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MODELING OF MECHANICAL TREATMENT OF NAPIFORM ONION TO DETERMINE THE RATIONAL PARAMETERS OF ITS CLEANING

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Досліджено процес механічної обробки цибулі ріпчастої під час її очищення комбінованим способом. Визначено раціональні параметри проведення комбінованого процесу очищення цибулі ріпчастої. Отримано величину необхідного коефіцієнта заповнення робочої камери апарата для очищення цибулі ріпчастої. Запропоновано математичну модель процесу механічної обробки цибулі ріпчастої під час її очищення. Розраховано мінімальну частоту обертання робочої камери апарата

Ключові слова: цибуля ріпчаста, комбінований процес, параметри очищення, попереднє проварювання, механічна обробка

Исследован процесс механической обработки лука репчатого во время его очистки комбинированным способом. Определены рациональные параметры проведения комбинированного процесса очистки лука репчатого. Получена величина необходимого коэффициента заполнения рабочей камеры аппарата для очистки лука репчатого. Предложена математическая модель процесса механической обработки лука репчатого во время его очистки. Рассчитана минимальная частота вращения рабочей камеры аппарата

Ключевые слова: лук репчатый, комбинированный процесс, параметры очистки, предварительный провар, механическая обработка

1. Introduction

Under conditions of modern economic development, there is a need to create new resource-saving processes and equipment that meet all international requirements. In this case, such indicators should be strictly monitored as quality of the manufactured product and ecological safety of conducting production processes.

Manufacturing food products from vegetable raw materials has important economic and social significance. Vegetables play an important role in the nutrition of all categories of population, which necessitates their presence in people's daily diet. Therefore, safety and quality of such food, the absence of physical, chemical and microbiological contamination should be warranted by manufacturers and processors. To guarantee the safety, producers should apply control measures along the entire chain of the production process – obtaining, processing and preservation of vegetables. These requirements imply high quality and ecological cleanliness of the products, as well as maximum mechanization and automation of the processes [1]. One of the main tasks for the vegetable-processing industry is to use modern advanced technology during production [2]. But the intensity of the pace of development is reduced due to the low degree of mechanization of most of the processes in the processing of vegetable raw materials, a high degree of manual work. As a result, it is impossible to manufacture the products that would meet European and world requirements [3].

One of the ways to ensure the chosen direction on resource- and energy-saving is the development and implementation into production of new technologies and equipment for cleaning vegetable raw materials. Despite the fact that at present sufficient volume of equipment is used to conduct the process of cleaning vegetables, there are many problematic issues that need to be addressed. It is known that during the process of cleaning, a large part of these raw materials is lost. This happens due to moral and physical wear of the equipment created earlier for the implementation of the cleaning process. Most of the devised processes of cleaning vegetable raw materials lost their relevance, since they are characterized by significant energy consumption and low quality indicators of products [4].

A promising trend of the intensification and mechanization of the process of cleaning vegetable raw materials is the development of new specialized devices, whose principle of functioning is based on the combination of thermal and mechanical processes [5]. Implementation of innovative combined ways of cleaning is complicated by the lack of comprehensive research in this direction as a whole, in particular, appropriate information on the typical structural-mechanical, physical-mechanical and thermal-physical properties of vegetable raw materials, techniques and experimental installations to determine their influence on the parameters of processes.

At the present stage of development of society, a relevant and important direction, providing for a more rational use of resources, is the development and implementation of new technological processes [6]. To date, there is an intensive development of food and processing industry and the introduction of new progressive technologies, energy- and resource-saving efficient technological processes of processing raw materials with maximum preservation of food and biological value [7].

But it should be noted that labor productivity at the Ukrainian enterprises that process agricultural raw materials is 2–4 times lower than that at the similar enterprises in developed countries; about 50 % of labor-intensive operations are performed manually and only 10 % of the existing equipment are running under automated mode [8]. To solve the problem of processing agricultural raw materials, it is necessary to design technical means not only for the industrial processing of agricultural raw materials but introduce manufacturing of compact equipment for restaurants, farms mini-shops and private enterprises. It is economically sensible to apply universally and multioperational compact equipment, which is capable of several processes, which will make it possible to process different kinds of raw materials and produce a variety of products with stable quality indicators. The development and implementation in the production of environmentally safe energy-saving equipment of the new generation, which implements principally new combined methods of comprehensive processing of agricultural raw materials is a relevant and priority task.

2. Literature review and problem statement

Processing of vegetable raw materials is important in the food industry and restaurant industry. One of the most labor-intensive processes that are used at the enterprises of restaurant business is the process of cleaning vegetable raw materials. The following methods for cleaning the vegetables are used: physical (thermal), steam water thermal, chemical, mechanical, combined and burning by air. All of the above mentioned methods of cleaning from inedible inner part have reached today a high degree of development and are effectively used in the processing industry. Of the considered techniques, mechanical method of cleaning has become the most widely used due to low energy consumption for the provision of the process, relative simplicity of design of the equipment, environmental friendliness, ease of service [9]. But mechanical cleaning method is characterized by high losses of raw materials.

