UDC 631.362.23
DOI: 10.15587/1729-4061.2017.102804

MODELING OF THE PROCESS OF OILSEED MEAT COOKING IN A MULTI-VAT COOKER DURING PROCESSING OF OIL RAW MATERIALS

V. Didur
Doctor of technical sciences,
Professor, Head of Department*
V. Tkachenko
PhD
Department of Scientific-research**
A. Tkachenko
PhD
V. Didur
PhD
Department of processes, machinery and
equipment of agroindustrial production**
A. Aseyev
Postgraduate student*
E-mail: anatolyi77777@gmail.com
*Department of technical service in agroindustrial complex
Tavria State Agrotechnological University
B. Khmelnitskoho ave., 18, Melitopol, Ukraine, 72310

Вивчені й проаналізовані процеси, що відбуваються при жарінні м’ятки масличної сировини в кожному чані багаточанної жаровні. Розроблено їх математична модель, що враховує гідродинаміку первинної і вторинної циркуляції, енергію зв'язку вологи з матеріалом. Чисельні рішення моделі дозволять обґрунтувати технологічні режими жаріння і конструктивні параметри жаровні. Складено і проаналізовано тепловий баланс кондуктивного і конвектівного тепло-, масопереносу при сушінні м’ятки

Ключові слова: модель жаріння, гідродинаміка переміщування, кондуктивна і конвективна сушка, багаточанна жаровня

Изучены и описаны процессы, происходящие при жарении мятки масличного сырья в каждом чане многочанной жаровни. Разработана математическая модель этих процессов, учитывающая гидродинамику первичной и вторичной циркуляции, а также энергию связи влаги с материалом. Составлен и проанализирован тепловой баланс кондуктивного и конвективного тепло-, массопереноса при сушке мятки. Численные решения модели позволят обосновать технологические режимы жарения и конструктивные параметры жаровни

Ключевые слова: модель жарения, гидродинамика перемешивания, кондуктивная и конвективная сушка, многочанная жаровня

1. Introduction

The complex technological process, which is carried out in a multi-vat cooker consists in evoking certain physico-chemical changes in oilseed meat and in the structure of its constituents. The oilseed meat thus obtained contributes to the best results in the oil extracting process. During cooking, a moving contact layer is formed above the hot surface of the vat bottom. However, it is important to know for how long this layer of oilseed meat remains on the heating surface. The temperature field of any oilseed meat layer in the direction away from the contact layer decreases continuously. A common process occurs successively in different vats of the multi-vat cooker. It can only be broken up among the vats by the time of the process.

Thus, physical and mathematical representation of these processes is a problem for making a mathematical model of conductive and convective heat and mass transfer in a multi-vat cooker. In this case, the model description should enable obtaining characteristics that estimate movement of the material and heat and moisture carrier, which are in different quantitative ratios.

The process of cooking oilseed meat in a multi-vat cooker during processing of oilseeds is one of the main processes for obtaining high-quality vegetable oils and high-protein forage from oilcakes and seed meat. The pulp resulting in the process of cooking must have a number of technological, sometimes contradictory properties. The particles of the compressed material must have sufficient plasticity. The degree of plasticity should be within certain limits. On the one hand, plasticity should not be below certain limits so as not to impede sufficiently complete plastic deformation of the particles. On the other hand, fluidity of the material should not be excessively high, otherwise the material creeps off the working space of the press or the individual particles are too quickly combined into a dense mass. Compounding of the particles during pressing should take place in a way making it possible to maintain porosity of the pulp. The oil obtained in the gaps between the surfaces must have paths to exit the pulp bed. At the same time, porosity of the cake should be maintained until the end of the pressing to ensure oil outflow.

The optimal conditions of the cooking process depend on many factors: the oilseed crop type, its initial technological properties, selected pressing conditions, requirements to the final products (vegetable oil and cake), location of the process in the processing line, further technology of reprocessing produced vegetable oil and cake.

The study results and practical experience [1–5] have shown that an increased oilseed meat moistening (up to

13.0–13.5 %) can result in obtaining high-quality oil containing minimal amounts of such concomitant substances as phosphatides, carotenoids, suspensions, etc. due to a low temperature of its production.

Experimental studies are necessary to select optimal conditions of the oilseed meat cooking process depending on the type of seeds and other technological properties. Using the methods of numerical studies, optimal technological conditions of the created mathematical models of the cooking process are determined.

2. Literature review and problem statement

Real processes occurring in the course of moisture-thermal treatment of oilseed meat in a multi-vat cooker were described in [6]. The method of constructing boundary conditions for differential equations of heat and moisture transfer during motion of material and heat carrier being in various quantitative correlations was used. However, the work did not take into account hydrodynamics of the primary and secondary circulation of pulp in each vat. Heat consumption for removal of the bound moisture from the solid phase was not taken into account.

As noted in [7], each cooker vat is a turbine stirrer with oblique flat blades. Here, a scheme of decomposition of the total velocity of the pulp in the cooker vat with a stirrer into its components is given and analytical dependences of the component velocities on the resultant unknown velocity are given. Thus, it is impossible to represent numerical solution of such a model.

Thermodynamic characteristics and values of the experimental potential of moisture transfer of sunflower seed elements were determined [8]. The data obtained can be used in calculation and numerical studies of sunflower seed oilseed meat.

Two approaches were used in modeling the process of drying dispersed material in a fluidized bed [9]: a statistical model and a model in generalized coordinates of the drying process. The first model was developed using semi-empirical zonal method of calculation. This model is valid for mathematical description of kinetics of the process of drying the object under study. The mathematical model in generalized coordinates was created for the possibility of spreading the results of the drying kinetics studies to such materials taking into account invariance of criteria and similarity simplex. The probable drawback of the proposed model is its inapplicability to theoretical modeling before conducting experimental studies.

Studies of drying and heat treatment of edible plant raw materials were carried out in [10]. The model of the process of drying grains with superheated steam was formulated and experimentally confirmed. However the work did not take into account heat consumption for removal of moisture bound with a solid phase.

At the present stage in the field of process description, it is necessary to make such mathematical models, which would allow one to carry out comparative calculation of various options of realizing the drying process, manage it and reliably transfer the results of laboratory studies to industrial facilities without excessive costs for carrying out experimental studies [11]. The issues of the product quality, energy saving and ensuring high efficiency of the drying stage in general are at the forefront in the hardware and technological design of the process. However, hydrodynamics of the primary and secondary circulation of material in the drying chambers and the heat consumption for removal of moisture bound with the solid phase were not taken into account when developing mathematical models of the drying processes.

