UDC 641.51:635.24:519.87
DOI: 10.15587/1729-4061.2017.103855

MODELING OF THE PROCESS OF PEELING JERUSALEM ARTICHOKE IN ORDER TO DETERMINE PARAMETERS FOR CONDUCTING PRODUCTION PROCESS

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Представлено результати досліджень впливу параметрів процесу термічної обробки, тривалості процесу механічного очищення, характеристик сировини на показники якості очищення бульб топінамбуру. Отримані математичні моделі процесу термічної обробки бульб топінамбуру парою. Запропоновано математичні моделі процесу механічного очищення топінамбура для визначення відсотка очищених бульб топінамбуру та відсотка виходу сировини за масою

Ключові слова: моделювання процесу, термічна обробка, механічне доочищення, відсоток втрат сировини, якість очищення

Представлены результаты исследований влияния параметров процесса термической обработки, продолжительности процесса механической очистки, характеристик сырья на показатели качества очистки клубней топинамбура. Получены математические модели процесса термической обработки клубней топинамбура паром. Предложены математические модели процесса механической очистки топинамбура для определения процента очищенных клубней топинамбура и процента выхода сырья по массе

Ключевые слова: моделирование процесса, термическая обработка, механическая доочистка, процент потерь сырья, качество очистки

1. Introduction

One of the main processes, which are used at the enterprises of restaurant business, is the process of peeling vegetable raw materials. Technological process of peeling the tubers of Jerusalem artichoke deserves serious attention. Despite the fact that several types of equipment are used at present to conduct the process of peeling Jerusalem artichoke, there still remain many problematic questions. The main problem is linked to the fact that during peeling a substantial part of the raw material is lost due to imperfect equipment, employed in the implementation of this process, which requires considerable modernization [1].

An improvement in the quality of peeling is the promising trend of processing vegetables, as well as a reduction in the losses of raw material during its processing. Peeling the tubers of Jerusalem artichoke is a rather labor-consuming process. For its realization, it is necessary to create equipment whose principle of work is based on the combined action of thermal and mechanical processes on the product [2]. However, the absence of comprehensive experimental studies into the application of the combined action of these processes on the product, taking into account the characteristics of product, substantially hampers development of new energy efficient equipment. When examining the process of peeling, attention should be paid to such indicators as the quality of peeling and the amount of waste [3].

At present, most common methods of peeling vegetables are mechanical and steam [4]. These methods have some advantages over other methods of peeling. In spite of this, they are characterized by certain shortcomings. The deficiencies in the existing equipment include material and energy consumption, insufficient quality of peeling a product, high percentage of waste, and the presence of auxiliary equipment [5].

Special attention should be paid to the process of cleaning the tubers of Jerusalem artichoke from the outer cover. Substantial part of this raw material is lost as a result of the fact that the realization of peeling employs equipment, which is obsolete. Under contemporary conditions of production, there arises the need to create equipment, which matches world requirements.

Very important for the healthy nourishment of humans are the products, prepared from the vegetable raw materials. Jerusalem artichoke contributes to the removal of toxic and radioactive materials, phosphates, nitrates from the organism. It is known that the tubers of Jerusalem artichoke have considerable nutrient value. Their composition includes vitamins, mineral substances, pectins, proteins, amino acids. Tubers of Jerusalem artichoke are balanced in terms of the macro- and microelement composition. By the content of phosphorus, potassium, iron, silicon and zinc, Jerusalem artichoke substantially exceeds such root crops as carrot, beet and potatoes. Pre-treatment of the tubers of Jerusalem artichoke before their use in the food industry has a complex character. Tubers of Jerusalem artichoke have irregular shape, there are many convexities and cavities. It is required, accordingly, to make significant efforts to peel the tubers. While conducting the process of peeling, the percentage of waste can reach 40 %. At present, the process of peeling is sufficiently labor consuming and requires the application of manual labor. Furthermore, during peeling a substantial part of the raw material is lost. This necessitates design of the equipment, which would ensure high efficiency of the process of peeling the tubers of Jerusalem artichoke.

2. Literature review and problem statement

Processing Jerusalem artichoke tubers is characterized by the fact that much of the raw material is wasted, more to the point: mostly during the peeling process. Given this, a method of peeling the tubers plays a significant role in the industrial processing of artichoke. One should also pay attention to the equipment that is used in the peeling process.

At present, the process of peeling Jerusalem artichoke and removing its various defects is one of the most complicated operations in preparation of raw material for processing. A peeling method is important for the economy of production since, during processing, the raw material waste can reach 50 %. Peeling of artichoke can be conducted by thermal, chemical and mechanical techniques. However, when using thermal and chemical methods, it is necessary to additionally apply mechanical post-treatment for complete removal of peel [6].

One of the most effective ways is considered to be peeling off the surface layer of artichoke by steam with a subsequent blow of jets of steam or water under pressure. To identify the main benefits and shortcomings, characteristic for the existing methods of peeling tubers, we shall consider and analyze them in more detail.

The most common and easy way of peeling the tubers of Jerusalem artichoke is a mechanical technique that predetermines a change only in the anatomical structure of a tuber without significant changes in the chemical composition and properties. A working surface of the peeling equipment can be made of different materials and have different shape [7].

