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IMPROVEMENT OF A MOBILE VACUUM EVAPORATOR FOR THE PRODUCTION OF MULTICOMPONENT VEGETABLE SEMI-FINISHED PRODUCTS WITH ADJUSTABLE THICKENING FOR NEW PRODUCT FORMULATIONS

The object of research is the process of manufacturing multicomponent vegetable semi-finished products with adjustable thickening of the mass from Jerusalem artichoke, carrot and pumpkin on an improved mobile vacuum evaporator. Traditional evaporators are characterized by high energy and metal consumption, the presence of a steam jacket with complex temperature range regulation, which leads to an increase in the cycle duration and losses of natural ingredients. The lack of mobility of traditional equipment does not allow it to be used in mobile lines of agricultural complexes and craft production, which is relevant for decentralized use of the device, for example, in front-line regions. In the course of improving the mobile vacuum evaporator, classical methods were used to analyze heat and mass transfer, determine the content and degree of preservation of useful natural ingredients in the conditions of mobile production of multicomponent semi-finished products with adjustable thickening. The design improvement is based on the use of a film-like electric heater of the radiant type, additional increase in the useful heat exchange surface due to the use of a mixer with a heating circuit and Peltier elements for secondary air recovery. Such actions contributed to increasing the resource efficiency of the technological cycle and stabilizing the temperature effect during the controlled thickening of natural masses.

The duration of controlled thickening of multicomponent masses was reduced by 37%, the specific heat consumption by 15.5%, the loss of vitamin C by 21%, the preservation of inulin (94%), β-carotene (87%) and 88% preservation of polyphenols. It is the introduction of electric heating of the working chamber of the apparatus and the artificial increase in the useful heat exchange surface actually due to the mixer circuit, which is heated by 27%, which contributes to the stabilization of the temperature field. And the use of an air thermal insulation jacket allows for the recovery of secondary warm air, further increasing the resource efficiency of the technological cycle. The improvement of the apparatus contributes to the resource-saving processing of plant raw materials into polycomponent semi-finished products of high readiness with adjustable thickening, in particular within 25–45% of dry matter for further introduction into the formulations of new products. A polycomponent semi-finished product of high readiness with adjustable thickening can be used in functional drinks, baby food, confectionery fillings and meat and vegetable products. A comparison of the improved design with basic evaporators is characterized by resource efficiency, mobility for agricultural sectors in conditions of decentralized processing, for example in front-line regions.

Keywords: *vacuum evaporator, film-like electric heater, polycomponent semi-finished products, heat recovery, polycomponent vegetable mass.*

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1. Introduction

Modern trends in the agricultural industry and potential consumers of natural new products require the search and implementation of engineering and technological solutions aimed at resource-saving mobile processing of raw materials into polycomponent semi-finished products of high readiness with adjustable thickening. The trend of using devices with low-temperature processing helps to reduce nutrient losses, including in craft delicatessen products, for example, meat products, which are a daily diet in many countries of the world [1]. The work [2] provides data on determining the practical efficiency of using a thermal radiation single-drum roller dryer to obtain a powder fraction (3–5%) of dry matter from pre-thickened polycomponent masses. Ensuring the production of high-quality natural semi-finished products due to low-temperature drying for further use in the formulations of new products. In [3], an improved technology for the production of pastilles is presented by introducing a multicomponent fruit and berry paste into the recipe, thereby expanding the functional and physiological properties of the product. In particular, the introduction of multicomponent plant semi-finished products of a high degree of

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readiness into product recipes allows for the production of modern new products in the conditions of the modern strategic direction of the development of the agro-industry of European countries in the conditions of the formation of competitiveness [4]. However, an important drawback of the processing of agricultural raw materials into multicomponent semi-finished products of a high degree of readiness is the thermolabile properties of natural raw materials and their perishability, which necessitate the improvement of existing heat and mass exchange devices for maximum preservation of natural properties. Existing previous studies prove an increase in the efficiency of heat and mass exchange in rotary-film devices in the conditions of replacing the steam jacket with electric heating [5], contributing to increased resource efficiency in the conditions of reduced energy costs [6]. Traditional vacuum evaporators are characterized by high energy and metal consumption, thereby significantly reducing the possibility of stabilizing the thermal regime of condensation and the mobility of the equipment. Emphasizing the relevance of implementing engineering solutions aimed at improving condensation devices with a comprehensive approach to modernizing the heating system, artificially increasing the useful heat exchange surface and recovering secondary air through Peltier elements.

