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IMPROVEMENT OF A SECTIONAL CASSETTE-CAPACITIVE APPARATUS FOR IMPLEMENTING PRELIMINARY THERMAL PROCESSING OF PLANT RAW MATERIALS

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This study investigates processes of preliminary heat treatment of plant raw materials, using the example of heating a fruit and vegetable semi-finished product based on apples, carrots, beets, and elderberries, as well as partial drying of apple slices in an improved apparatus. The task addressed is to improve resource efficiency in implementing preliminary heat treatment of raw materials by improving a sectional cassette-capacitive apparatus.

A feature of the improved apparatus is the combination of capacitive and cassette stations on a truck platform, generation of a local heat supply from a film electric heater of the radiant type to eliminate the intermediate heat carrier, networks. The usable heat exchange surface of capacitive stations was increased from 0.98 m² to 1.47 m² through engineering by using mixing devices equipped with a heating surface. The multifunctionality of the device is formed by using a capacitive station equipped with a hemispherical perforated bubbler and hermetic covers with Peltier elements.

The capacitive station was tested on the kinetics of heating a semi-finished product (40% apple, 25% carrot, 25% beetroot, and 10% elderberry). It was established that the duration of reaching a gentle stationary mode within 55°C was reduced by 240 s (prototype – 360 s). The cassette station was tested on performing a preliminary thermal operation to dry apple slices to a content of 30…35% dry matter. The process is implemented in an improved device for 45…55 min, while convective drying – 70…85 min. Comparison of technical and technological parameters of the improved design with a steamer and a convective dryer shows a decrease in the specific metal capacity from 387 kg/m² to 330 kg/m². Total heat consumption for heating 75 kg of polycomponent puree-like plant mass reduced from 21353 kJ to 11309 kJ

Keywords: plant raw materials, polycomponent mixture, preliminary heat treatment, film electric heater of radiant type

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1. Introduction

Considering limited energy resources and the development of agro-industrial sectors, including in frontline oblasts, there is a need to implement resource-saving solutions to improve approaches to processing thermolabile plant raw materials [1]. The properties of plant raw materials, seasonality of harvesting, and sensitivity to post-harvest processing and transportation conditions necessitate the implementation of innovative engineering and technological solutions for resource-saving processing from the moment of preparation for the basic technological processes [2]. The processing of plant raw materials is carried out at stationary production facilities in countries on using traditional heat and mass exchange equipment, for example single-operational devices for pre-processing, vacuum evaporation devices, various dryers, etc. In addition, in most designs, heating of the working environments of the devices is carried out through the use of intermediate heat carriers, most often steam, which leads to the need to use transport networks and generating devices. This leads to an increase in the metal content of the equipment and energy costs for the implementation of technological processes for processing raw materials using high-temperature media, thereby promoting the implementation of modern engineering and technological solutions aimed at developing resource-saving technologies for processing plant raw materials directly at harvesting sites, reducing transportation costs through improved packaging and technological stabilization of the production cycle. As well as the formation of multi-operational technological equipment for the simultaneous implementation of several gentle technological preliminary operations for the implementation of further initial heat and mass exchange processing of raw materials after collection.

Paper [5] describes the prospects for the use of modern technological and engineering approaches aimed at improving the quality, safety, and shelf life of food products. The data could be the basis for forming prerequisites for designing functional systems aimed at gentle heat and mass exchange processing of plant raw materials, including through the formation of multi-operational technological systems in a single complex, thereby supporting the modern development of multifunctional mobile units for preliminary processing operations in the resource-saving processing of plant raw materials directly at cultivation sites.

The above confirms the relevance of conducting scientific and practical research aimed at improving multifunctional mobile devices of the cassette-capacitive type for resource-saving implementation of preliminary heat treatment of plant raw materials at places of cultivation. The engineering solution for combining the cassette-capacitive type on a mobile platform will contribute to the formation of multi-operationality by implementing several preliminary processes of raw material preparation in parallel. Specifically. the processes of heating, warming, thermal stabilization, partial dehydration, infusion, extraction, partial thickening, and other operations, in accordance with technological needs under conditions of localized heat supply and recovery of secondary heat. Practical implementation of engineering solutions will contribute to the processing of thermolabile raw materials at places of cultivation under conditions of increasing resource-saving through the rejection of intermediate heat carriers and localization of heat supply to preserve physiologically functional properties.

2. Literature review and problem statement

Trends in the European evolution of the food sector require the implementation of solutions aimed at designing resource-saving equipment and technological cycles for the processing of thermolabile raw materials while preserving natural properties [6]. The properties of plant raw materials primarily require the implementation of gentle thermal mass exchange operations in the post-harvest operational stage before the production of single- and multi-component semi-finished products of a high degree of readiness, which can later be used as a product for self-consumption or a prescription natural multi-component semi-finished product of a wide range with original rheological, organoleptic properties and a concentrated content of physiologically functional ingredients for the finished product. However, it is precisely the equipment and technological solutions that drive competitiveness and contribute to the re-equipment of heat and mass exchange processes and equipment in terms of resource saving [7]. The disadvantage of classical thermal devices is associated with the use of intermediate jackets, single-operation of devices, and the desire to obtain high productivity of the production cycle through high temperature ranges.

Work [8] reports studies on the technological cycle of production of health-improving functional semi-finished products of a high degree of readiness, which are characterized by original organoleptic and rheological properties and have an increased content of physiologically functional ingredients. That became possible due to the rational blending of puree-like plant masses taking into account their rheological, organoleptic, and functional components. In turn, blending of raw materials contributes to obtaining an attractive color range of the product and awakens the demand among consumers for the consumption of attractive products as a component of choosing healthy food in the daily diet. However, in the course of research, the main direction is aimed directly at the implementation of the technological component of the production of multi-component semi-finished products without analyzing the engineering component of the production cycle from the initial operations of preliminary heat treatment.

Resource-saving technological equipment and the use of gentle heat and mass exchange modes at the first stages of processing agricultural raw materials are determining factors in the formation of the quality of finished products, which necessitates further research into complex hardware and technological solutions for processing plant raw materials.