The essence of mechanical peeling technique is erasing the external tissues by rough surfaces (mainly, abrasive) to remove the peel and cells. Mechanical treatment of washed, inspected and calibrated tubers is conducted in peeling machines under continuous feed of water for flushing and disposal of waste. When this method of peeling is implemented, the outer layers is removed by rough working surfaces. In this case, a tuber should be pressed to a rough surface with a certain effort so that parts of this surface deepen in the tuber, and at subsequent movement of the surface, a micro cut is to occur. Upon completion of the main process of peeling, it is necessary to conduct post-peeling. Post-treatment of tubers manually is an extremely labor consuming process with a large percentage of losses of raw materials.

In addition to the mechanical peeling method, one of the most common and effective ways to peel artichoke is a steam technique. This method has significant advantages in comparison with other ways of peeling. When using this method, the amount of waste reduces, eliminating the need for the calibration of raw materials because tubers of all shapes and size are well peeled. When a steam peeling method is used, tubers in steam plants are exposed to intensive water vapor. Treatment time is 1...2 min., at vapor pressure 0.4...1.1 MPa. After treatment, the pressure is dropped to the atmospheric. As a result of a sharp pressure drop, moisture in a layer under the peel boils and turns to steam, which helps peel off and tear the peel of the tuber. Due to an increase in the temperature of steam, the surface layer of tubers is boiled. The tubers peeled by a steam technique have crude (not blanched) flesh. Peeling is carried out in the units of periodic and continuous action. After a steam peeling unit, tubers arrive to a washing-peeling machine, where they are finally peeled off, the peel is washed off, as well as a partially boiled layer [8].

Products from artichoke manufactured using a steam method of peeling do not differ in quality from similar products, obtained by mechanical peeling treatment.

A steam technique provides high quality of peeling at low waste of raw materials. Nevertheless, equipment for the implementation of steam peeling method requires considerable production areas, has large dimensions, consumes large amount of electricity. In addition, this type of equipment is highly efficient as it is intended for large processing plants. That is why the steam peeling method is hardly used at the enterprises of restaurant business [9].

Widely applied at the enterprises in food industry is a chemical peeling method. During chemical peeling, tubers of Jerusalem artichoke are exposed to treatment with an alkali solution with subsequent peeling by a mechanical technique and neutralization of residual alkali by acid (vinegar or lemon). Alkaline peeling method implies treatment of Jerusalem artichoke with hot alkali solutions. They use mostly sodium hydroxide solutions, less often – caustic potassium. The raw materials to be peeled are immersed in a boiling 25 % solution of alkali. The peel is easily separated within 15 minutes and it is washed off with water in a washing machine. This requires complete removal of chemical residues from the tuber surface.

The disadvantages of this method include considerable cost of chemical components for conducting the process, as well as the need for special recycling of waste, as it may be hazardous for the environment [10].

In some cases, chemical and steam methods can be combined in an alkaline steam peeling method. When applying this method, they use chemical and steam plants. At the first stage, tubers are treated with a 12 % solution of caustic soda at a temperature of 80 °C for 10 minutes. Next, the tubers are exposed to sharp vapor at pressure 0.6 MPa for 1 min. Following the treatment of tubers of Jerusalem artichoke with steam, their post-peeling is conducted manually.

Alkali-steam peeling method implies treatment of tubers with alkaline solution and vapor in the plants under excessive or atmospheric pressure; in this case, they use weak (5 %) alkaline solutions. Given this, alkali consumption is sharply reduced (by about 10 times), waste is reduced compared to the alkaline technique. Waste of Jerusalem artichoke is not used when employing the method of alkaline peeling.

Minimal waste and losses of raw material are observed at alkaline (23.7 %) and alkaline-steam (28.1 %) peeling techniques; maximal – at water vapor (36.7 %) and mechanical (31 %) methods.

The lowest labor costs in the process of peeling and post-peeling are observed at alkaline peeling method, the largest – at mechanical. Consumption of supporting material at alkaline peeling method is significantly larger because their cost, in addition to water, steam and electricity, includes alkali, which significantly increases the cost of the peeled raw material [11].

When analyzing the existing methods and equipment for the implementation of the process of peeling tubers, it can be argued that, to date, the most common techniques to peel are mechanical and steam. Advantage of the mechanical method over other methods is the use of equipment that has small dimensions, low material and energy consumption. As compared to the mechanical, the steam mode is characterized by better quality of peeling, and there is also no need to pre-calibrate the raw materials. However, equipment for the steam peeling method is material- and energy-intensive and requires additional production facilities for the implementation of this method.

Steam peeling method has been applied at large processing enterprises and enterprises in the food industry. The enterprises in restaurant business employ mainly mechanical method to peel vegetables, this is due to the lack of equipment with limited capacity and with a simple design for the implementation of thermal and chemical peeling methods. However, the optimal technique of peeling, from the viewpoint of preserving nutrients at minimal waste, is considered to be a steam method [12].

At present, there is a need for the development of equipment to peel tubers rind. Equipment to be designed should be of a relatively small size, be energy efficient and ecologically friendly [13]. In order to intensify development of the new equipment, it is required to undertake a number of theoretical and experimental research. It is necessary to determine the effect of varietal characteristics of Jerusalem artichoke and peeling process parameters on the efficiency of peeling a product.

Currently, one of the most promising directions to improve quality of artichoke peeling and to reduce the losses of raw material is to create equipment whose operation principle is based on the combined effects of thermal and mechanical processes on the product. However, a lack of comprehensive experimental studies on the use of the combined effect of these processes on the product significantly impedes development of the new energy-efficient equipment. Thus, improving the process of tuber peeling through a combination of thermal and mechanical impact on the product and development of appropriate hardware is a promising and relevant scientific and technical task.