Despite the low level of mechanization of the process of cleaning onion at the restaurant enterprises, it is necessary to analyze possible expediency and efficiency of applying the methods and devices, which are used at the enterprises of vegetable-processing industry. A comprehensive treatment of onion is conducted, as a rule, on the onion-cleaning lines, which include a number of machines and auxiliary mechanisms [10]. The line includes a unit for sorting the onions, mechanisms for drilling the stems and cutting the neck by a knife with pressure fork, frictional installations of periodic action for peeling the bulbs from the husk with the mechanism of temporary control of the operation duration, scales to determine the amount of weighted material and water jet wash.

Some vegetable drying plants operate universal line for the preparation and drying of onion. The line includes machines for preparing the onion to drying, a dryer and equipment for processing dried onion. The line provides for the production of dried, sliced into rings, shredded onion and onion powder [11]. The amount of waste during operation of the line is from 20 to 26 %. Given the overall dimensions and high productivity of the technological line, its use in the restaurant business is not expedient.

In the course of mass processing of onion, the method of its cleaning is applied using carbon dioxide. A device for the implementation of this method is equipped with the unit for cleaning the hulls using chemicals, allowing facilitation and improvement in reliability of peeling the hulls from onion and the reduction in water consumption [12]. Considered machine requires significant production areas, has large dimensions, is highly productive as it is designed for large processing enterprises, and it cannot be used in restaurants.

Another issue that arises and requires a solution in the process of processing onion is cleaning slightly frozen and frozen onion. The design of device for cleaning frozen onion has certain peculiarities of operation [13]. The disadvantages of this device is the low quality of cleaning, a considerable amount of waste and loss of valuable parts of the bulb with the hulls through cleaning by cutting, the need to control the level of onion to ensure the implementation of the cleaning process, impossibility to use in restaurant business.

Hydraulic method to clean onion that is used primarily on vegetable drying plants is characterized by certain features of its application, the main being the need to additionally clean the bulbs. When cleaning the non-calibrated onion in the washer machine, they received: 39 % fully cleaned bulbs, which require additional neck and stem cutting, 38 % half-peeled and 23 % not-cleaned bulbs [14]. Labor productivity while additional onion cleaning, after its pre-treatment in the washer machine, increased by 36 % compared to when conducted manually.

Presented overview of equipment for cleaning onion demonstrates the impossibility of using existing designs, intended for use in the vegetable processing industry, in restaurant business. In addition, presented equipment do not provide for high quality of cleaning the onion from peel and have certain drawbacks. Machines for the pre-treatment of onion perform, as a rule, one operation. When using machines for the pre-treatment of onion, simultaneously with an increase in productivity compared with manual handling, the losses for cleaning increase. For the implementation of technological process of the pre-treatment of onion, the lines from a series of single-purpose machines are usually created that always have different performance efficiency and capacity, due to which the lines are large in size and low productive. When using the line to clean onion from the husk, a separate machine is necessarily required and when using the line to clean onion from the stem and neck, it is required to have mandatory quality calibration of each bulb and to use a separate machine [15]. The process of cutting onion is conducted in separate units, requiring certain time for reloading cleaned onion, and it reduces quality of the product when using the onion-cleaning lines. After the end of the processing, it is necessary to carry out additional manual cleaning and sorting of raw materials [16]. The machines and lines for the pre-treatment of onion imply a significant proportion of manual labor as the known machines do not allow conducting all basic technological operations for the pre-treatment of onion.

Thus, the known machines for the pre-treatment of onion are not universal, low efficient, and have a limited scope of application.

Based on analysis of the presented techniques for cleaning and the installations for their implementation, effectiveness of their work and the possibilities of applying in restaurant business and vegetable processing enterprises, we can conclude that the problem of cleaning has not been fully resolved up to now. One of the ways to ensure the chosen direction towards resource- and energy-saving is the development and implementation of environmentally safe equipment that realizes principally new combined methods for comprehensive processing of various types of agricultural raw materials with stable quality indicators. An implementation in one machine of multiple processes allows us to cut down on additional equipment for calibration, sorting, washing, pre-treatment, which, in turn, will ensure safety during production, contributing to the more rational use of resources [17].

On the basis of the conducted review of the literature data, it was proved that during the cleaning of onion, a significant part of the raw material is lost while effective quality control over final products is missing. Well-known machines for cleaning onion remain ineffective, require additional equipment and performing manual pre-treatment and have a limited segment of their application.

A promising trend of the intensification and automation of the process of high quality cleaning of onion is development of the device for cleaning onion ACR-10/160, the new specialized unit whose principle of functioning is based on the synthesis of thermal, hydrodynamic and mechanical processes of treatment. The country of origin is Ukraine. Design of the device is protected by the patent of Ukraine for invention No. 106813 [18].

3. The aim and tasks of the study

The aim of present work is to study the process of mechanical treatment of napiform onion during its cleaning by the combined method and to determine rational parameters of conducting combined process of cleaning napiform onion.

To achieve the set aim, the following tasks were to be solved:

– to devise methods and experimental installations for conducting the process of mechanical cleaning and to study its influence on the quality of cleaning and the percentage of losses of napiform onion;

– to determine impact of the duration of preliminary cooking with steam of the surface layer of napiform onion and structural parameters of working drum on the maximum degree of cleaning of raw materials;

– to explore dependence of the degree of cleaning the bulbs on the coefficient of filling the working volume of the drum and the depth of the product penetration;

– to build a mathematical model for the process of additional mechanical cleaning of raw materials for determining the most rational motion of product in the drum unit of the device.