There is a demand for multicomponent vegetable condensed semi-finished products of high readiness in the agro-industrial sector and craft production, as well as among consumer cooperatives due to the environmental situation, pandemics and military challenges [7]. In part, this is inherent in the factors of competitive production for obtaining condensed semi-finished products of plant origin and includes factors of quality, natural ingredients and affordable cost for all segments of the population [8]. The implementation of the technological process for obtaining multicomponent semi-finished products in conditions of rational blending of various fruit, vegetable and berry agricultural raw materials contributes to the production of semi-finished products with therapeutic and prophylactic properties, as an example, the study of the Flash Vacuum-Expansion process for avocado puree [9]. It should be noted that the main difficulty of resource-saving processing of agricultural raw materials into semi-finished products of high readiness is the shortcomings of traditional equipment for concentration in the form of high energy and metal consumption, lack of mobility and recovery systems. For example, in work [10], the improvement of tempering machines is studied to increase resource efficiency in conditions of reducing energy costs and metal consumption. A similar approach was considered in studies of improved technology for the production of marshmallows by introducing blended fruit and vegetable paste into the product formulation [11]. Also, in work [12], it is noted about increasing the efficiency of the production of functional pasty semi-finished products by rationalizing the recipe ratio of agricultural raw materials and heat and mass exchange equipment for implementing the thickening process. One of the practical solutions is to improve the rotary film evaporator for concentrating fruit and berry purees [13] by reducing the metal content and forming the preservation of biologically active substances (BAS) in the resulting thickened semi-finished product of high readiness. Foreign research data also confirm the effectiveness of using natural multicomponent thickened mixtures in recipes of traditional products to obtain new products for daily use, in particular, on the example of juices based on berries and apples [14]. However, the issue of resource-saving process of thickening multicomponent natural masses remains fully unsolved, which is partly due to studies of thickening taking into account recipe or functional properties without taking into account the influence of the hardware component. Issues related to the uniformity of heat supply and heating of thermolabile natural mass also remain out of focus. As well as the removal of secondary steam and recovery of exhaust air heat, which in turn significantly affects the ultimate resource efficiency of the condensation process in vacuum evaporators. Confirming the feasibility of scientific and practical research on the implementation of a low-temperature condensation process of polycomponent plant masses under conditions of uniform distribution of heat flow and recovery of secondary steam.

In the process of thickening multicomponent plant masses, significant attention is paid to the issues of preserving natural properties in the heat and mass transfer process, in particular vitamin C, β-carotenes and other thermolabile nutrients [15]. One of the practical ways to preserve natural nutrients is low-temperature processing of agricultural raw materials by gentle vacuuming in the temperature range of 45–70°C. The solutions available in practice are based mainly on classic stationary steam heating systems, which are characterized by high energy and resource consumption. One of the solutions is given in [15] during the development of resource-saving IR dryers by additional equipment with digital control of the technological process [16], which is also implemented on mobile solar dryers [17]. The relevance of the implementation of modern engineering and technological solutions aimed at the implementation of autonomous and mobile solutions is emphasized.

The practical integration of various heat and mass transfer solutions in the conditions of combination for the improvement of devices [18] in the conditions of research of rheological-organoleptic properties and preservation of BAS of plant raw materials in fruit and berry syrups [19] emphasize the expediency of resource-saving process. One of the solutions for effective low-temperature thickening is the use of electromagnetic generators [20]. However, they are characterized by the complexity of maintenance, limiting practical implementation. And among the disadvantages of basic vacuum evaporation devices is also the instability of the temperature range due to steam heating and excessive energy consumption of the thickening process, which can lead to BAS losses. In particular, in the work [21] the attention is focused on the expediency of practical implementation of innovative technologies aimed at improving the quality of polycomponent plant semi-finished products of high degree of readiness and preservation of BAS in finished products. For example, in [22], a data transmission mechanism was introduced in telecommunication systems as one of the reliable processes during the stabilization of condensation modes in evaporators, in particular during decentralized use. In addition, in [23], cost modeling in telecommunication services is presented as an example of the relevance of using economic and mathematical approaches, in particular, which can be adapted when assessing the energy intensity of food equipment. In turn, the practical use of steam generators leads to an increase in operating costs and prevents the formation of mobility and complexity of using devices in agro-industrial sectors in conditions of decentralized processing of agricultural raw materials and craft production. In addition, in [24], the effectiveness of using improved designs and rheological properties of the resulting product are presented.

