Досліджено процес концентрування овочевого соку в удосконаленому вакуум-випарному апараті з перемішуючим пристроєм, який одночасно є теплообмінним. Отримана математична модель, що описує кінетику розігріву продукту при постійному перемішуванні. Запропоновані рівняння дозволяють розрахувати тривалість виходу процесу нагріву на стаціонарний режим з урахуванням теплофізичних і реологічних характеристик досліджуваного продукту. Отримана залежність відрізняється тим, що в розрахунках було враховано зміну реологічних властивостей рідини, що переробляється, а саме ефективну в'язкість яка характеризує зсувні властивості неньютонівських рідин, якими переважно є більшість харчових мас. Досліджено процес сушіння морквяних вичавків в розробленій вібраційній вакуумній сушарці. Визначено залежність вмісту бета-каротину від робочих параметрів сушарки, а саме від амплітуди та частоти.

На підставі отриманих результатів дослідження колориметричних характеристик, було доведено, що запропонований спосіб виробництва концентратів сприяє збереженню та формуванню колориметричних характеристик готового продукту. Визначені кольорові характеристики дали змогу встановити, що при тепловій обробці дуже важливо зменшити тривалість обробки сировини та температуру. Визначені реологічні характеристики отриманого концентрованого соку залежно від відсотку введення вичавків, що довело можливість формування твердоподібних якостей концентрату. Дані дослідження довели перспективність виробництва концентрованих продуктів роздільним способом (розділення сировини на сік та вичавки, окреме уварювання соку та сушка вичавок, з'єднання компонентів в різній концентрації залежно від технологічних задач). Це дозволяє регулювати якісні показники кінцевого продукту колір, яскравість, консистенцію, в'язкість та фізико-хімічні властивості

Ключові слова: кінетика розігріву, концентровані продукти, випарні апарати, сушарки, колориметрична оцінка, бета-каротин

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STUDY INTO THE INFLUENCE OF OPERATING PROCESSING PARAMETERS ON QUALITATIVE CHARACTERISTICS OF THE CARROT CONCENTRATED PRODUCT

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1. Introduction

Technological development of industry is aimed at satisfying the basic society needs. Solving of the nutrition problems, namely, high-quality nutrition depends first of all at the level of development of raw material processing technologies and equipment for the implementation of these processes.

In connection with worsening of environmental conditions, the human need for biologically active substances is significantly growing. That is why people need products of medio-prophylactic and health-improving purpose. The human body will maintain healthy lifestyle despite negative environmental effects only due to such nutrition [1]. Many people are suffering from low-quality vegetarian food products or even because of their absence. There is an acute shortage of wholesome biologically active substances contained in products of plant origin. These include vitamins, macro- and microelements, organic acids, phytoncides, pectin substances and cellulose [2].

Urgency of the study aimed at production of concentrated products and continuous improvement of the final product quality is the main vector of society development leading to development of new technologies and equipment [3]. Currently, to solve the food quality problems, challenges of developing new technologies and devices for implementation of these processes need to be addressed [4].

2. Literature review and problem statement

An experimental method of processing raw materials for production of fruit and vegetable juices is proposed in [5]. The method consists in pasteurization under high pressure to preserve nutrients in juices, such as sulforaphane in broccoli juice. The results of the study suggest that the content of vitamin C depends on duration of treatment under pressure but it is not shown which treatment conditions were chosen as optimal.

A procedure of ultrasonic and ultraviolet irradiation of various fruit and vegetable juices was developed and its comparison with conventional thermal pasteurization is given in [6]. This study has confirmed usefulness of the proposed methods for processing raw materials to maintain quality of drinks while increasing storage duration, however, complexity of application of the proposed methods for juice processing and determination of the process speed is its main disadvantage.

Kinetics of vacuum drying, thermal history and qualitative kinetics of plant compositions were determined in [7]. As a result of the conducted studies, vacuum drying at 70 °C was recommended. Ascorbic acid dehydration conditions were determined depending on the tray temperature which is erroneous as the process of dehydration takes place inside the product layer and the product is heated through the tray wall which results in formation of a crust on the surface that slows down the dehydration process.

A new drying procedure developed in [8] uses a combination of ultrasonic and dehydration vacuuming to reduce drying time and improve quality of carrot slices. Carrots slices were dried by ultrasonic vacuuming and vacuum drying at 65 °C and 75 °C, respectively. The process speed was significantly influenced by drying technique and temperature, however, application of the combined procedures complicates the process and increases production costs.

