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DESIGN OF A COMBINED APPARATUS FOR LOW-TEMPERATURE PROCESSING OF CONFECTIONERY PRODUCTS BASED ON PLANT-BASED MULTICOMPONENT SEMI-FINISHED PRODUCTS

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The object of this study is the process of low-temperature processing of confectionery products, in particular marshmallows made on the basis of plant polycomponent semi-finished products, taking into account the parameters of infrared heating and preliminary air preparation. The task relates to the lack of effective technologies for low-temperature processing of confectionery products with plant polycomponent semi-finished products to preserve their quality and functionality.

A model of a combined apparatus for low-temperature processing of confectionery products, in particular marshmallows made on the basis of plant polycomponent semi-finished products, is given. The apparatus has a rectangular chamber with rounded edges for uniform heat flow, a film-like resistive electric heater of the radiant type (30…120°C), replaceable functional trays, and an autonomous ventilation system based on Peltier elements. Air is recirculated with preliminary drying and heating up to 45°C.

The uniformity of the heat flux distribution on the receiving surface has been confirmed: the central temperature was 46.0°C, the contour temperature was within 42.0…43.1°C. This thermal regime helps stabilize the structure of confectionery products during low-temperature processing. The experimental process of drying marshmallows demonstrates effective dehydration: classic marshmallows lose up to 20% of moisture in 50 min, marshmallows with plant polycomponent semi-finished products – up to 22% in 70 min, and marshmallows with plant polycomponent semi-finished products and amaranth – up to 24% in 80 min. The data indicate the need to extend the drying time of samples with plant ingredients because of their increased hydrophilicity.

Sensory evaluation has confirmed the high quality of the finished confectionery products. The highest indicators were obtained for marshmallows with RPN and amaranth (aroma – 5.0; taste – 4.9; structure – 4.8). The designed structure became the basis for assembling a device with high-quality low-temperature processing of confectionery products. The device is suitable for the production of pastilles, snacks, bakery products, and drying of plant raw materials in pharmaceuticals and cosmetics

Keywords: plant polycomponent semi-finished products, combined IR device, low-temperature processing, Peltier elements, functional confectionery products

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1. Introduction

The European integration of the modern agro-industrial complex is aimed at the implementation of innovative hardware and technological solutions in accordance with the concept of “from field to table” [1]. This involves minimal loss of nutritional values at all stages – from growing plant raw materials to consuming a high-quality final product. In this context, the processing of plant raw materials (fruits, berries, vegetables, spicy and aromatic raw materials) into food products with high biological value, original rheological and organoleptic properties is of particular importance [2].

Adaptive innovative approaches to the processing of plant raw materials into plant-based polycomponent semi-finished products (PPSPs) in the form of purees, pastes, powders of a high degree of readiness act as natural functional recipe ingredients for recipes for various products [3, 4]. At the same time, polycomponent semi-finished products are a source of natural vitamins, pectin substances, polyphenols, and antioxidants with original organoleptic and organoleptic properties.

The use of plant-based polycomponent semi-finished products contributes to the reduction or complete elimination of synthetic components in confectionery formulations, which, in turn, leads to an increase in demand for such products as health and functional products. The need for specific conditions arises both during heat treatment when obtaining functional polycomponent semi-finished products of a high degree of readiness, and at subsequent stages of the technological process. In particular, this applies to the stages of hardening and drying of confectionery products, which require a gentle temperature regime and uniform distribution of heat throughout the product volume. It is also important to adhere to a rational duration of thermal action to ensure the preservation of the structure, color, aroma, and functional properties of the finished product. Conventional drying units or chambers for thermal treatment of confectionery products do not guarantee uniformity and stability of thermal exposure under conditions of convective heat supply, which leads to losses of thermolabile compounds and a decrease in product quality. This is especially critical for products made on the basis of polycomponent fruit and berry masses.

Thus, the relevance of research aimed at designing an innovative combined apparatus for low-temperature processing of confectionery products based on plant-based polycomponent semi-finished products is due to the need of the agro-industrial complex for functional, energy-efficient, and technologically adaptive equipment. Such equipment can enable a sustainable production cycle with minimal losses of biologically valuable substances while meeting the challenges of climate, energy, and food security. The introduction of such technical solutions would contribute to the development of local production in the format of mini-shops, agro-processing cooperatives and farms, which is a key factor for integration into the modern European model "from field to table".

Support for the national agricultural sector under conditions of armed aggression, environmental risks, and instability in the field of resource supply is possible through the introduction of innovative equipment for gentle thermal processing of food products. In particular, it concerns the processing of products based on plant raw materials grown in Ukraine (for example, apples, Jerusalem artichoke, cranberries, amaranth, berries), in order to preserve their natural properties and nutritional value. The need to reduce dependence on imported synthetic ingredients and ensure food security stimulates the development of technologies for processing natural agricultural raw materials. Current scientific research in the area of food technologies should focus on designing functional, resource-saving, and technologically adaptive equipment that provides engineering support to the production sector, contributes to the implementation of the principles of sustainable development and localization of food production based on natural raw materials.

2. Literature review and problem statement

Innovative production of confectionery products based on plant-based polycomponent semi-finished products requires scientifically based approaches to low-temperature processing, in particular, drying, hardening, and drying. This is due to the growing demand for high-quality functional confectionery products.