In [25], data on corruption risks in the conditions of even ineffective management decisions for building competitive agro-industrial sectors in accordance with European trends in the conditions of sustainable development of enterprises are provided. This, in turn, is a direct factor influencing the ability of the agro-industrial sector to invest in innovative hardware and technological support of technological cycles, including the formation of mobile resource-saving systems for primary processing of agricultural raw materials. In [26], it is noted that national cybersecurity and risk analysis of digital infrastructures, including agro-industrial sectors, is important for the security of the production sector in the conditions of automated systems and remotely controlled devices. Similar positive conclusions are given in [27] for the protection of technological processes from cyber threats, as an important component of food security of the production cycle. This is especially important in the context of a decentralized production cycle and the use of new-generation mobile devices equipped with a Wi-Fi module and digital sensors for monitoring technological parameters to prevent the likely impact of various cyberattacks on the production process. For example, in [28], the relationship between

the digital environment and the production cycle is noted as a component of the formation of modern new management systems in agro-industrial sectors and craft industries. The introduction of modern practical solutions in the context of a comprehensive modernization of basic structures will contribute to the intensification of heat and mass exchange processes and the BAS preservation in the context of ensuring cyber protection and the stability of enterprises in the context of military and economic challenges. During the production of multicomponent plant semi-finished products, a well-founded choice of agricultural raw materials is important, taking into account the content of natural ingredients, organoleptic and rheological properties, as well as the recipe ratio in blends. The proposed basis of the blend (apple, carrot and pumpkin) is based on high functional physiological properties and biologically active substances contained in this agricultural raw material. Apple is a natural source of pectins, vitamin C, organic and other useful natural ingredients. Carrot has antioxidant properties with a significant content of β-carotene, and pumpkin has fiber, natural sugars and other components necessary for the daily diet. The resulting multicomponent plant mass is a balanced semi-finished product with predicted rheological, organoleptic and functional properties. Taking into account the results of previous studies confirms that the proposed technical solutions have not only engineering and technological, but also strategic importance for the food security of countries. Thus, in the work [25] it is emphasized that corruption risks are a significant obstacle to the sustainable development of agricultural enterprises. In the article [26], attention is focused on the growing importance of national cybersecurity for the stability of modern industries, including the agro-industrial sector. In the paper [27], an analysis of international and domestic experience in the field of cyber protection of information data is provided, which is important when implementing digitalization technologies in agro-industrial sectors for remote automated control of the hardware and technological cycle. For example, in the paper [28], the innovative development of Ukraine in the conditions of using digital environments to acquire modern innovative solutions to overcome today's challenges, including under the influence of cyberattacks, is presented. This approach contributes to the comprehensive implementation of modern engineering and technological solutions aimed at resource saving, the use of recuperation systems and the digitalization of decentralized solutions to increase the competitiveness of the agro-food system to the challenges of sustainable development, digitalization and security. The presented literature analysis confirms the wide range of available research aimed at the formation of a resource-saving process of thickening thermolabile natural raw materials in conditions of preservation of biologically active substances. However, the issues related to increasing the resource-sa ving index (reducing energy and metal consumption), the formation of mobility of equipment for decentralized production in agro-industrial sectors in places of raw material cultivation remain fully undefined. Ensuring uniform heat supply during heat-mass exchange processing over the entire mass of agricultural raw materials and the use of secondary thermal energy for the autonomy of certain structural elements, which is the scientific and practical component of the study.

The object of research is the process of manufacturing multicomponent vegetable semi-finished products with adjustable thickening of the mass from Jerusalem artichoke, carrot and pumpkin on an improved mobile vacuum evaporator.