A systematic approach was developed in [9] to select appropriate drying parameters. This approach can provide simple and comprehensive guidance for choosing suitable working parameters for any fluidized bed dryer with ability to maximize throughput when drying plant materials with high levels of impurities. These studies are aimed at the choice of drying parameters based on the process duration but do not include qualitative studies of the final product.

Fluidized bed dryers are widely used for drying raw materials or final products due to their advantages in mixing and the speed of heat and mass exchange processes [10]. Experimental studies were carried out on a dryer with fluoroplastic under laboratory conditions. Moisture content was measured during drying using selected particles as a standard. It was found that the use of vibration in drying the raw materials changes humidity but the study did not provide rational processing parameters and their correlation with qualitative indicators which makes impossible prediction of the final product properties.

The juice qualitative parameters related to discoloration as a function of duration and temperature of storage were studied in [11]. Importance of qualitative indicators for discoloration was evaluated for these indicators relative to each other (the reaction of sugar degradation and the reaction of ascorbic acid degradation) and it was found to be important for discoloration of pasteurized orange juice during its storage. However, the issues of dependence of qualitative indicators of the final product on basic parameters of processing of raw materials were not resolved.

Studies of quality of the food product raw materials such as vegetables subjected to convective drying in nonstationary conditions are presented in [12]. Influence of various frequencies and amplitudes of the periodically varying temperature of drying air on quality of dried carrots was studied. Qualitative indicators such as discoloration, water activity and preservation of β-carotene have been analyzed. It has been shown that nonstationary drying at a set temperature of alternating air significantly minimizes adverse effects of discoloration, degradation of β-carotene and decomposition phenomena. The problem of choosing optimal raw material processing parameters and their interrelation with the studied qualitative indicators was not solved.

All this suggests that it is expedient to conduct studies of influence of the working parameters of heat and mass exchange processing on qualitative characteristics of the final product and establish the relationship between selected conditions and qualitative indicators. For processing raw materials, we have chosen vacuuming equipment which makes it possible to substantially reduce boiling temperature in the working chamber (down to 45 °C) and enable preservation of thermolabile substances and as a result, improve quality and nutritional value of the final products. Color of the final product remains the main quality criterion for the consumer, namely proximity of the main colorimetric characteristics of the final products to the raw material. Therefore, the studies will be conducted in this direction.

3. The aim and objectives of the study

This study objective was to establish influence of heat and mass exchange processing parameters on qualitative characteristics of concentrated carrot products.

To achieve the objective, the following tasks were solved:

– to develop a mathematical model describing kinetics of heating the product in a vacuum evaporator for solving the problems of duration of concentrate boiling out;

– to design a vibration vacuum dryer with a cushioning spring for drying cake and determine rational operating parameters depending on indicators of β-carotene content in carrot cake;

– to study colorimetric characteristics of the obtained carrot concentrates;

– to establish dependence of rheological characteristics of the final product on percentage of cake added to the carrot concentrate.

4. The methods of heat exchange study and determination of colorimetric characteristics of the obtained concentrated product

4. 1. Design features of the experimental vacuum evaporator

A vacuum evaporator with a new device for stirring and heating viscous food products was developed for production of concentrates from vegetable raw materials, namely for the process of boiling out in vacuum. The main design features and operation principle of the unit are presented in [13].

The heat exchange process was studied with various vacuum evaporators, namely with the designed device for stirring and heating and a control device [14]. A distinctive feature of the developed vacuum evaporator is presence of a scraper-type stirrer with a hollow shaft which is steam heated similar to the unit shell. As a result, conditions of heat exchange and heating uniformity were substantially improved. This will reduce energy expenditures and increase productivity of the unit in general.

The procedure of conducting heat exchange studies is described in [15].

4. 2. Procedure of studying the process of vibro-vacuum drying of vegetable cake

The continuous vibro-vacuum dryer with a cushioning spring shown in Fig. 1 was developed to ensure continuous processing of carrot cake and improve the final product quality.