Work [5] reports a study on the use of infrared radiation in drying food products, emphasizing the technical and technological advantages of IR processing with a reduction in the duration of heat treatment and maximum preservation of product quality. However, questions about ways to optimize IR drying parameters depending on the type of food products, including plant-based confectionery products, remain out of focus. This is partly due to objective difficulties in the heat treatment of products with different physicochemical, rheological, and organoleptic properties and thermal lability. One way to overcome these difficulties is to introduce combined devices for combining uniform IR heating with modern methods for controlling technological modes (temperature and humidity).

This approach is described in [6] in the context of using thermoelectric Peltier elements to stabilize the temperature regime during drying, emphasizing the feasibility of research in this area. The authors revealed scalability problems, insufficient assessment of the impact of regimes on quality, as well as the need for economic efficiency and increased system reliability.

Paper [7] considers intermittent drying of food products as one of the innovative methods for increasing energy efficiency and preserving product quality. However, issues related to the practical implementation of the method under industrial conditions for plant-based confectionery products remain unresolved. The main reason for this is the technical difficulties in accurately controlling technological drying regimes during technological processing. One of the practical solutions is the introduction of modern sensor-based process control systems. The implementation of sensor control is considered in work [8] with a description of the features and use of sensor control with a Wi-Fi module for real-time control of technological processes. However, the authors do not consider the issue of adapting such systems to real mobile devices for heat treatment of confectionery products, which left open the issue of their integration into compact combined solutions although the implementation of modern solutions contributes to increasing production safety. In particular, work [9] considers the improvement of the rotary-film device, which directly resonates with the structural elements of the proposed mobile device and at the same time makes it possible to implement the boiling process to obtain vegetable semi-finished products. However, the work does not highlight how this approach could be integrated into a mobile device with infrared heating, which is relevant for the adaptation of innovative heat and mass exchange systems in the confectionery sector. But such innovative approaches are aimed at intensifying heat and mass exchange during resource-saving processing of vegetable raw materials with their subsequent use in the formulations of various products.

In [10], the process of drying food products was analyzed with a review of innovative developments in the food industry for further informed choice of the optimal method of heat treatment with maximum preservation of the initial properties. However, issues related to the adaptation of conventional drying methods to new types of products, which include plant-based confectionery, remained unresolved. This is due to the lack of a sufficient number of practical and analytical studies. However, one of the ways to address this issue is to conduct comprehensive experimental and practical studies aimed at determining the optimal drying parameters of functional products based on plant raw materials. Such an approach is reported in [11] on experimental studies of the process of drying marshmallows based on plant-based polycomponent semi-finished products as an alternative for energy-efficient drying of powdered gelatin. However, the issue of adapting this technology to products with a high content of pectin and fiber, characteristic of polycomponent semi-finished products, an important aspect for preserving the structure and quality, remains unresolved. This confirms the practical and experimental feasibility of research in this area.

In work [12], the use of infrared radiation under the conditions of drying food products, including confectionery products, is investigated. In the course of the research, the authors note the advantages of IR radiation in terms of reducing the drying time and improving product quality. In particular, in [13], issues related to the uneven distribution of the temperature field in the working chamber of the apparatus remain unresolved, which leads to uneven heat treatment. One of the reasons is certain objective difficulties associated with the geometry of the chamber and heat distribution. One of the options for overcoming the difficulties is to optimize the design of the chamber and use film resistive electric heaters. This approach is reported in work [14] during the design of a new structure for the apparatus with improved heat flux distribution. In addition, paper [15] emphasizes the advantages of film evaporation for preserving biological value, which coincides with the feasibility of processing vegetable paste as a vegetable semi-finished product for a specific purpose.

In [16], the influence of the geometry of pallets, including those with various fins, on the drying efficiency of confectionery products is determined, with a subsequent determination of the contribution of such an approach to the uniformity of heating and improvement of product quality. However, the specified material does not consider the adaptation of pallets to different shapes of confectionery products, which affects the uniformity of heating and product quality. However, in [17], the adaptation of pallets to different types of confectionery products remains an unresolved area. This may be due to the variety of shapes and sizes of confectionery products, and one of the practical ways to solve this drawback is the development of interchangeable functional pallets adapted to the type of product. This approach is reported in [18], which describes the use of interchangeable pallets for different types of products, confirming the relevance of research in this area. In [19], the use of Peltier thermocouples to maintain a stable temperature in vacuum chambers is determined. However, it has not been investigated how to integrate such elements into the working environment with direct contact of products without losing their organoleptic properties. In [20], the issues of integrating Peltier elements into the design of the device without affecting the functional properties remained unresolved. The likely reason is the objective difficulties associated with the placement of Peltier elements to ensure efficient operation. One of the options for solving these difficulties is to mount Peltier elements in pallet racks, which allows for the effective use of secondary heat. This approach is also confirmed in [21] with a detailed description of the future industrial design of the device with built-in Peltier elements, emphasizing the relevance of the research.

