

The Nanotechnological Innovation in Food Industry

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ABSTRACT

The perspectives of direct energy action (DEA) technologies are discussed. The new classification of DEA technologies is proposed. The possibilities of DEA technologies using in food nanotechnologies are analyzing. The concepts of heat mass transfer during extraction and drying are considered in terms of food industry. The hydrodynamic flows from food raw capillary structures are classified. The conditions of laminar and turbulent barodiffusion are determined. The problem of combined DEA technologies processes simulation and the objectives of experimental research are formulated. The new dimensionless number called as the number of energy action is discussed. It is shown that the impulse electromagnetic field is an effective instrument for DEA technology implementation

Keywords - barodiffusion, energy, food technologies, nanotechnology, simulation

I. INTRODUCTION

Energy resources support is a global problem of mankind [1-4]. Energy has become a scarce and expensive resource all over the world. Many of industry problems, dependent on resources use, are being tried to be solved by nanotechnologies (NT). At present a problem of energy support in food industry is becoming aggravated. Though, problems of food nanotechnologies (FNT) are not being engaged in. Fields of FNT are limited by using of nanoparticles and nanofilms for package [5]. Yet usage of nanotechnologies in food industry will allow to create brand new products which have no analogs in modern cookery. Whereas food systems are complex biological ones, nanotechnological approach is to be based on interdisciplinary, complex analysis of chemical, physical and biotechnological phenomena.

II. PROBLEM FORMULATION.

The main process of most food technologies is thermal treatment. This process determines the quality of final product, energy consumption and its production cost. Scientific and technical contradictions between increasing requirements to food product quality, its energy intensity and heat-and-mass transfer technique are obvious. A number of main food technologies solve the problems of energy resources usage paradoxically (Table 1).

A hypothesis, that solution of these contradictions is in the field of search of new heat-mass exchange organization principles, usage of unique capabilities of combined influences on transfer processes, forming the complex combinations of motive forces, directed to efficient target components extraction, is being put forward.

The hypothesis is based on new principles and nanotechnologies involvement. Food NT may be developed in two directions - revolutionary FNT with predominant influence of chemical interaction, and evolutionary ones – with predominant influence of physical processes. The first is manipulation of nanoscale elements for assembly of artificial products (milk, meat etc.). These technologies are based on “bottom-up” mechanism. This direction is quite difficult and disputable. Both modification of separate complexes and imparting of new properties to them can be attributed to the first direction. The second direction is control of transfer processes at food raw nanoscale objects level, improvement of traditional production processes, products and their applications by full using of nanoscale surface effects. This is a new, perspective scientific direction that firstly was presented by authors [5].

The subjects of researches in FNT are microorganisms (from 7 nm), nano-pores and nano-capillaries of vegetable material (from 5 nm), cell walls (7...30 nm), protein (10...100 nm), polysaccharides (1...100 nm) and water molecules ($\approx 0,15$ nm). These are the objects which the main steps of food technologies are aimed at. That's why biotechnology, sterilization, extraction, drying, juice output processes etc. can be organized at nanoscale level. The principles that can be implemented when food productions is moved up into nanotechnologies allows to decrease the energy intensity, to decrease considerably the level of thermal influence upon raw materials and product, to create basically new products. It is presented that it is reasonably to search the possibilities to control the transfer processes at food raw nanoscale objects level by full using of nanoscale surface effects. The paradigm and scientific fundamentals of food nanotechnologies that

is being elaborated at Odessa National Academy of Food Technologies include hypothesis of barodiffusion transfer from nanoscale raw material elements [1], thermodynamic scheme of nanoprocess and heat-mechanic model of vegetable cell [2], mass transfer kinetic model [3]. Development of FNT scientific fundamentals is associated with modeling of directed energy action technologies. Energetics becomes not only a characteristic, a main result of technology, but also a means of transfer processes in

different systems elements kinetics control. Development of technologies is to go the way of directed energy action (DEA) and to those raw material elements which require energy action. So, the thermolabile elements of material should be exposed to the minimal energy action. Special attention has to be paid to micro- and nanoscale structures. These elements in traditional technologies are not considered practically.

Table 1. The paradoxes of energy technologies of food industry.