Work [9] reports studies on determining the impact of regular consumption of berry and apple juice on the lipid profile of consumers with an emphasis on confirming the biological value of fruit and berry raw materials as necessary in the diet for the consumption of polyphenolic compounds and natural antioxidants. Systematic consumption of fruit and berry juice contributed to the improvement of certain indicators of cardiovascular health, which in turn confirms the feasibility of preserving biologically active substances of plant raw materials during technological processing. This indicates the need to minimize the loss of natural components at the stages of technological processing. In addition, modern trends in the development of the food system require the implementation of a green European course aimed at resource-saving complex processing with limited logistics, energy resources, and even in front-line regions, requiring experimental and practical confirmation when using multi-operational devices.

Paper [10] considers the issue of effectiveness of using engineering and technological approaches aimed at implementing preliminary heat and mass exchange processing of raw materials. The reduction of hardware and technological costs for implementing the process under conditions of direct processing of raw materials at places of cultivation and production of semi-finished products of a high degree of readiness is confirmed. The study was implemented under conditions of using single-operational devices, which determines the expediency of integrating several intermediate operations within a single complex.

In work [11], the effectiveness of using fruits and their processed products as a natural source of biologically active substances in the development of functional food products to provide a nutritionally adequate daily diet for various population groups, including individuals operating under extreme conditions, is considered. In the course of research, attention focused on the importance of preserving the natural properties of plant raw materials during technological processing, which creates prerequisites for improving engineering and technological solutions, thereby creating prerequisites for further scientific and practical improvement of mobile equipment for the implementation of several technological preliminary operations of plant raw materials, including at places of cultivation. For example, in [12], results from a practical study on the thickening of fruit and berry puree based on apples, quince, and black currants in a rotary film evaporator are reported. A feature of the design is the lower location of the separating space, screw unloading of the concentrated paste, and preheating of the puree with secondary steam. During the research, the structural and mechanical properties of blended purees were determined when the temperature changed within 55…75°C to establish an effective viscosity, which could contribute to the rationalization of the process. Therefore, even during the improvement of structures, the question arises about the need for preheating the puree mass with secondary steam, confirming the feasibility of conducting preliminary preparatory thermal operations before the main heat and mass exchange operations.

In [13], studies were conducted to determine the influence of pre-treatment of juniper berries on the yield of essential oils and drying kinetics when using electric heat energy sources, as a basis for engineering intensification of heat and mass exchange processes of raw material processing. During the research, a reduction in the duration of the technological cycle and resource costs during the improvement of classical thermal devices was confirmed. The data prove the effectiveness of improving heat and mass exchange processes, which in turn could make it possible to form a scientific basis for the modern development of mobile multifunctional hardware and technological systems.

In [14], an analysis of technological processes for drying plant raw materials while ensuring recirculation of secondary thermal air was carried out, with the determination of the level of energy consumption reduction and stabilization of the uniformity of heat supply. This emphasizes the expediency of carrying out gentle heat and mass exchange modes during the processing of plant raw materials to minimize the loss of natural properties. However, the connection between the preservation of biologically active substances and the practical implementation of design and technological aspects aimed at implementing gentle modes in multi-operational resource-saving devices remains insufficiently studied, which requires further combined design and technological improvement and refinement.

Research is ongoing to determine the impact of food products on the principles of processing, which could contribute to defining effective approaches and the feasibility of air media recovery, which in turn would lead to resource-saving technological cycles [15]. However, no detailed data on the effectiveness of multi-operational mobile devices for preliminary heat treatment of raw materials as a component of a single complex of effective processing, which creates the need for the development and implementation of resource-saving technologies, is provided.

In [16], the technologies of thermal processing of food products are considered with a detailed analysis of basic operations (pasteurization, blanching, thermal treatment, etc.) in combination with the influence of thermal media as the main reason for the decrease in the efficiency of the process. It is noted that the introduction of nanofluids as an alternative medium of intermediate carriers contributes to increasing the resource efficiency of the technological cycle; however, heat carrier networks, jackets, and heat generators remain, which leads to an increase in metal consumption and energy costs. In addition, studies on local heat supply to ensure a reduction in heat consumption of the production cycle and heating the apparatus as a whole are ignored. Although this is a promising engineering solution for local heat supply during preliminary heat treatment, especially when combined with the heated surface of the mixing device, which will contribute to an increase in the usable heat transfer area without the use of intermediate media. The lack of research may be due to the need to improve the apparatus for complex research, although the task seems practical and could contribute to resource-saving production cycle. In turn, local heat supply, in addition to the elimination of intermediate heat carriers, the need to use steam jackets contributes to the formation of autonomy in the use of a structural and technological multifunctional system, adapting to the needs of agricultural sectors.

In work [17], the heat transfer coefficient was determined using the example of a rotary film evaporator with a heating film-forming element for stabilizing hydraulic movement during boiling of organic plant raw materials and compared with a classic welder. It was established that the elimination of intermediate heat carriers and the use of an improved apparatus contributes to a decrease in the specific metal content of the improved apparatus with a film-forming element – 57 kg/m^2, while this indicator for a vacuum evaporator is 410 kg/m^2. Despite the advantages of using electric heaters and eliminating intermediate heat carriers, the feasibility of recovering secondary air remains an unresolved issue, which may be associated with the lack of appropriate design solutions.

In [18], studies on changes in the rheological properties of baby purees in the temperature range of 5…65°C using heat and mass exchange devices to determine the fluidity index of the puree mass depending on the recipe ratio were reported. In the gentle temperature range, the range of shear rates also changed within 5…200 s^{-1} and, therefore, the fluidity of blended purees changed, emphasizing the influence of the use of preliminary thermal operations before the final technological processes. However, the work did not disclose the type of equipment for thermal treatment, the possibility of its use in agricultural sectors, and the presence of resource saving, which contributes to the search for engineering solutions aimed at combining multifunctionality and mobility under conditions of hardware and technological resource saving.