In [22], the effect of air preheating on the efficiency of drying confectionery products was investigated, establishing the effectiveness of air preheating in reducing the drying time and improving product quality. However, the possibility of combined pre-drying and IR heating in a mobile combined marshmallow machine was not investigated. But in [23], issues related to the implementation of the air preheating chamber in the design of the machine remained unresolved. The likely reason is objective difficulties associated with ensuring uniform heating and avoiding uneven heating due to the geometry of the chamber with non-technological zones, and therefore a decrease in the final quality of the product. One of the options for getting out of this situation is the further use of film electric heaters and Peltier modules to control technological modes (temperature, humidity, and air flow rate). This approach, in particular, is implemented in work [24] with a detailed description of the design of the preheating chamber using the above-mentioned structural elements, however, this direction also requires detailed research. Paper [25] indicates the need to use digital transformation of innovative systems in production processes. This is especially relevant in an unstable environment, which directly supports the concept of implementing sensor control and autonomous control systems (including those based on the OVEN controller) in a mobile multifunctional device. In turn, paper [26] highlights anti-crisis approaches to ensuring regional stability and efficiency of local production, which confirms the feasibility of developing modular resource-saving equipment as a tool to support the agro-industrial sector during the post-war recovery period. Modern production of functional confectionery products is focused on the use of natural raw materials to reduce the content of synthetic components and artificial flavors, which requires the introduction of mild low-temperature processing modes. However, conventional drying and curing methods often lead to degradation of bioactive substances, disruption of product texture, and the need for preservatives. One of the key problems is the insufficient level of technical support for the processing of products based on plant-based polycomponent semi-finished products, in particular, insufficient versatility, energy efficiency, and the ability to ensure uniform delicate drying.

In this context, it is important to state the problem related to the lack of effective technologies for low-temperature processing of vegetable confectionery products, which would ensure the preservation of their quality characteristics with minimal resource consumption. Our review of the literature reveals unresolved issues regarding the combination of infrared heating with preliminary air preparation and the implementation of resource-saving solutions for optimizing technological processes. This approach could ensure the preservation of quality, stability of the structure, and minimize the use of artificial ingredients. Designing such equipment is an important prerequisite for supporting the agricultural sector as it contributes to the use of domestic agricultural raw materials in the food industry. This, in turn, meets the modern requirements of sustainable development, waste-free production, and the implementation of food security principles within the framework of the "from field to fork" concept, especially under conditions of armed aggression and global challenges to the country's agricultural system.

3. The study materials and methods

The purpose of our research is to design a combined apparatus for low-temperature processing of confectionery products made from plant polycomponent semi-finished products of a high degree of readiness. The apparatus would provide a uniform, delicate temperature environment that could help preserve the structure, nutritional value, and sensory properties of the product, while minimizing the use of preservatives and synthetic stabilizers. The developed technical solution is aimed at integration into production chains with an orientation on the concept of "from field to table", contributing to increasing the functionality, safety, and environmental friendliness of domestic confectionery products.

To achieve this aim, the following objectives were accomplished:

– to design a structurally-adaptive model of a combined apparatus for implementing low-temperature processing processes (hardening, drying, etc.) of confectionery products made using plant polycomponent semi-finished products of a high degree of readiness (puree, pastes, powders);

– to investigate the influence of operating parameters (temperature, duration) on the quality indicators of finished products in a combined apparatus in comparison with conventional drying methods.

4. The study materials and methods

The object of our study is the low-temperature processing of confectionery products, in particular marshmallows, made on the basis of plant polycomponent semi-finished products, taking into account the parameters of infrared heating and preliminary air preparation. The hypothesis of the study assumes that the integration into the design of a combined apparatus of film infrared heating, a module of pre-drying of air and autonomous ventilation based on Peltier elements, could enable uniform, delicate low-temperature drying of confectionery products made on the basis of plant polycomponent semi-finished products of a high degree of readiness. This would contribute to the preservation of the geometric shape, stability of the foam structure, organoleptic indicators and could make it possible to achieve higher quality of the finished product compared to conventional convective methods of heat treatment. Practical testing of innovative hardware and technological solutions was implemented under the conditions of the front-line Kharkiv oblast at the scientific and educational center "Innovative resource-saving technologies for processing organic products", the State Biotechnological University (Kharkiv, Ukraine).

Testing of the combined apparatus was implemented during the study of low-temperature processing of marshmallow made according to the classic recipe (in line with DSTU GOST 6441-2003), and marshmallow with the addition of vegetable polycomponent semi-finished products in the experimental ratio of ingredients:

– apple, Jerusalem artichoke, cranberry (45 gr. : 40 gr. : 15 gr.);

– apple, Jerusalem artichoke, cranberry (40 gr. : 45 gr. : 15 gr.);

– apple, Jerusalem artichoke, cranberry, amaranth (35 gr. : 35 gr. : 15 gr. : 15 gr.).

The ratio of ingredients of the experimental samples of marshmallow was selected taking into account the balance of nutritional value (pectin, inulin, fructose) and functionality (structure formation, moisture binding capacity). Combinations of plant raw materials (apple, Jerusalem artichoke, cranberry, amaranth) make it possible to obtain formulations with increased biological value. The use of selected components ensures artificial fortification of marshmallow with functional ingredients and increases functional value, giving the mass a balanced pectin, inulin, and fructose composition, moisture-retaining capacity, and the necessary foam structure. In addition, the use of amaranth paste as a whole will increase nutritional value and opens up the opportunity to create an innovative product line (Vegan+, Fit+, Superfood). The control variant was classic marshmallow in accordance with DSTU GOST 6441-2003 without the addition of PPSPs. It was compared with samples with the addition of plant polycomponent semi-finished products, which made it possible to identify differences in functional and organoleptic indicators. At the same time, the comparison of experimental samples was carried out in a series of identical drying conditions under technological modes for maximum reliability of the analysis of the efficiency of low-temperature processing in a combined apparatus.

