PULSED ENERGY SUPPLY IN OIL PRODUCTS' DRYING PROCESS

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Abstract: This type of processing provides possibility of SHF electromagnetic fields' application as a source of thermal energy for oil products' dehydration. It was obtained an optimal regime for the application of this energy in form of pulses. Action duration of internal heat source on the product and rest duration between two consecutive drives were calculated in such a way, that the temperature gradient (which is one of the driving forces of the drying process) in the product maintains maximal values throughout the process. Field strength was chosen such a way, that the temperature gradient to obtain the maximum value, that is recommended by the product temperature regime given by the product drying technology. Pulse amplitude and frequency optimization has allowed a considerable reduction of energy consumption and drying temperature and duration.
Key words: microwave drying, oil products, pulse.

1. INTRODUCTION

Oil products' drying has a special significance in the technological chain of their processing. Requirements in agricultural productions drying are the following: to reduce the drying period, specific energy consumption and to improving the quality of the final product.

Drying processes of agricultural products (particularly oil products) are complex processes based on thermodynamic regularities. Flows (temperature, humidity, concentration, pressure etc.) are functions of material, energy or momentum transfer, for the case when gradients which they are provided by produce are nonzero.

So, the requirements put forward by the drying process can be easily obtained by applying as an energy source the high (UHF) and super high (SHF) frequency electromagnetic fields, in which these gradients are directed from the inner layers of production to the periphery [Ginsburg, A.S., 1973], [Mustyatsa, V.T., 1985], [Rogov, I.A., et al., 1986], [Rudobashta, S.P., et al., 1996]. Moreover, at application of energy in the form of pulse, occurs the amplification of mentioned gradients, which gives way to enhance the drying process even at low temperatures of the production, which is important for oil products (which can be easily oxidized).

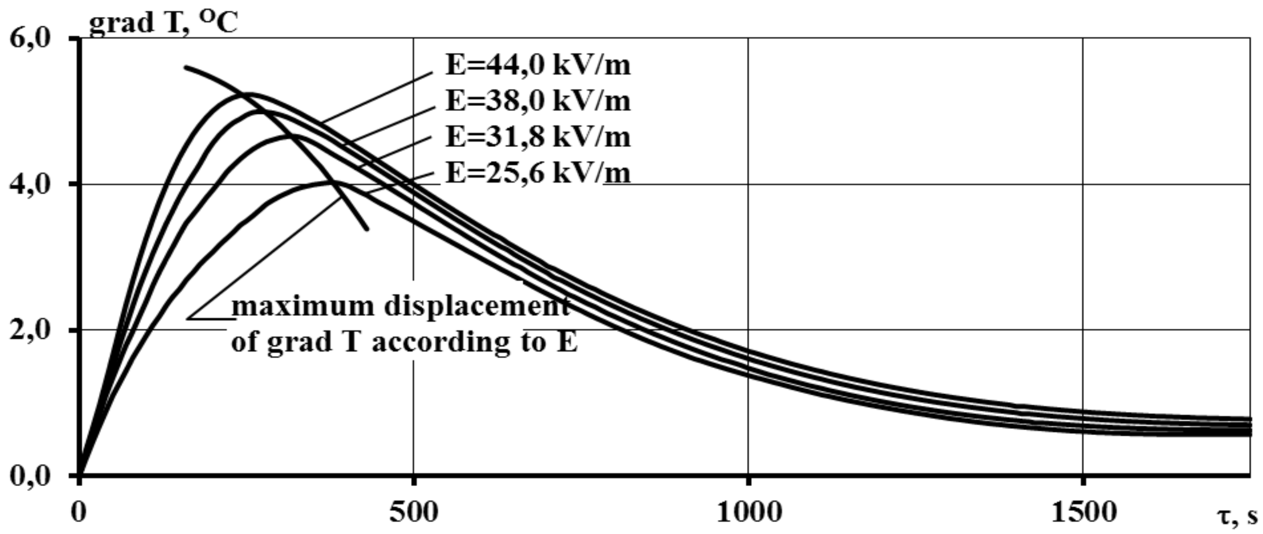

Fig. 1.Temperature gradient variation curves for sunflower seeds, depending on time, when heated in the electromagnetic field f=27.0 MHz, environment temperature 20.0 ^{O}C; product thickness – 0,04m

2. RESULTS AND DISCUSSIONS

Variation of temperature gradient ($\nabla\vec{T}$) in the product, at application of electromagnetic fields is well shown in the graphs in figure 1, obtained experimentally. As shown in the graphs at the initial stage $\nabla\vec{T}$ increases rapidly to a maximum and then decreases slowly. This is due to the thermo physical properties of the production, namely the correlation between the rate of heat transfer within the product and the speed of the heat failure from the surface to the environment.