№	Problem	Customary solutions	Hypothesis
1	The deactivation of micro-organisms	Energy is transferred to the whole volume of product with microorganisms	It is possible to establish the address energy transfer directly to microorganism.
2	The product dehydration	Energy is supplied to an intermediate flow that transforms water into vapor.	It is possible to establish the address energy transfer directly to the water in the products volume.
		All water converts to vapor before removing.	It is possible to organize the water removing in two-phase flow.
3	The target components extraction	Dissolving of compounds and its diffusion into extract.	The additional transfer of insoluble components from cells and intercellular space is possible.

III. THE DIRECT ENERGY ACTION TECHNOLOGIES SIMULATION

DEA technologies have selective action on food raw material elements and biological objects. DEA-nanotechnologies are noted for that energy action direction is nanoscale objects, micro- and nanoscale structures. Both in first and second cases a task of selective energy action is fields control, summation of low fields force action directions, organization of flow from micro- and nanocapillary structure, forming the composition of these flows, directing of force action on microbiological objects such as cell walls etc.[6].

For food systems the energy consumption decreasing leads not only to the process radiant efficiency increasing and the product cost decreasing, but also reduces the thermal influence on product) That will result in saving of biologically active constituents of food materials. For example, food products and ready-to-serve food, received by DEA will meet the requirements of functional nutrition.

Efficiency of food technologies (productivity, specific energy consumption, final

product quality, useful components extraction rate etc.) are determined substantially by capability of actions on cell walls, microorganisms, pores, capillaries etc. A task to find the effective principles approaches for local actions, directed to intensive, low power-intensive operations with food material, and even with particular nanoscale elements of this material is set. It is important to develop fundamental bases of evolutionary nanoscale phenomena and processes. From the position of today [7] the development of DEA-technologies can be forecasted the following way (fig.1).

Nanotechnological methods in water solutions separation by freezing will find an application in problems of low temperature concentration of juices, extracts, wine stock and other water solutions, in water demineralization (including in deep purified water production), in ice and salt crystal growth [6]. Wave and mechanical diffusive technologies can become a basis for new effects in mass transfer problems [6]. Let us consider the barodiffusion effects in capillary porous media.

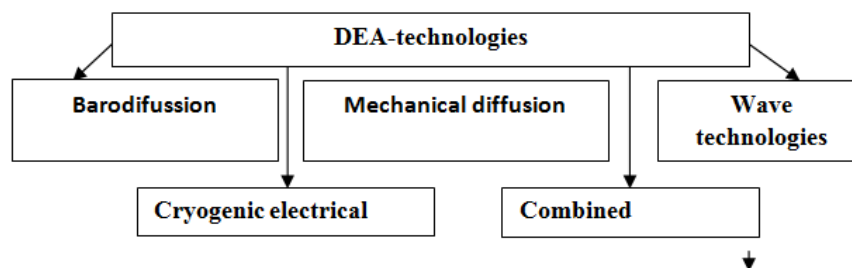


Fig. 1 classification of the DEA-technologies.

IV. BARODIFFUSION MECHANISM

On the basis of nanoprocess thermodynamic scheme [8, 9] the mechanism of combined nano- and macrotransfer of moisture (and other components) from fibrous structure to the flow is explained by scheme (fig. 2.).

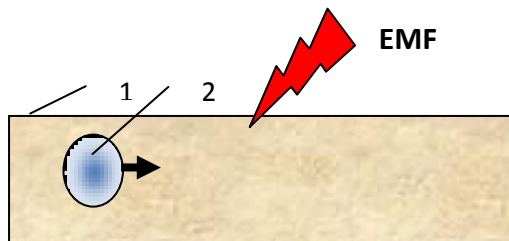


Fig.2 thermophysical barodiffusion model.

Let us consider the liquid volume motion on basis of the balance of respective forces, which are formed inside the capillary 1 by forming of vapor bubble 2 (fig.2). Vapor bubble forming is caused by electromagnetic field (EMF) action.

Resultant of these forces will determine the flow velocity. Subject to surface tension forces that are characteristic for microcapillaries, relation of pressure difference inside the capillary (ΔP) is determined by the velocity of liquid (w), its density (ρ), total local resistance (ξ), surface tension forces (σ):

$$\Delta P = \frac{\rho w^2}{2} \left[\frac{\lambda l}{d} + \sum \xi \right] + \rho g l + \frac{\sigma}{d} \quad (1)$$

Product of ΔP and moved liquid volume (V) gives the necessary for the process energy (E). This is a quantity of energy which is necessary in mechanic action on liquid in capillary that is the filtration process.