Solution of Lykov equations [12] for the non-stationary grain drying process in analytical form by the method of decomposition into modified Fourier series with their organization enabling retaining of one summand during decomposition was obtained. When using the system of Lykov differential equations, it is more expedient not to specify the law of potential variation to the medium but to use balance equations that directly reflect the changes in potentials.

A technology was proposed for enzymatic extraction of vegetable oil with obtaining high-protein cake from oilseeds [13]. Enzymatic extraction treatment (EAEP) as a possible alternative to screw pressing and the technology of organic solvent extraction is a promising method for simultaneous extraction of oil and protein from oilseed. This method includes disintegrating extraction buffers and enzymes, which ensure obtaining of a number of oils and proteins though various problems arise in the course of the process. The necessity of acceptable, high free oil yields and protein purity are always incompatible in many processes.

To use castor seeds in production of castor oil, a method is described for extracting soluble proteins, which include ricin toxin without formation of a fine, dangerous to inhale powder [14]. The method involves homogenizing the seeds in toluene followed by extraction into a buffer and centrifugation. Samples prepared using the two methods had similar levels of ricin but the use of toluene and extraction of the buffer resulted in a higher throughput for ricin analysis and eliminated the inhalation hazard of castor acetone powders.

Technologies based on vibration spectroscopy can continuously monitor quality of edible oils in the production line [15]. Portable devices give quick information about oil characteristics at various steps of production. Obviously, such systems enable raising level of both production and experimental studies.

An improved method of extracting castor oil from seeds for detecting toxins has been proposed [16]. For ricin analysis, a pair of monocloned antibodies was found that could distinguish structurally between toxin protein and agglutinin associated with it. This method made it possible to determine the quantitative ratio of the two toxin fractions.

Methods for producing biodiesel fuel from castor oil were described in [17]. Biofuel was obtained from castor oils obtained by cold and hot pressing. The received fuel was used for diesel engines of any modification. However, this technology was developed for the local conditions of Africa and was not commercially applicable for other conditions.

The European Union planned to increase the land area under oil crops by almost 12 million hectares [18] in 2016–2017. The growth in this area was announced at the expense of all three main oil crops: rape, sunflower and soy. The growth was expected in such main producing countries as Spain, Romania and Bulgaria. It should compensate small declines in France, Hungary and especially Italy. Greater sunflower seeding areas were motivated by a better profit margin.

The analysis made by European Union concerning growth of oilseed yield in 1913 compared with 1912 is given [19]. The main contributor was rape with a yield of 21.0 million tons (+9.2 %) followed by sunflower with 9.2 million tons (+28.6 %). Good harvests were obtained due to weather conditions, especially in southern Europe (+40.7 % in Spain, +34.5 % in Italy) compared to 2012.

The literature analysis shows that the subject under consideration is of concern in Ukraine and Russia. Abroad, a great preference is given to the technology of processing castor seeds. However, sunflower, rape and soy are leading oil-bearing crops in Europe.

Among the sources considered, no studies on kinetics and dynamics of oilseed meat motion in the vats of a multi-vat cooker were found. Conductive and convective heat exchange cannot be described without a mathematical description of the hydrodynamics of the primary and secondary circulation of the oilseed meat in each vat.

3. Objective and tasks of the study

This work objective was to develop an improved mathematical model of the processes that occur in cooking oil-bearing raw materials in a multi-vat cooker taking into account hydrodynamics of the oilseed meat and the energy of bond of moisture with the material. Numerical solution will enable substantiation of the design and technological parameters of the device for moisture-thermal preparation before oil extraction. To achieve this goal, it was necessary to solve the following tasks:

– to determine geometric dimensions of the device and an optimum number of sections;

– to determine dynamics of oilseed meat motion across the blades of the turbine mixer in the cooker vat;

– to propose a heat balance of conductive and convective heat and mass transfer.

4. Materials and methods of research into the process of cooking oilseed meat

When studying the general processes of motion of two pulp phases, a method of soil mechanics for studying the consolidation processes was used. However, the method should be further developed for the conditions of the oilseed meat consolidation processes. It is necessary to revise rheological equations for each phase of the pulp, the nature of interaction, the changes in the ratio of the pulp phases in a unit volume in time and in the working cavity of the device. It is important to take into account the impact of joint action of steam and water treatment.

The transition from modeling individual devices to modeling complex schemes is associated with a significant increase in complexity and dimension of the problems being solved and characterized by a large number of equations and variables. Therefore, one of the peculiarities of the problem is reduction in dimensionality of the problem being solved. It is often achieved by reducing the problem of large dimensionality to a certain set of interrelated tasks of smaller dimensionality.

The performed research is of a purely theoretical nature, it reveals a number of important processes and features when cooking oilseed meats in a multi-vat cooker. The work makes it possible to compile a program of experimental studies and clarify the possibility of applying research methods. For this purpose, a laboratory complex has been designed, built and put into operation to study the processes of oilseed meat cooking and oil extraction from the resulting pulp.

5. Results of studies into the process of oilseed meat cooking

Single-chamber fluidized bed devices have a significant drawback consisting in an uneven processing of individual material particles. As is well known, this unevenness is caused by the difference in the time of staying of individual particles or groups of particles of bulk material in the fluidized bed [20]. This worsens processing conditions for individual particles and reduces the overall depth of drying.

On the other hand, a long residence time in the device leads to a prolonged overheating of the dried particles at the maximum temperature and deterioration in quality of materials, especially thermolabile ones.

The simplest way to eliminate this drawback is sectioning of the fluidized bed device. With an increase in the number of successive sections, the material particles are more evenly distributed in time of staying in the device approaching the distribution of complete displacement. It results in a more even and deep drying of the material.

Therefore, the main task in modeling the cooking process is determining geometric dimensions of the device, an optimum number of sections and technological parameters of the drying process. Application of the proposed device parameters will make it possible to obtain a product of a specified quality. This product will have required average humidity and moisture dispersion $\sigma^2(u)$:

$$\sigma^2(u)=\int_0^\infty u^2\rho(u)du-\left(\int_0^\infty u\rho(u)du\right)^2. \qquad (1)$$

Moisture dispersion $\sigma^2(u)$ is set in a percentage of the final moisture content u_{fin} in the material.