To obtain PPSPs, resource-saving technological modes were used with the application of low-temperature heat and mass exchange equipment based on a universal multifunctional apparatus and a rotary film apparatus. The main mode parameters when obtaining PPSPs are as follows: apple was pre-crushed to a puree-like mass and blanched in a steam environment at a temperature of 60°C for 5…8 min. Jerusalem artichoke was blanched in a steam environment at a temperature of 65°C for 12…15 min. Cranberries were kept in a steam environment at a temperature of 55°C for 4…6 min. Amaranth was previously germinated for 36…40 hours, ground to a puree-like mass, and pasteurized at a temperature of 57°C for 3…6 minutes. Then the process of recipe mixing of components was implemented in accordance with the above-mentioned ratios with subsequent boiling. PPSPs based on apple, Jerusalem artichoke, and cranberry: temperature 58°C, for 60…90 seconds. PPSPs based on apple, Jerusalem artichoke, cranberry, and amaranth: temperature 55°C, for 75…100 seconds. After that, the homogeneous paste-like PPSP mass was added to the confectionery product recipe.

The initial and final mass fraction of moisture in marshmallow samples was determined by the gravimetric method by drying to a constant mass (103 ± 2°C). The temperature in the working chamber of the combined apparatus was controlled using the digital thermocouples THK-1388, placed at nine points of the spatial grid. The values were recorded every 2 minutes via the microcontroller system "OWEN" (Kharkiv, Ukraine). The temperature field was determined within 30 min after turning on the apparatus, which corresponds to the conditions for stabilizing the operation of the apparatus and makes it possible to determine the efficiency of temperature distribution, the operation of heaters and fans, and predict the quality of the final product. The duration of drying was determined as the time interval from the beginning of the technological process of low-temperature treatment until the sample reached stable humidity (± 0.2%) in accordance with the established target limit. In the process of studying the drying of marshmallow and pastilles, an adaptive temperature regime was used with an initial increase in temperature, subsequent decrease, and stabilization in a gentle range. Evaluation of experimental samples of marshmallow after drying in a combined apparatus was carried out at the scientific and educational center by 7 experts by tasting and coding the samples with numbers and a temperature of 20 ± 1°C on a 5-point scale. The tests were carried out under stable conditions in modes adapted to the recipes with the addition of plant raw materials with the registration of the basic parameters (temperature, duration, and residual moisture) in accordance with the requirements of the standards and conditions of the engineering model of the apparatus. Approbatory and experimental studies were carried out in five-fold repeatability using traditional methodologies for mathematical processing of the results, which ensured a relative error of no more than 3%.

5. Results of designing a structure of a combined apparatus for low-temperature processing of confectionery products based on plant polycomponent semi-finished products

5. 1. Design of a model of a combined apparatus for low-temperature processing of confectionery products

When testing engineering and technological solutions of the model structure of a combined apparatus for low-temperature processing of confectionery products with plant polycomponent semi-finished products of a high degree of readiness, measures were investigated aimed at:

– ensuring uniform heat supply and delicate low-temperature processing of confectionery products by optimizing the geometry of the working chamber under the conditions of using a flexible infrared electric heater, reducing the negative impact of convective drying (preventing the drying of product surfaces in the first place);

– stabilization of the infrared thermal regime by using an air pre-drying module that works in conjunction with Peltier elements and simultaneously aims at autonomous operation of fans;

– adaptation of the design to various types of confectionery products based on PPSPs, which in terms of marketing competitiveness will make it possible to produce eco-, vegan-, or clean-label products.

A model structure of the combined apparatus for low-temperature processing of confectionery products based on plant polycomponent semi-finished products is shown in Fig. 1. The geometric chamber of the apparatus is a rectangular surface with rounded edges 1 to minimize the existing non-technological zones inherent in rectangular structures of apparatus for temperature processing of confectionery products. The body of the apparatus is made of stainless steel. The outer frame of the apparatus is additionally covered with heat-insulating material 2, and the internal space is made in the form of a film-like resistive electric heater of the radiant type 3 [27]. The temperature range of the combined apparatus for low-temperature processing of confectionery products is taken within 30...120°C, which is provided by the power of electric heaters (2.5 kW).

The combined device provides for the use of various interchangeable functional trays 4, which will ensure the use of the device for different types of confectionery.

In particular, for different types of confectionery. it is proposed to use different types of trays:

– for marshmallow – rounded-rectangular perforated trays, which provide uniform blowing and prevent the appearance of condensate;

– for pastilles – rectangular smooth trays, which contribute to easy removal of the product with a homogeneous structure;

– for marmalade – cellular molded trays, which provide clear formation of geometry and preservation of the shape of the product;

– for cakes and biscuits – metal mesh trays with free passage of air.

At the same time, Peltier elements 6 are installed in the internal space of racks 5 for trays (those on the right).

This approach makes it possible to convert the secondary heat of heated racks 5 into a low-voltage supply voltage (0.2 A) for the operation of autonomous brushless fans 7 mounted in channels 8. The upper channel with the fan performs the technical purpose of extracting the air medium from the working chamber, forming a free movement of the air medium in the apparatus. Lower channel 8 is additionally connected by technical heat-insulating main 9 with a valve for recirculating the exhaust air to the preliminary preparation chamber and drying incoming air 10. Chamber 10 is thermally insulated and has fine filter 11 in the lower part to increase the safety of the closed chain of confectionery production in the following fashion: loading into the apparatus/low-temperature processing/packaging.