In [19], studies on heat recovery systems are reported to confirm the efficiency of using secondary thermal energy generated during the implementation of production cycles to increase resource saving. In practice, heat pump-based recovery systems are widely used but their practical efficiency depends on the structural design of the technological equipment, the stability of thermal processes, and the possibility of recovering the secondary air environment. For example, in [20], data are provided on the analysis of the heat recovery system in the spray dryer processes in the production of soybean powder. The recovery circuit is a water circuit with a heat pump designed to preheat the ambient air for the dryer and, in comparison with the classical spray dryer system, makes it possible to save 21.3% energy. On the one hand, studies confirm the effectiveness of secondary air recovery for heating the ambient air. On the other hand, recovery systems should have a simple structure and not consume additional energy, for example, for pumps, which is relevant for mobility and the formation of resource efficiency in general.

Thus, in [21], research was conducted into advanced methods of technologies for minimal post-harvest processing of plant raw materials to determine the potential and identify key parameters for increasing the level of consumption of fresh fruits and berries. The review describes the effects of each treatment and their feasibility on subsequent logistics matrices, temporary storage, and sale. Despite the considerable potential of plant raw materials, the extended transportation and distribution chain necessitates the development of innovative processing approaches directly at harvesting sites. This would contribute to improving resource efficiency in production and expanding the range of high-value semi-finished products with a high degree of readiness. This is possible when using mobile multifunctional devices, which would contribute to the rejection of single-operation devices, process several types of raw materials at once, and support the agro-industry in countries even during military conflicts.

In [22], practically employed technologies for drying plant raw materials are considered; the advantages of using advanced hybrid resource-saving systems are emphasized, including those based on IR radiation and combined heat supply systems during drying. Drying helps reduce energy consumption by 30...50% with a technological duration of up to 70% while simultaneously preserving thermolabile physiologically functional properties. However, the available wide range of dryers is characterized by stationarity, high productivity, and low structural and technological adaptability to mobile resource-saving processing at the places of raw material collection. Research was continued in work [23] in the field of identifying practical approaches to the formation of sustainable development of innovative technologies for drying raw materials when using solar energy, recovering secondary heat, and rationalizing the control process. It is emphasized that even high-quality organization of technological processes under conditions of gentle heat and mass exchange processing of raw materials and the use of recovery systems contributes not only to the preservation of natural properties but also to the reduction of energy technological costs. It has been established that the combination of low-temperature drying modes with recovery systems contributes to the reduction of energy costs and the improvement of the quality of finished products.

Based on our literature review, it was found that most research focuses on stationary processing of raw materials using classic single-operation equipment, limiting mobility and constructive use at places where raw materials are grown. Conventional technological processes for the implementation of thermal operations are aimed at preliminary preparation of plant raw materials during the implementation of the processes of heating, blanching, extraction, and partial thickening, which are in most cases implemented in single-operation capacitive devices. And the processes of drying and thermal stabilization are implemented in cassette-type drying chambers. In turn, the use of single-operation devices leads to a complication of the production cycle and an increase in the operating duration and number of auxiliary intermediate operations. This emphasizes the feasibility of a combined capacitive and cassette station in a single mobile device. Most practical solutions and scientific research are aimed at improving certain heat and mass transfer processes, reducing production and technological costs, in particular by using secondary heat through recovery, thereby improving the quality of the final product. In turn, issues related to the implementation of engineering solutions for combining several previous technological operations in a single mobile device remain insufficiently covered. This especially applies to solutions aimed at rationally combining in a single complex of processes for the implementation of heating, partial condensation, extraction and drying under local heat supply conditions and recovery of secondary heat.

The aforementioned emphasizes the feasibility of conducting scientific and practical research into improving mobile cassette-capacitive devices for preliminary heat treatment of plant raw materials, including at places of cultivation.

3. The aim and objectives of the study

The purpose of our study is to improve the sectional cassette-capacitive apparatus for the implementation of resource-saving preliminary heat treatment of thermolabile plant raw materials with adaptation to use under field conditions. This will make it possible to verify the design idea of combining capacitive and cassette stations on a mobile platform and use local heat supply, partial recovery of secondary warm air. Such solutions in general could contribute to the preliminary preparation of raw materials into single- and multi-component semi-finished products of a high degree of readiness.

To achieve the goal, the following tasks were set:

– to substantiate the design and technological solutions aimed at improving the sectional cassette-capacitive apparatus for the preliminary heat treatment of plant raw materials;

– to define the structural and technological efficiency of the proposed solutions for the implementation of resource-saving preliminary operations using plant raw materials.

4. The study materials and methods

The object of our study is the processes of preliminary heat treatment of plant raw materials, using the example of the processes of heating a fruit and vegetable semi-finished product based on apples, carrots, beets, and elderberries, as well as partial drying of apple slices in an improved device.

The principal hypothesis assumes that the implementation of combined design and technological solutions to improve the sectional cassette-capacitive device could contribute to increasing the resource efficiency of the processes of preliminary heat treatment of plant raw materials. This becomes possible due to the mobility of the self-propelled platform, multi-operation, local heat supply, and partial recovery of secondary heat. The technical difference, in addition to mobility, is the complex functional combination of the capacitive and cassette station, which contributes to the implementation of the maximum number of technological preliminary operations. The use of a film electric heater of the radiant type (FEhRT) ensures the repetition of the geometry of the working surfaces of heat exchange with a simultaneous additional increase in the usable surface of heat exchange due to additional heating of the internal circuit of the mixing devices. The introduction of Peltier elements contributes to increased resource efficiency by converting part of the secondary thermal energy (air environment) into low-voltage power supply for autonomous fans.

Practical testing of the improved sectional cassette-capacitive apparatus for preliminary heat treatment of plant raw materials was carried out at the State Biotechnological University (Kharkiv, Ukraine). During the research of single-component and multi-component experimental samples, ripe raw materials collected on the territory of the Bogodukhiv community in the Kharkiv front-line zone were used. During the selection of raw materials, attention was paid to the seasonality of ripening, the level of demand during further implementation, the content of physiologically functional ingredients, and the ability to form multi-component masses. The classic basis chosen included apples of the Antonivka variety, which is a source of pectin substances; carrots of the Koroleva Oseni variety as a source of carotenoids; table beets of the Borna variety as a source of betanin compounds; and elderberries of the Black Lace variety as a source of polyphenol antioxidants.