The situation in question is applicable to the theory of a multi-vat cooker for cooking oilseeds. In this case, only two parameters can be independent: the cross-sectional area of the vat and the number of vats. The rest must be specified or determined from other conditions: steam flow rate, steam inlet temperature and the bed height. Fig. 1 is a block diagram for calculating the continuous drying process in a multi-vat cooker. The following designations were taken in Fig. 1: $\bar{u}$, u_{fin} are average and final moisture contents in the material respectively, $\sigma^2(u)$ is moisture dispersion; ε is permissible deviation of the absolute humidity difference $|\bar{u}-u_{fin}|$; Δu is permissible deviation of moisture dispersion.

In work [7], each cooker vat is presented as a turbine mixer with inclined flat blades. The particle motion along the horizontal disk rotating around the vertical axis and having straight, vertically fixed blades on it was considered in work [21], (Fig. 2).

Based on the applied forces, a differential equation of particle motion in the direction of the blade was made:

$$m\xi''=mr\omega^2\cos\psi-fmg+fmr\omega^2\sin\psi-2fm\omega\xi', \qquad (2)$$

where ψ is the angle between the radial direction and the direction of the blade; f is the coefficient of friction on the disk surface; ω is the angular velocity; m is the mass of the oilseed meat particle; r is the radius of the mixer disk; ξ' is relative velocity of the oilseed meat particle moving in the direction of the blade plane; ξ'' is acceleration of the oilseed meat particle in relative motion parallel to the blade plane. The initial equation (2) was presented in a more practical form:

$$\xi'' + 2f\omega\xi' - \omega^2\xi = r_0\omega^2\frac{\cos(\psi_0 \pm j)}{\cos j} - fg, \qquad (3)$$

where ψ_0 is the initial value of the angle ψ, j is the angle of friction; r_0 is the distance of the blade beginning from the disk center.

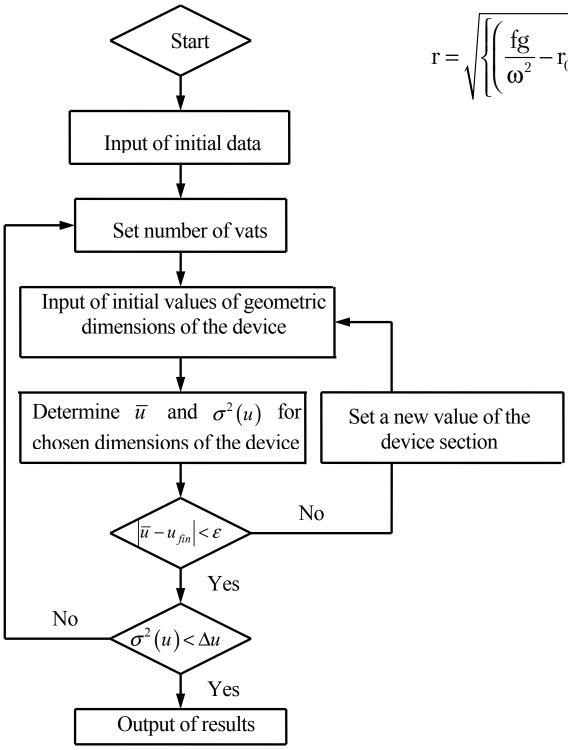

Fig. 1. Block diagram of calculation of the continuous cooking process in a multi-vat cooker

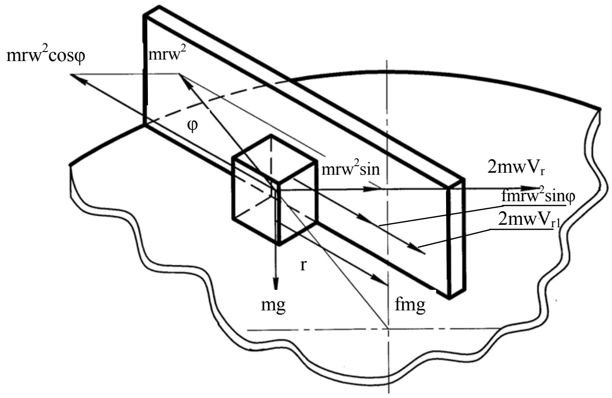

Fig. 2. Diagram of applying forces to the particle of the oilseed meat when moving on a horizontal disk with straight blades [21]

When the blade is tilted forward, $\cos(\psi_0+j)$ must be used.

When the blade is tilted backwards, $\cos(\psi_0-j)$ must be used.

Characteristic equation of the differential equation (3) of the additional function has the form:

$$\lambda^2 + 2f\omega\lambda - \omega^2 = 0, \qquad (4)$$

where λ_1 and λ_2 are the roots of the characteristic equation (4)

$$\lambda_1 = \omega\left(\sqrt{1+f^2} - f\right); \quad \lambda_2 = \omega\left(-\sqrt{1-f^2} - f\right).$$

Solution of equations (2), (3) can be written in a form convenient for practical use in calculations as:

$$r = \sqrt{\left\{\left(\frac{fg}{\omega^2} - r_0\frac{\cos(\psi_0 \pm j)}{\cos j}\right)\left[\frac{1}{\lambda_2 - \lambda_1}\left(\lambda_2 e^{\lambda_1 t} - \lambda_1 e^{\lambda_2 t}\right) - 1\right] + r_0\cos\psi_0\right\} + r_0^2\sin^2\psi_0}. \qquad (5)$$

The relative velocity of the particle movement in the blade direction

$$\xi' = v_\xi = \left(\frac{fg}{\omega^2} - r_0\frac{\cos(\psi_0 \pm j)}{\cos j}\right)\left[\frac{\lambda_1\lambda_2}{\lambda_2 - \lambda_1}\left(e^{\lambda_1 t} - e^{\lambda_2 t}\right)\right], \qquad (6)$$

where t is time, s.

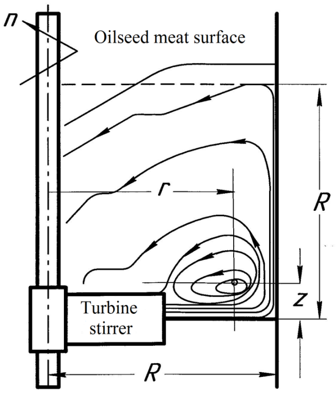

Fig. 3. Structure of the secondary flow circulation in a turbine stirrer [22]

For carrying out numerical studies, establish initial data of the mathematical model:

– the friction coefficient of the castor seed oilseed meat is equated to the friction coefficient of the castor seed core: f=0.35 for sheet steel; tgϕ=0.35; ϕ=19.29°=0.3367 rad;

– the stirrer disc radius r=0.4 m;

– the stirrer rotation speed n=21÷35 rpm;

– the height of the oilseed meat layer in the vat H==350÷400 mm, the initial value of angle ψ_0=0°÷15°.