The aim of research is to improve the mobile vacuum evaporator by using a film-like electric heater of the radiant type, increasing the useful heat exchange surface by using a mixer with a heating circuit and Peltier elements for secondary air recovery. For the production of multicomponent semi-finished products (based on: Jerusalem artichoke, carrot and pumpkin) of a high degree of readiness with adjustable dry matter content, functional-rheological and organoleptic properties.

To achieve the set aim, it is necessary to perform the following objectives:

– improve the design of a mobile vacuum evaporator by using a film-like electric heater of the radiant type, increasing the useful heat exchange surface by using a mixer with a heating circuit and Peltier elements for secondary air recovery;
– determine the optimal technological parameters of the thickening process of multicomponent masses with a regulated DM content under conditions of preserving BAS and assess the effectiveness of improving the mobile apparatus in terms of resource saving and quality of thickened semi-finished products.

2. Materials and Methods

The testing of the improved mobile design was carried out on the own agricultural raw materials of the front-line Kharkiv region (Ukraine). The multicomponent vegetable semi-finished product was obtained on the basis of Jerusalem artichoke of the "White Kyiv" variety (50%), carrots of the "Shantan" variety (30%) and pumpkin of the "Ukrainian multifruited" variety (20%) taking into account the regulation of thickening. The choice of the specified agricultural raw materials is explained by the high content of natural ingredients important for the daily human diet: Jerusalem artichoke (main – inulin and others), carrots (β-carotene and others) and pumpkin – pectin substances and other ingredients. The first stage of preparation of agricultural raw materials for thickening was the purification of the raw materials with subsequent grinding to a puree-like consistency and mixing to a homogeneous multicomponent mass at a temperature of 20 ± 2°C with a mixer.

The control experimental sample was obtained using a similar technological process by concentrating in a traditional vacuum evaporator with a steam jacket, without artificially increasing the useful heat exchange surface and without recuperation of secondary air. The proposed recipe ratio of components (50:30:20) ensures the production of multicomponent vegetable semi-finished products of high readiness with a regulated DM content for further use in the formulations of new products. Including: functional drinks, baby and diet food, confectionery and dairy fillings, meat and vegetable products for the formation of increased nutritional value and original organoleptic and rheological properties.

3. Results and Discussion

The research was carried out on the basis of the scientific and educational center "Innovative resource-saving technologies for processing organic products" of the State Biotechnological University (Kharkiv, Ukraine). The improved design of a mobile vacuum evaporator for obtaining multicomponent plant semi-finished products with adjustable thickening within 25–45% DM for further introduction into the formulations of new products is shown in Fig. 1. The improvement was achieved by using a film-like electric heater of the radiant type, increasing the useful heat exchange surface by using a mixer with a heating circuit and Peltier elements for secondary air recovery and an additional air jacket. The proposed combined approach contributes to the formation of resource-saving technological cycle under conditions of uniform heat transfer, which is important when obtaining multicomponent semi-finished products of high readiness with adjustable thickening in the DM content. The improved mobile design is characterized by a reduction in the duration of the thickening process of thermolabile plant raw materials, reduction of BAS losses. The proposed engineering solutions contribute to the use of the device in conditions of decentralized production of multi-component semi-finished products and use by small and medium-sized enterprises of the agro-industrial sector. Including in conditions of front-line territories, where mobility, resource efficiency and rational processing of agricultural raw materials with preservation of BAS are important.

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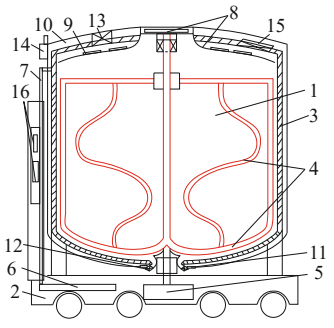

Fig. 1. Scheme of an experimental model of an improved mobile vacuum evaporator based on a film-like electric heater, a mixer with a built-in heating circuit, Peltier elements and an air jacket for heat recovery: 1 – working chamber; 2 – movable platform; 3 – film-like electric heater of the radiant type [29] with a heat-insulating surface; 4 – mixer with a heating circuit; 5 – electric drive with a worm gear; 6 – vacuum pump; 7 – flexible vacuum line; 8 – receiving surface of the recovery heat with an autonomous exhaust fan; 9 – Peltier elements; 10 – air jacket for heat recovery; 11 – technical line for the removal of the spent recirculation air and condensate drain; 12 – automated discharge pipe; 13 – pipe for loading raw materials; 14 – control and safety valves; 15 – inspection and maintenance window; 16 – control unit with Wi-Fi module

