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IMPROVED VACUUM EVAPORATOR FOR CONCENTRATING FRUIT AND BERRY RAW MATERIALS

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This study considers the process of heat and mass transfer during the boiling of fruit and berry pastes in a vacuum evaporator with a mixer that has heating blades. The vacuum evaporator has been improved by modernizing the heat supply system with a flexible film-like electric heater of the radiant type. The heating element is evenly placed on the outer surface of the working container; the unified mixer has its own heating surface with an area of 0.7 m^2. This solution not only provides a stable thermal field throughout the volume of the apparatus but also reduces the time for the system to enter the operating mode. In addition, this solution makes it possible to reduce the inertia of the heating process, improve resource efficiency, and avoid local overheating of the product, which is especially important when boiling thermolabile fruit and berry masses.

The process of boiling a semi-finished product from apples, jujubes, and blueberries was tested. It was found that at a temperature of 25°C, a paste with a mass fraction of dry matter of 30% has a dynamic viscosity coefficient of 428 Pa·s, which is 1.5 times higher than that of a puree with 15% dry matter (290 Pa·s). It was determined that under boiling conditions at temperatures of 52…55°C and a residual pressure of 13…16 kPa, the effective viscosity of a product with a dry matter content of 15 to 30% is within 12…28 Pa·s (shear rate of 1 s^{-1}). The transient characteristic during heating in the improved apparatus is 30% less than that in the basic one. The metal consumption indicators of the improved structure are reduced by 45%, and the boiling time of fruit and berry puree (from 15% to 30% dry matter) is reduced by 16%, which is explained by the increase in the heating surface to a value of 4.4 m^2. The specific heat consumption for heating the system decreased from 134.5 to 119 kJ/kg, which confirms the positive effect of the structural solution proposed in this work

Keywords: vacuum evaporator, film electric heater, concentration, fruit and berry paste, mixer with heating blades

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1. Introduction

Concentrated semi-finished products from natural organic raw materials occupy a significant niche in the food industry due to their wide application possibilities and the growing demand for natural food products. Such demand is formed under the influence of deteriorating environmental situation in many countries over the past decades and the orientation of consumers towards products that combine high quality and affordability [1]. This actualizes the search for advanced engineering and technological solutions aimed at intensifying the processes of concentrating organic raw materials and improving the equipment for their implementation.

The basic resource for the production of concentrated semi-finished products is plant raw materials, which quickly undergo physicochemical changes after harvesting. This requires processing them directly at sites of growth, which makes it possible to reduce the loss of initial properties, preserve nutritional value, and decrease transportation costs [2].

Continuous improvement of concentration technologies makes it possible to reduce the duration of heat treatment, minimize the degradation of biologically active substances, and ensure resource conservation. The use of advanced heat and mass exchange resource-saving equipment contributes to better preservation of the natural properties of raw materials and increases the competitiveness of the resulting products [3]. At the same time, the structural and technological implementation of the boiling process has a significant impact on the final quality of pasty semi-finished products of high readiness. Conventional vacuum evaporation plants are often characterized by increased metal consumption, complex connections, as well as high energy consumption, which does not always ensure stable quality of the finished product.

In view of the above, devising innovative structural and technological solutions for improving concentration processes is a relevant area of research. A promising direction is to retrofit vacuum evaporation devices by increasing the effective heat exchange surface and changing the principle of heating the working chamber. Such approaches make it possible to ensure the stability of the thermal regime, increase resource efficiency, and obtain competitive concentrated semi-finished products of natural origin with high biological value.

2. Literature review and problem statement

In [4], the expansion of the market for high-quality plant products of natural origin, which have a high content of biologically active substances and attractive sensory characteristics, was studied. The issue of preserving biologically active components during concentration remained unresolved since conventional steam jackets create an uneven thermal effect. This is due to the inertia of the heat carrier and the lack of flexible control over heat flows. One solution was proposed in [5], which substantiated the use of flexible film-like electric heaters in multifunctional devices for processing organic raw materials. In [6], attention focused on the growth of demand for functional products and the formation of trust in their quality. At the same time, the issue of stabilizing the temperature regime during concentration remained unresolved. This is due to local overheating in conventional steam systems. A similar problem was considered in [7], in which it was established that the efficiency of concentrating fruit and berry purees depends on the uniformity of the temperature field in the rotary film evaporator. Both sources emphasize the feasibility of introducing radiant-type electric heaters with controlled heat supply within 45...75°C.