To assess performance of the cooker vat with a stirrer, use the concept of circumferential (peripheral) and radial-axial circulation [23]. These parameters take into account decomposition of the total liquid flux from the stirrer into two circulation streams. The liquid particles in these fluxes move along the circles concentric to the device axis in horizontal planes perpendicular to the axis. Also, the particles move in vertical (meridional) planes intersecting the device axis.

Circumferential circulation (also called primary circulation) is associated with rotation of the whole mass around the stirrer axis of rotation. The structure of the secondary circulation for a turbine stirrer in each vat of a multi-vat cooker is shown in Fig. 3. The turbine stirrer creates a flow of oilseed meat having radial and tangential components.

On the wall of the cooker, this stream slows down, changes its direction to the axial one, rises up to the free surface and again turns from there in the stirrer direction.

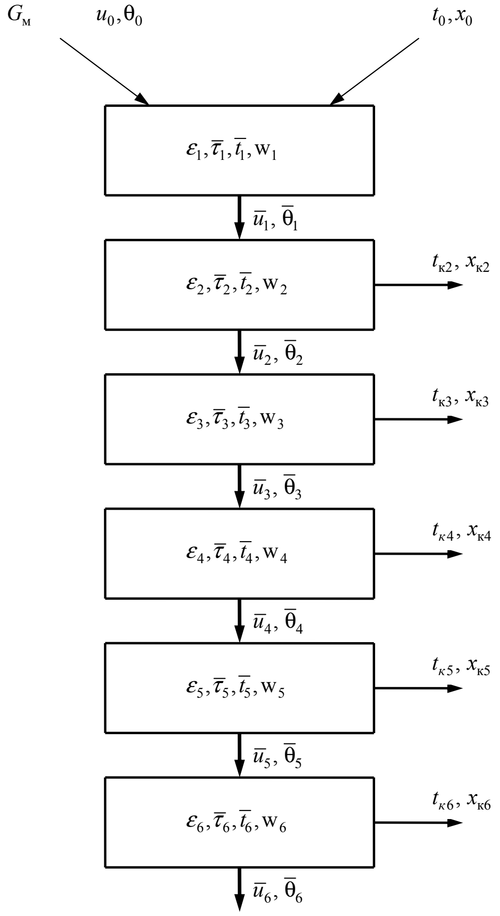

Fig. 4. Calculation scheme of a six-vat cooker

Thus, closed circulation loops with center 0 are formed. Point 0 represents a location where the radial and axial velocity components are zero. For devices without partitions, $V=1.9V_0$.

Fig. 4 shows the calculation diagram of the six-vat cooker. The following designations are used in this figure: G_M is productivity of the cooker in processing oilseed meat with an initial humidity u_0 and temperature θ_0; t_0, x_0 are the initial temperature of the heat-carrying agent and its moisture content; ε, τ, w are separatel of the layer, the time of cooking in one vat and the average velocity of the oilseed meat particle flow respectively. The applied indices 1, 2, ..., 6 correspond to the vat order numbers starting from the upper vat where the initial oilseed meat enters.

The main calculation option is a line with a productivity of 15 tons/day operating 24 hours a day without preliminary husk separation. Then the average hourly capacity of the line is 625 kg/h. Loading of the vats will depend on the selected number of vats and the technological time of cooking.

The algorithm for the multi-vat cooker (Fig. 4) consists of a sequential application of the calculation dependencies given when considering cooking calculation in each of the vats, which makes it possible to calculate "from vat to vat". In this case, the output parameters of the previous vat serve as the input parameters of the subsequent vat.

Discrete model of the moving contact layer in the vat

When cooking, a moving contact surface is formed at the hot surface of the vat bottom. The temperature field of any oilseed meat layer in the direction away from the contact layer decreases continuously. The moisture content distribution in the drying process is uneven and asymmetrical: it is minimal in the layer contacting the hot surface and increases in the direction from the hot surface. The difference in moisture contents within the contact layer is created thru vaporization which occurs at different intensities depending on the layer coordinate.

However, the process of cooking, more precisely the heat and mass transfer from the heated vat surface to the free surface of the oilseed meat taking into account evaporation of moisture due to contact heating, can be only described in space and time. In space and time' means, first of all, in which vat of the multi-vat cooker by the order number (starting from the top) the process is considered. If the total cooking time is τ_c and the number of vats is N, then the cooking time in one vat

$$\tau_v = \frac{\tau_c}{N},$$

where N takes values of 1, 2, ..., N.

It is the study of the processes in time, which is determined by the velocity of hydrodynamic fluxes of pulp in each vat in the entire multi-vat cooker that allows the process to be tied to a specific design of the multi-vat cooker.

In the study of hydrodynamics of the elementary oilseed meat layer in a separate vat of the n-vat cooker, a separate cycle of processing this elementary layer will be considered. The cycle consists of heating it on the hot bottom surface for an elementary time interval τ_H, and the time τ_H of motion from the vat bottom surface to the free surface of the oilseed meat. The heating time τ_H is equal to the time of the oilseed meat staying on the bottom disc with radius r and determined in studying travel of the oilseed meat along the disk with straight blades. The travel time τ_H is determined from the already known axial velocity v_0 and the height H of the oilseed meat layer:

$$\tau_H = \frac{H}{v_o}. \quad (7)$$

To analyze the temperature field and the moisture content distribution at the hot surface of the vat bottom, represent the moving contact layer as a discrete model. This model consists of elementary layers of the processed material altering in elementary time intervals [24]. Represent the thick oilseed meat layer H as a sum of n thin elementary i-th layers with their height of Δl (m). Divide time τ of drying in one vat into m elementary j-th layers with their length equal to the time interval Δτ (s).

Moisture evaporated by contact heating of the oilseed meat gives its heat to the higher and colder oilseed meat layers partially condensing on them. The water vapor L at the entrance to the elementary layer i at time j has initial moisture content equal to the final moisture content (j–1) of the layer at time (j–1) and the initial temperature equal to the final layer temperature (j –1) at time (j–1).