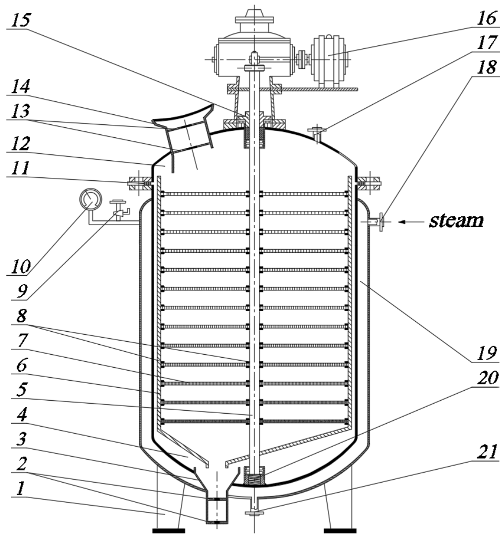

Fig. 1. Vibration vacuum dryer for continuous drying of vegetable raw materials: supports 1, shut-off valve 2, neck 3, working chamber 4, working shaft 5, frame for trays 6, trays with apertures of variable section 7, solid welded connection 8, pressure relief valve 9, pressure gauge 10, clamping device 11, lid of the unit 12, metering valve 13, loading hopper 14, sealer 15, vibrator 16, pipeline of the evacuation system 17, connection for heat carrier supply 18, steam jacket 19, cushioning spring 20, connection for condensate drainage 21

Drying is carried out in the unit as follows: carrot cake from the loading hopper is measured out with the valve and falls on the trays with apertures of variable size. The trays are fixed to the working shaft with continuous welds. The working shaft is connected to the vibrator generating mechanical vibrations and the cushioning spring. The working chamber is heated by steam supplied into a steam jacket through the connection and measured by the pressure gauge. The excess steam is discharged through the valve. The dried product is unloaded with the help of a shut-off valve, through the neck since the dryer operates continuously and the product is taken from the unit periodically, that is, the shut-off valve is actuated automatically after reaching the set weight of the product. This principle makes it is possible to maintain vacuum in the unit. The working vacuum chamber is sealed with metal seals and clips that fix the unit lid.

4. 3. Method for determining the content of β-carotene in carrot cake

To determine total amount of carotenoids, samples of carrot cake were used. A set amount of fresh plant material refined with the use of solvent (hexane) is placed in a porcelain mortar and pestled with addition of quartz sand and anhydrous sodium sulfuric acid. The method for determining β-carotene content in carrot cake is described in [16].

4. 4. Evaluation of structural and mechanical properties of obtained concentrates according to shear characteristics

Rheological characteristics of the concentrated products were determined by means of the Reotest-2 rotary viscometer according to Cuette procedure in which the product under study is placed in the annular gap between coaxial rotary and stationary cylinders. The procedure for the study of structural and mechanical properties of the concentrated products is described in [17].

4. 5. Procedure for determining colorimetric characteristics of the obtained concentrates prepared from vegetable raw materials

One of the problems during storage and processing of food products prepared from natural raw materials is the change of qualitative properties, first of all, color. This necessitates analysis of methods for determining color properties of raw materials in order to find a cheaper express analysis method [18].

The color characteristics of the samples were determined by the CIE *XYZ* method (CIE *XYZ* International Coordinate System) based on the tricolorimetric color model. Blue, green, and red are base colors. Other colors are formed by mixing the base colors in corresponding ratios determined by the chromaticity coordinates x, y, z. If the sum is 1, i. e. $x+y+z=1$, the color is white [19]. In this case, the colored surface is perceived in its own specific color because of reflection of light of a certain length, and other waves are absorbed [20].

With the help of this method, reflection spectra for non-transparent substances and materials can be obtained by measuring the spectral diffusion reflection coefficient R_λ [21].

5. Results of studying the heating-up kinetics and colorimetric characteristics of the obtained concentrate

5. 1. The study of heating-up kinetics of the vegetable juice in the experimental vacuum evaporator

A model of kinetics of heating-up the product in the vacuum evaporator was obtained taking into account growth of the heat exchange area and rheological properties of the product. In presence of convective heat exchange due to the rotary shaft with scrapers, the main thermal resistance to the heat transfer is resistance of the boundary layer of the product near the moving surface and resistance of the metal wall separating the heat carrier and the heated product. In this case, equation of thermal balance is as follows:

$$c\rho V\frac{dt}{d\tau}=-kF_T\left(t_T-t\right), \qquad (1)$$

where c is specific heat of the product, J/kg·K; ρ is the product density, kg/m^3; V is the volume of product in the unit, m^3; t is the average temperature of the product, °C; t_T is the heat carrier temperature, °C; k is the coefficient of heat transfer from the heat carrier to the product, W/(m^2·K); F_T is the area of heat exchange, m^2; τ is the current time, s.