4. Materials and methods of research into mechanical processing of vegetable raw materials

In order to minimize the loss of raw materials and to improve at the same time quality of cleaning the surface of the napiform onion, there is a need to conduct research into determining the duration of conducting the process of mechanical cleaning, depending on the effort to remove the husk.

We propose to use in the designed experimental setup (Fig. 1) a rotating drum as a working chamber. Based on the above selected factors, which need to be explored, we devised a technique to examine the process. This technique of examining the process of vegetable raw materials mechanical treatment is presented in detail in paper [19].

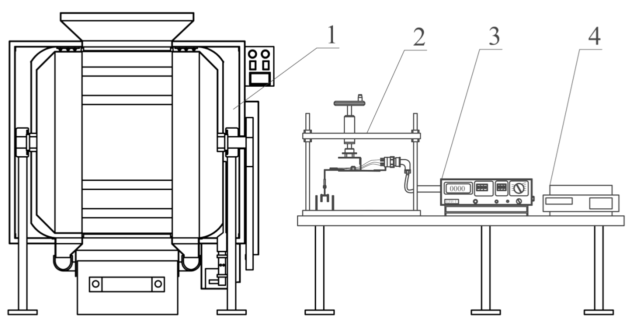

Fig. 1. Schematic of the experimental set-up for examining the process of cleaning napiform onion: 1 — experimental drum module; 2 — tensometric module; 3 — CTI-1; 4 — electronic scales

5. Research results of mathematical modeling of the process of mechanical treatment of napiform onion and determining rational parameters for conducting the process of its cleaning

For theoretical modeling of the process of mechanical cleaning of onion in the proposed drum-type device, we shall use general theory of drum mills. This theory examines the motion of a layer of solid spherical particles in the drum, which rotates at a certain frequency. This model can be expanded to the motion of napiform onion in the proposed device because the basic assumptions of the model remain the same:

– particles – solid balls with a diameter much smaller than the diameter of the drum;

– for the mode of developed motion of the layer of particles, the equation of only one particle is considered;

– a particle is in contact with the inner surface of the drum until the moment of separation from it;

– in the moment of breaking, the particle loses contact with the drum.

Depending on the rotation frequency of the drum, there are three operating modes of motion of the layer of particles (Fig. 2), which are defined by the ratio of rotation frequency to the critical frequency:

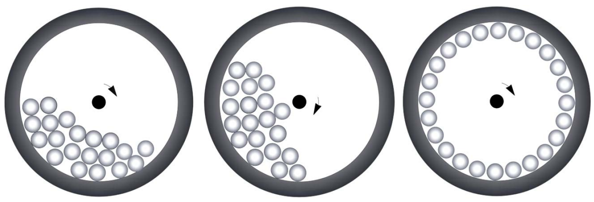

Fig. 2. Scheme of motion of solid particles in the drum depending on the rotation frequency: *a* — mode I, n=0,4...0,6 n_{cr}; *b* — mode II, n=0,6...0,8 n_{cr}; *c* — mode III, $n \geq n_{cr}$

Critical rotation frequency of the drum is determined under conditions of equality of the centrifugal force and the force of gravity:

$$m\omega^2 R = mg. \tag{1}$$

Hence, taking into account connection between cyclic frequency and rotation frequency $\omega = \pi n / 30$, we obtain:

$$n_{cr} = \frac{29{,}9}{\sqrt{R}}, \tag{2}$$

where m is the mass of a particle, kg; ω is the cyclic rotation frequency of the drum, rad/s; n_{cr} is the drum rotation frequency, min^{-1}; R is the inner radius of the drum, m.

Under the first mode of motion of the layer of particles at n=0,4...0,6n_{cr}, there is the equilibrium state of the layer without destroying its shape due to the fact that the forces of friction and the force of gravity exceed the centrifugal force and the main interaction between the particles and the inner surface of the drum occurs due to friction. The layer of particles under the influence of friction force is trying to move up, but the growing component of the force of gravity eventually makes the whole layer shift into the equilibrium state. Periodically, this oscillatory motion is repeated. In terms of the process of cleaning onion, it is an ineffective mode because the equilibrium of all forces applied to the bulb may be less than the effort to remove its husk.

The third mode at $n \geq n_{cr}$ is also ineffective in terms of cleaning because it lacks the motion of bulb relative to the inner surface of the drum with the cutting openings.

It is obvious that the optimal mode is the second mode at n=0,6...0,8n_{cr} when the layer of bulbs loses equilibrium state and the sliding forces occur relative to the inner surface of the drum, which, together with the force of friction, determine the effort of cutting the neck and stem of bulbs. In this case, removal of husk is achieved due to the friction between individual bulbs.

Based on this analysis, we shall define theoretical conditions for the work of the set-up for cleaning onion under optimum mode. First, we shall obtain necessary geometrical ratios (Fig. 3).

