modes of drying are compared, and the results are presented in Table 5. The basic mode (no. 1) includes traditional convection dryers, and no. 2 dryers are particularly used for grain. Dryers can be improved with a thermosiphon system (no. 3). No. 4 Dryers are characterized by a targeted energy delivery to the product using evaporating thermosiphons is found in the product preheating zone. In no. 5 dryers, this targeted energy delivery is also performed in the drying zone. This substantially decreases the waste in heat energy with exit gases. nos. 4 and 5 dryers are second–generation plants.

Third–generation dryers nos. 6 and 7, in which energy is delivered directly to the moisture in the product, do not have generally accepted heat efficiencies, and the Bu number reflects the trends in drying equipment [7].

Table 4. Electrodiffusion models of drying technologies

No.	Mass transfer pattern	Fields	
		P	t
1		↓	↑
2		↑	↑
3		↑	↑

The energy action number successfully generalized the experimental data bases in the processes of inactivation, dehydration and extraction [7–19]. It appears that the Bu number can be used to properly characterize the energy-specific nature of all problems of the targeted energy delivery.

INNOVATION ELECTROTECHNOLOGIES OF PASTEURIZATION

In traditional technologies, the problem of pasteurization is technically solved by heating the whole product volume up to the lethal temperature (Fig. 6). Because the allowable content of microorganisms in food raw materials is prescribed (for example, for the second-grade milk, up to 40×10^{-6} of the total volume) the energy consumed directly by the microorganisms, is not greater than 0.004%. Taking into account the fact that after pasteurization, cooling is performed by refrigeration machines, the energy efficiency is reduced by an order of magnitude.

It is hypothesized that, with the conformity between the hydrodynamic parameters of the processable liquid and the characteristics of the EMF, it is possible to use the differences in the electrophysical characteristics of a microorganism and a food product, to effectively realize the mechanisms of the selective (directed) energy action on a microorganism, and to reduce the level of temperature in product processing [15, 16].

The task is to input parallel energy to the product (Q_P) and to the microorganism (Q_M). Softer modes of thermal processing will be obtained, the product quality will be improved, and energy consumption will be reduced (Fig. 6).

Table 5. Estimated energy efficiency of drying equipment

No.	Drying device design	MJ/kg of removed moisture	Heat efficiency, %	Bu number
1	Basic convective	6.00–8.00	0.30–0.38	2.60–3.50
		Grain drier		
2	Basic first generation	4.26–6.30	0.36–0.50	1.85–2.70
3	Improved first generation	3.80–5.10	0.45–0.60	1.67–2.22
4	Block second generation	3.54	0.65	1.54
5	Recuperative sescond generation	2.70–2.88	0.80–0.85	1.18–1.25
6	Third generation (obtained result)	1.90	–	0.82
7	Third generation (expected result)	0.20	–	0.09

Table 6. Results of microwave pasteurizer tests

Consumption, mL/s	Warmup time, min	32°C	34°C	36°C	38°C	40°C
0.6	14	5	10	25	80	100
0.4	17	33	85	100		
0.3	18	50	90	100		

With increases in Q_M, values of Q_P decrease, and the total consumption of energy for pasteurization is reduced. Product temperatures drop, and the functional properties of the raw materials are preserved. In relation to this, the possibility of a substantial increase in the energy efficiency of the pasteurization process appears.

In MW pasteurization, the hydrodynamic parameters of the flow are important. Let us consider the conditions for the EMF processing of microorganisms (Fig. 7). The effect of selective heating manifests itself to a greater extent for microorganisms on the surface of the product. The current lines for the microorganism in the product bulk tend to be curved, which leads to greater dissipation of energy. Therefore, experiments were carried out to determine the influence of the thickness of the product layer (Fig. 7). The tests were conducted at a magnetron frequency of 2.2 GHz.