The coefficient of heat transfer in this case consists of two thermal resistances:

$$k=\frac{1}{\frac{1}{\alpha}+\frac{\delta}{\lambda_\delta}}, \qquad (2)$$

where α is the coefficient of heat transfer, W/m^2·K; δ is thickness of the wall separating the heat-carrier and the heated product, m; λ_δ is the coefficient of thermal conductivity of the wall, W/m·K.

The heat transfer coefficient in heating a non-Newtonian fluid to a boiling point can be calculated using the criterion equation [22].

Solution of the differential equation of thermal balance under initial conditions $t(0)=t_0$ has the form:

$$t(\tau)=t_T+(t_0-t_T)exp\left[-\frac{\tau}{C\rho R_V\left(\frac{1}{\alpha}+\frac{\delta}{\lambda_\delta}\right)}\right], \quad (3)$$

where $R_V=V/F_T$ is the ratio of the product volume to the area of heat exchange surface, m^2.

Fig. 2 shows the calculated kinetics of heating the product in the developed vacuum evaporator depending on the rotational speed of the working shaft.

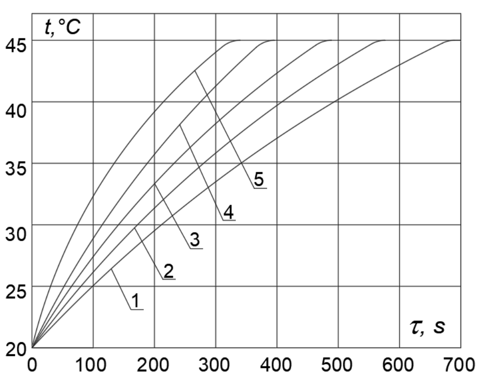

Fig. 2. Kinetics of heating the product in a vacuum evaporator with a heated shaft: n=0.5 s^{-1} (1); n=1.0 s^{-1} (2); n=1.5 s^{-1}(3); n=2.0 s^{-1} (4); n=2.5 s^{-1} (5)

It should be borne in mind that for a unit with a heated shaft and scrapers, the effective area of heat exchange increases due to ribbing. In this case, total area of heat exchange consists of the shell heating area and the ribbing area.

$$F_T=F_{shell}+F_{shaft}+E\cdot F_{scrapers}; \quad (4)$$

where F_{shell} is the area of heat transferring surface of the shell, m^2; F_{shaft} is the area of the heat transferring surface of the shaft, m^2; $F_{scrapers}$ is the area of ribbing of the scrapers, m^2; E is the coefficient of ribbing efficiency calculated as follows:

$$E=\frac{th(z\cdot l_{equ})}{z\cdot l_{equ}}, \quad (5)$$

$$z=\sqrt{\frac{2\alpha}{\lambda_\delta\delta}}, \quad (6)$$

$$l_{equ}=0.35\left[d_{equ}-0.11\left[1+0.35ln\left(\frac{d_{equ}}{0.11}\right)\right]\right], \quad (7)$$

$$d_{equ}=\sqrt{\frac{4F_{scrapers}}{\pi}}. \quad (8)$$

Kinetics was calculated in accordance with the obtained equation (3) taking into account the experimental data. The results of calculations show that with an increase in rotational speed of the stirrer, difference in the heating rate of the product becomes smaller that is caused by deceleration of growth of the heat transfer coefficient.

Duration of the product heating-up is determined from equation (3):

$$\tau_{heat}=C\rho R_V\left(\frac{1}{\alpha}+\frac{\delta}{\lambda_\delta}\right)\cdot ln\left(\frac{t_0-t_T}{t_k-t_T}\right), \quad (9)$$

where t_K, °C is final product heating-up temperature.

Fig. 3 shows the results of calculating the product heating-up duration in the vacuum-evaporator according to equation (9).

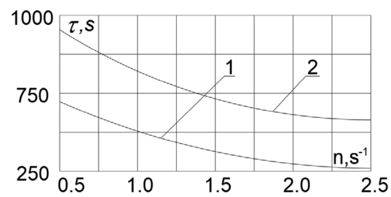

Fig. 3. Duration of the product heating-up in the vacuum evaporator with a heated shaft (1) and in a vacuum unit with a nonheated shaft (2) depending on the rotational speed of the stirrer

Calculation was made for two cases: for the developed unit and the control one.