So, we can conclude that to improve the drying process is sufficient to maintain the maximum temperature gradient, even at lower average temperatures of the production. It may be possible to apply discrete UHF field, allowing us to continue repeating the increasing values of the temperature gradient.

Heating period (active) and rest period (passive) were determined by solving Lycov's differential equations of mass and heat transfer [Lykov, A.V. et al., 1957], [Lykov, A.V., 1948]

$$\frac{\partial T}{\partial \tau} = a\frac{\partial^2 T}{\partial x^2} + \frac{\varepsilon \cdot r}{c}\cdot\frac{\partial u}{\partial \tau} + \frac{Q_V}{c\cdot\rho} \qquad (1)$$

$$\frac{\partial u}{\partial \tau} = a_m\left(\frac{\partial^2 u}{\partial x^2} + \delta\frac{\partial^2 t}{\partial x^2}\right) + \varepsilon\frac{\partial u}{\partial \tau} \qquad (2)$$

$$\frac{\partial p}{\partial \tau} = a_p\frac{\partial^2 p}{\partial x^2} + \frac{\varepsilon}{c_b}\cdot\frac{\partial u}{\partial \tau} \qquad (3)$$

where a is temperature diffusion coefficient, m^2/s;

ε – phase transformation criterion;
r – latent heat of vaporization, J/kg;
c – specific heat capacity, J/(kg·K);
ρ – wet body's dry side density, kg/m^3;
u – humidity, %;
a_m – potential diffusion coefficient, m^2/s;
δ – Sore's coefficient for wet body, K^{-1};
a_p – pressure transfer coefficient, m^2/s;
c_P – mass specific capacity, J/(kg·M);
Q_V – internal heat source W/m^3.

To solve the problem there have been accepted the following boundary conditions:

$$\frac{dT}{dx}(0,\tau) = f(\tau);\quad T(x,0) = \psi(x) \qquad (4)$$

$$\frac{du}{dx}(0,\tau) = f_u(\tau);\quad u(x,0) = \psi_u(x) \qquad (5)$$

$$\frac{dp}{dx}(0,\tau) = f_p(\tau);\quad p(x,0) = \psi_p(x) \qquad (6)$$

At the moment there exist a lot of methods for solving equations (1-3): variable solving method, source method, Laplace operational methods, Fourier string method, Deir method, Gruenberg method, Gudman integration, iterative integration, using of δ functions' properties etc. [Vaenskiy, V.N., 2000]. For the case of impulsion heating with internal heat source, two methods are more efficient: source method and using of δ functions properties. We will examine the source method.

We assume that $T(\xi,\tau)$ is the equation solving:

$$\frac{\partial T}{\partial}(\tau) = a\frac{\partial^2 T}{\partial x^2} + \frac{Q}{c\cdot\rho}\varepsilon\cdot r\cdot\frac{\partial U}{\partial \tau}\,. \qquad (7)$$

Action of the elementary internal source within a body in the case of a one-dimensional heat flow is described with the source function on an infinite section $G(x,\xi,\tau'-\tau)$ [Vaenskiy, V.N., 2000]:

$$G(x,\xi,\tau'-\tau) = \frac{1}{2\sqrt{\pi a(\tau'-\tau)}}\left[e^{-\frac{(x-\xi)^2}{4a(\tau'-\tau)}} - e^{-\frac{(x+\xi)^2}{4a(\tau'-\tau)}}\right]. \qquad (8)$$

where ξ is a spatial coordinate in which the Q_V heat source were applied, m;

x – spatial coordinate which the temperature field was registered in, m;
τ – period of time the Q_V heat source was applied, s;
τ` – period of time from internal heat source applying till temperature fields registration, s;.