It has been established that the dependence of the lethal temperature for microorganisms on the thickness of the product layer is nonlinear (Fig. 7). For this, the greatest effect is typical for microlayers. Further, if the lethal temperatures differ many times over for

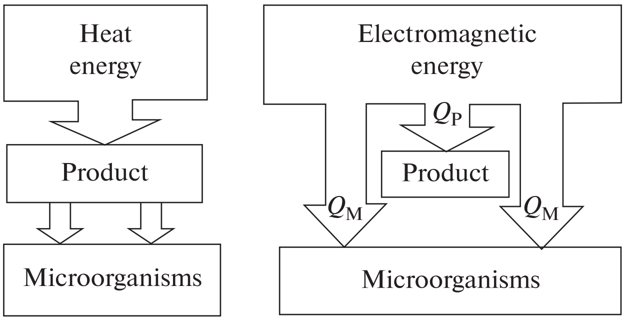


Fig. 6. Diagrams of energy input: (a) traditional diagram and (b) microwave pasteurizer.

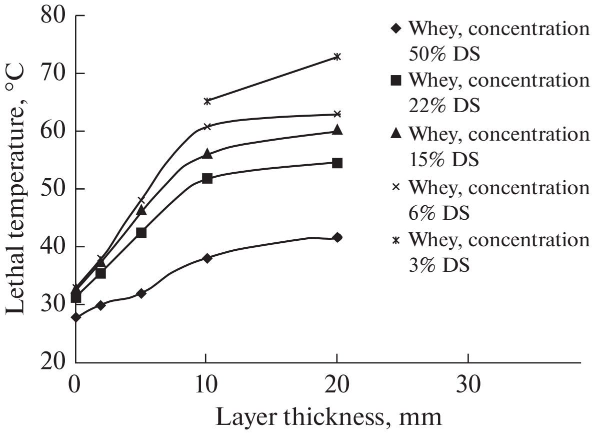


Fig. 7. Mechanism of microwave product processing.

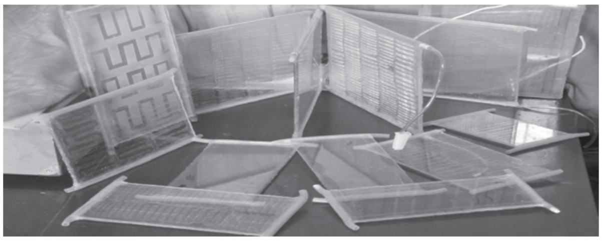


Fig. 8. Конструкции пастеризационных модулей.

products with different concentrations of water at a layer thickness of 20 mm, then at thicknesses up to 1.5 mm this dependence is smoothed over (Fig. 7). Therefore, the modules for the prototype unit of the electrophysical pasteurizer were made with a working gap between the radiotransparent plates of 0.75–2 mm (Fig. 8).

The developed modules (Fig. 8) were tested as a component of the MW pasteurizer. The tests were carried out using a wine material, and the inactivation degree of the microorganisms was estimated using conventional methods in the plant laboratory. The percentage of inactivated microorganisms is determined by the product expenditure and temperature conditions (Table 6).

Test results (Table 6) showed that in the case of correct conformity between the power of the EMF, the module structure, and the product flow mode, the temperature level of its processing decreased by 50–55°C. It is seen that even at a temperature of 36°C, a complete inactivation of microorganisms in the flow took place (Table 6). In this situation, the product fully preserved its nutritional qualities. In addition, energy consumption is an order of magnitude lower (Table 7).

Table 7. Technical characteristics of microwave pasteurizer

Parameter	Traditional approach	Microwave pasteurizer, obtained/expected result
Energy capacity, MJ/kg	0.2	$0.02/2 \times 10^{-5}$
Temperature, °C	80–100	30/10–20
Efficiency, %	0.004	0.04/20–40

CONCLUSIONS

The EMF can initiate the onset of hydrodynamic flow from the intercellular space of food raw materials. This hydraulic flow is barodiffusion, and its moving force is the pressure difference between the bulk of the raw materials and the environment. Barodiffusion works in parallel to classic diffusion flow, but its power may be by orders of magnitude greater than traditional flows. To initiate barodiffusion, a distinct conformity is required between the structural characteristics of the raw materials, the peculiarities of the liquid phase, and the parameters of EMF. Depending on this conformance, laminar and turbulent barodiffusion can develop. The result of these processes may be an increase in the output of target components, the transfer of valuable components into the solution that could not be extracted using traditional methods (aromatic complexes, taste components, and so on).

The mechanisms of the selective energy input in the system of the solution microorganisms can be used as a tool to control the process of microorganism development. A certain critical density of the electromagnetic energy flow exists, the approach to which activates the growth of microorganisms, and the excess of which causes their inactivation.

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