The value of ΔP is determined by the power of electromagnetic field (EMF) and electrophysical parameters of capillary contents. Exactly by the EMF power it is possible to control the barodiffusion flow.

V. THE CLASSIFICATION OF REGIMES OF FLOW FROM MICRO- AND NANOSCALE STRUCTURE.

For barodiffusion under energy action initiation it is required to overcome the channel resistance at the expense of transition of liquid into vapor phase. According to EMF power the regimes of laminar (fig. 3) and turbulent barodiffusion are possible (fig 4).

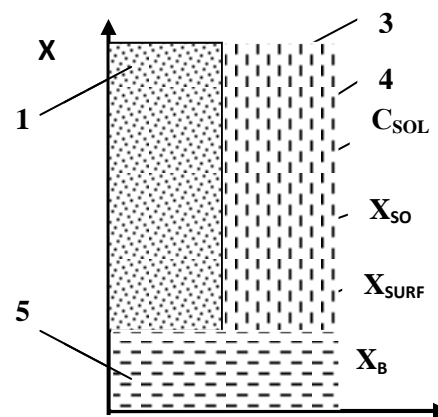


Fig.3 laminar barodiffusion

Laminar barodiffusion is characterized by usual for classical mass transfer problem concept: inner and outer diffusion resistances (Fig. 3).

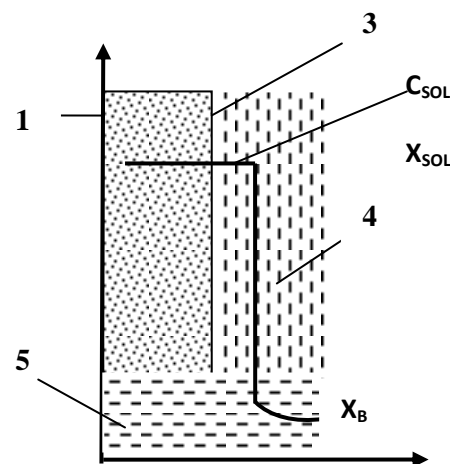


Fig.4 turbulent barodiffusion.

The task of barodiffusion is to intensify the process of inner diffusion mass transfer. As the energy action rises, the pressure in capillary structure will rise too. As a result a powerful ejection of liquid from solid phase may appear. This is the "turbulent barodiffusion" regime. The concentration field in this case will differ from classical view (Fig.4).

In turbulent diffusion regime such concepts as wall boundary layer and respective diffusion resistances are smoothed over. Solid phase is characterized by average value of concentration (C_{SOL}) (fig.3). The flow with concentration (X_{SOL}) goes into the volume (5), concentration in which is (X_B). In comparison with classical diagram the intensive contents (4) of capillaries travel is noted. The degree of process intensity is determined by the velocity of outflow from capillaries. While laminar barodiffusion intensifies only inner diffusion mass transfer, turbulent barodiffusion intensifies both

inner and outer diffusion mass transfer. Let us consider the model of barodiffusion initiating.

VI. THE STATEMENT OF BARODIFFUSION MODELING TASK.

Non-stationary one-dimensional field of soluble substances concentrations is determined by the Fick's convective diffusion equation:

$$\frac{dX}{d\tau} = D \frac{\partial^2 X}{\partial x^2} + \frac{\partial X}{\partial x} w \quad (2)$$

The x coordinate coincides with the capillary axis. In certain conditions the second summand in relation (2) can practically determine the intensity of transfer both soluble constituent and insoluble one.

Consecutive series of diffusion resistances consists of the sum: $\Sigma R = R_{HK} + R_{MK} + R_{MO}$. The convective mass output process from the product surface to the flow has the lowest diffusion resistance (R_{MO}). Its value is determined by the velocity of extractant flow, its properties, and geometry of phase contact surface. Further let us consider diffusion microcapillaries resistance (R_{MC}) and nanocapillaries resistance (R_{NC}) separately. Soluble substances move inside microcapillaries to the product surface. This is the convective diffusion in straitened conditions. Nanocapillaries in which, the constraint of the diffusion processes is maximal, are, naturally, characterized by the highest diffusion resistance. These are the capillaries that determine the intensity of mass exchange processes in extraction and the degree of valuable constituents extraction from solid phase. The concentration of target constituents in solid phase after extraction is determined by diffusion resistances R_{MC} and R_{NC} . Analogous mechanisms are in drying.