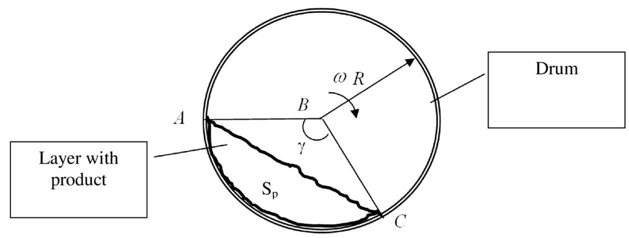

Fig. 3. Scheme of position of the layer of onion in the drum

Let us find the magnitude of coefficient of filling the drum:

$$\beta = \frac{S_p}{S_d}, \tag{3}$$

where β is the coefficient of filling the drum with a layer of product; S_d is the cross-sectional area of the drum; m^2; S_p is the cross-section of the drum filled with product, m^2.

The magnitude S_p will be found as the difference between areas of sector ACBA and triangle ABC with AC ground.

$$S_p = S_{\cup ACBA} - S_{\Delta ABC}. \tag{4}$$

Obviously:

$$S_{\cup ACBA} = \frac{\gamma}{2\pi}\pi R^2, \tag{5}$$

$$S_{\Delta ABC} = \frac{1}{2} 2R \sin\left(\frac{\gamma}{2}\right) \times$$
$$\times R\cos\left(\frac{\gamma}{2}\right) = \frac{1}{2}R^2 \sin(\gamma), \tag{6}$$

where γ is the central angle of the segment with product, rad.

Accordingly, the area of the layer of product:

$$S_p = \frac{\gamma}{2\pi}\pi R^2 - \frac{1}{2}R^2 \sin(\gamma). \tag{7}$$

Substituting (7) into (3), and taking into account the area of cross-section of the drum:

$$S_d = \pi R^2 \tag{8}$$

we obtain the magnitude of coefficient of filling the drum with a layer of product:

$$\beta = \frac{1}{2\pi}\big(\gamma - \sin(\gamma)\big). \tag{9}$$

The mass of the product in the set-up will be found with regard to the bulk density of the product and coefficient of filling the drum with product:

$$m_p = \rho_{pb} S_p b = \frac{1}{2}\rho_{pb} R^2 b(\gamma - \sin(\gamma)), \tag{10}$$

where ρ_{pb} is the bulk density of product, kg/m^3; b is the length of the drum, m.

The distance to the center of masses of the segment of product is determined by the known formula:

$$r_c = \frac{4}{3}R\frac{\sin^3(\gamma/2)}{\gamma-\sin\gamma}, \qquad (11)$$

where r_c is the distance from the axis of rotation of the drum to the center of masses of the segment of product.

The next step will define the boundary conditions for the existence of the first mode of motion of the layer of bulbs when the layer retains its shape and moves as a whole one. This, as stated above, is not optimal mode in terms of cleaning, but the particular boundary conditions of this regime determine the minimum rotation frequency of the drum, above which the second one starts – the optimal mode of operation of the set-up.

Let us find connection of angle α_1, at which we may rotate the layer of product relative to the horizontal axis of the drum without disturbing its shape (Fig. 4).

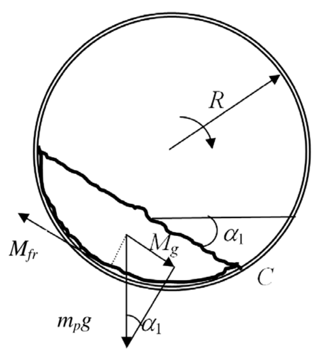

Fig. 4. Scheme of the forces that determine angle of lifting the layer of product a_1 under the first mode of the drum operation

The equilibrium of product segment with mass m_p is determined from the condition of equality of oppositely directed moments of forces – friction M_{fr} and moving component M_g of weight M_g=mgsin(α_1). Force of friction F_{fr} is written down as the product of coefficient of external friction f_{fr} and force of normal pressure; the latter is the sum of the centrifugal force acting on the centre of gravity of segment $F_c=m_p r_c \omega^2$ and radial component of force of gravity mgcos(α_1), that is

$$F_{fr} = f_{fr}(m_p r_c \omega^2 + m_p g\cos\alpha_1). \qquad (12)$$

Shoulder of the force of friction is equal to radius of the drum R, shoulder of the moving force of gravity is equal to the distance to the center of masses of segment r_c (14). Equality of these moments determines the conditions for the equilibrium of entire segment of the product:

$$f_{fr}(m_p r_c \omega^2 + m_p g\cos\alpha_1)R = m_p g\sin\alpha_1 \cdot r_c. \qquad (13)$$

The last equation is convenient to represent for analysis in the dimensionless form. After simple transformations, we obtain

$$Fr = \frac{1}{f_{fr}}\sin\alpha_1 - \frac{3}{4}\frac{\gamma-\sin\gamma}{\sin^3(\gamma/2)}\cos\alpha_1, \qquad (14)$$

where

$$Fr = \frac{\omega^2 R}{g}$$

is the Froude number; R is the radius of the drum, m; ω is the cyclic rotation frequency of the drum, rad/s; g is the free fall acceleration, m/s^2.