The assumptions adopted before the start of our study were based on assuming the thermophysical properties of the experimental plant raw materials to be constant and FEhRT to provide local heat supply. Among the accepted simplifications is a separate testing of the capacitive and cassette station without considering high-temperature regimes.

To obtain a homogeneous plant multicomponent puree mass, the ripe raw materials were pre-crushed with subsequent rubbing on a double rubbing machine with a rubbing sieve opening within $0.2...0.6 \cdot 10^{-3}$ m. The rubbed puree mass was mixed according to the experimental ratio: apples – 40%, carrots – 25%, beets – 25%, and elderberries – 10%. In addition, the elderberries were additionally partially dried before rubbing in the cassette section of the improved apparatus to preserve polyphenolic compounds and antioxidants. The initial dry matter content (DM) of the puree-like multicomponent mass was 14...18%. During the drying of apple slices, an apple with an initial DM content of 14...16% was pre-cut to a thickness of 5...8 mm for further pre-processing to a DM content of 30...35%.

For temperature measurement and control, contact thermocouples (chromel-alumel) with a range from 0 to 200°*C* and an error of no more than ±0.5°*C* were used. In the capacitive and cassette sections of the improved apparatus, the thermocouples were located on the inner and outer surfaces of the container, in the boundary layer of the raw material, the surface of the mixing device, the bottom, the lid and in the central zone of the capacitive medium. In the capacitive section, the air medium was additionally measured after passing through the recuperation coil, and in the cassette station, the temperature was additionally measured on the surface of the apple slices. The air flow velocity in the range of 0.1...5.0 m/s was determined by a thermal anemometer Testo 405i (Germany) with an error of no more than ±0.05 m/s. The working range of rotation of the mixing device in the range of 10...60 rpm was determined by a non-contact digital tachometer NS2234 (China), and the level of vacuum was controlled by a vacuum gauge DM 05160 M (China) in the range: 0...20 kPa. The content of DM in the experimental sample of the multicomponent puree-like semi-finished product and apple slices was determined by weighing during drying to constant mass at a temperature of 105°*C*. The registration of experimental data was carried out with an interval of 30 s during the study of the preliminary thermal operation of heating and 60 s during the testing of the process of partial dehydration and preliminary thickening. The technological process was controlled by the control unit "OWEN". The experimental testing was repeated in five-fold repeatability with a relative error of no more than 3% when using traditional methodologies for processing experimental and practical data based on thermal processes.

5. Results of the implementation of hardware and technological solutions for resource-saving preliminary heat treatment of raw materials

5. 1. Design and technological solutions aimed at improving the sectional cassette-capacitive apparatus

The improved sectional cassette-capacitive apparatus for preliminary heat treatment of plant raw materials contributes to the resource-saving processing of raw materials: fruits, vegetables, berries, spicy and aromatic raw materials, as well as various crushed blends. The wide range of raw materials processed in the improved apparatus forms its multifunctionality and contributes to the implementation of further basic heat and mass exchange operations at processing and production facilities in the production of semi-finished products of a high degree of readiness.

Below is a general view of the improved sectional cassette-capacitive apparatus for preliminary heat treatment of plant raw materials (Fig. 1, *a* – top view) for use under field conditions mounted on a mobile vehicle platform 1 with wheels of increased cross-country ability. Control panel 2 is centrally mounted on the auto platform, around which sections for the location of rolling containers (vats) 3 and two cassette stations 4 are located. The engineering division of the apparatus into functional sections (capacitor and cassette station) helps reduce the restrictions associated with the operational need to process various raw materials without the use of single-operation apparatuses while implementing the maximum number of preliminary operations.

Rolling tanks (Fig. 1, *b* – vats, volume – 25 l and 50 l) 3 provide preliminary thermal preparation of various plant raw materials in the form of crushed fraction, single and multi-component puree / paste-like masses, extraction processes, and semi-liquid food systems. The inner surface of the rolling vats is made of stainless steel; it has a heat-insulated outer casing with a sloping bottom and built-in drain system 5 of an expanded diameter for processing raw materials from extraction solutions to thickened semi-finished products. The heating of the rolling vats is carried out by FEhRT 6, installed on the outer walls and bottom of the tanks with the possibility of simultaneous heating of vat walls and bottom or separately the walls and bottom.

The use of independent drives 7 with a variable speed within 10...60 rpm facilitates the use of the device for a wide range of raw materials of various consistencies. It also facilitates the installation of variable mixing devices 8 in accordance with technological needs. As mixing devices, frame-blade or anchor mixers are used depending on the consistency of the raw materials, in the internal cavity of which FEhRT is mounted for additional heating of the raw materials and intensification of the heat treatment process. Basic parameters of the mixing devices are given in Table 1.