The improved mobile vacuum evaporator consists of a working chamber 1 mounted on a movable platform 2 with brakes for fixation during the condensation process. The heating of the working surface of the apparatus is carried out by a film-like electric heater of the radiant type 3 with a heat-insulating surface under conditions of repeating the geometry of the chamber for uniform heating of the multicomponent mass. In addition, from a constructive point of view, the improvement provides for an increase in the useful heat exchange surface by using a mixer with a heating circuit 4. This is important during resource-saving processing of thermolabile plant raw materials. The device has an adjustable speed of rotation of the mixer 4 from an electric drive with a worm gear 5. To increase the preservation of BAS of thermolabile plant raw materials, the thickening process is implemented during vacuuming from a vacuum pump 6 due to its connection to the working chamber of the device with a flexible vacuum line 7. The thickening process with an adjustable DM content is implemented at a temperature of 45–70°C to prevent significant losses of BAS and organoleptic properties. The thickening temperature at 45°C is explained by the need to reduce losses of vitamin C and polyphenols, and at 70°C, it contributes to rational evaporation capacity with minimal losses of pectin and β-carotene.

The upper part of the working space of the device has a built-in heat recovery system in the form of a receiving surface for the recovery heat of secondary air with an autonomous exhaust fan 8. In turn, due to the location of Peltier elements 9 on the outer surface of the receiving surface 8, autonomous operation of the exhaust fan is ensured by converting heat into low-voltage power supply. Exhausted secondary air in the temperature range of 35–40°C enters the additional air jacket 10, creating an additional thermal jacket from the thermal energy of the exhaust air, increasing the stabilization of the technological cycle and resource-saving condensation. From the additional air jacket 10, cooled air with a temperature of 25–28°C is discharged through an autonomous main and condensate drain 11. The recovery system operates independently of the vacuuming of the working chamber by forming an air circuit in the form of an autonomous circulation system outside the vacuuming zone, thereby creating resource-saving processes. Upon completion of the technological cycle, the multicomponent vegetable semi-finished product with a regulated DM content is discharged through the pipe 12, and the loading of the puree mass into the apparatus, in turn, is carried out through the pipe 13. The apparatus under vacuum conditions is equipped with a classic system of control and safety valves 14 with digital temperature sensors (on the walls of the working chamber, in the layer of experimental raw materials and in the recovery air main) and vacuum sensors. From a structural and technological point of view, the improved device is equipped with an inspection and maintenance window 15 with autonomous LED backlight. The technological process of thickening is controlled by a unit 16 with a Wi-Fi module for remote monitoring of the technological cycle during decentralized use.

The rheological properties of the studied samples of multicomponent vegetable semi-finished products (Jerusalem artichoke 50%, carrots 30%, pumpkin 20%) with a regulated DM content were compared with the control sample – Jerusalem artichoke (50%), Table 1.

Table 1

Comparison of the rheological properties of multicompo nent vegetable semi-finished products based on Jerusalem artichoke, carrots and pumpkin (50:30:20) with a regulated thickened DM and the control sample (Jerusalem artichoke – 50%)

Sample	Dry matter content, %	Dynamic viscosity (25°C, Pa · s)	Dynamic viscosity (55°C, Pa · s)	Rheological structure
Control sample	30	480	120	Pseudoplastic
Blend 1	30	525	133	Pseudoplastic
Blend 2	40	750	210	Plastic-viscous
Blend 3	45	980	300	Thick paste

When the DM content in the experimental blends increases from 30% to 45% (blend 1 – 30%, blend 2 – 40% and blend 3 – 45%), the predicted increase in the dynamic viscosity of the thickened multicomponent semi-finished product is observed, which is practically doubled. Compared to the control sample (50% Jerusalem artichoke), a higher initial viscosity is observed, which is due to the presence of pectin substances in carrots and pumpkin. This, in turn, creates the need to use a controlled speed mixer with a heating circuit during the thickening process to maintain a homogeneous mass of the recipe ingredients of the blend. Also, a change in the content of the main plant ingredients was determined (Table 2).