3. Research goal and objectives

The goal of present work is to study the process of combined peeling of Jerusalem artichoke tubers, as well as to determine rational parameters of conducting combined peeling process.

To accomplish the set goal, the following tasks had to be solved:

– to develop procedures and experimental installations to examine the process of thermal treatment of Jerusalem artichoke with steam;

– to investigate the effect of steam pressure and duration of treating Jerusalem artichoke with steam on the surface layer of tuber;

– to explore the impact of duration of the process of mechanical post-peeling of Jerusalem artichoke on the quality of surface cleaning and losses of raw material;

– to receive mathematical models of the process of thermal treatment of Jerusalem artichoke with steam to determine a depth of thermal treatment of the surface layer and an effort to peel off the rind, as well as mathematical models of the process of mechanical post-peeling of Jerusalem artichoke to determine the percentage of peeled tubers and the percentage of the yield of peeled tubers by weight.

4. Materials and methods for examining the process of combined peeling of Jerusalem artichoke tubers

The developed combined method of peeling consists of the process of thermal treatment of Jerusalem artichoke tubers with steam at excess pressure and mechanical post-peeling. Priority task when conducting research into combined peeling process of Jerusalem artichoke was determining the rational modes of thermal treatment. These parameters include duration of the thermal treatment of Jerusalem artichoke with steam and steam pressure. To study the influence of thermal treatment on Jerusalem artichoke tubers, we designed an experimental installation.

More details on the materials and methods that were employed to study the process of combined peeling of Jerusalem artichoke tubers can be found in article [14].

5. Results of examining the process of combined peeling of Jerusalem artichoke tubers and determining the rational parameters for conducting the process

The main objective of study into the combined process of Jerusalem artichoke peeling was to determine rational modes of Jerusalem artichoke thermal treatment with steam. Parameters of the process of Jerusalem artichoke thermal treatment are steam pressure, temperature and duration of treatment.

We propose a mathematical model of dependence of the thermal treatment depth of the surface layer of Jerusalem artichoke tuber on the steam pressure, duration of treatment, the content of dry substance in the tubers of Jerusalem artichoke and their storing period. Construction of the mathematical model of the process of thermal treatment of Jerusalem artichoke tubers implied the following. At the first stage, we found a mathematical model for dependence of boiling penetration depth on the duration of Jerusalem artichoke thermal treatment in the form:

$$\delta(\tau) = f_1 (\tau + f_3)^{f_2}. \quad (1)$$

At the second stage, using a correlation analysis, we determined that coefficients f_1 and f_2 depend on steam pressure while coefficient f_3 on the content of dry substances only. At the third stage, regression equations were found for the dependence of functions f_1, f_2, f_3 on the process factors in the form:

$$f_1(p) = z_3 p^{z_4}, \quad (2)$$

$$f_2(p) = z_5 p^{z_6}, \quad (3)$$

$$f_3(K) = z_1 + z_2 K. \quad (4)$$

Resulting mathematical model of dependence of depth of thermal treatment of the surface layer of Jerusalem artichoke on the duration of thermal treatment process takes the following form:

$$\delta(\tau_{h.t.}, p, K) = z_3 p^{z_4} \left(\frac{\tau_{h.t.} + z_1 + z_2 \cdot K}{60} \right)^{z_5 p^{z_6}}, \quad (5)$$

where δ is the depth of thermal treatment, mm; p is the steam pressure, MPa; K is the content of dry substances, %; $\tau_{h.t.}$ is the duration of treatment, s; $z_1, z_2,..., z_i$ are the empirical coefficients.

Experimental data and their approximation with equation (5) are shown in Fig. 1.

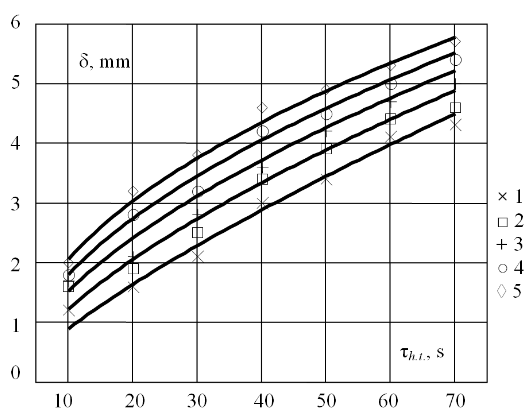

Fig. 1. Dependence of depth of Jerusalem artichoke thermal treatment (the content of dry substances is 18 %) and storage period to September 1 on the duration of treating a tuber with steam: 1 — 0.3 MPa; 2 — 0.4 MPa; 3 — 0.5 MPa; 4 — 0.6 MPa; 5 — 0.7 MPa

Dependence presented in Fig. 1 indicates that with increasing duration of the Jerusalem artichoke treatment, depth of thermal treatment of Jerusalem artichoke surface increases accordingly. Graphical dependence presented in Fig. 1 indicates that steam pressure and duration of treatment have an effect on the depth of thermal treatment of the surface layer. Depth of thermal treatment increases with increasing steam pressure and duration of thermal treatment.

Fig. 2 shows a correlation field between experimental data, which are given in Fig. 1, and the mathematical model (5). Relative error of the model is 4.5 %. Mathematical model holds within the limits of change in the examined factors: steam pressure is from 0.3 to 0.7 MPa, treatment duration is from 10 to 70 s, the content of dry substances is from 18 % to 26 %.