In [8], the prospects for using fruit processing by-products as functional ingredients were investigated. The issue of preserving thermolabile compounds during prolonged heating of viscous masses remained unresolved. The reason is burning during static heating. This is due to insufficient mixing in conventional evaporators.

In study [9], it was confirmed that during the production of pasty functional semi-finished products, the most effective is the operation of a mixer with heating blades, which prevent local overheating. In work [10], heat and mass exchange processes on outdated equipment with high energy consumption were considered. The issue of resource-saving structures was ignored. The reason is the excessive metal consumption of the devices and the complexity of connections. Similar results are reported in [11], in which a tempering machine for confectionery masses was improved by reducing heat loss and stabilizing the temperature field. The solution is to introduce low-inertia electric heaters that reduce specific energy consumption to 20...25%.

In work [12], the positive effect of concentrated berry products on the human immune status was studied. The issue of preserving aromatic substances during evaporation remained unresolved. The reason is the uncontrolled loss of volatile components during secondary steam removal. This is due to the lack of selective condensation systems. In [13], the effect of heat treatment on the sensory characteristics of food products, in particular color, aroma, and taste, which determine their naturalness and quality, was investigated. At the same time, the issue of preserving these properties during the concentration of dense organic masses due to local overheating and exceeding the optimal temperature remains unresolved. This is due to the lack of a stable thermal field in vacuum evaporators with steam jackets, where an uneven distribution of energy is observed.

In [14], consumer factors in the choice of functional food products were investigated and the importance of temperature control for preserving the taste, color, and aroma of fruit and berry raw materials was emphasized. However, under industrial conditions, the issue of sensory profile stability remains unresolved because of the lack of adaptive temperature control that takes into account the thermal inertia of dense media. This is due to the use of conventional steam systems with uneven heat supply. In [15], it was confirmed that pre-concentration of fruit and berry pastes using uniform heating makes it possible to preserve the natural color and aromatic profile of finished products.

In [16], selective energy supply during the evaporation of food solutions is described, which allowed the authors to design a low-temperature structure of the evaporator. The problem of the complexity of servicing electromagnetic generators remains unresolved. The reason is the complex control system. This is due to the need to involve qualified personnel.

In [17], the rheological properties of fruit purees at different temperatures, pH levels, and concentrations of dry substances were investigated; the dependence of viscosity on heating conditions was determined. The issue of integrating these parameters into the design calculations of evaporators remains unresolved, because of the lack of adaptive systems for mixing dense masses. This is due to the fixed speeds of the mixers in conventional devices.

In [18], the dynamics of heat transfer during the boiling of plant raw materials and the influence of the layer thickness on the concentration rate are studied. However, the issue of uniform heat supply in viscous media due to the formation of temperature gradients remains unresolved. This is due to the use of rigid metal heating elements that do not provide stable contact with the product. In [19], the intensification of heat and mass transfer processes in low-temperature raw material processing technologies by combining different heat sources was investigated. However, the issue of energy synchronization of such systems remains unresolved because of the complexity of their coordination. This is due to the lack of modular control in conventional evaporators.

In [20], a technique for low-temperature concentration of apple juice by freezing was devised. However, the issue of thermal stabilization during conventional evaporation remains unresolved. The reason is the lack of precise control over the temperature field. This is due to the low sensitivity of temperature sensors in standard models. In [21], the issue of closed concentration systems with a liquid drying layer is discussed, which reduce the duration of the process. However, the issue of modernization of existing evaporators remains unresolved. The reason is the complexity of integrating such systems into industrial lines. This is due to their high cost.

In [22] it was proven that the introduction of a recovery unit into a standard evaporator allows the use of secondary heat without significant structural changes. In [23] the feasibility of using concentrated fruit and berry pastes in food product formulations was investigated. The issue of the stability of the quality of semi-finished products during scaling remained unresolved. The reason is the technological limitations of the equipment. This is due to the difficulties of maintaining a stable temperature and vacuum regime. In [24] a solution is reported – combined heating of the housing and mixer using film heaters, which ensures product homogeneity.

Summarizing results from the related literature and our own research, it was found that the main problems of modern vacuum evaporators are uneven heat transfer, increased energy consumption and metal consumption of structures. In addition, significant losses of volatile and biologically active components and the difficulty of maintaining a stable temperature field during the boiling of dense organic masses significantly reduce the efficiency of such devices. Thus, in [25] it is noted that the uniformity of heat treatment to obtain functional additives and their rational selection directly affect the formation of the structure and texture of finished food products. Such results confirm the importance of controlled heat transfer and stabilization of the thermal regime.