It is obvious that the maximum angle of lifting the segment of product is equal to the angle of natural bevel of the layer of bulbs max(α_1)=α_y and maximum central angle of the segment with product in this case γ=180°, because at larger values of angles α_1 and γ, the entire segment of product will be destroyed (upper bulbs of the segment will be rolled along its outer surface). Taking into account these considerations, the Froude number's boundary value for the first mode of motion is equal to:

$$Fr_{min} = \frac{1}{f_{тр}}\sin\alpha_y - \frac{3}{4}\frac{\pi-\sin\pi}{\sin^3(\pi/2)}\cos\alpha_y. \qquad (15)$$

If we substitute in (15) the value of natural bevel angle of the layer of bulbs α_y=40° and coefficient of friction of a bulb with metal f_{fr}=0,29, then we receive the condition to determine minimum rotation frequency of the drum:

$$Fr_{min} = 0.41. \qquad (16)$$

That is

$$\omega_{min} = \sqrt{\frac{Fr_{min}\, g}{R}}, \qquad (17)$$

or, with regard to the connection between cyclic rate and rotation frequency

$$n_{min} = \frac{30}{\pi}\sqrt{\frac{0.41g}{R}} = \frac{19.19}{\sqrt{R}}, \qquad (18)$$

where n_{min} is the minimum rotation frequency of the drum, min^{-1}; R is the radius of the drum, m.

Let us note that this formula is valid only for the maximum permissible load of the drum under the first mode of motion, which is easy to calculate by substituting in formula (9) values $\gamma=\pi$, then β_{max}=0.5.

If the load is less, then the first mode of motion of product in the drum will occur at larger rotation frequencies because moment of moving force $m_p g\sin\alpha_1 \cdot r_c$ increases (due to r_c), and, to compensate for it, it is necessary to increase the force of normal pressure. This dependence, based on (15) and data for onion α_y=40° f_{fr}=0.29, takes the following form:

$$Fr_{min} = 2{,}22 - 0{,}58\frac{\gamma-\sin\gamma}{\sin^3(\gamma/2)}. \qquad (19)$$

In this formula, central angle of the segment with product varies in the range $0<\gamma\leq\pi$, corresponding to the coefficient of loading according to (9) within $0<\beta\leq0.5$. Formula (19), together with (18), allows us to calculate the minimum rotation frequency of the drum for the transition into optimal mode of motion of the layer of onion at random drum load, in contrast to (16).

As noted above, optimal conditions for cleaning onion in the drum occur under the second mode of the motion of its layer, the upper limit of which is the critical rotation frequency (2). It should be noted that formula (2) does not correspond to the real situation since, when receiving it, the assumption was made that the layer of product is infinitely thin, meaning the load factor of the drum $\beta \to 0$. When actually loaded, the bulbs in the drum will take up a certain volume, the thickness of their layer for the third mode of motion is related to the load factor by obvious ratio:

$$\beta = \frac{\pi R^2 - \pi R_1^2}{\pi R^2}, \quad (20)$$

where R_1 is the inner radius of the layer of product, m.

Hence

$$R_1 = R\sqrt{1-\beta}. \quad (21)$$

The equilibrium conditions for the layer of product under the third mode of motion will be determined by centrifugal force for the smallest radius of the layer, that is,

$$m\omega_{max}^2 R_1 = mg, \quad (22)$$

from where, given (21) and expression for Froude number, we shall receive boundary condition for critical (maximum) rotation frequency of the drum:

$$Fr_{max} = \frac{1}{\sqrt{1-\beta}}. \quad (23)$$

When Froude numbers exceed Fr_{max}, the third motion mode will be provided for the entire layer of product. Thus, the optimal mode of operation of the set-up for cleaning onion is defined by the following range:

$$Fr_{min} < Fr < Fr_{max}. \quad (24)$$

With regard to (19), (23) and (9), we shall receive

$$2{,}22 - 0{,}58\frac{\gamma - \sin\gamma}{\sin^3(\gamma/2)} < Fr < \frac{1}{\sqrt{1-\frac{1}{2\pi}(\gamma - \sin(\gamma))}}. \quad (25)$$

In practice, it is convenient to use as an argument not the central angle of the segment with product γ, but the coefficient of filling the drum β, but expressing the relationship γ(β) from transcendental equation (9) is not possible, that is why we proposed approximate equation, found by the method of regression analysis, which describes exact decision (2) with error of 5 % in the range β=0,2...0,8 (Fig. 5).

$$\gamma(\beta) = 3.04\left(\frac{0.99\beta}{1-\beta}\right)^{0.22}. \quad (26)$$

Then condition (26) can be written down through coefficient of filling the drum:

$$2.22 - 0.58\frac{\gamma(\beta) - \sin[\gamma(\beta)]}{\sin^3[\gamma(\beta)/2]} < Fr < \frac{1}{\sqrt{1-\beta}}. \quad (27)$$

Fig. 6 displays dependences of determinant criterion Froude on the coefficient of filling the drum with onion. As already discussed above, the region of optimal modes of the set-up for cleaning onion lies between the lines of maximal and minimal Froude numbers, that is, it corresponds to mode II.