Table 2

Changes in the content of the main plant ingredients in the initial experimental raw material and the multicomponent plant semi-finished product with regulated thickening by the content of dry substances (using the example of a blend of 1 – 30% DM)

Indicator	Initial mass (average value)	Multicomponent vegetable semi-finished product with adjustable thickener (30% DM)	Loss, %
Vitamin C, mg/100 g	28 ± 1.2	22 ± 1.0	21.4
Inulin, g/100 g	11.5 ± 0.5	10.8 ± 0.4	6.1
β-carotene, mg/100 g	9.2 ± 0.4	8.0 ± 0.3	13.0
Polyphenols, mg/100 g	210 ± 9	185 ± 8	11.9

In the obtained multicomponent vegetable semi-finished product with adjustable thickening (30% DM) on an improved mobile design of a vacuum evaporator, the losses of natural ingredients are relatively small and are within 6–21%. Better storage of inulin is observed (94% of the initial value), thereby confirming the rational functional value of the obtained semi-finished product of a high degree of readiness. Thermolabile vitamin C is lost by 21% compared to the average value of the initial mass, but its amount remained sufficient to provide the product with antioxidant properties.

At the beginning of the research, a comparison was made of the technical and technological parameters of the basic design of the vacuum evaporator M3-2C-241a (Ukraine) with the improved mobile design (Table 3).

Table 3

Comparative technical and technological parameters of the basic design of the vacuum evaporator M3-2C-241a with an improved mobile design

Indicator	M3C-320 (basic design)	Advanced mobile device
Mass of the device, kg	$m^* = 900$	$m = m^* - m_{jacket} + m_{FFREHRT} = 900 - 350 + 20 = 530$
Working surface of heat exchange, m^2	$F^* = 2.2$	$F = F^* + F_{mixers} = 2.2 + 0.5 = 2.7$
Stability of the temperature range	Periodic oscillations	Stable control
Specific metal content, kg/m^2	$m = M/F = 900/2.2 = 409$	$m = M/F = 530/2.2 = 196.3$
Duration of the thickening process, s	$\tau = Q/F \cdot k \cdot \Delta T = 1.049 \cdot 10^6/2.2 \cdot 1464 \cdot 80 = 4071$	$\tau = Q/F \cdot k \cdot \Delta T = 1.04 \cdot 10^6/2.7 \cdot 1800 \cdot 80 = 2674$
Specific heat consumption, kJ/kg	$q_s = Q_{TOT}/m = 85 \cdot 870/700 = 122.7$	$Q_s = Q/m = 70 \cdot 690/700 = 100.9$
Heat of heating of the device, kJ	$Q_d = m_1 \cdot c_c(t_2 - t_1) + m_2 \cdot c_c(t_3 - t_1) =$ $= 480 \cdot 0.48(50 - 25) + 320 \cdot 0.48(120 - 20) = 21120$	$Q_d = m_1 \cdot c_c(t_2 - t_1) =$ $= 495 \cdot 0.48(50 - 25) = 5940$
Heat of heating of the polycomponent mass, kJ	$Q_p = m \cdot c(t_f - t_s) = 700 \cdot 3.7(50 - 25) = 64750$	$Q_p = m \cdot c(t_f - t_s) = 700 \cdot 3.7(55 - 25) = 64750$
Total heat, kJ	$Q_{tot} = Q_d + Q_p = 85870$	$Q_{tot} = Q_d + Q_p = 70690$
Duration of processing	$\tau = Q/F \cdot k \cdot \Delta t = 1049112/2.2 \cdot 1454 \cdot 87 = 3769$ s	$\tau = Q/F \cdot k \cdot \Delta t = 1049328/2.8 \cdot 1820 \cdot 87 = 2366$ s
Time of reaching the stationary mode, s (determined experimentally)	760	535

Note: * – calculations were performed without prior consideration of heat losses to the environment

During the comparison of the technical and technological parameters of the devices, a reduction in the mass of the device by 34% was determined by calculation and experiment, contributing to the formation of the mobility of the improved device. The total useful working surface of heat exchange due to the use of a mixer with a heating circuit is artificially increased by 27%, contributing to the intensification of the thickening process of thermolabile raw materials under conditions of a reduction in the duration of the technological cycle by 37%. The specific heat consumption is reduced by 15.5%, increasing the resource-saving indicator of the technological cycle of thickening and will contribute to reducing the cost of production of multicomponent plant semi-finished products with a regulated DM content for use in the formulations of new products.