Then, the moisture content U in a discrete model can be described by a matrix of size m×n where i is the row number and j is the column number and its elements denoted by u_{ij} are at the intersection of rows and columns

$$U=\begin{bmatrix} u_{11} & u_{12} & \dots & u_{1n} \\ u_{21} & u_{22} & \dots & u_{2n} \\ \dots & \dots & \dots & \dots \\ u_{m1} & u_{m2} & \dots & u_{mn} \end{bmatrix},\ i=1, 2,\dots, m;\ j=1, 2, \dots, n. \tag{8}$$

The moisture mass in the thick oilseed meat layer is determined by the matrix

$$B=C\cdot U, \tag{9}$$

where C is row vector of the dry matter

$$C=\left[m_1\ m_2\ \dots\ m_m\right], \tag{10}$$

where m is the mass of the dry oilseed meat substance in the elementary layer i.

The average-volume moisture content of the oilseed meat in the whole layer $\bar{U}$

$$\bar{U}=B/M_t, \tag{11}$$

where $M_t=m_t\cdot m$ is mass of dry matter in the thick layer.

When analyzing the heat balance of conductive and convective heat and mass transfer, consider three periods of the process:

- evaporation of moisture by heating oilseed meat using contact method;
- cooling water vapor to the temperature of wet thermometer with the return of its heat to the surrounding layers of the oilseed meat;
- vapor condensation at the temperature of wet thermometer and heat transfer to the surrounding layers.

Evaporation of moisture due to oilseed meat heating by contact method.

Simplify the basic equation of heat and moisture exchange for contact drying on the heating surface and determine equivalent thermal conductivity, temperature gradient and density of heat and moisture fluxes [25]

$$q=-\lambda_e\cdot \mathrm{grad}(t)=r_{swe}j_{mo}, \tag{12}$$

where λ_e is the equivalent coefficient of thermal conductivity taking into account heat transfer by steam as well, W/(m·K); grad (t) is temperature gradient inside the material at the interface with the heated surface, K^0/m; r_{swe} is specific heat of evaporation, J/kg; j_{mo} is density of moisture flow, kg/(m^2·s).

Due to the small thickness of the contact layer, the temperature gradient inside the material near the heating surface can be determined from the following relationship:

$$\mathrm{grad}(t)=\frac{t_{warm}-t_{con}}{h_{con}}. \tag{13}$$

Density of the heat flux produced by the indirect heating vapor of the bottom of the vats is determined from expression:

$$q_q(\tau)=\frac{D(i-q)}{F}, \tag{14}$$

where q_q (τ) is the heat flux density, W/m^2; D is consumption of indirect heating vapor, kg/s; i is the heating steam enthalpy, J/kg; q is the heat content of condensate, J/kg; F is the area of the cooker vat bottom, m^2.

Density of steam flux [6]:

$$j_{vap}=\frac{\frac{D(i-q)}{F}+\lambda_q\frac{dt}{dn}}{h_{se}}, \tag{15}$$

where λ_q is the coefficient of thermal conductivity, W/(m·K); h_{se} is the specific enthalpy of steam, J/kg.

By using relationship (15), it is possible to calculate the vapor flux density in the material sections located near the heating surfaces.

Cooling water vapor down to the wet thermometer temperature with the return of its heat to the surrounding oilseed meat layers. To determine moisture content and temperature of steam/air mixture when leaving each elementary layer, construct equations of the material and heat balances of the cooking process for an elementary layer.

Represent *material balance* of the elementary layer proceeding from the evaporated moisture by the following expression:

$$L\left(\bar{x}_{fin}-\bar{x}_{ffin}\right)=m_{т}\left(u_{fin}-u_{in}\right), \tag{16}$$

where $L=L_{vap}+L_{mo}$ is consumption of the vapor/air mixture, kg in time Δτ, s; the amount of air coming into the cooker vat $L_{в}=1{,}6\frac{p_{п}}{p_{в}}\Delta W$, kg [26] where ΔW is the amount of moisture evaporated in the vat, kg; p_{vap} is partial pressure of vapor in a vat, ata; p_{air} is partial pressure of air in the vat, ata; xf_{in}, xf_{fin} is the moisture content of the vapor/air mixture at the entrance to the i-th elementary layer and at the exit from the i-th elementary layer respectively, kg/kg in a time interval Δτ from τ_j to τ_{j+1}; m_r is mass of the dry matter in the elementary oilseed meat layer; u_{in}, u_{fin} is the moisture content of the oilseed meat at the beginning and the end of the i-th elementary layer respectively, kg/kg.

Heat balance of drying the i-th layer in the period of speed fall, according to the law of conservation of energy:

$$Q_{dg.in}+Q_{vap.in}+Q_{sp.in}+Q_{mo.in}= \\ =Q_{dg.fin}+Q_{vap.fin}+Q_{sp.fin}+Q_{mo.fin}+Q_{b.mo.fin}+Q_{loss}, \tag{17}$$

where $Q_{dg.in}$, $Q_{dg.fin}$ is heat of the initial and spent dry agent; $Q_{vap.in}$, $Q_{vap.fin}$ is the heat of the initial and spent vapor phase of the agent; $Q_{sp.in}$, $Q_{sp.fin}$ s the initial and final heat of the hard oilseed meat phase; $Q_{mo.in}$, $Q_{mo.fin}$ is initial and final heat of the wet phase; $Q_{b.mo}$ is the heat spent on removing bound moisture from the hard oilseed meat phase; Q_{loss} is heat loss, J.

The indices used here, dg, var, sp, mo, b.mo, loss mean dry gas, vapor, solid phase, moisture, bound moisture, heat loss, respectively; indices in and fin are the initial and final states, respectively.

$$Q_{dg}=c_{dg}L_{mo}t_i,$$

where

$$c_{dg}=c_{air}=1{,}01\ \mathrm{kJ/(kg{\cdot}K)}\ \text{(at constant pressure) [27]}$$

$$Q_{vap}=L_{vap}\left(r_0+c_{vap}t\right)=L_{vap}\left(2500+1{,}875t\right),$$

where

$$c_{vap} = 1{,}875\ \text{kJ/(kg·K)};$$

$$Q_{sp} = c_{sp} m_{sp} t_{sp};$$

$$Q_{mo} = c_{mo} \bar{u}_{sp} m_{sp} t_i;$$

$$Q_{b.mo} = \frac{1}{18}\left(\bar{u}_{i.in} - \bar{u}_{i.fin}\right) m_{sp} R\left(273 + t_i\right) \ln j; \tag{18}$$

Q_{loss} is heat loss, J.