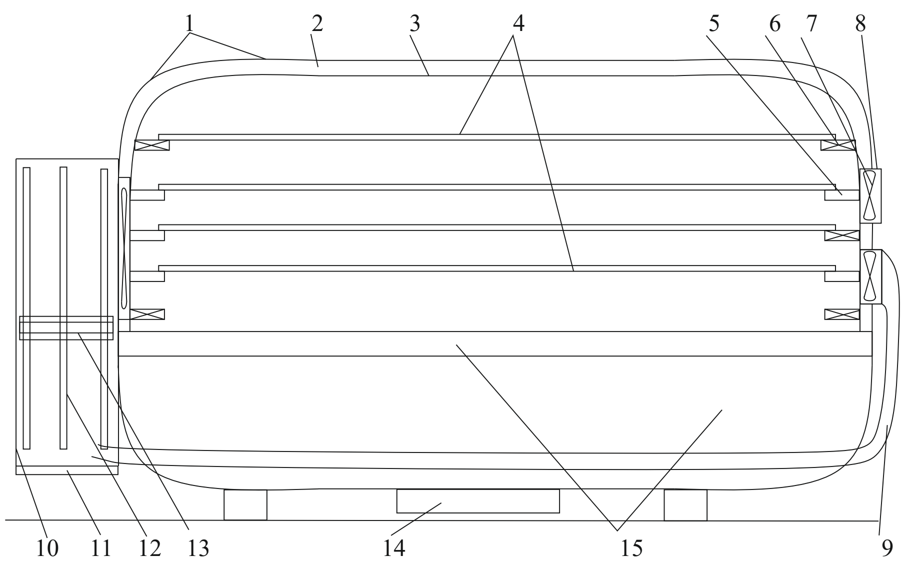

Fig. 1. Schematic diagram of a model sample of the combined apparatus for low-temperature processing of confectionery products: 1 – working chamber in the form of a rectangular surface with rounded edges; 2 – heat-insulating material; 3 – film-like resistive electric heater of the radiant type; 4 – replaceable functional pallets; 5 – racks for pallets; 6 – Peltier elements; 7 – autonomous brushless fans; 8 – air duct; 9 – technical heat-insulating main; 10 – chamber for preliminary preparation and drying of incoming air; 11 – fine filter; 12 – racks in chamber 10 for the location of film electric heater 3; 13 – Peltier module with condensate collector; 14 – sensor control module with Wi-Fi unit; 15 – hinged loading hatch/door with adjustable opening height of the hinged type

In the inner space of chamber 10, film electric heater 3 is mounted on racks 12 (to increase the initial air temperature to 45°C). In the center, a Peltier module with condensate collector 13 is mounted to further reduce the relative humidity due to condensation. After chamber 10, the dried and heated air is supplied to the main working chamber through a distribution channel with autonomous brushless fan 7. At the same time, the treated air evenly enters the working chamber of the apparatus, film electric heater 3 provides delicate low-temperature heating of the surface of the products. The proposed arrangement of autonomous fans 7 promotes circulation due to low-voltage voltage from the Peltier elements. The power of film electric heater 3 for heating and dehumidifying air was determined by calculation ($Q = m \cdot c \cdot \Delta T$ (where $m = 0.0167$ kg/s; c = 1005 J/kg·K; ΔT = 50 – 25 = 25°C). Therefore, the power of the film heater in chamber 10 is 420 W. The results of our research showed that with an increase in the temperature of the film electric heater from 30°C to 80°C, the relative humidity of the air after drying decreases from 60% to 35%, confirming the feasibility of preliminary drying before the working chamber.

The combined device is equipped with sensor control module 14 based on a controller for regulating temperature, duration, and humidity with a Wi-Fi unit for monitoring and controlling the technological process in real time. The working chamber of the device has hinged loading hatch/door 15 with adjustable opening height of the hinged type, providing technical and operational access to the interior of the device.

During the research, the temperature field in the working chamber of the combined device for low-temperature processing of confectionery products was determined (Fig. 2).

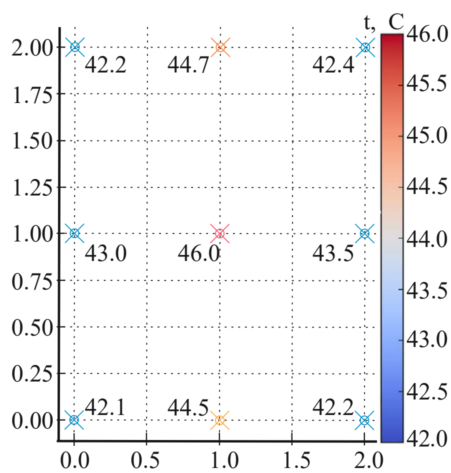

Fig. 2. Temperature field in the working chamber of the combined apparatus for low-temperature processing of confectionery products (30 min of drying process)

The temperature measurement in the working chamber of the combined apparatus was implemented by nine thermocouples mounted on a 3 × 3 grid with subsequent placement on the surface of replaceable functional trays for confectionery products. In the center of the chamber (position 1,1) the temperature was 46.0°C (maximum value), and on the periphery of the thermocouple grid, in the range of 42.0...43.1°C. Thus, the average deviation along the grid plane does not exceed 4.0°C, which confirms sufficient uniformity of the thermal field on the receiving surfaces and is permissible according to the technical requirements for drying marshmallow products.