5. 2. Influence of modes of vibration vacuum drying on the content of beta-carotene in carrot cake

As is known from the theory of kinetics of chemical reactions, the greater amount of the substance reacted in the corresponding reaction the greater temperature and the exposure time at that temperature. In the case of beta-carotene decomposition reaction in the drying process, the greater its loss the higher drying temperature and the longer drying duration.

To this end, experiments were conducted to study the effect of drying modes of the vibration vacuum dryer on the content of beta-carotene in carrot cake. These data are presented in Table 1. The procedures of drying and determining the content of beta-carotene in cake samples are given in sections 4.2 and 4.3, respectively.

The drying mode at normal atmospheric pressure and no vibration was taken in the experiments as the control mode. Temperature in the working chamber was maintained constant in all experiments and amplitude and frequency of vibration varied according to the experiment design.

Analysis of the experimental data on the content of beta-carotene in carrot cake depending on drying duration is shown in Fig. 4.

According to the data presented, content of beta-carotene in carrot cake has decreases almost twice with an increase in the drying duration by 1.5 times. This means that with an increase in the carrot cake exposure time at a given temperature, loss of beta-carotene grows.

The obtained dependence is described by empirical equation of the form

$$C_\beta = a_0 - a_1\tau^{0.5} + a_2\tau^{1.2}, \quad (10)$$

where C_β is content of beta-carotene, g·10^{-3}/g; τ is drying duration, s; a_0=469; a_1=60.5; a_2=0.78.

Table 1

Dependence of beta-carotene content in carrot cake on drying modes

Item No.	Name	Amplitude A, m	Frequencyf, Hz	Pressure, MPa	Drying duration, min	Beta-carotene content, mg/g
1	Mode 1	0	0	0	140	46.4
2	Mode 2	0	0	0,09	110	52.1
3	Mode 3	0.003	6	0.09	100	56.9
4	Mode 4	0.003	8	0.09	96	60.1
5	Mode 5	0.005	6	0.09	88	73.4
6	Mode 6	0.005	8	0.09	82	76.3
7	Mode 7	0.007	6	0.09	85	70.1
8	Mode 8	0.007	8	0.09	80	75.4

The type of function of approximation of experimental data was taken according to general recommendations for regression analysis. Exponents were determined as follows: at first, experimental data were approximated by polynomial dependence. According to the Fisher criterion, the most significant polynomial order was determined as a competitive model. At the second stage, fractional order of polynomial was determined by the method of nonlinear regression analysis using standard procedures of the Mathcad package.

According to Table 1, drying duration is influenced by vibration modes. The vibration energy is directly proportional to the square of oscillation amplitude and the square of frequency. Therefore, there is obviously a correlation between drying duration and vibration parameters (amplitude and frequency). This dependence is presented in Fig. 5.

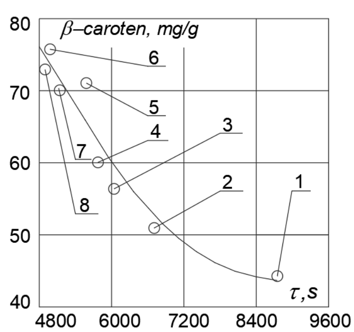

Fig. 4. The content of beta-carotene in carrot cake depending on drying duration: mode 1(1), mode 2 (2), mode 3 (3), mode 4 (4), mode 5 (5), mode 6 (6), mode 7 (7), mode 8 (8)

According to the data obtained, an increase in oscillation energy (the square of product of oscillation amplitude and frequency) affects drying time. Compared to the control mode (no vibration and no vacuum), drying time decreases by about 1.5 times. However, at values $(Af)^2$>0.002 m^2/s^2 (oscillation energy), drying time is practically unchanged. Thus, an increase in oscillation energy beyond this value is economically unfeasible as it causes growth of energy consumption by the vibrodrive.