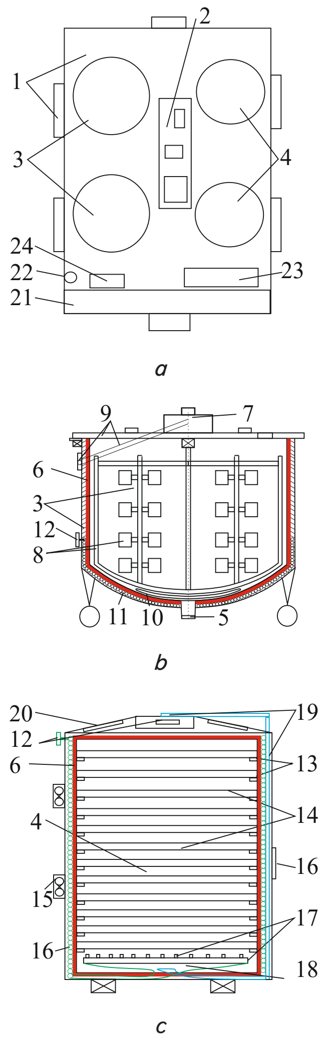

Fig. 1. Improved sectional cassette-capacitor apparatus for preliminary heat treatment of plant raw materials:
a — general view from above; *b* — rolling vat, volume — 50 l; *c* — cassette station 4 of cylindrical type — longitudinal section); 1 — mobile auto platform; 2 — control panel; 3 — rolling capacities (vats); 4 — two cassette stations; 5 — drain system; 6 — film electric heater of radiant type (FEhRT [23]); 7 — independent drives; 8 — mixing device; 9 — hinged cover with rubber seal, retainers, and gas shock absorber; 10 — hemispherical perforated bubbler; 11, 16 — coil; 12 — autonomous fan; 13 — retainers of functional pallets; 14 — hinges of semi-cylindrical surface; 15 — quick-release fasteners; 17 — perforated aeration collector; 18 — technical chamber; 19 — exhaust auger; 20 — Peltier element, 21 — photovoltaic panel; 22 — charge controller; 23 — battery; 24 — inverter

During technological cycles, the rolling vats are covered with hinged cover 9 with a rubber seal and a gas shock absorber for lifting and a retainer for sealing and creating a moderate vacuum. On the cover are the technical quick-removable nozzles for loading raw materials, supplying vacuum, as well as means of automation and viewing windows.

For the parallel implementation of several technological operations, the device is equipped with two interchangeable rolling vats. Additionally, vats can be equipped with a hemispherical perforated bubbler 10, which is offset from the central axis of the moving device to prevent contact between the moving part and the bubbler. The bubbling of the viscous plant mass was carried out in the range of 0.02...0.06 m^3/min, which prevented foaming. The stirring device is fixed with a quick-release coupling. To prevent destabilization of the uniformity of the temperature field in the bubbling zone and to prevent the inflow of cold air, preheating of the incoming air with accumulated secondary thermal energy is structurally provided for. This is realized due to the structural placement on the outer surface of the lower part and the bottom of coil 11, forming the passage of ambient air through it with the help of autonomous fan 12. Due to the passage of external air first through the filter and then through coil 11, it is heated to a temperature of 30...55°C and enters the perforated bubbler 10. From a practical point of view, a pulsed bubbling mode with cyclicity is implemented: 5...20 s supply and 20...60 s – pause to prevent foaming and intense air saturation of the mass of raw materials undergoing preliminary heat treatment. Such actions contribute to the stabilization of the temperature process without using additional sources of thermal energy to heat the primary air before bubbling.

Equipping the improved apparatus with a capacitive section facilitates the implementation of preliminary technological operations, namely heating / warming, displacement, infusion, soft extraction, balancing of recipe ingredients, preliminary boiling, and thickening. To maintain a resource-saving, gentle technological and technical cycle of processing plant raw materials, it is proposed to carry out preliminary heat treatment of vegetable and fruit masses in the range of 50…75°C and the cycle duration is 10…60 min (the recipe and physicochemical properties are taken into account). The extraction process with a liquid phase is in the range of 50…65°C and pulsed bubbling to intensify the transition of target substances into the liquid phase. Pre-boiling of multicomponent plant masses – in the range of 65…75°C to increase the dry matter content (DM) within 3…5%, thereby preparing the mass for boiling or drying processes. The process of soft low-temperature blanching for apple slices in the range of 45…55°C for 3…8 min, berry raw materials, in the range of 40…50°C, for 2…6 min. For carrots for 5…10 min at a temperature of 55…70°C and table beets – for 10…15 min at a temperature of 60…75°C. The blanching process is implemented using a perforated insert for immersing the experimental raw materials in a liquid working medium.

Table 1

Basic parameters of variable mixing devices

Technical and technological parameter	Frame-blade mixer (in Fig. 1, *a*, pos. 8)	Anchor mixer
Technological purpose	multicomponent puree-like and medium-viscosity vegetable masses	multicomponent pasty and thickened masses
Rotation frequency	20…60 rpm	10…35 rpm
Calculated usable heating surface of the mixer	$F_{mixer} = 0.28$ m^2	$F_{mixer} = 0.36$ m^2
Total usable heating surface	$F = F^*_{vessel} + F_{mixer} = 1.15 + 0.28 = 1.43\ m^2$	$F = F^*_{vessel} + F_{mixer} = 1.15 + 0.36 = 1.51\ m^2$
Nature of movement	more intensive mixing of the volume	effective work near walls and bottom

Note: $F_{vessel} = 1.15$ m^2 – total usable heating surface of two rolling vats.

The capacity section using two rolling containers (vats) with a volume of 25 l (50 l) makes it possible to load 35 kg (60 kg) of single and multi-component vegetable semi-finished products, taking into account viscosity and consistency.

The second structural part of the improved device is a thermally insulated two cassette stations 4 of cylindrical type (Fig. 1, *c*) and an external heat-accumulating lining of dark color with clamps 13 of functional pallets 14 and the possibility of opening in half. The cassette section has twelve trays and a distance between the pallets of 90 mm – with a single loading. The cassette station has an internal diameter of 780 mm, a height of 1650 mm, and an inter-pallet distance of 90 mm. The functionality of the pallets is achieved by using a perforated / mesh bottom, rigid sides to facilitate fixation in the working space, as well as interchangeable inserts to expand the range of use of raw materials of different fractional composition. Loading of functional pallets occurs with pre-prepared plant raw materials (berries – 10...20 mm, vegetables – 20...40 mm) on a technological table with subsequent manual loading into the working chamber. This helps control the mass of the load and the even distribution of raw materials over the area of the pallets. After loading the functional pallets, the operator closes the second open part of the semi-cylindrical surface movable on hinges 15 with quick-release clamps 16.