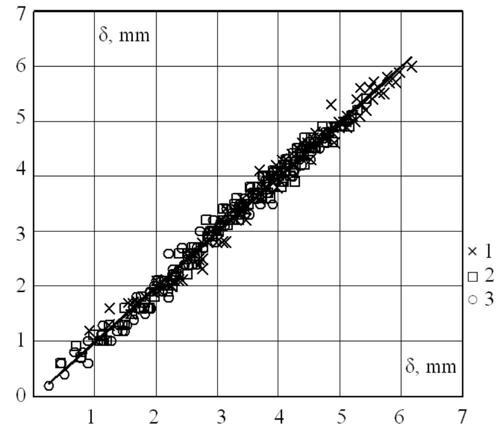

Fig. 2. Correlation field between experimental data on depth of the thermal treatment of Jerusalem artichoke surface layer and the mathematical model (5): 1 — to September 1; 2 — from September 1 to December 31; 3 — from January 1

Estimated dependences and experimental study confirmed assumptions on that the depth of thermal treatment of Jerusalem artichoke surface layer is affected by the tuber storage duration. When implementing a combined vegetable peeling process, it can be assumed that an increase in the depth of thermal treatment of Jerusalem artichoke surface layer will increase the percentage of losses of raw material during mechanical post-peeling. That is why it becomes necessary to reduce the depth of thermal treatment of Jerusalem artichoke layer by reducing the duration of thermal treatment and the values of steam pressure. However, when bringing down these indicators, separation of rind from the tuber of Jerusalem artichoke may prove to be ineffective.

In order to assess the effect of thermal treatment on the surface layer of raw material, it is necessary, in addition to the depth of thermal treatment, to introduce additional indicator. Efficiency of peeling off Jerusalem artichoke after thermal treatment can be assessed by measuring the value of effort required to separate the rind from the tuber of Jerusalem artichoke.

Based on the type of data received, we proposed a mathematical model of dependence of the effort required to separate the rind of Jerusalem artichoke on the duration of thermal treatment and steam pressure for Jerusalem artichoke tubers with different content of dry substances.

At the first stage, we proposed a mathematical model for dependence of the depth of thermal treatment on the duration of thermal treatment of Jerusalem artichoke in the form:

$$F(\tau) = \frac{1}{f_1 \cdot \tau^{f_2} + f_3}. \quad (6)$$

At the first stage, coefficients f_1, f_2, f_3 were considered to be constant dependence coefficients (6), which can be represented in the form of power dependence:

$$\frac{1}{F} = f_1 \cdot \tau^{f_2} + f_3. \quad (7)$$

At the second stage, we found equations of mathematical models for functions f_1, f_2, f_3, in the form:

$$f_1(K,p) = (e_1 + e_2 K) p^{(e_3+e_4 \cdot K)}, \quad (8)$$

$$f_2(K,p) = (e_5 + e_6 \cdot K) p^{(e_7+e_8 \cdot K)}, \quad (9)$$

$$f_3(K,p) = e_9 + (e_{10} + e_{11} K) p^2. \quad (10)$$

To this end, we employed a method of sequential regression analysis. Resulting mathematical model of dependence of the effort required to separate the rind of Jerusalem artichoke on the duration of thermal treatment of Jerusalem artichoke and steam pressure for Jerusalem artichoke takes the following form:

$$F(\tau_{h.t.},p,K) = \frac{1}{(e_1+e_2 \cdot K) \cdot p^{(e_3+e_4 \cdot K)} \cdot (\tau_{h.t.})^{(e_5+e_5 \cdot K) p^{(e_7+e_8 \cdot K)}} + e_9 + (e_{10}+e_{11} K) \cdot p^2}, \quad (11)$$

where F is the effort required to separate the rind of Jerusalem artichoke, N; p is the steam pressure, MPa; K is the content of dry substances (in fractions of unity); $\tau_{h.t.}$ is the duration of thermal treatment with steam, s; e_1, e_2, ..., e_i are the empirical coefficients.

Dependence of the effort required to separate the rind of Jerusalem artichoke on the duration of thermal treatment and steam pressure is shown in Fig. 3.

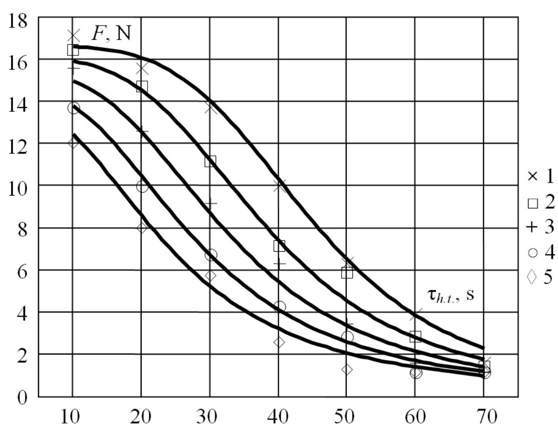

Fig. 3. Dependence of the effort required to separate the rind from a Jerusalem artichoke (the content of dry substances is 18 %) and storage period to September 1 on the duration of thermal treatment: 1 – 0.3 MPa; 2 – 0.4 MPa; 3 – 0.5 MPa; 4 – 0.6 MPa; 5 – 0.7 MPa

Efforts required for separating the rind from Jerusalem artichoke tubers range from 17.12 N to 1.142 N. Maximal value of effort to separate the rind (17.12 N) is observed at treatment duration 10 s and steam pressure 0.3 MPa. This indicates that the bond between the cells of the surface layer is not broken enough to separate the rind. Fig. 4 shows a correlation field between experimental data on the effort required to separate the rind of Jerusalem artichoke and mathematical model (6).