VII. MATHEMATICAL MODEL OF COMBINED BARODIFFUSION PROCESSES

Let us explain the transfer mechanism from solid phase to solution in extractors by DEA-technologies.

Diffusion in solid phase obeys the Fick's equation. Mass flow j depends on diffusion coefficient in solid phase: $j = -D dc_{\tau} / d\delta$.

Then soluble substances with concentration X_B move inside the capillary to exterior surface where concentration is X_{SURF} . This is convective diffusion in straitened conditions, which intensity is determined by effective mass transfer coefficient β_C . The same flow is given by convection diffusion process (which intensity is determined by mass transfer coefficient β_K) to extractant flow centre with concentration \bar{X}_E :

$$j_1 = \beta_C (X_B - X_{SURF}) = \beta_K (X_{SURF} - \bar{X}_E) \quad (3)$$

Parallel to the flow j_1 in microwave field a flow j_2 appears. Per se it is a barodiffusion which is determined by raised pressure in capillaries. That is particular capillaries, in which conditions for vapor phase are reached, start to eject the liquid from capillaries to the flow periodically. The frequency of ejections from capillaries and the number of functioning capillaries increases with the rise of microwave radiation power. The analogy with boiling liquid vaporization centers is offered [6].

Mass flow j_2 is determined by effective specific mass-transfer coefficient β_P and pressure differential in capillary P_C and flow P_E :

$$j_2 = \beta_P (P_K - P_D) \quad (4)$$

Flow j_2 makes the boundary layer turbulent. General mass flow is: $j = j_1 + j_2$.

The flow j is determined by solid phase diffusion resistance. The j_1 flow overcomes resistances of mass transfer in capillary straitened conditions and convection diffusion sequentially.

At the same time more powerful transfer mechanism which determines j_2 flow that may be several orders major than j_1 is turned on.

The task of further analysis is the problem of concentration distribution on scheme Fig.3. Let us identify the prospects of analytical methods for this purpose.

On the first stage let us imagine solid phase as a plate, washed by laminar layer of liquid. Then representative cell of system will take on the form, depicted on fig. 3. Thickness of boundary layer δ is considerably smaller than plate length L . Longitudinal velocity w changes from 0 on the plate to w_{δ} on the outer boundary of layer. "Plane" diffusion equation which determines concentration C allocation in time τ in one point, convective concentration change while transiting from point to point, which depends on velocity components w_x and w_y has the form [6]:

$$\frac{\partial c}{\partial \tau} + w_x \frac{\partial c}{\partial x} + w_y \frac{\partial c}{\partial y} = D \left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} \right) \quad (5)$$

The first part of equation (5) characterizes molecular diffusion.

Let us set a task to define $c(\tau, x, y)$ function in layer δ , considering that length and width of a plate 1 (Fig.3) rank over the thickness δ substantially. Using Fourier two-dimensional complex transform with infinite limits of integration [6] with initial conditions $c(\tau, x, y)|_{\tau=0} = 0$ and appropriate boundary conditions it is possible to receive the solution under the assumption that velocity components w_x and w_y are set and do not depend on coordinates, diffusion process is plane-parallel and does not depend on Z coordinate. Supposing that desired function $c(\tau, x, y)$ meets the Dirichlet conditions, after assigning two-dimensional transformant of desired function,

performing double integration, changing the exponential expression with first terms of its decomposition on power series subject to problem symmetry (Fig.3), the solution of boundary value problem is being found [6].

On the second stage mass transfer while solution moving inside cylindrical canal is considered. Cases with plane and parabolic velocity profile are analyzed. When plane velocity profile (velocity of solution motion is constant through whole pipe cut) and component A diffuses from canal surface to flow, it is more convenient to represent diffusion equation with coordinates on current radius r:

$$w_0 \frac{\partial X}{\partial Z} = D \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial X}{\partial r} \right] \quad (6)$$

The quantity $D(\partial^2 X/\partial Z^2)$ that characterizes diffusion lengthwise of the channel is negligible as compared with convection component $w_0(\partial X/\partial Z)$.