Heating of cassette stations 4 is provided by FEhRT – 6, which operates in an adjustable temperature range of – 30...85°C and is installed in the walls of the stations, as well as in the upper and lower parts to form a uniform heat supply. To recover secondary thermal energy, coil 16 is installed along the height of the stationary semi-cylindrical plane, along which air moves using autonomous fan 12 (the air in front of the coil passes through a filter). This makes it possible to preheat the ambient air by 8…18°C. In addition, in the lower part of the cassette station there is technical chamber 18, which is connected to perforated aeration collector 17 with a hole diameter of 3 mm, contributing to the distribution of recirculated air in the working environment. It intensifies the implementation of preliminary thermal operations for heating and partial dehydration of plant raw materials without the use of internally mounted mechanical moving elements in the circulation channels. Part of the exhaust air from the cassette station through exhaust auger 19 using an adjustable slide mounted in the air duct additionally enters technical chamber 18, thereby ensuring partial recirculation of secondary air and additional heating of the filtered air from coil 16 before spraying through collector 17. Increased resource efficiency of the improved mobile device is due to the additional use of thermoelectric Peltier elements 20, which are installed on the lids of the vats and the inner upper surface of the cassette stations and in the internal space of exhaust auger 19. Peltier elements are aimed at recovering part of the heat flow with subsequent conversion into low voltage (3…12 W). The energy obtained is used to support the operation of autonomous fan 12, automation means, and Wi-Fi module installed on control panel 2.

The proposed technical solution increases the level of automation and resource efficiency of the device. The proposed cassette stations make it possible to process a variety of plant raw materials of different fractional composition. Pre-heating of the raw materials is carried out at a temperature of 35…50°C with weak air circulation (0.3…0.6 m/s) to prepare the surface tissues of the raw materials for further technological processes. Preliminary thermal stabilization operations take place in the range of 60…70°C. Partial dehydration of the raw materials takes place at a temperature of 45…65°C and an air flow velocity of 0.5…2.0 m/s under conditions of partial recirculation within 30…45% of the total volume of circulating air to intensify the process.

The FEhRT is powered in the field by available energy sources and generators. Partial use of solar energy is also provided to support automation for 6…12 hours, recirculation of air flows and remote monitoring of technological processes. This is achieved by winding photovoltaic panel 21 (with a power of 200…600 W), a charge controller 22 (12/24 V), battery 23, and inverter 24 onto mobile auto platform 1, thereby facilitating the use of the device in the field when processing plant raw materials. The Wi-Fi module facilitates remote monitoring of technological parameters by controlling the temperature in the working environments and on the surface of the mixing devices and their rotation speed, the modes of raw material dehydration, and the state of the solar station.

Pre-processed plant raw materials after unloading from cassette stations are sent for preliminary storage in gastro-capacities, and condensed polycomponent semi-finished products and extracts after unloading from roller vats are stored in hermetic food containers. The cassette station, when loading 12 functional pallets in each section and placing 1.5…2.5 kg of raw materials on each pallet with a layer thickness of 10…40 mm, makes it possible to process 36…60 kg in one cycle, taking into account the fractionality of the raw materials.

Therefore, the total productivity of the improved apparatus, taking into account the joint operation of the capacitive and cassette stations, is 70…120 kg, and with the duration of the technological cycle of preliminary heat treatment (30…60 min), the total productivity corresponds to 50…90 kg/h. The improved mobile device does not provide for the simultaneous implementation of the aforementioned previous thermal operations, but it contributes to the rational use of two capacitive and cassette stations for the combined processing of plant raw materials.

5. 2. Determining the structural-technological efficiency of the proposed solutions

When processing plant raw materials of various fractions and consistencies, resource-saving implementation of auxiliary heat and mass exchange operations is important, including warming up, thermal stabilization, partial dehydration, extraction and preliminary thickening of single- and multi-component systems before implementing the basic technological processes of concentration and drying in the production of semi-finished products of a high degree of readiness.

To test the capacitive section of the improved apparatus, practical studies were carried out to determine the course of the kinetics of heating of a fruit and vegetable multi-component semi-finished product. The heating of the experimental mass occurred from an initial temperature of 20°C and a heat exchange surface temperature of 60…65°C using a frame-blade mixer with a heated FEhRT surface. The heating process was compared with the MZ-2S-316 boiler (Fig. 2).

Analysis of the resulting kinetics of heating the experimental puree mass in comparative devices makes it possible to conclude that the improved device helps reduce the duration of reaching the operating mode of 55°C and reaches it in 240 s, while the prototype requires 360 s.

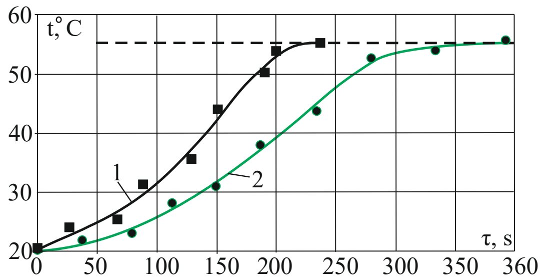

Fig. 2. Experimental and practical data on the kinetics of heating of fruit and vegetable multicomponent semi-finished products: 1 — improved sectional cassette-capacitive apparatus; 2 — MZ-2S-316 cooker (prototype)

Further testing of the improved device using a cassette station was carried out under conditions of partial drying of apple slices. Pre-cut apples with a thickness of 5...8 mm were laid out on the surface of functional mesh pallets with subsequent loading into the working space. The drying temperature was within 50...60°C with compliance with the air flow speed of 0.8...1.6 m/s and partial recirculation of secondary air at the level of 40...50%. The research results were compared with practical data on the use of a cabinet-type convective drying device, which acted as a prototype (Sh-2, country of manufacture – Ukraine). The duration of drying apple slices to a content of 30...35% DM in the prototype is 70...85 min, while in the improved apparatus it is 45...55 min (Fig. 3).

The reduction in the duration of the technological course of the drying process is explained by the combination of the use of FEhRT in conjunction with the geometry of the working chamber with a uniform spherical temperature distribution and recirculation of secondary air in the working space. The technical and technological parameters of the improved sectional cassette-capacitor apparatus in comparison with conventional designs are given in Table 2.