Fig. 2 shows the results of the heating kinetics of experimental samples of plant masses with a controlled change in the DM content during condensation in an improved vacuum evaporator and the basic design.

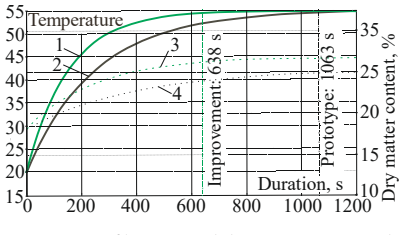

Fig. 2. Kinetics of heating and dry matter content during condensation in an improved mobile model of a vacuum evaporator and a basic design (M3-2C-241a): 1 – temperature of the improved mobile device; 2 – temperature of the basic design (M3-2C-241a); 3 – dry matter content (improved mobile device); 4 – dry matter content (basic design, M3-2C-241a)

According to the data, the improved mobile design of the vacuum evaporator reaches a stationary temperature regime of boiling of thermolabile plant mass (54.5°C) in 535 s, and the basic design reaches the specified temperature in 760 s. This confirms the reduction in heating duration by 26.9%. At the beginning of the research, the technological condensation of multicomponent plant semi-finished products was simultaneously monitored for the level of achieving the regulated content of dry matter. For example, an improved mobile device provides accumulation of up to 26.7% DM, while the basic design – only up to 25.4% DM. The kinematic curves presented in Fig. 2 are characterized by optimal heating of polycomponent vegetable mass and technological thickening. Taking into account the obtained experimental and practical results in the conditions of obtaining polycomponent vegetable semi-finished products with a regulated content of SR of a high degree of readiness formed in the conditions of further prescription use in new products. The optimal values of the regulated DM content are proposed, namely: for functional drinks – 12–15% DM, for baby food – 16–18% DM. For vegetable pastes – 20–25% DM, for dessert products – 28–32% DM and for meat semi-finished products – 30–32% DM. Confirming the formation of resource-saving technological cycle of thickening in the conditions of using an improved mobile device to obtain semi-finished products with a regulated DM content for further use in recipes in new products. Also, target DM values for the formation of a list of new products, the formulation of which can be introduced polycomponent vegetable semi-finished product of high readiness (Table 4) are determined.

Table 4

Regulated content of dry substances in thickened polycomponent vegetable semi-finished products of high readiness for further introduction into recipes of new products

Direction of use in new product formulations	Regulated dry matter content, %	Functional purpose
Functional drinks	25.0–30.0	Basic thickened concentrate for displacement with water while preserving easily digestible natural nutrients
Baby food	30.0–35.0	Balanced nutrient composition for purees, sauces, cereals
Confectionery fillings	40.0–45.0	Thick thickened rheological structure for jelly products, cake layers
Meat and vegetable products	35.0	Plant component to increase the content of the juice-containing component and functional value

The production of multicomponent vegetable semi-finished products of high readiness with adjustable thickening by the DM content within 25.0–45.0% allows for a wide range of use in the formulations of new products, and not only as an independent product. For example, in the technological process of producing various beverages, easy solubility without sediment formation and preservation of taste are important when introducing thickened semi-finished products of plant origin into the formulation. In the production of baby food, it is important to maintain a soft consistency without lumps and maintain optimal rheological properties, in particular – density, and when introducing them into the formulations of confectionery products, it is important to maintain

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a stable texture. In the technological cycle of the production of meat and vegetable products, the introduction of thickened natural semi-finished products into the formulations contributes to increasing functionality and moisture-holding capacity during heat and mass transfer processing, while maintaining the juiciness of the product.