Then, partial derivative of $\frac{\partial}{\partial \tau}(GT)$ will be:

$$\frac{\partial}{\partial \tau}(GT) = G\frac{\partial T}{\partial \tau} + T\frac{\partial G}{\partial \tau}\,. \qquad (9)$$

Taking into consideration the equation (7) and relation $\frac{\partial G}{\partial \tau} = a\frac{\partial^2 G}{\partial x^2}$, equation (9) can be presented in the following form:

$$\frac{\partial}{\partial \tau}(GT) = a\left[G\frac{\partial^2 T}{\partial \xi^2} - T\frac{\partial^2 G}{\partial \xi^2}\right] + \\ + \frac{GQ^*}{c\rho} + \frac{\varepsilon\cdot r}{c}\left[G\frac{\partial u}{\partial \tau} - u\frac{\partial G}{\partial \tau}\right]. \qquad (10)$$

If integrating the equation (10) in limits for ξ from 0 to ∞ and for τ from 0 to τ`-α, where $0<\alpha<\tau'$, then we obtain:

$$\int_0^\infty (GT)_{\tau=\tau'-\alpha} d\xi = \int_0^\infty (GT)_{\tau=0} d\xi - a \int_0^{\tau'-\alpha} \left(T \frac{\partial G}{\partial \xi} \right)_{\xi=0} + \\ + \int_0^{\tau'-\alpha} d\tau \int_0^\infty G \frac{Q}{c\rho} d\xi + \\ + \frac{\varepsilon r}{c} \left[\int_0^\infty (Gu)_{\tau=\tau'-\alpha} d\xi - \int_0^\infty (Gu)_{\tau=0} d\xi \right] \tag{11}$$

Now we will go to the α parameters limit. If we accept $\alpha \to 0$, then:

$$\lim_{\alpha \to 0} \int_0^\infty (GT)_{\tau=\tau'-\alpha} d\xi = T(x,\tau), \tag{12}$$

Therefore:

$$T(x,\tau) = \frac{1}{2\sqrt{\pi a \tau}} \int_0^\infty \psi(\xi) e^{-\frac{x^2}{4a\tau}} d\xi - \sqrt{\frac{a}{\pi}} \int_0^{\tau'} \frac{f(\tau)}{\sqrt{\tau'-\tau}} e^{-\frac{x^2}{4a(\tau'-\tau)}} dx + \\ + \frac{1}{2\sqrt{\pi a}} \int_0^{\tau'} \frac{d\tau}{\sqrt{\tau'-\tau}} \int_0^\infty \frac{Q}{c\rho} e^{-\frac{x^2}{4a(\tau'-\tau)}} dx + \frac{\varepsilon r}{c} [u(x,\tau) - \\ - \frac{1}{2\sqrt{\pi a_m \tau}} \int_0^\infty u(\xi) e^{-\frac{x^2}{4a(\tau'-\tau)}} dx \tag{13}$$

Assuming the initial temperature $\psi(\xi) = T_0$, and $\frac{dT}{dx} = T_x = \varphi(\tau) = -\frac{\alpha}{\lambda}(T_P - T_C)$, for active period $\frac{Q}{c\rho} = const \neq 0$ and for passive one – 0, then (13) obtains the following form:

$$T(x,\tau) = \frac{T}{4} erf\left(\frac{x}{2\sqrt{a\tau}} \right) + \sqrt{\frac{a}{\pi}} \int_0^{\tau'} \frac{\alpha}{\lambda} \frac{(T_P - T_C)}{\sqrt{\tau'-\tau}} e^{-\frac{x^2}{4a(\tau'-\tau)}} d\tau + \\ + \frac{1}{2\sqrt{\pi a}} \int_0^{\tau'} \frac{d\tau}{\sqrt{\tau'-\tau}} \int_0^\infty \frac{Q}{c\rho} e^{-\frac{x^2}{4a(\tau'-\tau)}} dx + \\ + \frac{\varepsilon r}{c} \left[u(x,\tau) - u_o erf \frac{x}{2\sqrt{a_m \tau}} \right] \tag{14}$$

During constant drying rate, the moisture transfer depends largely on the temperature and pressure gradient.

For the case of critical moisture content (in products microcapilars is more humidity), these gradients are similar, and facing the same direction.