5. 2. Testing the technological modes of the combined apparatus for low-temperature processing of confectionery products and comparison with conventional methods

During experimental and practical studies, a drying plot (Fig. 3) for marshmallow was constructed, including based on PPSPs, which makes it possible to visualize changes in the moisture content of samples during low-temperature processing in the combined apparatus.

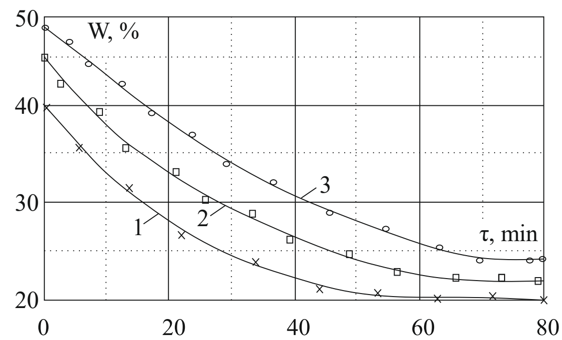

Fig. 3. Marshmallow drying schedule:
1 – classic marshmallow; 2 – marshmallow with the addition of plant polycomponent semi-finished products (apple (45%), Jerusalem artichoke (40%) and cranberry (15%));
3 – marshmallow based on plant polycomponent semi-finished products with added amaranth

For classic marshmallow, a decrease in moisture content is observed: from the initial value of 40% to a stable moisture content within 20% after 50 min of drying. This result is typical of a protein-agar system with a conventional structure that holds its shape well at high temperatures. In the experimental marshmallow sample with the addition of PPSPs in the ratio of apple (45%), Jerusalem artichoke (40%), and cranberry (15%), the initial moisture content is 45%. Achieving the target moisture content within 22% occurs within 70 min of implementing the technological process of drying in the designed apparatus.

In the marshmallow sample based on PPSPs with added amaranth (15%), the initial moisture content is 48% and, within 80 min of drying, it decreases to 24%.

Fig. 4 shows data on adaptive temperature regimes for drying marshmallow and pastilles made by classical methods for experimental testing of the combined apparatus on various confectionery products.

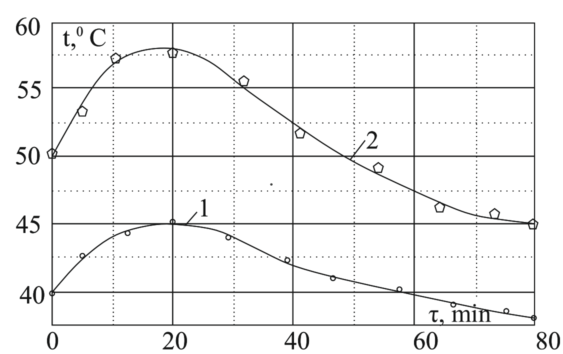

Fig. 4. Temperature regimes for drying confectionery products: 1 – marshmallow; 2 – pastilla

The temperature curves simulate the adaptive drying mode of confectionery products sensitive to overheating and are relevant for products based on PPSPs, ensuring maximum preservation of natural properties. For marshmallow, the temperature profile fluctuated within 38...40°C, with a peak value of the drying process – 45.0°C on minute 20. This allows for the gradual removal of moisture from the surface layers without disturbing the structure of the protein-pectin foam of the product.

The temperature curve of pastille is more intense: the maximum temperature reached 58.0°C on minute 20, then decreased to 45°C at the final phase. This mode is acceptable for a denser, concentrated confectionery mass with slow moisture movement. During the testing of the structure of the combined apparatus for low-temperature processing of confectionery products, a comparison of the technological process of drying marshmallow was carried out. In particular, classic marshmallow and functional product with the addition of PPSPs to the recipe based on apple, Jerusalem artichoke, and cranberry pastes (in 2 compositions) and PPSPs with the addition of amaranth (Table 1).

The difference in the target moisture content and temperature range of the technological process of drying between the specified marshmallow samples is explained by the differences in the structural and chemical composition of the formulation of the experimental products. In particular, the classic marshmallow is characterized by a stable foam system based on a sugar-protein complex with agar and is dried at a temperature of 55.0°C until reaching a final moisture content of 18.0%. However, the experimental samples with the addition of different PPSPs are characterized by a higher initial moisture content due to the addition of plant ingredients and require a low-temperature drying range (up to 45°C). At the same time, the target moisture content was within 20...24%. In marshmallow with PPSPs and amaranth, an even higher initial moisture content is observed, which is explained by the content of inulin, amino acids, dietary fiber, and other structures. This, in turn, causes a decrease in the drying temperature (40.0°C) and an increase in the target moisture content with a simultaneous increase in the duration of low-temperature treatment. Comparative analysis of the indicators of drying marshmallow revealed a statistically significant difference between the control variant and the experimental samples using plant polycomponent semi-finished products. According to the HIP criterion ($p \leq 0.05$), the differences in the residual moisture content, drying temperature, and process duration exceed critical values, which confirms the significant influence of the introduced plant ingredients on the heat treatment modes.