Having written the boundary conditions, using Bessel's first kind functions, for parabolic velocity profile according to Navier-Stokes equation solution the following equation has been received [6]:

$$w_{\max} \left[1 - \left(\frac{r}{0,5d} \right)^2 \right] \frac{\partial X}{\partial Z} = D \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial X}{\partial r} \right) \quad (7)$$

Finally subject to boundary conditions, the relation (7) is reduced to the kind:

$$\frac{X'' - X'}{X - X'} = 1 - \sum_{n=1}^n a_n \exp - b_n \left(\frac{D}{w_{c.p} 0,25d^2} \right) Z \quad (8)$$

where average flow velocity $w_{CP} = 0,5w_{\max}$ and constants a_n and b_n have values, given in [6].

On the third stage a model of diffusion from a point source to flow is received. This model takes into account barodiffusion action.

The result of microwave field action is the growing pressure gradient inside open pore or capillary (P_C) and in extractant flow (P_E). At the condition $P_C > P_E + P_{HD}$ an ejection from capillary to liquid flow occurs. The capillary hydraulic resistance P_{HD} is included in solution.

Let us consider diffusion flow j of extractive constituents A, ejected to extractant flow that moves in the direction Z with constant velocity w_0 (Fig. 4). In this case the equation $w_0(\partial X/\partial Z) = D\nabla^2 X$ is to be solved.

At the following boundary conditions [6]:

$$\begin{aligned} X|_{l \rightarrow \infty} &= 0; \quad \text{when } l \rightarrow \infty \\ -4\pi l^2 D(\partial X/\partial r) &= M_A, \text{ when } l \rightarrow 0 \\ l^2 &= x^2 + y^2 + z^2 \end{aligned} \quad (9)$$

where l – distance from source; Z – distance from source along the flow; M_A – component A flow rate.

In the case when flow velocity is constant (w_0) and regime is stabilized, the solution with

boundary conditions (9) will be [6]:

$$X = \frac{M_A}{4\pi \cdot D l} \exp \left[- \left(\frac{w_0}{D} \right) (l - z) \right] \quad (10)$$

The problem of point source has practical importance in analysis of concentration profile in flow.

It is obvious that even at so serious reductions of problem that are done above while its formulation, joint solutions (5), (8) and (10) are quite doubtful. Hydrodynamic situation in flow is determined by turbulent flow of extractant, complicated by vertical diffusion from solid phase canals.

Obviously, the promising way of research is experimental modeling. It is known that scientific base of experiment is similarity theory and “dimensional analysis” method.

VIII. THE NUMBER OF ENERGY ACTION.

When combining the extraction process with impulse electromagnetic field the extractant flow from capillaries is initiated. Extract from nanocapillaries ejects to microcapillaries. The frequency of these blowouts and the number of functioning capillaries rise with the radiation power (N) increasing.

The extractant flow turbulizes the boundary layer, barodiffusion mass transfer resistance (R_{PM} and R_{PH}) (Fig. 4) can be by several digits lower than in traditional mass output schemes.

Let us denote barodiffusion flows from nanocapillaries and microcapillaries as j_{NC} and j_{MC} respectively. Reverse extractant flow to capillaries is written as j_E . Then under EMF action (flow I) the priority of flows will be the following: $I \rightarrow j_{MC} \rightarrow j_{NC} \rightarrow j_E \rightarrow I$.

The effectiveness of target constituents extraction from solid phase depends on harmonization of flow I impulses duration and power. At little duration the flow j_{NC} and even flow j_{MC} may not have time to be formed. At long duration and large-scale power the undesirable overheating of solid phase is possible. At more delicate energy supply organization it is rational to change EMF parameters in time according to momentary solid phase dielectric properties values (presence of liquid phase inside), extract concentration in canals, its quantity. EMF magnitude should be coordinated with canals' diameter too – in smaller canals greater pressure difference is required for barodiffusion flow initiation.

The number of energy action offered by author [6] $Bu = N(r \cdot w \cdot d^2 \cdot \rho)^{-1}$ takes into account electromagnetic field action. Correlation between radiation energy and energy, that is necessary for similar processes in conventional technologies,

determines both energy efficiency of equipment and mass transfer regime. Up to certain Bu number values the laminar liquid motion regimes in solid phase canals take place. The Bu number can show the conditions of transition to more intensive mass transfer that is logically to be called turbulent barodiffusion regime. In general form the number of energy action describes ratio of energy consumption of innovation technology (Q) and basic version (traditional technology): $Bu=Q/Q_0$.