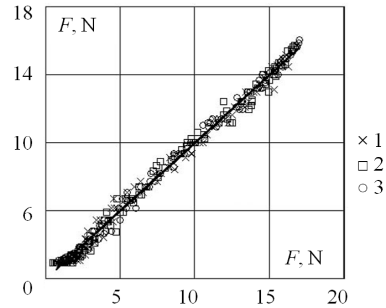

Fig. 4. Correlation field between experimental data on the effort required to separate the rind of Jerusalem artichoke and mathematical model (6): 1 – to September 1; 2 – from September 1 to December 31, 3 – from January 1

Increasing steam pressure leads to a decline in the effort required to separate the rind. During treatment that lasts 40 s and at steam pressure 0.3 MPa, the rind is separated at effort 9.991 N. At 0.7 MPa, the effort is 2.569 N. With an increase in the treatment to 70 s, the effort for separating the rind gradually decreases and reaches 1.559 N at a steam pressure value of 0.3 MPa, and 1.142 N at steam pressure 0.7 MPa. In the case when the value of separation effort is 1.142 N, bond between the rind and the tuber of Jerusalem artichoke is practically broken.

Mechanical peeling is the final stage in the combined process of peeling the tubers of Jerusalem artichoke. In order to improve peeling quality of Jerusalem artichoke tubers and to minimize losses of raw material, it is necessary to identify all of the factors that influence this process. Direct impact on the process of mechanical post-peeling will be exerted by such parameter as the duration of the process. In the case of increasing duration of the process of mechanical post-peeling, the durability of the action of working bodies of the plant to the surface layer of tubers simultaneously increases, which in turn may lead to increased losses of raw material. Nevertheless, if we reduce duration of mechanical peeling, there is a probability to compromise the quality of peeling. Duration of the process of mechanical post-peeling of Jerusalem artichoke tubers will be affected by tuber storage period, depth of thermal treatment of the tuber surface layer and the effort required to separate the rind. Conducted studies into the process of mechanical post-peeling of Jerusalem artichoke tubers have shown that the depth of tuber thermal treatment will directly affect the percentage of losses of raw materials while the effort required to separate the rind affects the percentage of peeled tubers. Thus, there is a need for determining rational length of the process of mechanical post-peeling depending on the effort required to separate the rind of Jerusalem artichoke and depth of thermal treatment. Based on the results of statistical processing of data on dependence of the percentage of peeled tubers on the effort required to separate the rind of Jerusalem artichoke, we proposed a mathematical model in the form:

$$S(F) = f_1 + f_2 \cdot F. \quad (12)$$

At the first stage, functions f_1, f_2 were considered to be constant coefficients of linear dependence (12). At the second stage, we derived equations of mathematical models for functions f_1, f_2 in the form:

$$f_1(\tau) = a_1 + a_2 \tau_{h.t}. \quad (13)$$

$$f_2(\tau) = a_3 + a_4\tau_{h.t}. \quad (14)$$

Resulting mathematical model of dependence of the percentage of peeled tubers on the effort required to separate the rind of Jerusalem artichoke and duration of treatment takes the form:

$$S(\tau_{m.p.}, F) = (a_1 + a_2\tau_{m.p.}) - (a_3 + a_4\tau_{m.p.}) \cdot F, \quad (15)$$

where S is the percentage of peeled tubers, %; F is the effort required to separate the rind of Jerusalem artichoke, N; $\tau_{m.p.}$ is the duration of mechanical post-peeling, s; $a_1, a_2, \ldots, a_i$ are the empirical coefficients.

Corresponding experimental data and their approximation with equation (15) are shown in Fig. 5.

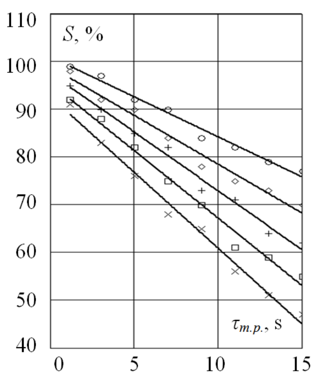

Fig. 5. Dependence of the percentage of peeled Jerusalem artichoke tubers, storage period to September 1, on the effort required to separate the rind and duration of the process of mechanical post-peeling, s: × – 30; □ – 50; + – 70; ◊ – 90; ○ – 110

The resulting dependence shows that the percentage of peeled tubers is reduced when using Jerusalem artichoke with a larger effort to separate the rind. During mechanical post-peeling of tubers whose effort to separate the rind is 1.142 N, the percentage of fully peeled tubers is equal to 91 %, at process duration of mechanical post-peeling 30 s. The percentage of peeled tubers of Jerusalem artichoke at effort to separate the rind of 7 N Peel will be 68 %. In the case when the effort to separate the rind is 15 N, the percentage of peeled tubers will amount to 47 %. Conducted experimental studies have shown that using Jerusalem artichoke whose depth of effort to separate the rind exceeds 15 N leads to incomplete removal of the rind from tuber surface. The use of such raw material is not appropriate, since, in this case, it is not possible to attain the required tuber peeling quality. Under condition of extension of the process of mechanical post-peeling, there is a gradual increase in the percentage of peeled Jerusalem artichoke tubers. At duration of the process 70 s, the percentage of peeled tubers increases by 4...9 % compared to the duration of treatment of 30 s. In the case when duration of mechanical post-peeling is 110 s, the percentage of peeled tubers will increase by 4...15 % in comparison to the duration of 70 s.