Maximum gradient values may also be determined by analyzing the formula (14) to the extreme:

$$\frac{dT}{dx}(x,\tau) = \frac{T_0}{2\sqrt{\pi a \tau}} e^{-\frac{x^2}{2a\tau}} - \frac{1}{2\sqrt{\pi a}} \int_0^{\tau'} \frac{f(\tau)}{\tau^{3/2}} d\tau + \\ + \frac{x}{2\sqrt{\pi a}} \int_0^{\tau'} \frac{f(\tau)}{\tau^{3/2}} e^{-\frac{x^2}{4a\tau}} \left(-\frac{2x}{4a\tau} \right) d\tau + \\ + \frac{1}{2\sqrt{\pi a}} \int_0^{\tau'} \frac{dt}{\sqrt{\tau}} \frac{Q}{cr} e^{-\frac{x}{4a\tau}} d\tau = 0 \tag{15}$$

$$\frac{T_0}{\sqrt{\tau}} e^{-\frac{x^2}{4a\tau}} - \int_0^{\tau'} \frac{f(\tau)}{\tau^{3/2}} e^{-\frac{x^2}{4a\tau}} d\tau - \frac{x^2}{2ac} \int_0^{\tau'} \frac{f(\tau)}{\tau^{5/2}} e^{-\frac{x^2}{4a\tau}} d\tau - \\ - \int_0^{\tau'} \frac{f(\tau)}{\sqrt{\tau}} \frac{Q}{c\rho} e^{-\frac{x^2}{4a\tau}} d\tau = 0 \tag{16}$$

In this case:

$$\frac{dT}{dx}(x,\tau) = \frac{T_0}{2\sqrt{\pi a \tau}} e^{-\frac{x^2}{4a\tau}} + \sqrt{\frac{a}{\pi}} \int_0^{\tau'} \frac{\alpha}{\lambda} \frac{\Delta T}{\sqrt{\tau'-\tau}} e^{-\frac{x^2}{4a\tau}} \left(-\frac{2x}{4a\tau} \right) d\tau + \\ + \frac{1}{2\sqrt{\pi a}} \int_0^{\tau'} \frac{1}{\sqrt{\tau'-\tau}} \frac{Q}{c\rho} e^{-\frac{x^2}{4a(\tau'-\tau)}} d\tau \tag{17}$$

Taking into consideration that the initial temperature doesn't influence much the temperature gradient from internal materials layers, then we can admit that $\frac{T_0}{2\sqrt{\pi a \tau}} e^{-\frac{x^2}{4a\tau}} \approx 0$, and:

$$\frac{d}{d\tau}(gradT) = \sqrt{\frac{a}{\pi}} \cdot \frac{\alpha}{\lambda} \cdot \frac{\Delta T}{\sqrt{\tau'-\tau}} e^{-\frac{x^2}{4a\tau}} \left(-\frac{2x}{4a\tau} \right) + \\ + \frac{1}{2\sqrt{a\pi}} \cdot \frac{Q_V}{c\rho} \cdot \frac{e^{\frac{-x}{4a(\tau'-\tau)}}}{\sqrt{(\tau'-\tau)}} = \\ = \sqrt{a} \cdot \frac{\alpha}{\lambda} \cdot \frac{\Delta T}{\sqrt{\tau'-\tau}} \left(-\frac{2x}{4a\tau} \right) + \frac{1}{2\sqrt{a}} \cdot \frac{Q_V}{c\rho} = 0. \tag{18}$$

Therefore:

$$\sqrt{a} \frac{\alpha}{\lambda} \Delta T \left(-\frac{1}{2} \cdot \frac{x}{a\tau} \right) + \frac{Q_V}{2\sqrt{a} \cdot c\rho} = 0, \tag{19}$$

$$\sqrt{a} \frac{\alpha}{\lambda} \Delta T \frac{x}{a\tau} = \frac{Q_V}{\sqrt{a} \cdot c\rho}, \tag{20}$$

$$\tau_A = \frac{\alpha}{\lambda} \cdot \frac{c\rho x}{Q_V} \Delta T \Big|_d = \frac{\alpha}{\lambda} \cdot \frac{c\rho d}{2Q_V} (T_S - T_M). \tag{21}$$

where α is the coefficient of heat transfer, W/(m^2·K);

λ – coefficient of thermal conductivity, W/m·K;

d – characteristic size of material, m;

Q_V – internal heat source power, W/m^3;

T_S – material surface temperature, K;

T_M – ambient temperature, K.