For analyzed processes the structures of models in generalized variables and correlations for Bu number calculation are defined by similarity theory methods (Table 2)

This number generalized the bases of experimental data in dehydration and extraction processes successfully [6]. It is envisaged that Bu number can appropriately characterize energy specificity of all problems used in DEA-technologies.

Usage of DEA-technologies in drying of food materials gives a possibility to intensify the process considerably [6]. Organization of two-phase flow composed of vapor and highly dispersed water drops from material volume leads to the result which can not be estimate by traditional thermal efficiency (Table 3). And Bu number allows to give such estimation.

Formulated hypotheses are confirmed practically, the facts that can be explained only from nanosciences positions exist. Such facts, obtained at the Department of Processes and Apparatuses of ONAFT are: changing and transformation of product flavouring and aromatic complexes structure, products sterilization at low temperatures etc. The cause of these facts is common – electromagnetic

field action.

In cognac production the tests of extractor with electromagnetic intensifier have passed successfully. In different operation regimes the intensity of mass-transfer increased dozens and thousands times. The testing results confirmed the proposed mechanism of combined extraction process and the technology perspectives. Degustators discovered the great special mention of product positive structural changing and foremost the aromatic constituents changing.

The regimes of self-cleaning of heat-and-mass recoverer surface are realized in the line of sugar drying and instant coffee production. The 14% decrease of fuel consumption was reached, up to 99 % of powder from used heat carrier was extracted, and aromatic components were captured.

Laboratory tests of cryoelectric freezing-out equipment for lactoserum concentration have shown that a possibility of lactoserum proteins fractionation i.e. receipt of commercially valuable functional ingredients from secondary raw materials has been found.

In food production raw materials have nanoscale elements. These natural nanostructures determine the quality of product and efficiency of technology. Organization and control of action on these natural nanostructures with combination of nano- and macrokinetics capabilities under process impulse-cyclical character conditions opens new perspectives in food technologies.

Formulated hypotheses are confirmed by numerous experiments. Conventional methods do not provide such intensification degree as barodiffusion technologies usage does [10-14].

Table 2. The key equations for DEA-technologies models.

Process	Bu number	Equation
Activation and deactivation of microorganisms	$Bu = N(\zeta VCp\Delta tp)^{-1}$	$Fo = A Re^n Pr^m Bu^k$
Extraction	$Bu = N(rwd^2 \rho)^{-1}$	$Sh = A Re^n Sc^m Bu^k$
Drying	$Bu = N(rV \rho)^{-1}$	$Sh = A Re^n Sc^m Pe^p Bu^k$

Table 3. The drying equipment energy efficiency.

Water removing concept	Specific energy consumption MJ/kg	Heat efficiency factor, %	Bu number
Basic convective drying	6 - 8	0,3 - 0,38	2,6 – 3,5
Grain drying			
- basic 1 st generation	4,26 – 6,3	0,36 – 0,5	1,85 – 2,7
- upgraded 1 generation	3,8 - 5,1	0,45 – 0,6	1,67 - 2,22
- modular 2 nd generation	3,54	0,65	1,54
- recuperative 2 nd generation	2,7 - 2,88	0,8 – 0,85	1,18 - 1,25
-3 rd generation (achieved)	1,9	-	0,82
- 3 rd generation (expected)	0,2	-	0,09

IX. CONCLUSION

Local action on nanoscale elements of food material allow to give new approaches to processes in agricultural sector. New scientific area of food nanotechnologies – the control of transfer processes in nanoscale food structures phase boundary is being developed [15]. The direct energy action may become the instrument of such control. This area is called “DEA-technologies” i.e. technologies of directed (selective) energy action on raw material elements. Subsection of this area is nanoenergy technologies – technologies of directed energy supply to food material nanoscale elements.

For some nanoproceses (Fig. 4), progressing at combined nano- and microproceses action, it is possible to set the modeling tasks when nanoscale influence mechanisms are obvious or predictable. Thus a powerful instrument of nanokinetics initiation is impulse electromagnetic field. Exactly in IEMF conditions it is possible to organize directed local energy supply to polar molecules of food material, i.e. to implement DEA-technologies.

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