Fig. 6 shows a correlation field between experimental data and mathematical model (15). Relative error of the mathematical model is 1.7 %. The model holds within the limits of change in the examined factors: the effort to separate the rind ranges from 1.0 to 15 N, duration of the process of mechanical peeling ranges from 30 to 110 s.

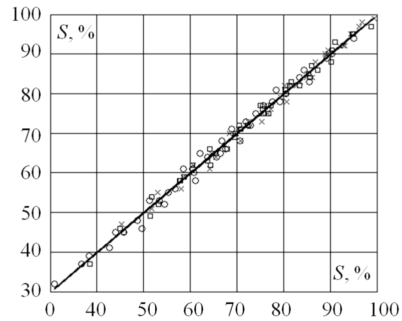

Fig. 6. Correlation field between experimental data on the percentage of peeled tubers and mathematical model (4): × – to September 1; □ – from September 1 to December 31; ○ – from January 1

As a result of statistical processing of data on dependence of the percentage of losses of raw material on the depth of thermal treatment δ, we proposed a mathematical model in the form of power dependence:

$$V(\delta) = f_1 \cdot \delta^{f_1}. \quad (16)$$

At the first stage, functions f_1, f_2 were considered to be constant coefficients of power dependence (16). At the second stage, we found equations of mathematical models for functions f_1, f_2 in the form:

$$f_1(\tau_{m.p.}) = \gamma_1 + \gamma_2\tau + \gamma_3\tau^2, \quad (17)$$

$$f_2(\tau_{m.p.}) = \gamma_4 + \gamma_5\tau + \gamma_6\tau^2. \quad (18)$$

Resulting mathematical model of dependence of the percentage of losses of raw material on the depth of thermal treatment δ and duration of the process of mechanical post-peeling $\tau_{m.p.}$ of Jerusalem artichoke takes the form:

$$V(\tau_{m.p.}, \delta) = \left(\gamma_1 + \gamma_2 \cdot \tau_{m.p.} + \gamma_3 \cdot \tau_{m.p.}{}^2\right) \cdot \delta^{(\gamma_4 + \gamma_5\tau_{m.p.} + \gamma_6\tau_{m.p.}{}^2)}, \quad (19)$$

where V is the percentage of losses of raw material, %; δ is the depth of thermal treatment of tuber, m; $\tau_{m.p.}$ is the duration of mechanical post-peeling, s; $\gamma_1, \gamma_2, \ldots, \gamma_i$ are the empirical coefficients.

Fig. 7 shows dependence of the percentage of losses of raw material on the depth of thermal treatment and duration of the process of mechanical post-peeling of Jerusalem artichoke whose storage period is to September 1.

The results obtained indicate that there is a substantial increase in the percentage of losses of raw material depending on the duration of mechanical post-peeling and depth of thermal treatment. The percentage of losses of raw material ranges from 8 to 22 %. Duration of the process of mechanical post-peeling in this case is 30 s. Depth of thermal treatment of Jerusalem artichoke is $1 \ldots 5 \cdot 10^{-3}$ m. A growth in the percentage of losses of raw material is due to the fact that during mechanical post-peeling the surface layer of Jerusalem artichoke, which was boiled during preliminary thermal treatment, is gradually peeled off along with the rind. That is why, when the value of depth of thermal treatment is $1 \cdot 10^{-3}$ m, duration of the process of mechanical peeling does not exert any significant impact on the percentage of losses of raw material. At duration of the process of mechanical peeling 30 s, the percentage of losses of raw material is 8 %, and while increasing duration of the process to 110 s, the percentage of losses of raw material is changed to 1 %. However, when using Jerusalem artichoke whose depth of thermal treatment is $5\cdot10^{-3}$ m, range of changes in the percentage of losses of raw material reaches 22...35 %. During the process of mechanical post-peeling that lasts 110 s, the surface layer of Jerusalem artichoke is almost completely peeled. At a consequent increase in the duration of mechanical post-peeling, the percentage of losses of raw material does not grow. Thus, there is a need to determine the impact of storage period of Jerusalem artichoke tubers on the percentage of losses of raw materials.

Fig. 8 shows a correlation field between experimental data on the percentage of losses of raw material and mathematical model (19).

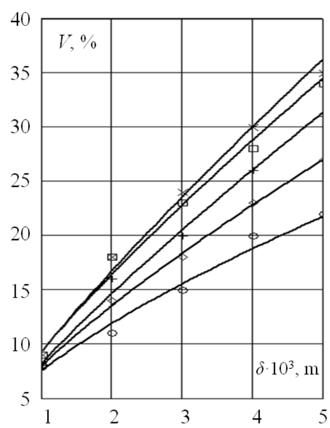

Fig. 7. Dependence of the percentage of losses of raw material for Jerusalem artichoke tubers with storage period to September 1 on the depth of thermal treatment of the surface layer and duration of the process of mechanical post-peeling, s: × – 30; □ – 50; + – 70; ◊ – 90; ○ – 110

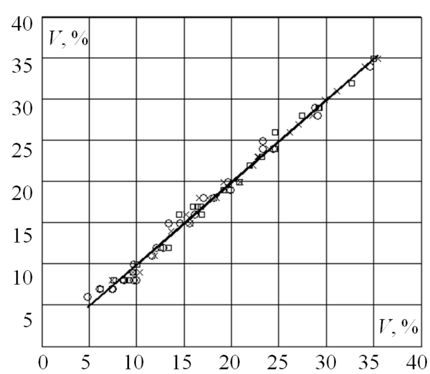

Fig. 8. Correlation field between experimental data on the percentage of losses of raw material and mathematical model (19), × – to September 1; □ – from September 1 to December 31; ○ – from January 1