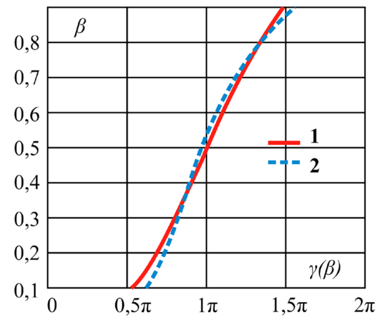

Fig. 5. Relationship between the coefficient of filling the drum and central angle of the segment with product: 1 — equation (9); 2 — approximate equation (26)

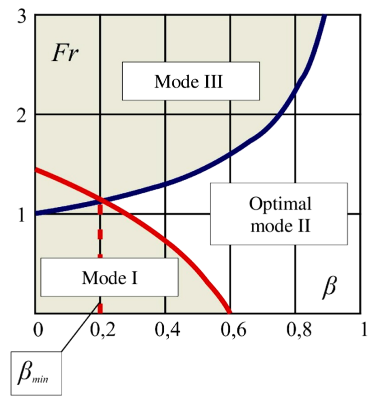

Fig. 6. Dependence of the Froude number's limiting values on the coefficient of filling the drum with onion

With a decrease in the coefficient of filling, the range of optimum modes narrows and at values β<0.2, there is no second motion mode of the layer of bulbs in the drum, that is, the existence of either the first or the third mode of motion is possible, but, as noted at the beginning of the section, they are ineffective in terms of mechanical cleaning. It should be noted that the results presented will certainly be subject to experimental refinement because the resulting model only in the first approximation represents complex real processes that occur when moving a product in the centrifugal drum. These data were used in planning further experimental research, the purpose of which was to find the optimal modes of operation of the set-up for mechanical cleaning of onion.

The effectiveness of removing husk of onion after thermal treatment can be evaluated by measuring the magnitude of effort to remove the husk from onion. Fig. 7 displays dependence of influence of the duration of thermal processing of onion on the effort for removing its husk.

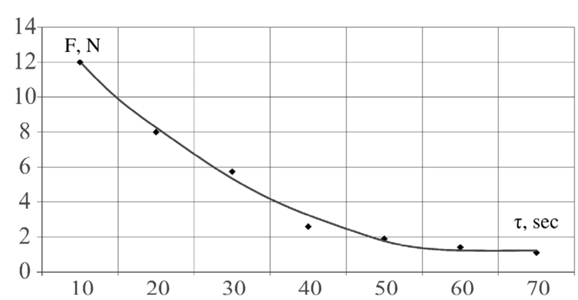

Fig. 7. Dependence of the effort of removing the husk of onion on the duration of its steam treatment

Reducing the magnitude of the effort for removing the husk will occur as a result of weakening bonds between cells of the surface layer of napiform onion. The conducted studies allowed us to find out that during the process of mechanical cleaning, the depth of thermal treatment of napiform onion will significantly affect the percentage of losses of raw materials, and the effort to remove the husk will affect the percentage of cleaned bulbs and duration of the process of mechanical cleaning of onion. In order to improve quality of cleaning and minimize the loss of raw materials, it is necessary to identify all the factors that influence this process. A direct impact on the process of mechanical cleaning will be exerted by the duration of this process. An increase in the duration of the process of mechanical cleaning leads to increased losses of raw materials, but their reduction could lead to deterioration in the quality of cleaning the product.

In order to minimize the loss of raw materials and to improve at the same time the quality of cleaning the surface of napiform onion, there is a need to conduct research into determining the duration of carrying out the process of mechanical cleaning, depending on the effort to remove its husk. Results of these studies are presented in Fig. 8.

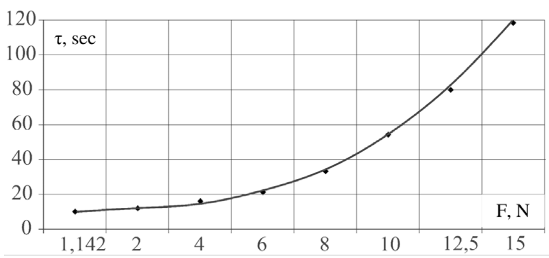

Fig. 8. Dependence of duration of mechanical cleaning of napiform onion on the effort to remove its husk

The results of research presented indicate that onion, whose husk is separated with a large effort, requires longer mechanical cleaning.

A correlation analysis revealed that the largest degree of correlation is demonstrated by the percentage of cleaned bulbs and the thickness of penetration through the surface layer of bulbs. That is why, by the methods of regression analysis (Table 1), we established the following dependence of the percentage of cleaned bulbs on the thickness of penetration through their surface layer:

$$P = a_1 + a_2 \cdot \delta + a_3 \cdot \delta^2, \quad (28)$$

where P is the percentage of cleaned bulbs, %; δ is the thickness of penetration through the surface layer of onion, mm; a_i are the regression coefficients.

Fig. 9–11 demonstrates the calculated data, built according to model (28), to determine the percentage of cleaned bulbs from the thickness of penetration through the surface layer of a bulb.

The obtained data allow us to state that the maximum degree of cleaning the bulbs is approaching 100 %; in this case, at a low drum filling factor 0.3...0.5, we observe two extrema in the range of thickness of the penetration 4...4.5 mm for K_y=0.3 and 3.5...5 for K_y=0.5. The curves are divided into two families: curves 1, 2, 4 have a smaller area of openings of the drum than curves of 3, 5, 6. At the same time, for the drum filling factor at 0.7, there is only one extremum at δ=4.8 mm.