According to our data (Table 2), there is a 1.5-fold increase in the usable heat exchange surface of the capacitive section due to the use of a stirring device that is heated from 0.98 m^2 to 1.47 m^2. The indicator of the specific metal capacity of the structure decreases by 14.6% (387 to 330 kg/m^2), contributing to the formation of a decrease in thermal inertia. The total heat consumption when heating 75 kg of the experimental polycomponent mass is reduced by 47.0%, namely from 21353 kJ to 11309 kJ, with a simultaneous reduction in the duration of reaching the stationary temperature regime (55°C) by 32.4%. When implementing a partial dehydration process, the duration is reduced by 37.5% compared to conventional designs.

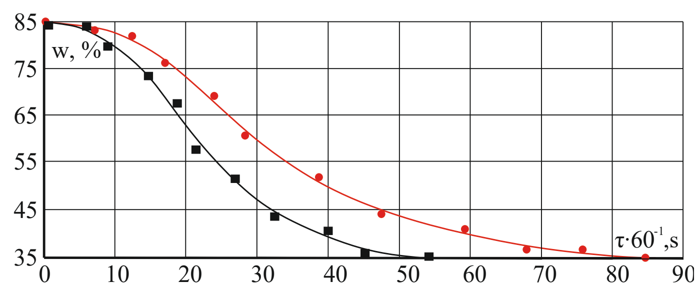

Fig. 3. Results of experimental and comparative progress of the process of preliminary heat treatment using drying apple slices as an example: ■ — improved apparatus; ● — convective drying apparatus of the cabinet type

Table 2

Technical and technological parameters of an improved sectional cassette-capacitive apparatus for preliminary heat treatment of plant raw materials in comparison with conventional designs

Technical indicator	Improved sectional cassette-capacitor apparatus	Boiler MZ-2C-316	Cabinet-type convection dryer
1	2	3	4
Structural solution	2 roller vats and 2 cassette stations	steam jacketed boiler capacity	convection dryer chamber
Working space: – volume of the capacitive section	$V = 25 + 50 = 75$ l	$V = 250$ l	–
– number of functional pallets	2 * 12 = 24 pcs.	–	12 pcs.
Single load: – capacitive section	$G = 45...75$ kg	to 240 kg	–
– cassette section	$G = 24·(1.5...2.5) = 36...60$ kg	–	40...60 kg
Total single load	$G_{\Sigma} = 80...120$ kg	to 240 kg	40...60 kg
Type of heat supply	FEhRT of walls, bottom, mixing device with heating surface, recirculation	Steam/water jacket	Convective heating
Usable heating surface of the pans	$F_{vessel} = 1,15$ m^2	$F = 0.98$ m^2	–
Usable heating surface of the mixers	$F_{mixer} = 0.28...0.36$ m^2	–	–
Total heating surface of the capacity section	$F = F_{vessel} + F_{mixer} =$ $= 1.15 + 0.28...0.36 = 1.43...1.51$ m^2	$F = 0.98$ m^2	–
Average calculated value of the surface	1.47 m^2	0.98 m^2	–
Technical mass of the structure	$M = 470...520$ kg	$M = 380$ kg	$M = 600...650$ kg
Specific metal capacity of the capacitive part	$M = M/F = 485/1.47 = 330$ kg/m^2	$m = M/F = 380/0.98 = =$ 387 kg/m^2	–
Operating temperature range	30...85°C	55...145°C	45...90°C
Pre-condensation temperature	65...75°C	90...100°C	–

Continuation of Table 2

1	2	3	4
Partial dehydration temperature	45...65°C	–	55...85°C
Agitator rotation speed	10...60 rpm	20...60 rpm	–
Secondary air recirculation rate	30...45%	–	0...20%
Air flow rate	0.5...2.0 m/s	–	0.8...1.5 m/s
Temperature unevenness (Δt)	±4...7 °C	±8...14 °C	±10...15 °C
Duration of entering stationary gentle mode (55°C)	240...300 s	340...370 s	–
Duration of drying apple slices to 30...35% DM	45...55 min	–	70...85 min
Heat of heating the test sample	$Q_{sample} = m \cdot c \cdot (t_k - t_{initial}) =$ $= 75 \cdot 3.7 \cdot (55 - 20) = 9\,713$ kJ	$Q_{sample} = m \cdot c \cdot (t_k - t_{initial}) =$ $= 75 \cdot 3.7 \cdot (55 - 20) = 9\,713$ kJ	–
Heat of heating the apparatus*	$Q_{apparatus} = m_1 \cdot c_c(t_2 - t_1) =$ $= 95 \cdot 0.48 \cdot (55 - 20) = 1\,596$ kJ	$Q^*_{apparatus} = m_1 \cdot c_c \cdot (t_2 - t_1) +$ $+ m_2 \cdot c_c (t_3 - t_1) =$ $= 200 \cdot 0.48 \cdot (55 - 20) +$ $+ 138 \cdot 0.48 \cdot (145 - 20) =$ $= 11640$ kJ	–
Total heat consumption*	$Q_{total} = 9713 + 1596 = 11309$ kJ	$Q_{total} = 9713 + 11640 =$ $= 21353$ kJ	–
Specific heat consumption*	$q = 11309 / 75 = 151$ kJ /kg	$q = 21353 / 75 = 285$ kJ /kg	–
Photovoltaic panel	200...600 W	–	–
Battery support for auxiliary systems of the device	6...12 hours	–	–
Practical performance	50...90 kg/h	80...120 kg/h	40...70 kg/h

Note: Theoretical and practical calculations were carried out at a loading weight of the devices of 75 kg and heat treatment within 20...55°C. During the research on fruit and vegetable polycomponent semi-finished products, the average value of heat capacity was assumed: c = 3.7 kJ/(kg·K). For the MZ-2S-316 boiler [24], the heat consumption for heating the steam jacket with an intermediate heat carrier (145°C) was taken into account.

6. Discussion of results related to the efficiency of the improved apparatus

The rationalization of engineering and technological solutions for combining on a mobile auto platform of capacitive and cassette stations forms a general resource-saving complex for the preliminary preparation of raw materials for the subsequent manufacture of semi-finished products of a high degree of readiness. Ensuring the repeatability of the FEhRT geometry of the working heat exchange surfaces of the capacitive and cassette station forms a rational heat supply without the use of intermediate heat carriers and pipeline networks and generating devices, reducing the material and energy intensity of the production cycle. Work [17] also reflects the effectiveness of the implementation of modern engineering solutions in the improvement of mobile devices for the rationalization of heat treatment, which contributes to the preservation of physiologically functional ingredients.