During the research, a sensory evaluation of marshmallow was carried out after its low-temperature treatment in a combined apparatus (Table 2).

According to expert assessments, all marshmallow samples had certain advantages in terms of evaluation indicators after low-temperature processing in the developed apparatus. Classic marshmallow after drying retains the classic taste of the product. Marshmallow with PPSPs (apple, Jerusalem artichoke, cranberry) at a ratio of 45:40:15 is characterized by a pronounced taste with a fruit-berry sour aftertaste and a stable structure when the drying temperature is maintained (43.0°C). Marshmallow with PPSPs at a ratio of (40:45:15) is characterized by a soft texture and a light fruit-berry aroma with a moderate structure that requires drying. The marshmallow product with PPSPs and amaranth is characterized by a stable rheological structure due to the protein-pectin base and a rich taste.

Table 1

Comparative analysis of marshmallow properties during low-temperature processing in a combined apparatus

Type of marshmallow product	Initial moisture content, %	Target moisture content, %	Drying temperature, °C	Process duration, min
Marshmallow DSTU GOST 6441–2003)	40.0 ± 2	18.0 ± 1	47.0 ± 2	55.0 ± 5
Marshmallow with PPSPs (apple, Jerusalem artichoke, cranberries, 45:40:15)	45.0 ± 2	21.0 ± 1	43.0 ± 2	65.0 ± 5
Marshmallow with PPSPs (apple, Jerusalem artichoke, cranberry, 40:45:15)	47.0 ± 2	23.0 ± 1	41.0 ± 2	70.0 ± 5
Marshmallow with PPSPs (apple, Jerusalem artichoke, cranberry, amaranth, 35:35:15:15)	48.0 ± 2	24.0 ± 1	40.0 ± 2	75.0 ± 5
HIP ($p \leq 0{,}05$)	2.1	1.5	2.0	4.5

Table 2

Results of sensory evaluation by an expert board of marshmallow test samples after low-temperature processing

Indicator	Classic marshmallow	Marshmallow with PPSPs	Marshmallow with PPSPs and amaranth
Shape (stability of the structure of the marshmallow product)	5.0	4.6	4.8
External appearance	5.0	4.7	4.5
Texture (to the touch)	4.8	4.5	4.7
Texture (to taste)	4.9	4.6	4.8
Color	4.8	4.7	4.6
Taste	4.8	4.8	4.9
Flavor	4.7	4.9	5.0
General organoleptic evaluation	4.86	4.69	4.76

6. Discussion of results regarding the effectiveness of the proposed hardware and technological solutions

The design of a combined apparatus for low-temperature processing of confectionery products, the recipe component of which includes plant polycomponent semi-finished products, is aimed at implementing adaptive engineering and technological solutions in accordance with the modern requirements within the "from field to table" concept [2]. Compared with conventional drying devices, the proposed structure is based on the principles of infrared low-temperature heating, preliminary drying of the air environment, and the use of autonomous energy-saving elements.

In the course of research, a model of a combined apparatus for low-temperature processing of confectionery products based on plant polycomponent semi-finished products of a high degree of readiness was designed. Optimization of the geometry of the working chamber with rounded edges (Fig. 1, item 1) in combination with the use of a film infrared heater (item 3) is aimed at ensuring uniform heat supply, minimizing overheating and overdrying of the surface of products. Such a structural approach is considered in parallel in [12], indicating the advantages of IR technologies during low-temperature uniform processing.

The presence of a pre-air conditioning chamber (Fig. 1, item 10), equipped with a drying module based on Peltier elements with a power of 420 W and a condensate collector, is of great importance. It is aimed at stabilizing the parameters of the incoming air flow. This is achieved by bringing the air temperature to 45°C and reducing the relative humidity to 35%. Similar technical solutions are reported in [18] with a further determination of the efficiency of pre-drying when drying sensitive products, which is relevant for plant raw materials. In particular, reducing the relative humidity from 60% to 35% is critically important when processing hygroscopic plant raw materials. The use of autonomous brushless fans powered by Peltier elements contributes to energy-efficient air circulation in the working chamber. In turn, the use of autonomous fans powered by Peltier elements ensures air circulation without additional energy consumption and is considered in [23]. The device is equipped with interchangeable functional trays: for marshmallow – round perforated, for pastilles – smooth flat, for marmalade – molding, for biscuits – mesh. Such modularity increases the versatility of the device in small-scale production.

The temperature field in the working chamber of the combined device (Fig. 2) was determined by nine thermocouples placed in a 3 × 3 pattern on the surface of the trays. Accordingly, in the center of the chamber the temperature is 46.0°C, and on the periphery – 42.0...43.1°C, with an average deviation between points of no more than 4.0°C. Thermographic measurement data confirm the uniformity of heat distribution since the temperature fluctuation does not exceed ±2.0°C on a 3 × 3 plane in the processing zone. Prevention of local overheating contributes to the preservation of the structure of confectionery products.

The increase in moisture in the experimental samples, in contrast to the classic marshmallow during the implementation of the technological process of drying in the developed apparatus (Fig. 3), can be explained by the high content of pectin substances, organic acids, and fiber in PPSPs. This contributes to the retention of moisture at the capillary-molecular level and is also explained by the high hygroscopicity of amaranth, the content of lysine, inulin, and complete protein. Marshmallow recipes with PPSPs during the research require delicate, prolonged drying with controlled thermal load, which can be implemented in the IR field of the combined apparatus. At the same time, the rate of dehydration directly depends on the recipe composition: the more hydrophilic components in PPSPs (inulin, pectin, dietary fiber), the slower the drying. The presented differentiation of thermal regimes (Fig. 4) makes it possible to take into account the different thermal resistance of confectionery formulations, including those based on PPSPs, to provide the necessary technological structure under conditions of preservation of bioactive substances.