Table 1

Values of regression coefficients for different shapes and diameters of openings

Shape and diameter of openings	a_1	a_2	a_3
load factor 0,3			
Circle, 12 mm	–111	95	–11.46
Circle, 17 mm	–94	75	–7.99
Circle, 22 mm	–312	176	–18.96
Ellipse, 12×18 mm	–104	92	–11.19
Ellipse, 17×23 mm	–134	103	–11.86
Ellipse, 22×28 mm	–265	163	–18.21
load factor 0,5			
Circle, 12 mm	–168	135	–17.96
Circle, 17 mm	–101	74	–7.44
Circle, 22 mm	–318	174	–18.09
Ellipse, 12×18 mm	–107	87	–9.75
Ellipse, 17×23 mm	–152	104	–11
Ellipse, 22×28 mm	–445	230	–24.28
load factor 0,7			
Circle, 12 mm	–121	76.3	–7.09
Circle, 17 mm	–132	90.7	–9.53
Circle, 22 mm	–278	157.6	–16.63
Ellipse, 12×18 mm	–17	7.6	2.02
Ellipse, 17×23 mm	–176	105.3	–10.52
Ellipse, 22×28 mm	–130	100.8	–11.09

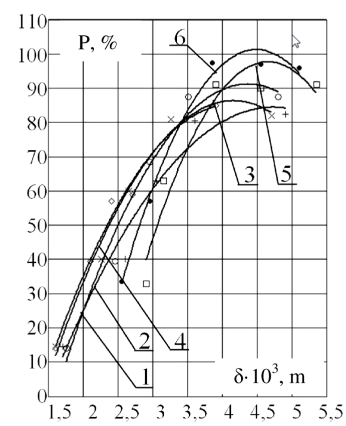

Fig. 9. Influence of the thickness of penetration through the surface layer of bulb on the degree of cleaning the bulbs at load factor 0.3 and shape and diameter of openings: 1 – circle, 12 mm; 2 – circle, 17 mm; 3 – circle, 22 mm; 4 – ellipse, 12×18 mm; 5 – ellipse, 17×23 mm; 6 – ellipse, 22×28 mm

Thus, depending on the filling factor, the maximum of degree of cleaning is observed for openings with a larger area, but at different depth of the penetration.

Let us separately consider the question of rational rotation speed of the drum during mechanical cleaning.

Fig. 12 demonstrates results of regression analysis of dependence of the degree of cleaning on the drum rotation frequency.

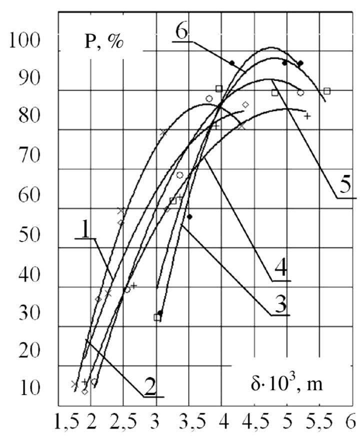

Fig. 10. Influence of the thickness of penetration through the surface layer of bulb on the degree of cleaning the bulbs at load factor 0.5 and shape and diameter of openings: 1 – circle, 12 mm; 2 – circle, 17 mm; 3 – circle, 22 mm; 4 – ellipse, 12×18 mm; 5 – ellipse, 17×23 mm; 6 – ellipse, 22×28 mm

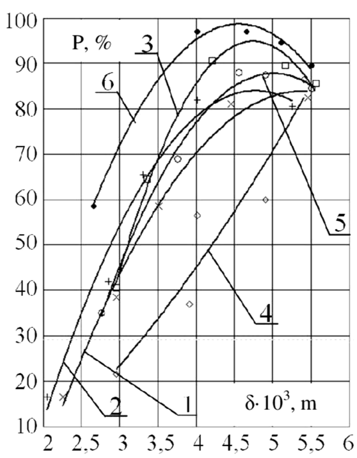

Fig. 11. Influence of the thickness of penetration through the surface layer of bulb on the degree of cleaning the bulbs at load factor 0.7 and shape and diameter of openings: 1 – circle, 12 mm; 2 – circle, 17 mm; 3 – circle, 22 mm; 4 – ellipse, 12×18 mm; 5 – ellipse, 17×23 mm; 6 – ellipse, 22×28 mm

As we can see, the optimal value of rotation frequency by the indicator of quantity of removed parts of a bulb corresponds to value 100 min^{-1}.

Corresponding regression equation takes the following form:

$$K = -168 + 4{,}68 \cdot n - 0{,}021 \cdot n^2, \qquad (29)$$

where K is the number of removed parts of a bulb, %; n is the drum rotation frequency, min^{-1}.

The presence of characteristic optimum of rotation frequency n=100 min^{-1} directly follows from the theoretical model of the process of cleaning. According to this model, at high rotation frequencies, there occurs the so-called third non-working mode of the drum when the layer of bulbs is pressed to the inner surface of the drum by centrifugal force and at which efforts for cutting do not occur.

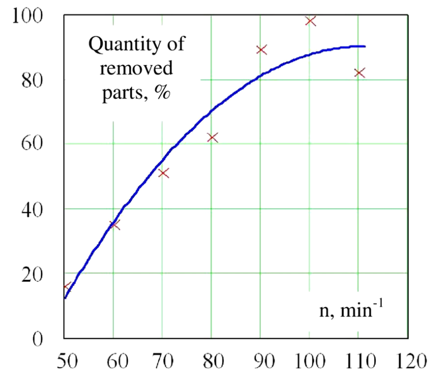

Fig. 12. Determining optimal drum rotation frequency by the indicator of quantity of removed parts of a bulb: × – experimental research; ——— – correlation curve

6. Discussion of results of examining the process of mechanical cleaning of napiform onion

The research results of the combined process of cleaning napiform onion allow us to specify the duration of its pre-boiling to the condition that provides for the maximum degree of cleaning and minimum percentage of losses of raw materials during subsequent mechanical treatment.