Experimental and practical testing of the improved apparatus on an example taking into account the engineering solution for combining capacitive and cassette stations on the platform was carried out separately for each station and during the implementation of various preliminary operations. Testing of the capacitive section of the improved apparatus (Fig. 1, *b*) was carried out on the example of determining the course of the kinetics of heating of a fruit and vegetable polycomponent semi-finished product. Heating of the puree-like mass from 20°C at a temperature of the heat exchange surface within – 60...65°C and mixing of the mass with a frame-blade mixer with a heated FEhRT surface (Table 1).

Additional use of FEhRT in the internal space of the mixing device increased the usable heat exchange surface of the capacitive section by 1.47 m^2 (Table 2). The improved device helps reduce the duration of entering the operating mode of 55°C and reaches it in 240 s, while the prototype requires 360 s (Fig. 2). The testing of the cassette station (Fig. 1, *c*) was implemented on the intermediate technological operation of drying apple slices for 45...55 min in the temperature range of 50...60°C. In this case, the air flow speed was within 0.8...1.6 m/s with secondary air recirculation within 40...50%. In turn, similar processing of apple slices using a convective dryer (prototype) required 70...85 min (Fig. 3) and, therefore, engineering solutions in improving the device contribute to reducing the technological cycle by 37.5%. This is explained by the creation of engineering conditions for intensification of heat exchange through the use of FEhRT and the cylindrical geometry of cassette chambers, which contributes to the uniform distribution of heat flow and the recovery of secondary air media.

According to our data, the comparison of the technical and technological parameters of the improved sectional cassette-capacitor apparatus for preliminary heat treatment of plant raw materials with conventional designs (Table 2) confirms the reduction in the specific metal capacity of the apparatus from 387 kg/m^2 to 330 kg/m^2. At the same time, with the same mass of heating of the puree-like polycomponent mass (75 kg), the total heat consumption decreases from 21353 kJ to 11309 kJ. According to the comparative data, the complexity of using classical evaporators is confirmed, including MZ-2S-316, primarily due to the presence of intermediate heat carriers, which affects the inertia of the cycle as a whole [7]. For example, in [25], studies of a vacuum evaporator using an improved mixer with a surface heated by an intermediate heat carrier are reported; however, this also leads to complications in hardware and technological use.

Additional use of Peltier elements, autonomous superchargers, and photovoltaic panels contributes to the functioning of auxiliary systems of the improved mobile device under autonomous mode under field conditions, increasing the resource efficiency of the technological cycle. In turn, along with engineering and technological advantages, the improved device requires the use of auxiliary technological equipment. In particular, for the implementation of preliminary operations for grinding and rubbing plant raw materials before entering the capacity station, thereby reducing the autonomy of the mobile complex. However, one of the solutions to eliminate this drawback is to mount a universal drive with replaceable working bodies on the auto platform for grinding and rubbing raw materials, in accordance with technological needs.

Improvement of the sectional cassette-capacitive apparatus for preliminary heat treatment of plant raw materials generally contributes to resource-saving processing at places of cultivation with preservation of functional properties.

Among the limitations of the study, it should be noted that the apparatus was tested only on fruit and vegetable raw materials under low-temperature processing conditions. At the same time, no investigations were carried out under high-temperature regimes typical of high-performance industrial production. However, this is reasonably explained by the concept of an improved apparatus for gentle thermal treatment of plant raw materials and mobile resource-saving.

The shortcomings of our study include the lack of full-fledged practical testing of the improved apparatus with the simultaneous implementation of several preliminary technological operations, which necessitates further research. Further studies should be aimed at rationalizing the technological processes of preliminary heat treatment of raw materials in the form of generalized recommendations for the use of improved equipment and mathematical modeling of heat transfer in capacitive and cassette stations.

7. Conclusions

1. We have substantiated the design and technological solutions for improving the mobile sectional cassette-capacitive apparatus for preliminary heat treatment of plant raw materials by combining a capacitive and cassette station on a mobile vehicle platform. The use of a radiant film electric heater as a heater contributed to the formation of local heating of the working surfaces of capacitive and cassette stations with the simultaneous use of mixing devices, the surface of which is additionally heated. Such steps led to an increase in the usable heat exchange surface of the capacitive station from 0.98 m^2 to 1.47 m^2 and a decrease in the specific metal content of the apparatus from 387 kg/m^2 to 330 kg/m^2.

2. The structural and technological efficiency of the improved apparatus was established during preliminary operations of heating the fruit and vegetable polycomponent semi-finished product and partial dehydration, namely drying apple slices. The reduction in the duration of entering the operating mode (55°C) for 240 s was established, while for the prototype it was necessary to spend 360 s. The duration of preliminary operation for drying apple slices to a content of 30…35% dry matter in the prototype was 70…85 min, and in the improved apparatus – 45…55 min. Drying took place in a gentle temperature range – 50…60°C, air flow speed – 0.8…1.6 m/s, and partial recirculation of secondary warm air within – 40…50%. Based on the results of a comparative analysis of the technical and engineering parameters of the improved device with classical prototypes, a decrease in the specific metal capacity from 387 kg/m^2 to 330 kg/m^2, as well as a decrease in the total heat consumption for heating 75 kg of the experimental multicomponent mass from 21,353 kJ to 11,309 kJ, were determined.

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 and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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 the full control of the authors.

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

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

Andrii Zahorulko: Conceptualization; **Iryna Voronenko**: Data Curation, **Iryna Bozhydai**: Investigation, **Hennadii Tesliuk**: Validation; **Olesya Lebedenko**: Visualization; **Ruslan Zakharchenko**: Methodology; **Oleksandr Kletskov**: Visualization; **Eldar Ibaiev**: Formal analysis.

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