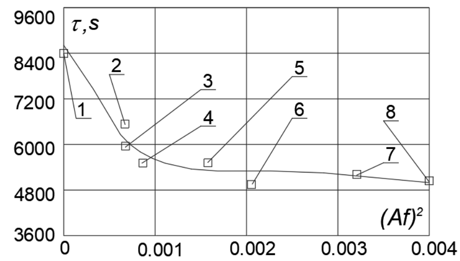

Fig. 5. Drying duration depending on the operating parameters of drying: mode 1 (1), mode 2 (2), mode 3 (3), mode 4 (4), mode 5 (5), mode 6 (6), mode 7 (7), mode 8 (8)

The type of the function of approximation of dependence of beta-carotene content on vibration parameters was chosen according to general recommendations for the regression analysis. Initially, correlation analysis was performed and a statistically significant correlation between drying duration and vibration parameters was found, namely, the complex of the product of amplitude and frequency since the energy of oscillations in vibration is directly proportional to the square of amplitude of oscillations and the square of frequency.

The experimental data were further approximated by polynomial dependence.

Dependence of drying time on vibration parameters is described by empirical equation of the form

$$\tau = a_0 - a_1(A\cdot f)^2 - a_2(A\cdot f)^3 - a_3(A\cdot f)^4, \quad (11)$$

where τ is the drying duration, s; A is amplitude, m; f is frequency, Hz; a_0=140; a_1=1.28×10^5; a_2=3.39×10^6; a_3=2.53×10^7.

Thus, vibration parameters significantly affect drying duration, so they obviously should correlate with the change in beta-carotene content in carrot cake in the course of drying.

The graph of the obtained empirical dependence is presented in Fig. 6.

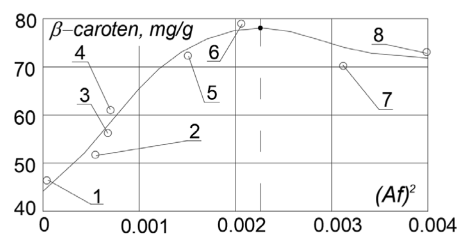

Fig. 6. The content of beta-carotene in carrot cake depending on the operating parameters of drying: mode 1 (1), mode 2 (2), mode 3 (3), mode 4 (4), mode 5 (5), mode 6 (6), mode 7 (7), mode 8 (8)

The obtained dependence of the beta-carotene content on vibration parameters (amplitude and frequency) is described by the following empirical equation

$$C_\beta = a_0 + a_1(A\cdot f)^{3.4} - a_2(A\cdot f)^4 + a_3(A\cdot f)^{4.4}, \quad (12)$$

where C_β is the beta-carotene content, (g 10^{-3})/g; A is amplitude, m; f is frequency, Hz; a_0=43,8; a_1=1.88×10^7; a_2=2.28×10^8; a_3=3.95×10^8.

According to the obtained dependence, there is a local maximum of the beta-carotene content depending on vibration modes which corresponds to the value $(A\ f)^2$= =2.36 10^{-3} m^2/s^2. The content of beta-carotene calculated by (12) is C_β=76.3 mg/g at this point. To compare Table 1 with the optimum obtained, the mode 6 (A=0.005 m, f=8 Hz) is the optimum experimental mode of drying. The optimum of dependence (12) was defined as maximum of the function of content of beta-carotene on the parameter of product of the square of oscillation amplitude and the square of frequency and fully corresponds to the experimental data obtained.

5. 3. Studying the rheological characteristics of the concentrated product

Studies were carried out to find rheological characteristics of the concentrated product obtained, namely, concentrated juice with addition of various percentages of dried carrot cake. Experiments were carried out with Reotest-2 rotary viscosimeter using coaxial cylinders. The speed of rotation of the moving cylinder was set by means of a 12-range gearbox and the range of shear strain rates was 0.333...145.8 s^{-1}. Cylinders S2, H included in the device set were used in measurements. Experimental data were processed by the standard method [17]. The flow curve in Fig. 7 shows a significant increase in thickness of the product with addition of a higher percentage of carrot cake, namely, the dynamic shear stress is doubled in accordance with curve 3.

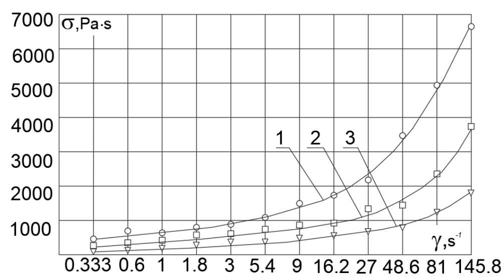

Fig. 7. Dependence of tangential stress on shear rate at different concentrations of cake: 20 % (1); 10 % (2); 0 % (3)

Analysis of rheological curves in Fig. 8 showed that the product viscosity has also significantly increased: twofold when 10 % of cake was added and fourfold when 20 % of cake was added.