The obtained data enable us to state that the maximum degree of cleaning the bulbs is 88...98 %, coefficient of filling the volume of working drum is 0.3...0.7.

As a result of regression analysis of dependence of the degree of rotation frequency of the drum, we defined rational value of its rotation frequency by the indicator of quantity of removed parts of a bulb, which corresponds to 100 min^{-1}. A larger rotation frequency leads to pressing the layer of bulbs onto the inner surface of the drum by centrifugal force; in this case, efforts on cutting do not occur.

A mathematical modeling of the process of mechanical treatment of napiform onion with the purpose of defining rational parameters of the combined process of cleaning is a new study to date. Based on the conducted theoretical and experimental research, we designed a device for the combined cleaning of onion and specified rational modes of its operation. This will substantially intensify and mechanize the cleaning process, will provide high quality of cleaning the product and minimize the loss of raw materials. Designed device for the combined cleaning of napiform onion might be used in restaurant business, purchasing departments and at the enterprises of food industry. Further studies are planned for conducting design calculations of the device for the purpose of its improvement, which will provide the possibility to take the size of the bulbs into account, as well as their varietal features in the process of cleaning.

7. Conclusions

1. We designed an experimental installation with the appropriate methodology that allows studying the process of mechanical cleaning of napiform onion and determined

dependence of the percentage of losses of raw materials on the process parameters.

2. Research results allowed us to define the duration of pre-cooking of onion to the condition that provides for the maximum degree of cleaning. Thus, at load factor 0.3, rational duration of cooking onion in the drum with openings' area within $(3.07...4.84)\cdot 10^{-4}m^2$ is 140 s and, accordingly, rational duration of cooking in the drum for the same openings at load factor 0.5 is 170 s, and at load factor 0.7 – 180 s.

3. It was established that the maximum degree of cleaning the bulbs is 88...98 %; in this case, at a low coefficient of filling the drum (K_y) 0.3...0.5, we observed two extrema in the range of thickness of the penetration: 4...4.5 mm for K_y=0.3 and 3.5...5 for K_y=0.5, and for drum filling coefficient at 0.7, there is only one extremum at δ=4.8 mm. Therefore, depending on the coefficient of filling, maximum degree of cleaning is observed for the openings with a larger area, but at varying depth of the penetration.

4. A mathematical model is proposed on the quality level for the process of treating napiform onion during its mechanical cleaning, which theoretically substantiates that the optimal mode of motion of the product in the drum device for cleaning is the mode, at which a layer of bulbs lose equilibrium state and there occur sliding forces relative to the inner surface of the drum, which, along with the force of friction, determine the effort for cutting the neck and stem of a bulb. Mathematical model, found by the method of regression analysis, has error of 5 % within the value of coefficient of filling the drum β=0.2...0.8. Mathematical model takes the form of a system of inequalities, which is characterized by the Froude criterion. It connects the coefficient of filling the drum and central angle of the segment with a product.

We obtained equations to calculate the limiting modes of motion when moving in the drum, which explicitly take into account the friction coefficient, the angle of natural bevel of the layer of product and the magnitude of drum load.

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EXPLORING THE PROCESSES OF CRYOMECHANODESTRUCTION AND MECHANOCHEMISTRY WHEN DEVISING NANO-TECHNOLOGIES FOR THE FROZEN CAROTENOID PLANT SUPPLEMENTS

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Виявлено закономірності та механізми комплексної дії процесів глибокої переробки каротинвмісної рослинної сировини заморожування та кріомеханодеструкції на збереження і вилучення каротиноїдів, зв'язаних в нанокомплексах з біополімерами, у вільну та гідрофільну форми. Встановлено, що при розробці нанотехнологій кріопюре відбувається екстракція β-каротину у вільну форму в 3…3,5 рази більше, ніж у вихідній сировині

Ключові слова: кріомеханодеструкція, нанотехнології, каротиноїди, рослинні добавки, руйнування нанокомплексів, біополімери, зв'язані форми

Выявлены закономерности и механизмы комплексного действия процессов глубокой переработки каротинсодержащего растительного сырья, замораживания и криомеханодеструкции на сохранение и извлечение каротиноидов, связаных в нанокомплексах с биополимерами, в свободную и гидрофильную формы. Установлено, что при разработке нанотехнологий криопюре происходит экстракция β-каротина в свободную форму в 3…3,5 раза больше, чем в исходном сырье

Ключевые слова: криомеханодеструкция, нанотехнологии, каротиноиды, растительные добавки, разрушение нанокомплексов, биополимеров, связанные формы

1. Introduction

Provision of population with rational and balanced nutrition is one of the most important problems of mankind. It is much more complicated by the fact that the dynamics of growth of the total population of the Earth is larger than the possibility of providing for the food products that are necessary for life activity, affordable in price and traditional for the given region. According to the estimates of scientists, to date, about 50 % of the world population is beyond poverty and are starving [1, 2]. To address the global problem of hunger, various countries of the world initiated the pro-