Thus, our review of scientific advancements reveals that existing research mostly focuses on individual aspects of the concentration process – resource saving, heat transfer, recovery or selective energy supply. At the same time, there are no integrated solutions that combine temperature zoning, film IR heaters, Peltier elements, PLC control, and air recirculation in one device. The main reason is the difficulty of combining these systems in a compact housing with precise parameter control and uniform heat supply of dense masses.

3. The study materials and methods

The aim of our work is to improve the vacuum evaporation apparatus for concentrating organic fruit and berry raw materials into paste-like semi-finished products of high degree of readiness. This will make it possible to enable resource-efficient low-temperature processing of organic raw materials with preservation of biologically active components and improvement of the quality of the semi-finished product.

To achieve the set goal, the following tasks were set:

– to improve the heat supply system of the model of the vacuum evaporation apparatus with a unified mixer equipped with heating blades;

– to carry out an experimental test of the efficiency of the proposed model design of the vacuum evaporation apparatus, determining its technical indicators and level of competitiveness.

4. The study materials and methods

The object of our study is the process of heat and mass transfer during the boiling of fruit and berry pastes in a vacuum evaporator with a mixer equipped with heating blades.

The hypothesis of the study assumes that equipping the vacuum evaporator with a unified mixer with heating blades could enable an increase in the active heat exchange surface and the elimination of stagnant zones. Accordingly, it would involve an intensification of the evaporation process without overheating and thermal destruction of the product. The proposed structural solutions will help reduce the duration of boiling, increase resource efficiency of the process, and improve the quality of the final concentrate.

The implementation of the proposed heat supply system of a vacuum evaporator with a unified mixer equipped with heating blades could reduce specific heat consumption and enable uniform heat treatment of the product without burning.

Experimental and practical studies were conducted at a laboratory of the State Biotechnological University (Ukraine). Under laboratory conditions, a model installation of a vacuum evaporator with a working chamber capacity of 0.05 m^3 was fabricated, equipped with a unified mixer with heating blades. Control over the technological parameters of the apparatus was executed by using an automated system of the company "OWEN" (Kharkiv, Ukraine), which measures, registers, and stabilizes temperature, pressure, and process duration. The obtained data were processed using standard methodologies from mathematical statistics, taking into account measurement errors.

We determined the structural and mechanical characteristics of the experimental samples of fruit and berry semi-finished products on a rotational viscometer "Rheotest-2". The viscometer assesses the change in the effective viscosity of the puree mass depending on the temperature and shear rate, as well as establishes the nature of the rheological behavior.

The testing of the improved structure of the vacuum evaporation apparatus was carried out on a blended puree made according to the devised recipe of apple, jujube, and blueberry, borrowed from work [9].

5. Results of determining the effectiveness of solutions in improving the vacuum evaporator

5. 1. Improving the heat supply system of the vacuum evaporator model with a unified mixer equipped with heating blades

The improved model of the vacuum evaporator (VE) for concentrating fruit and berry and vegetable raw materials into paste-like semi-finished products of a high degree of readiness is shown in Fig. 1. The design feature of the improved device is the engineering and structural rejection of the conventional steam jacket and its replacement with flexible film-like electric heaters of the radiant type (FFEhRT). The use of this heating technique will enable a uniform distribution of the temperature field over the surface of the evaporation chamber of the device and the unified mixer.

Pureed multicomponent plant-based raw materials are fed into the evaporation chamber of apparatus 1 through loading nozzle 2 and evenly distributed by unified mixer 3 which has heating blades with a built-in flexible film-like electric heater of the radiant type 4. This prevents local burning of the raw materials and helps maintain a constant viscosity of the concentrated mass of a high degree of readiness. Heating of the improved model of the vacuum evaporation apparatus is carried out by a flexible film-like electric heater of the radiant type 4 at a rated power of 11 kW, by structurally arranging it cylindrically outside the apparatus body and on the working surface of the mixer. To control the temperature range of boiling, the improved structure has built-in temperature sensors 5 to maintain the boiling temperature within 45…75 °C at a vacuum of 10…30 kPa, with an error of ±1.5 °C.