It was found that the initial moisture content of marshmallow with PPSPs reaches 45...48%, and the final moisture content is 22...24%, depending on the recipe ratio (Table 1). At the same time, the drying time under the optimal temperature regime of 40...45°*C* is 65...80 min, compared to 55 min at 47°*C* for classic marshmallow. This indicates the increased hydrophilicity of products based on PPSPs and the need for delicate low-temperature processing, which can be implemented in the designed apparatus.

Sensory evaluation (Table 2) confirmed the high organoleptic quality of the samples: marshmallow with PPSPs and amaranth had the highest score for aroma (5.0) and taste (4.9) under the conditions of production of the premium segment of natural confectionery products. Study [28] considered the effect of combined convective and infrared heating on the quality of bakery products. The results showed that the combination of these heat treatment methods contributes to uniform heating of the dough, improving the texture and preserving nutrients in the finished product. This indicates the possibility of adapting the proposed mobile multifunctional device not only for the production of confectionery but also bakery products, ensuring versatility and efficiency in various segments of the food industry. Thus, the device combines engineering, resource-saving, and technological solutions under the conditions of stable low-temperature processing of functional products. The combined device for low-temperature processing of confectionery products based on plant-based multicomponent semi-finished products can be effectively used in other sectors of the food industry. In particular, in the bakery industry, technologies are used to stabilize wet semi-finished products and glazes. In the production of pastilles, fruit plates and snacks, gentle drying is used, which maximally preserves biologically active substances. In addition, the device has the potential to be used in the processing of fruit and vegetable raw materials and phytocomponents for pharmaceutical and cosmetic purposes, which emphasizes its versatility and compliance with the requirements of modern sustainable production in the “from field to table” system. The device ensures effective use at low-capacity workshops, hotel and restaurant businesses, and specialized catering.

The proposed design solutions, in particular the use of a rectangular chamber with rounded edges, provide a more uniform heat flow. This makes it possible to improve the quality of low-temperature processing of confectionery products, eliminating the problem of uneven heating, identified during the analysis of modern technologies. Our experimental results confirm the effectiveness of such structural changes for achieving stability of the thermal regime and preserving the quality characteristics of the product.

The creation of optimal conditions for the operation of a film-like resistive electric heater of the radiant type in the temperature range of 30...120°C is ensured.

Replaceable functional pallets provide the possibility of use for different products, and the autonomous ventilation system based on Peltier elements provides air recirculation with preliminary drying and heating up to 45°C. This will contribute to increasing the resource efficiency of the technological process and is a feature of the design implementation.

The limitations of our study relate to the application of the designed structure in line with the specified technological parameters, raw material quality, device dimensions, and low-temperature processing modes. The disadvantages of the study are the limited scaling of the results for industrial use, the need for additional testing of the stability of the temperature regime when changing the load, and the need for further study on the influence of various plant components on the heat and mass transfer characteristics of the process.

Further research will focus on expanding the range of formulations, in particular with the addition of innovative plant ingredients in the context of building mathematical models of dehydration for predicting low-temperature processing modes depending on the composition of the confectionery product.

7. Conclusions

1. A model structure of the combined apparatus for low-temperature processing of confectionery products, in particular marshmallow, made on the basis of plant polycomponent semi-finished products, has been designed. The structure of the apparatus includes a rectangular working chamber with rounded corners to minimize existing non-technological zones. The internal space of the apparatus is made in the form of a film-like resistive electric heater of the radiant type with the ability to provide a temperature regime within 30...120°C. The apparatus uses replaceable functional trays for different types of confectionery products. Peltier elements mounted in the racks are aimed at converting secondary heat into low-voltage supply voltage (0.2 A) for the operation of autonomous brushless fans. Exhaust air recirculation and heating of the incoming air to 45°C are provided (the estimated power of the electric heater is 420 W). The temperature field in the working chamber of the apparatus during the 30-minute technological process showed that the temperature in the center is 46.0°C, and on the periphery – within 42.0...43.1°C, which indicates uniform heat distribution with a maximum deviation of no more than 4.0°C. This is a critical indicator for preserving the structure of foam products and ensuring stable quality of the final product.

2. As a result of our technological research, the efficiency of dehydration of marshmallow with the addition of plant components has been established in comparison with the classical sample. For marshmallow based on DSTU GOST 6441–2003, a decrease in humidity from 40% to 20% in 50 min was established; for marshmallow with PPSPs (apple, Jerusalem artichoke, cranberry) – from 45% to 22% in 70 min, and with PPSPs with amaranth – from 48% to 24% in 80 min. The drying temperature regime was in a gentle range: 38...45°C. This proves the need to adapt technological regimes for samples with increased hydrophilicity. The experimental samples demonstrate satisfactory sensory quality, with the highest scores being given to marshmallow with PPSPs and amaranth (aroma – 5.0; taste – 4.9; structure – 4.8), which confirms the feasibility of using a combined apparatus for delicate processing of PPSP-based products.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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