So, in order to obtain a maximum temperature gradient during the thermal treatment process in the electromagnetic field, products active heating period the heating of the product may be determined by formula (21). Namely in period τ_A, temperature gradient reaches the maximal value. Then the temperature gradient begins to decrease, so it is not reasonable to continue heating the material, which can only reduce its quality indices.

After disconnecting the internal heat source, the temperature gradient decreases continuously after some law dependent on thermo physical properties of the material and environment. The numerical value of temperature gradient during this period tends to zero at an infinite period of time.
That is why there is difficult to determinate the rest period duration, depending on behavior analysis of the temperature gradient during lack of energy source.
It is known that while drying using electromagnetic fields of high or super high frequency, the temperature gradient is directed from the center toward the outer layers of material [Dolinskiy, A.A., et al., 1996], [Kovalyova, L.A., et al., 2004], [Malejik, I.F., et al., 2005]. But in some specific conditions, the distribution of humidity can have an opposite character - on the material surface accumulates more moisture than in the center, so the moisture concentration gradient is directed from the surface to the center and prevents moisture transfer to the surface. This is not only due to moisture diffusion, but in particular the presence of steam source inside the material. Evaporation takes place throughout the volume, but in center is more intensive than at the surface. Waters vaporization speed is bigger than steam transfers speed through materials capilars.
As a result, the pressure gradient does appear which due to increased temperature in the center of the material is accompanied by diffusion with sliding in macrocapilars and microcapilar air effusion.
At the presence of free moisture in the material, the pressure gradient becomes the main driving force of the steam transfer at products surface [Ginsburg, A.S., 1973], [Lykov, A.V., et al., 1957].
Temperature distribution on the thickness of the material is described by a parabola, while the pressure is different: the center corresponds to the maximum value and the periphery – to the pressure in the drying chamber.
Stopping the heat source causes excess pressures rapidly relaxation according to an exponential function, which confirms once again major resistance of steam mixtures molar movement into the material.
Rapid relaxation is a consequence of water vapors condensation in the absence of heat source, which in some cases may even cause the creation of vacuum.
So, the relaxation period (lack of internal heat source) is rational to be determined from the analysis of product pressure field.
After switching off the heat source, the removed moistures quota from the phase transfers account is reduced (we can admit that $\varepsilon = 0$) and pressure gradient created within the material relaxes.
During the pressure relaxation, the humidity is removed from the material without the phase transfer "liquid-steam" only due to mechanical extrusion under the action of pressure excess inside the material.
Pressure field from the material is described by the third equation from Lycovs differential equation system, presented in the following way:

$$\frac{\partial p}{\partial \tau} = a_P \frac{\partial P}{\partial x} \tag{22}$$

For this equation resolving, we admit the following initial conditions:

$$p(x,0) = p(x), \tag{23}$$

and boundary conditions:

$$p(0,\tau) = 0 \tag{24}$$

Using the same source method, we obtain the following resolving for equation (23):

$$p = \frac{1}{2\sqrt{a_P \pi \tau}} \int_0^\infty p(x) e^{-\frac{x^2}{4a_P\tau}} dx \tag{25}$$

From equation (25) we determine the pressure gradient in material:

$$\frac{dp}{dx} = \frac{1}{2\sqrt{a_p \pi \tau}} p(x) e^{-\frac{x^2}{4a_P\tau}} . \tag{26}$$

Now we can determine the pressure gradient extreme for relaxation stage (lack of heat source), namely the case when it equals:

$$\frac{d}{d\tau} gradP = -\frac{1}{4\sqrt{a_P \pi \tau^3}} p(x) e^{-\frac{x^2}{4a_P\tau}} + \\ + \frac{1}{2\sqrt{a_P \pi \tau}} p(x) e^{-\frac{x^2}{4a_P\tau}} \left(\frac{x^2}{4a_P \tau^2} \right) = 0 \tag{27}$$

From (2.27), with some changes, we obtain the time duration from heat source disconnection, to pressure gradient disappearance:

$$\tau_P = \frac{x^2}{2a_p} = \frac{d^2}{8a_p} , \tag{28}$$

where d is the thickness of the materials layer, m;
a_p – molar diffusion coefficient, m^2/s.
As seen from the formula, pulse parameters, namely UHF energy intake during the active and passive periods, are functions dependent on thermo physical properties, product and environment temperature and internal heat source power. In turn, these parameters depend on product moisture.
Because for most materials, the molar diffusion coefficient is unknown, it is proposed a method of

determining the physical parameter for a wide range of production.