The curve rate shows changes in the product structure: visco-plastic deformation for the concentrated juice and an avalanche structure destruction for the concentrate with cake addition (curves 2 and 3) are characteristic features because of the fact that cake addition increases the structure porosity, therefore, plasticity decreases.

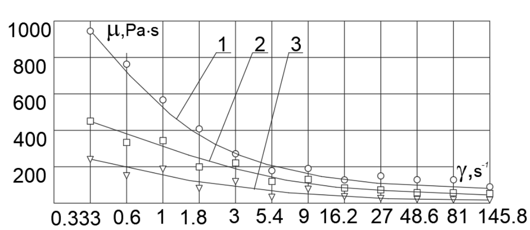

Fig. 8. Dependence of viscosity on shear rate at various concentrations of cake in the concentrate: 20 % (1); 10 % (2); 0 % (3)

5. 4. Studying the colorimetric characteristics of the concentrates prepared from vegetable raw materials

The results of study of colorimetric characteristics of the concentrates prepared are presented in Fig. 9. The plotted curves make it possible to study dynamics of changes in reflection spectra depending on percentage of dried cake introduced into concentrated juice which will make it possible to prove later the chosen method of production, i. e. separate concentration of juice and cake and their subsequent mixing in proportions depending on technological tasks.

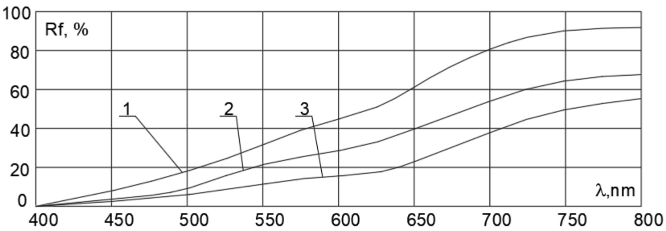

Fig. 9. Reflection spectra of samples of the final concentrated product depending on the amount of added cake (Rf, %): 20 % (1); 10 % (2); 0 % (3)

The specimen reflection spectra have a low intensity in the range from 400 to 550 nm which increases in the range from 550 to 800 nm and corresponds to the red-orange color proving that addition of cake to the concentrate improves qualitative characteristics of the product, namely tone saturation of and color purity.

The growth of reflection intensity in the red region of the visible spectrum corresponds to its growth in the red component of light.

The wave-length dynamics in the red region of the visible spectrum as well as the portion of color grow indicating an increase in contribution of the red spectrum component.

The obtained results of colorimetric assessment of quality of carrot concentrate depending on cake content are presented in Table 2.

Table 2

Colorimetric assessment of quality of concentrate from carrots depending on cake content

Specimen	Chromaticity coordinates		Dominating wave length, lnm	Brightness, T %	Color purity, P %	Spectral color (dominating tone)
	x	y				
Juice (reference)	0.4959	0.4541	582.4	45.41	90.76	Orange
Concentrate, 0 %	0.4212	0.4149	583.6	41.49	63.49	Red
Concentrate, 10 %	0.4332	0.4153	586.3	43.61	74.68	Red-orange
Concentrate, 20 %	0.4562	0.4264	587.7	44.68	78.24	Red-orange

6. Discussion of results obtained in the study of heating kinetics and colorimetric characteristics of the concentrates obtained

As a result of theoretical and experimental studies, a mathematical model describing kinetics of product heating in a vacuum evaporator was obtained. The obtained equations make it possible to calculate duration of the product heating from initial to the set final temperature taking into account thermophysical and rheological characteristics of the non-Newtonian fluid.

It has been theoretically proved that presence of an additional heating area due to the shaft ribbing leads to a decrease in duration of the product heating. Accordingly, the energy consumption was 40 % smaller in the range of the stirrer speeds of 0.5...2,5 s^{-1} in comparison with the device which is heated only from the outer shell.