Upon substituting values of the incoming and spent heat components into equation (17) and corresponding transformations, vapor temperature at the exit from the elementary i-th layer is obtained:

$$\begin{aligned} t_{vap.fin} = {} & \frac{1}{1{,}875 L_{vap.fin}} \times \\ & \times \left[c_{dg} L_{mo} \left(t_{i.in} - t_{i.fin}\right) + c_{sp} m_{sp} \left(t_{i.in} - t_{i.fin}\right) + \right. \\ & \left. + c_{mo} m_{sp} \left(\bar{u}_{sp.in} t_{i.in} - \bar{u}_{sp.fin} t_{ifin}\right) \right] - \\ & - \frac{1}{1{,}875 L_{vap.fin}} \times \\ & \times \left[\frac{1}{18}\left(u_{i.in} - u_{i.fin}\right) m_{sp} R\left(273 + \bar{t}_i\right) \ln j + 2500 L_{vap.fin} \right]; \end{aligned} \tag{19}$$

where c_{dg}, c_{vap}, c_{sp}, c_{mo} is the specific heat capacity of dry air, vapor, dry oilseed meat matter, water, respectively, kJ/kg·deg; $\frac{1}{18}\left(\bar{u}_{i.in} - \bar{u}_{i.fin}\right) m_{sp}$ is conversion of moisture evaporated in the elementary layer into the number of water molecules; 18 is molecular mass of water.

Under mild drying conditions, when the temperature of the solid phase (seeds) is below 100 °C, moisture moves under the effect of moisture-content gradient and temperature gradient. In this case, the total moisture flux can be arbitrarily divided into two fluxes: the flux caused by the mass conductivity (moisture conductivity) and the flux caused by thermal-mass conductivity (thermal-moisture conductivity):

$$q_m = q_{mu} + q_{mt}, \tag{20}$$

where q_m is the total moisture flux, q_{mu} is the flux due to mass conductivity; q_{mt} is the flux due to thermal-mass conductivity.

In its expanded form, equation (20) is written as:

$$q_m = -a_m \gamma_o \cdot \text{grad}(u) - a_m \gamma_o \delta \cdot \text{grad}(t), \tag{21}$$

where $a_m = \frac{\lambda_m}{c_m \gamma_o}$ is the coefficient of potential conductivity of the substance, m^2/h; λ_m is coefficient of mass (moisture) conductivity, kg/(m·h); c_m is the material mass content, kg/kg; γ_0 is density of dry material, kg/m^3; grad(u) is gradient of moisture content, m^{-1}; δ is thermogradient coefficient, 1/°C; grad (t) is temperature gradient, °C/m.

At a negative sign of the moisture content and temperature gradients in equation (21), direction of the moisture flux vector does not coincide with the direction of the gradients and moisture moves from the inner layers to the outer layers (drying).

At a positive sign of gradients, equation

$$q_m = a_m \gamma_o \cdot \text{grad}(u) + a_m \gamma_o \delta \cdot \text{grad}(t), \tag{22}$$

will correspond to the moisture movement from the outer layers to the inner (humidification). As usual, this situation occurs in the first vat when the oilseed meat is moistened to specified initial moisture content.

For severe drying conditions, instead of equation (20), it is necessary to write the following:

$$q_m = q_{mu} + q_{mt} + q_{mp}, \tag{23}$$

where q_{mp} is density of the moisture flux moving due to the pressure gradient.

Equation (23) is written in an extended form as follows:

$$\frac{du}{d\tau} = a_m \frac{d^2u}{dx^2} + a_m \delta \frac{d^2t}{dx^2} + D \frac{d^2p}{dx^2}. \tag{24}$$

At a high-temperature (>100 °C), hard drying, moisture transfer proceeds mainly under the influence of the pressure gradient, and the role of the gradients of moisture content and temperature is very small. In equation (23), the principal role is played by the pressure term:

$$\frac{du}{d\tau} = D \frac{d^2p}{dx^2}. \tag{25}$$

The coefficient of diffusion of water vapor into air is determined as:

$$D = D_o \frac{P_o}{P} \left(\frac{T}{T_o}\right)^{1.5}, \tag{26}$$

where D_0 is the coefficient of water vapor diffusion into air under normal conditions (T_0=273 R, P_0=101,325 Pa). D_0=2.2·10^{-5} m^2/s.

Condensation of vapor at the wet thermometer temperature and heat transfer to the surrounding layers. When gradual cooling of the moist gas takes place, then depending on the water vapor content in it, the maximum possible density of water vapor ρ_H comes, a saturated state of water vapor at which air of the given state becomes saturated and vapor condensation comes.

To determine the moisture content and temperature of a vapor/air mixture at the exit from each elementary layer, formulate equations of material and heat balance of the cooking process for an elementary layer.

Represent *the material balance* of the elementary layer proceeding from the evaporated moisture as:

$$L\left(\bar{x}_{f.in} - \bar{x}_{f.fin}\right) = m_{sp}\left(\bar{u}_{in} - u_{fin}\right), \tag{27}$$

$L=L_{\text{п}}+L_B$ is vapor/air mixture consumption, kg in time $\Delta\tau$, s;

The heat balance of the i-th layer drying during vapor condensation at the wet thermometer temperature, according to the law of energy conservation when the heat input to the cooker should be equal to its consumption will have the following form:

$$\begin{aligned} & Q_{dg.in} + Q_{vap.in} + Q_{sp.in} + Q_{mo.in} = \\ & = Q_{dg.fin} + Q_{mo} + Q_{sp.fin} + Q_{mo.fin} + Q_{b.mo} + Q_{loss}, \end{aligned} \tag{28}$$

where $Q_{dg.in}$, $Q_{dg.fin}$ is heat of initial and spent dry agent; $Q_{vap.in}$, Q_{mo} is heat of the initial vapor phase of the agent and its spent liquid phase; $Q_{sp.in}$, $Q_{sp.fin}$ is initial and final heat of the hard oilseed meat phase; $Q_{mo.in}$, $Q_{mo.fin}$ is initial and final heat of the wet phase; $Q_{b.mo}$ is the heat spent for removal of the bound moisture from the hard oilseed meat phase; Q_{loss} is heat loss, J.