We chose as a criterion of quality of the peeling process maximal value of the percentage of peeled tubers at maximal possible yield of the finished product by weight of tubers. The maximal value of the percentage of peeled tubers can be written as follows:

$$S(\tau_{h.t.},\tau_{m.p.},p,K)=\left(a_1+a_2\cdot\tau_{m.p.}\right)-\left(a_3+a_4\cdot\tau_{m.p.}\right)\times$$
$$\times\left[\beta_4+\beta_3\cdot\exp\left(-\beta_1\cdot(z_3\cdot p^{z_4}\cdot\left(\left(\frac{\tau_{h.t.}+z_1+z_2\cdot K}{60}\right)^{z_5\cdot p^{-z_6}}\right)^{\beta_2}\right)\right]. \quad (20)$$

Given the resulting dependence (15) for the losses of raw material on duration of mechanical peeling and depth of thermal treatment, we obtain equation for the indicator of peeling quality; in particular, the maximally possible yield of peeled tubers by weight

$$Q(\tau_{h.t.},\tau_{m.p.},p,K)=100-\left(\gamma_1+\gamma_2\cdot\tau_{m.p.}+\gamma_3\cdot\tau_{m.p.}^{\;2}\right)\times$$
$$\times\left(z_3\cdot p^{z_4}\cdot\left(\frac{\tau_{h.t.}+z_1+z_2\cdot K}{60}\right)^{z_5\cdot p^{-z_6}}\right)^{(\gamma_4+\gamma_5\cdot\tau_{m.p.}+\gamma_6\cdot\tau_{m.p.}^{\;2})}, \quad (21)$$

where Q is the yield of peeled tubers by weight, %.

Fig. 9–11 show dependences of quality indicators of the process of mechanical post-peeling of Jerusalem artichoke with different storage period, depending on the depth of thermal treatment and duration of the process of mechanical peeling.

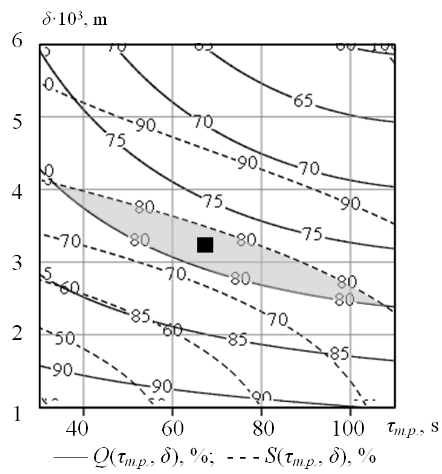

Fig. 9. Quality indicators of the process of mechanical peeling of Jerusalem artichoke, with storage period to September 1, depending on the depth of thermal treatment and duration of the process of mechanical peeling: ■ – rational mode of mechanical post-peeling

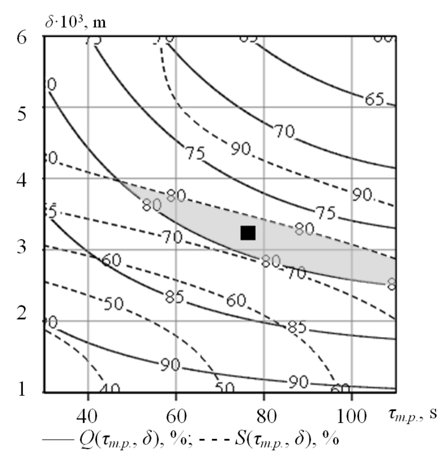

Fig. 10. Quality indicators of the process of mechanical peeling of Jerusalem artichoke, with storage period from September 1 to December 31, depending on the depth of thermal treatment and duration of the process of mechanical peeling: ■ – rational mode of mechanical post-peeling

Chosen rational parameters of the process of mechanical peeling (Table 1) for the designed plant provide maximally possible quality indicator not less than 80 % by the percentage of peeled tubers and the yield of peeled tubers by weight.

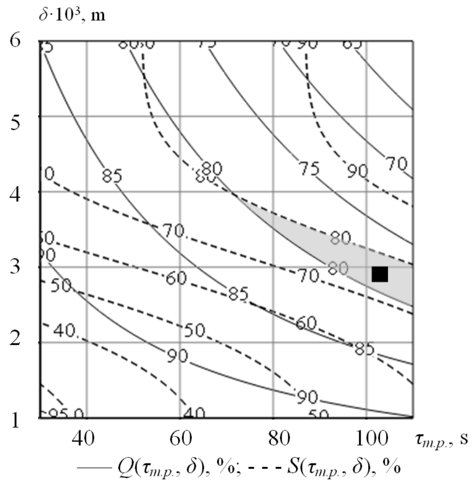

Fig. 11. Quality indicators of the process of mechanical peeling of Jerusalem artichoke, with storage period from January 1, depending on the depth of thermal treatment and duration of the process of mechanical peeling: ■ – rational mode of mechanical post-peeling

Table 1

Rational parameters of the process of mechanical post-peeling of Jerusalem artichoke tubers

Storage period	Duration of post-peeling, $\tau_{m.p.}$, s	Required depth of thermal treatment in the process of thermal treatment, $\delta \cdot 10^{-3}$ m	S, %	V, %
to September 1	70	3.2	80	20
from September 1 to December 31	85	3.1	80	20
from January 1	105	2.8	80	20

The obtained model of the process of thermal treatment for dependence of the depth of thermal treatment on factors that characterize the process of thermal treatment makes it possible to calculate the required process parameters that provide maximal peeling quality indicators. Corresponding parameters of the process of thermal treatment of Jerusalem artichoke tubers are given in Table 2.