The molar diffusion coefficient a_P is very difficult to be determined by the analytical method, but can be easily obtained from the study of pressure relaxation in the product.

In the period of pressure relaxation we can admit phase transfer coefficient $\varepsilon = 0$. For this we shall solve the system of differential equations of A.V. Lycov, namely the form shown in (22).

We accept the following boundary conditions:

$$P(x,0) = f(x), \qquad P(R,\tau) = 0 .$$

Taking into consideration (28), solving of the equation will be written as follows:

$$P = \frac{1}{2\sqrt{a_P \pi \tau}} \int_0^{\infty} P(x) e^{-\frac{x^2}{4a\tau}} d\xi . \tag{29}$$

Integral (29) can be solved by decomposition in Fourier series:

$$P = \frac{2}{R} \sum_{n=1}^{\infty} \sin \frac{\pi n \tau}{e} \exp\left(- \frac{n^2 \pi^2 a_P \tau}{R^2} \right). \tag{30}$$

For small intervals of the report $\frac{a\tau}{R^2} \geq 0{,}1$ we can limit it to the first member of the string:

$$P \approx \exp\left(- \frac{\pi^2 a_m \tau}{4R^2} \right). \tag{31}$$

From (31) we obtain:

$$a_P = \frac{4R^2}{\pi^2} \left(\frac{\ln P_2 - \ln P_1}{\tau_2 - \tau_1} \right) \tag{32}$$

That is why, in order to optimize energy intake mechanism, have been obtained functions $\tau_p = f(W)$ and $\tau_p = f(W)$ of second order polynomial form.

$$\tau_A(W) = a_1 \cdot W^2 + b_1 \cdot W + c_1 \tag{33}$$

$$\tau_p(W) = a_2 \cdot W^2 + b_2 \cdot W + c_2 \tag{34}$$

where the coefficients a, b and c are functions dependent of thermo-physical properties of production and internal heat and power source. (4.30)

Functions' charts 33 and 34 for sea buckthorn, almond kernels and sunflower seeds are presented in figures 2 and 3. They were calculated for sea-buckthorn drying temperature of 60 ^{O}C (electromagnetic fields intensity E = 17.4 kV/m) and almond kernels drying temperature of 80 ^{O}C (E = 44.0 kV/m). From the graphics is observed that both active and passive drying period, thus decreasing humidity, are increasing.

Increasing of energy intake duration is the result polar molecules content reduction, which determines the heat source power, while increasing of rest duration (passive period) is determined by changing of electro-physical parameters, thermal conductivity and specific heat capacity.

After applying the obtained model for the electromagnetic fields' application, total duration of the studied oil products' drying process fell by about 17% and UHF energy intake duration - 30%. The average products temperature was reduced by 3-4 ^{O}C, and the temperature gradient increased by about 200%.