It should be noted that the obtained dependence (10) is notable for the fact that the calculations took into account rheological properties of the processed fluid, namely the apparent viscosity which characterizes shear properties of non-Newtonian fluids including the majority of food products. This approach will be of interest when calculating and simulating flow of viscous liquids in pipes and channels of heat exchangers regardless of the substance nature but proceeding from whether the liquid is Newtonian or non-Newtonian. For example, in [23] when modeling oil flow in the channels of plate heat exchangers, dependences were proposed that take into account kinematic and dynamic viscosity of oil which is incorrect. Oil is a non-Newtonian liquid and its viscosity during movement (shear deformation) changes significantly which materially affects the results of calculations and a rational approach to modeling. This example shows a broad field of rheological studies to address issues of rationalizing and optimizing calculations and equipment designs. In the dependences obtained in this paper, modified likeness criteria were used in thermal calculations. They take into account variable viscosity of the boiling fluid: the range of its variations is from 17 to 300 Pa·s depending on the shear strain rate (according to the viscosimetry results). This enables obtaining of theoretical models substantially approaching the experimental conditions.

Rheological studies of the obtained concentrate produced from vegetable raw materials with various contents of added cake were conducted. The experiments have shown a significant increase in thickness of the product due to addition of a higher percentage of cake. This is explained by the fact that cake contributes to formation of a coarse suspension and growth of the system density.

The conducted studies have proven the perspectivity of production of concentrated products in a separated way, with subsequent addition of various percentages of cake to the concentrated juice. This opens up the opportunity to regulate organoleptic characteristics of the final product, namely color, brightness, consistency, viscosity and physical and chemical properties. By varying percentage of cake in the final product, it is possible to form both its consistency and, as a consequence, its technological purpose and color.

The study disadvantage is the choice of only carrots as the raw material which limits experimentation to determine quality. Further studies may be aimed at studying other qualitative indicators of the final product through the change of raw materials (vitamin C, polyphenols, etc.).

This study development may consist in a change of heat carrier in the vacuum evaporator and the dryer, e. g. for IR heaters and the study of their influence on the qualitative indicators of the processed product, establishment of interrelations between certain quality criteria and processing conditions. Besides, addition of various percentages of cake and other components to the heated-up juice substantially changes rheological properties of the product (viscosity, shear stress) which opens the way to further studies.

7. Conclusions

1. A mathematical model describing kinetics of heating-up the product in a vacuum evaporator with a stirrer has been obtained. The obtained equations make it possible to calculate the product heating duration from an initial to a set final temperature taking into account thermophysical and rheological characteristics of the non-Newtonian fluid. It has been proved theoretically that availability of an additional heating area due to the shaft ribbing decreases duration of the product heating and, accordingly, energy consumption by 40 % in the stirrer speed range of 0.5...2.5 s^{-1} in comparison with a unit heated only from the external shell.

2. A mathematical model that describes the change of beta-carotene content in carrot cake during drying in various modes of the vibration vacuum dryer was obtained. An optimum vibration mode for vacuum drying has been theoretically established and experimentally confirmed at a set boiling point of 50 °C and a pressure of 0.09 MPa: vibration amplitude A=0.005 m and vibration frequency ν=8 Hz. The criteria for choosing these parameters were as follows: drying duration: 82 min, final content of carotene in carrot cake C_β=76.3 mg/g.

3. Colorimetric characteristics of the concentrate prepared from vegetable raw materials were investigated, a multifactorial experiment was conducted which has made it possible to determine dependence of color parameters of the final product on the amount of added dried cake in the concentrated juice. Based on the results of the study of colorimetric characteristics determined by reflection spectroscopy, it was proved that this method of concentrate production contributes to preservation and formation of colorimetric characteristics of the final product. It has been established that technological processing affects the objective colorimetric characteristics of plant materials, namely, deviation of the values of the dominant wavelength, color purity and brightness from the reference sample values. The determined color characteristics have made it possible to establish that it is very important to reduce duration of processing of raw materials and temperature during heat treatment.

4. Rheological characteristics of concentrated juice with various contents of cake were studied. They revealed a relationship between the content of cake in the concentrate and the change of structural and mechanical properties of the product, namely, improvement of its density qualities which makes it possible to obtain products for various purposes (juice, candy mass, paste, filling for confectionery products, biological supplements for health-improving nutrition).

Thus, the designed unit and the proposed method for production of concentrated products make it possible to preserve qualitative properties of products, and adding of various percentages of dried cake to the concentrated juice can affect consistency and viscosity of the concentrate which makes it possible to use the product in a number of the food industry sectors.

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