By analogy with the heat balance (17), disclose values of the components in (28)

$$\begin{aligned}
&L_{dg}c_{dg}t_{i,in}+L_{vap}\left(2500+1.875t_{i.vap.in}\right)+\\
&+c_{sp}m_{sp}t_{i.in}+c_{mo}\overline{u}_{sp.in}m_{sp.in}t_{i..in}=\\
&=L_{dg}c_{dg}t_{i.fin}+L_{vap}c_{mo}t_{i.fin}+c_{sp}m_{sp}t_{i.fin}+\\
&+c_{mo}\overline{u}_{sp.in}m_{sp}t_{i.fin}+\\
&+\frac{1}{18}\left(u_{i.in}-u_{i.fin}\right)m_{sp}R\left(273+\overline{t}_i\right)\ln j+Q_{loss}.
\end{aligned}\tag{29}$$

As a result, temperature at the exit from the i-th layer in the period following the vapor condensation

$$\begin{aligned}
t_{i.fin}=&\frac{\left(L_{dg}c_{dg}+c_{sp}m_{sp}+c_{mo}\overline{u}_{sp.in}m_{sp}\right)}{L_{dg}c_{dg}+L_{vap}c_{mo}+c_{sp}m_{sp}+c_{mo}\overline{u}_{sp.in}m_{sp}}+\\
&+\frac{L_{vap}\left(2500+1.875t_{i.vap.in}\right)}{L_{dg}c_{dg}+L_{vap}c_{mo}+c_{sp}m_{sp}+c_{mo}\overline{u}_{sp.in}m_{sp}}-\\
&-\frac{\frac{1}{18}\left(u_{i.in}-u_{i.fin}\right)m_{sp}R\left(273+\overline{t}_i\right)\ln j+Q_{loss}}{L_{dg}c_{dg}+L_{vap}c_{mo}+c_{sp}m_{sp}+c_{mo}\overline{u}_{sp.in}m_{sp}}.
\end{aligned}\tag{30}$$

The equations given in this section for the relative velocity of the particles moving in the blade direction make it possible to describe numerically hydrodynamics of the primary and secondary circulation of the oilseed meat flux in each cooker vat. In hydrodynamics of the primary and secondary circulation of the oilseed meat flux in the cooker vat with a stirrer, the concepts of circumferential (peripheral) and radial-axial circulation are used. These parameters make it possible to compose the heat balance of conductive and convective heat and mass transfer in the oilseed meat taking into account the heat spent for removal of the moisture bound with the solid phase.

6. Discussion of the results obtained in the study of the oilseed meat cooking process

The process of moisture-thermal treatment of oilseed meat requires a uniform distribution of particles in volume and time when the particles are located at the points of this volume. A long time of staying in one volume leads to a prolonged overheat of the dried particles under extreme conditions and deterioration of the material quality. The simplest remedial action consists in partitioning of this device. It is advisable to choose a rational number of multi-vat cooker vats proceeding from the condition of the specified average humidity and moisture dispersion.

Based on the design features of the existing cookers, each vat in them can be conveniently viewed as a turbine stirrer with inclined flat blades. To create an algorithm describing conductive and convective heat and moisture transfer, it is necessary to describe hydrodynamics of the oilseed meat flux in the vat cooker. Application of the existing theory of particle motion along a horizontal disk with straight blades makes it possible to accomplish this task. The total oilseed meat flux is decomposed into two main streams. Movements along concentric circles perpendicular to the axis of the device in horizontal planes are made. Also, the particles move in vertical (meridianal) planes intersecting the device axis.

Stirrer blades create radial and tangential components. This flux slows down on the cooker wall changing its direction to the axial one. It rises up to the free surface and again turns from there in the stirrer direction. Experimental data on turbine stirrers give a relationship between the velocity along the blade and the axial velocity along the inner surface of the stirrer.

The time of the oilseed meat passage along the stirrer blade makes it possible to describe conditions of conductive heat-and-moisture exchange. The time of transit along the vat axis allows one to describe the process of convective heat-and-moisture exchange.

When calculating thermal balance of the convective oilseed meat drying, the heat spent to remove the bound moisture from the solid phase is taken into account, which ensures more exact calculations of the technological conditions of cooking.

This work shortcoming consists in absence of consideration of the issues touching the equation of the state of the resulting pulp which links the cooking and oil pressing processes

The results of the conducted studies are useful in that they extend and deepen the theoretical base of the cooking process. The obtained regularities can be used both in determining optimal process conditions for building and modernization of small-tonnage enterprises and in the practice of the fat and oil industry.

The prospects for further researches can include numerical studies of the proposed mathematical tools, definition of rational conditions of the cooking process, development of technology and equipment for the small-scale enterprises processing castor seeds.

7. Conclusions

1. A new procedure for determining design, process-dependent parameters and the number of the cooker vats for the moisture-thermal oilseed meat treatment has been proposed. The feature of this technique is that the criteria of validity of the calculation data are the specified values of mean and mean-square moisture of the oilseed meat.

2. A mathematical model of hydrodynamics of the oilseed meat particle motion in the cooker vat was developed as a single process of motion of the oilseed meat fluxes along both horizontal concentric circles and in a vertical (meridian) direction traversing the vat axis. Hydrodynamics makes it possible to determine time of motion of the oilseed meat particles on the heated vat bottom and in the direction of the vat axis. The time of oilseed meat passage along the stirrer blade makes it possible to substantiate conditions of conductive heat exchange. The time of passage along the vat axis allows one to substantiate conditions of convective heat exchange.

3. A discrete model of the moving contact oilseed meat layer at the hot surface of the vat bottom was made. The moisture content in oilseed meat was described by a matrix of rows the number of which is equal to the number of elementary layers and the number of columns is equal to the

number of elementary time intervals. The mass of the dry oilseed meat matter is determined by the row vector of the dry matter mass in the thick layer. This discrete model enables a compact expression of the subsequent results of calculation in a form of an alternating field of moisture content in the oilseed meat in the cooker vat.

4. The thermal balance of conductive and convective heat and mass transfer in the process of oilseed meat drying was compiled taking into account the heat spent to remove moisture bound with the solid phase, which will enable more accurate calculations of the cooking process conditions.