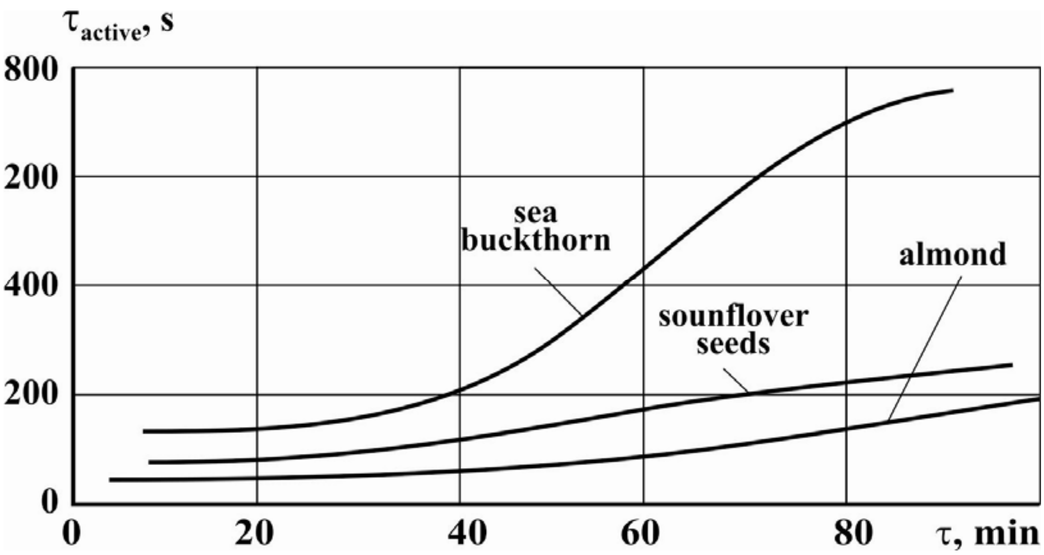

Fig. 2. Active duration of the pulse at UHF energy application for oil products' drying

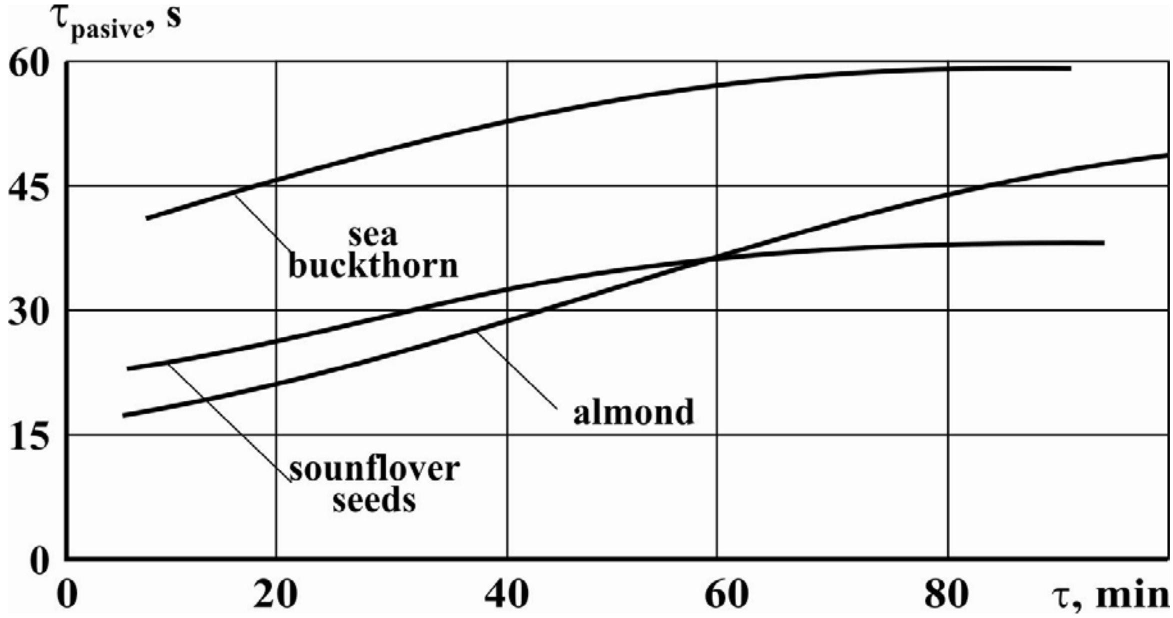

Fig. 3. Pulse duration at UHF energy application for oil products' drying

6. CONCLUSIONS

- Following research carried out to determine the variation of the temperature gradient during thermal treatment of oil products in the electromagnetic field. It was found that ∇T initially increase to a certain maximum value and then decreases to the value "zero" or a minimum constant value, dependent on environmental parameters.
- It was demonstrated the possibility and advantage of the regular application of internal heat source, so during the whole drying process ∇T can maintain maximum values.
- It was determined the heat input period, during an impulse, proceeding from the considerations that ∇T is maximum. It also was obtained the mathematical correlation between τ_A and products' thermo physical properties and other parameters, such as humidity and electromagnetic field strength.
- It was determined the rest period during an impulse, proceeding from considerations of not to allow the inner layers of pressure to be below zero. It was obtained the mathematical correlation between τ_p and thermo physical properties of the product and some parameters of the drying process, such as humidity and electromagnetic field strength.

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