The improved design of the mobile vacuum evaporator is adapted to the conditions of decentralized use in agro-industrial sectors and craft production of new products to the formulation composition of which thickened products with a regulated content of SR are introduced. The modern engineering and technological solutions proposed during the improvement of the design allow the design to be used directly at the places of collection or primary processing of agricultural raw materials. In addition, the possibility of completing the device with wiping machines and intermediate tanks for preliminary storage of thickened multicomponent plant masses is preserved, ensuring a closed technological production cycle. The results obtained in the course of scientific and practical research correlate and complement previous studies, which are considered in the works [5, 7, 13] and are aimed at ensuring resource-saving processing of thermolabile raw materials under conditions of uniform heat supply during thickening. The improved device provides thickening of multicomponent plant masses with adjustable DM content and BAS preservation with the subsequent possibility of low-temperature drying to expand the spectrum of use of semi-finished products in the formulations of various new products.

The use of a film-like electric heater of the radiant type in conditions of repeating the geometry of the working chamber of the device contributes to uniform heating of thermolabile plant masses. Engineering solution for artificially increasing the useful surface of heat exchange by using a mixer with a heating circuit and Peltier elements for autonomous operation of the exhaust fan of the secondary air recovery system. In general, they contribute to increasing the resource efficiency of the thickening production cycle with a simultaneous reduction in duration and the formation of mobility of the device by reducing metal consumption and installing the structure on a mobile platform. With simultaneous minimization of losses of natural BAS in conditions of uniform heat supply and gentle operating temperature ranges.

One of the main limitations of research is obtaining scientific and practical research results on a certain agricultural raw material (Jerusalem artichoke, carrot and pumpkin), which necessitates the need for preliminary research for other agricultural raw materials and adaptation of regimes. In addition, the obtained scientific and practical results on an improved mobile design during scaling up to the industrial level require additional research and the formation of a single base of technological processes. Confirming the feasibility of further research aimed at analyzing the processes of thickening various blends based on agricultural raw materials in the conditions of using digital control systems to form an automated resource-saving thickening system in the conditions of decentralized production of semi-finished products.

4. Conclusions

1. The mobile design of the vacuum evaporator has been improved by replacing the classic steam jacket with a film-like electric heater of the radiant type. The introduction of a mixer with a heating circuit artificially increases the useful heat exchange surface by 27% (2.7 m^2 versus 2.2 m^2 in the basic apparatus), contributing to a reduction in the duration of the thickening process by 37%.

2. The optimal technological parameters of the thickening process of a multicomponent mass with a regulated dry matter content have been determined: temperature 45–70°C during vacuuming (10–30 kPa). This contributes to the preservation of up to 94% of inulin, 87% of β-carotene and 88% of polyphenols in the resulting multicomponent semi-finished product based on Jerusalem artichoke, carrot and pumpkin with regulated thickening by dry matter content. Based on the results of comparing the technical and technological parameters of the basic design of the vacuum evaporator M3-2C-with the improved mobile design, the main indicators of resource efficiency and quality of condensed semi-finished products were determined. The specific metal content is actually reduced by half (409 kg/m^2 versus 196 kg/m^2), the specific heat consumption by 15.5%. The obtained condensed semi-finished products are suitable for use in functional new products for various purposes (baby food, confectionery and dairy products, functional drinks, etc.).

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors declare that generative artificial intelligence tools were used exclusively for language editing, grammar checking and technical formatting of the manuscript under full human control.

Artificial intelligence was not used to create, process or interpret scientific data, form conclusions or other elements of the scientific results of the article.

Tool used: ChatGPT (OpenAI GPT-5, version 2025).

The authors bear full responsibility for the content, reliability and scientific correctness of the submitted material.

Authors' contributions

Lyudmila Chuiko: conceptualization of the study, general scientific guidance, editing and validation of the results; ***Nataliia Tytarenko***: experimental studies, development of heat treatment modes and data processing; ***Andrii Milenin***: engineering design of the apparatus, modeling of heat and mass transfer processes and visualization of the structure; ***Hanna Chmil***: forecasting of the economic assessment of resource efficiency and commercial potential of the development, preparation of analytical conclusions; ***Sergei Sabadash***: conducting comparative experiments, preparation of test methods and analysis of product quality indicators; ***Eldar Ibaiev***: participation in testing the apparatus, preparation of graphic materials and tables.

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