Table 2

Rational parameters of thermal treatment of Jerusalem artichoke tubers

Indicator	Content of dry substances, %			Depth of thermal treatment, $\delta \cdot 10^{-3}$ m
	18	22	26	
Storage period to September 1				
Steam pressure, MPa	0.3	0.3	0.3	3.2
Duration of post-peeling, $\tau_{m.p.}$, s	45	40	35	
Storage period from September 1 to December 31				
Steam pressure, MPa	0.3	0.3	0.3	3.1
Duration of post-peeling, $\tau_{m.p.}$, s	55	50	45	
Storage period from January 1				
Steam pressure, MPa	0.3	0.3	0.3	2.8
Duration of post-peeling, $\tau_{m.p.}$, s	60	55	50	

Rational parameters of conducting a combined process of peeling the tubers of Jerusalem artichoke can significantly reduce losses of raw material and improve peeling quality of the product.

6. Discussion of results of examining a combined process of peeling Jerusalem artichoke

Result of the undertaken research is a developed combined method for peeling the tubers of Jerusalem artichoke. The method presented is based on the effect of thermal and mechanical processes of peeling tubers. The first stage in the process of combined peeling of Jerusalem artichoke tubers is their treatment with steam at excess pressure; the second stage is the process of mechanical post-peeling of Jerusalem artichoke tubers.

An increase in steam pressure and duration of the process of thermal treatment increases the depth of thermal treatment of the surface layer of Jerusalem artichoke and reduce the effort required to separate the rind from the tuber. Jerusalem artichoke with high content of dry substances and shorter storage period has a larger depth of thermal treatment and lower effort to separate the rind.

An increase in the duration of the process of mechanical post-peeling increases the percentage of peeled Jerusalem artichoke tubers, but results in greater losses of raw material. It was determined that reducing the effort to separate the rind of artichoke during thermal treatment makes it possible to reduce duration of the process of mechanical post-peeling. It was established that an increase in the depth of thermal treatment of Jerusalem artichoke surface layer leads to increasing losses of raw material. It was proven that the tubers of Jerusalem artichoke, which have a longer storage period, require an increase in the duration of their mechanical peeling in order to ensure the required quality of peeling.

We determined rational parameters for conducting the process of combined peeling of Jerusalem artichoke tubers. Steam pressure during thermal treatment should equal 0.3 MPa at duration 35...60 s. Duration of the process of mechanical post-peeling should be maintained within the range of 70...105 s, depending on the storage period of the product and the content of dry substances in tubers.

7. Conclusions

1. We designed an experimental installation, which allows us to study the process of thermal treatment of Jerusalem artichoke with steam at excess pressure. We established effect of the process of thermal treatment on the surface layer of Jerusalem artichoke. Results of the study indicate that an increase in steam pressure and duration of treatment increases depth of the thermal treatment of surface layer of Jerusalem artichoke tubers.

2. We established effect of the thermal treatment of surface layer of Jerusalem artichoke, storage period of tubers and duration of the process of mechanical post-peeling on the percentage of losses of raw materials. Losses of raw material increase depending on duration of mechanical post-peeling and depth of the thermal treatment. Increasing percentage of losses of raw material is caused by the fact that during mechanical post-peeling the surface layer of Jerusalem artichoke, which was boiled during preliminary thermal treatment, is gradually peeled off along with the rind.

3. A mathematical model is proposed of the process of thermal treatment of Jerusalem artichoke with steam to determine a depth of thermal treatment of the surface layer of tubers. Mathematical model shows a change in the depth of thermal treatment of the surface layer of Jerusalem artichoke depending on the variety of Jerusalem artichoke, duration of treatment process and steam pressure.

4. A mathematical model is proposed to determine dependence of the effort to separate the rind of Jerusalem artichoke on the depth of thermal treatment with steam that takes into account a storage period of tuber. Mathematical model allows us to calculate the effort required to separate the rind of Jerusalem artichoke depending on the variety of Jerusalem artichoke, duration of treatment process and steam pressure.

5. Mathematical models are proposed for the process of mechanical post-peeling of Jerusalem artichoke to determine the percentage of peeled tubers and the percentage of yield of the peeled tubers by weight. Mathematical models make it possible to calculate the percentage of peeled tubers and the percentage of losses of raw material depending on the effort to separate the rind of Jerusalem artichoke, depth of the thermal treatment of tuber, duration of thermal treatment, duration of mechanical post-peeling.

6. We established rational modes of conducting a combined process of peeling the tubers of Jerusalem artichoke, which make it possible to minimize losses of raw material and to provide high peeling quality of the product. Steam pressure during thermal treatment should equal 0.3 MPa at duration 35...60 s. Duration of the process of mechanical post-peeling should be maintained within the range of 70...105 s, depending on a storage period of the product and the content of dry substances in tubers. Rational parameters of the process of mechanical peeling for the designed apparatus provide maximally possible quality indicator not less than 80 % by the percentage of peeled tubers and the yield of peeled tubers by weight.

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