References

1. Kopeykovskiy, V. M. Tekhnologiya proizvodstva rastitel'nyh masel [Text] / V. M. Kopeykovskiy, S. I. Danil'chuk, G. I. Garbuzova. – Moscow: Legkaya i pishchevaya promyshlennost', 1982. – 416 p.
2. Goldovskiy, A. M. Teoreticheskie osnovy proizvodstva rastitel'nyh masel [Text] / A. M. Goldovskiy. – Moscow: Pishchepromizdat, 1958. – 446 p.
3. Maslikov, V. A. Tekhnologicheskoe oborudovanie proizvodstva rastitel'nyh masel [Text] / V. A. Maslikov. – Moscow: Pishchepromizdat, 1962. – 424 p.
4. Shcherbakov, V. G. Himiya i biohimiya pererabotki maslichnyh semyan [Text] / V. G. Shcherbakov. – Moscow: Pishchevaya promyshlennost', 1977. – 168 p.
5. Didur, V. A. Technology of castor-oil plant seeds processing at small-capacity plants [Text] / V. A. Didur, V. A. Tkachenko // Visnyk Ukrayins'koho viddilennya Mizhnarodnoyi akademiyi ahrarnoyi osvity. – 2014. – Issue 2. – P. 21–35.
6. Didur, V. A. Mathematical model of conductive and convective heat and mass transfer in a multivat brazier [Text] / V. A. Didur, V. A. Tkachenko, A. V. Tkachenko, V. V. Didur // Visnyk Ukrayins'koho viddilennya Mizhnarodnoyi akademiyi ahrarnoyi osvity. – 2016. – Issue 4. – P. 14–31.
7. Didur, V. Matematicheskaya model protsessa podgotovki maslichnogo syrya v mnogochannoy zharovne [Text] / V. Didur, V. Tkachenko, A. Tkachenko, V. Didur // MOTROL Commission of motorization and energetics in agriculture an international journal on operation of farm and agri-food industry machinery. – 2016. – Vol. 18, Issue 1. – P. 29–36.
8. Didur, V. A. Thermodynamic characteristics of elements in sunflower seeds [Text] / V. A. Didur, A. V. Tkachenko // Naukoviy visnyk Natsional'noho universytetu bioresursiv i pryrodokorystuvannya Ukrayiny. Seriya: tekhnika ta enerhetyka APK. – 2016. – Issue 251. – P. 19–30.
9. Aleksanyan, I. Yu. Modelirovanie processa sushki diskretnogo materiala v kipyashchem sloe [Text] / I. Yu. Aleksanyan, L. M. Titova, A. H. Nugmanov // Tekhnika i tekhnologiya pishchevyh proizvodstv. – 2014. – Issue 3. – P. 96–102.
10. Shevcov, A. A. Tekhnika i tekhnologiya sushki pishchevogo rastitel'nogo syr'ya [Text] / A. A. Shevcov, A. N. Ostrikov. – Voronezh: Voronezhskiy gosudarstvennyy agrotekhnologicheskiy universitet, 2014. – 289 p.
11. Rudobashta, S. P. Sushka dispersnyh materialov [Text] / S. P. Rudobashta // Plenarnye doklady. – 2002. – Vol. 1. – P. 26–35.
12. Shevcov, A. A. Analiticheskoe reshenie matematicheskoy modeli svyazannogo teplomassoperenosa pri konvektivnoy sushke zerna [Text] / A. A. Shevcov, I. O. Pavlov, E. V. Voronova, D. A. Britikov // Izvestiya vuzov. Pishchevaya tekhnologiya. – 2010. – Issue 4. – P. 99–104.
13. Liu, J. Enzyme-assisted extraction processing from oilseeds: Principle, processing and application [Text] / J. Liu, M. A. A. Gasmalla, P. Li, R. Yang // Innovative Food Science & Emerging Technologies. – 2016. – Vol. 35. – P. 184–193. doi: 10.1016/j.ifset.2016.05.002
14. McKeon, T. A. Improved method for extraction of castor seed for toxin determination [Text] / T. A. McKeon, D. L. Brandon, X. He // Biocatalysis and Agricultural Biotechnology. – 2016. – Vol. 5. – P. 56–57. doi: 10.1016/j.bcab.2015.12.007
15. Tzompa-Sosa, D. Fractionation of insect oils: the case of yellow mealworm oil [Text] / D. Tzompa-Sosa, W. University, M. Verbreek, H. van Valenberg // INFORM: International News on Fats, Oils, and Related Materials. – 2016. – Vol. 27, Issue 7. – P. 24–27. doi: 10.21748/inform.07.2016.24
16. AL-Harbawy, A. W. Production and Characterization of Biodiesel from seed oil of Castor (Ricinus communis L.) plants [Text] / A. W. AL-Harbawy, M. K. AL-Mallah // International Journal of Science and Technology. – 2014. – Vol. 3, Issue 9. – P. 508–513.
17. McKeon, T. A. Castor (Ricinus communis L.) [Text] / T. A. McKeon // Industrial Oil Crops. – 2016. – P. 75–112. doi: 10.1016/b978-1-893997-98-1.00004-x
18. McKeon, T. A. Introduction to Industrial Oil Crops [Text] / T. A. McKeon, D. G. Hayes, D. F. Hildebrand, R. J. Weselake // Industrial Oil Crops. – 2016. – P. 1–13. doi: 10.1016/b978-1-893997-98-1.00001-4
19. Romankov, P. G. Sushka vo vzveshennom sostoyanii [Text] / P. G. Romankov, N. B. Rashkovskaya. – Leningrad: Himiya, 1979. – 272 p.
20. Vasilenko, P. M. Teoriya dvizheniya chasticy po sherohovatym poverhnostyam sel'skohozyaystvennyh mashin [Text] / P. M. Vasilenko. – Kyiv: Ukrainskaya Akademiya sel'skohozyaystvennyh nauk, 1960. – 280 p.
21. Spravochnik konstruktora sel'skohozyaystvennyh mashin. Vol. 1 [Text] / M. I. Kleckin (Ed.). – izd. 2-e per. i dop. – Moscow: Mashinostroenie, 1967. – 722 p.
22. Strenk, F. Peremeshivanie i apparaty s meshalkami [Text] / F. Strenk. – Leningrad: Himiya, 1975. – 384 p.
23. Tkachenko, A. V. Oborudovanie i tekhnologiya sushki semyan podsolnechnika vysshih reprodukciy [Text] / A. V. Tkachenko, V. A. Didur. – Lambert Academic Publishing, 2014. – 165 p.
24. Lykov, A. V. Teoriya sushki [Text] / A. V. Lykov. – Moscow: EHnergiya, 1968. – 472 p.
25. Maslikov, V. A. Primery raschyotov oborudovaniya proizvodstva rastitel'nyh masel [Text] / V. A. Maslikov. – Moscow: Pishchepromizdat, 1959. – 226 p.
26. Pavlov, K. F. Primery i zadachi po kursu processov i apparatov himicheskoy tekhnologii [Text]: uch. pos. / K. F. Pavlov, P. G. Romankov, A. A. Noskov; P. G. Romankov (Ed.). – Leningrad: Himiya, 1987. – 576 p.