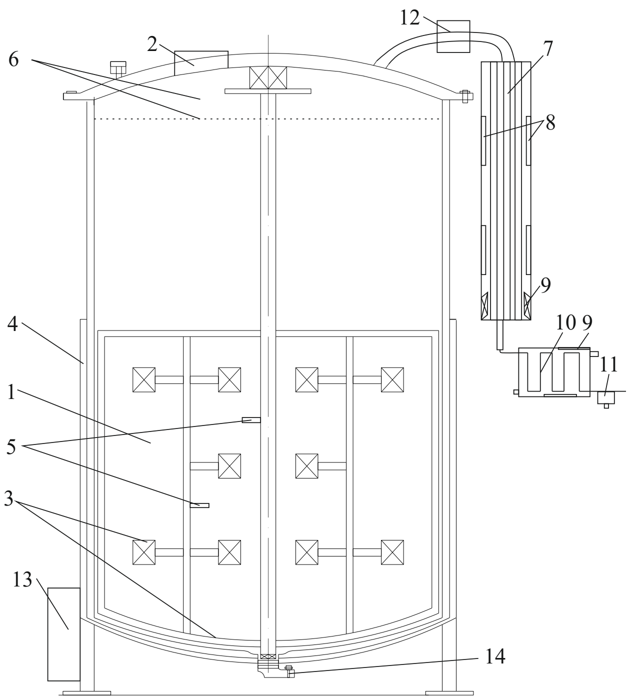

Fig. 1. Improved model of a vacuum evaporator with flexible film-like electric heaters and a heat and aromatic substances recovery system: 1 – evaporation chamber of the apparatus; 2 – loading nozzle; 3 – unified mixer, which has heating blades with a built-in flexible film-like electric heater of the radiant type; 4 – flexible film-like electric heater of the radiant type; 5 – built-in temperature sensors; 6 – separation space with a separate perforated plate; 7 – condenser collector; 8 – Peltier elements; 9 – autonomous fans; 10 – recovery unit; 11 – light compounds (aromatic substances) selection unit; 12 – stripping unit; 13 – control unit; 14 – automatic nozzle for draining the cooked polycomponent semi-finished product of high degree of readiness

To remove secondary vapors, the design of the improved apparatus has separation space 6, separated from the intensive boiling chamber by a perforated plate. Secondary vapor from separator 6 is supplied via a main line to collector condenser 7, on the side wall of which Peltier elements 8 are mounted. This structural implementation make it possible to convert the secondary heat flow into a low-voltage supply voltage for auxiliary autonomous fans 9. This ensures the autonomy of the cooling system and reduces dependence on external power supply of the technological cycle. The first autonomous fan 9 is mounted in the condenser housing, enabling intensification of heat exchange in the condenser, creating stable blowing of the cold surface for more effective condensation of vapors. Their installation in this zone is justified by the fact that the condenser is the most critical point of heat transfer, where the efficiency of the entire process and the preservation of aromatic substances depend on the cooling rate.

The exhausted warm air is directed to recovery unit 10, where the supply air or process water is heated. The technical implementation of the heat recovery unit contributes to the reuse of the energy potential of the exhaust air and boiling vapors. Through the tubular heat exchanger, heat is transferred from the hot moist flow to the cold supply air or to the intermediate heat carrier (water, glycol), which is then used for auxiliary technological purposes (preheating of raw materials, washing equipment, ventilation). Thereby, making it possible to stabilize the heat balance of the system and increase the overall resource efficiency of the concentration process.

In addition, from a structural point of view, auxiliary exhaust autonomous fans 9 are installed in the heat recovery and air exhaust units, operating at the outlet of the system. They generate a controlled flow of exhaust air, directing it through the heat exchanger for heat reuse. Installing fans at the outlet makes it possible to provide the necessary draft throughout the circuit, avoid stagnant zones, and stabilize the operation of the recuperator regardless of variable pressure conditions inside the evaporation chamber. Part of the condensate from the steam-air mixture enters the light compounds (aromatic substances) selection unit 11, which makes it possible to obtain spicy-aromatic fractions for further use in food technologies. The aromatic substances selection unit in the improved vacuum evaporator performs the function of selective extraction of volatile compounds formed during boiling of fruit and berry and vegetable raw materials. Before feeding steam to the main condenser, the secondary steam-air mixture is directed through special stripping unit 12, where, owing to the maintained vacuum and controlled temperature gradient, condensation of highly volatile aromatic components (essential oils, organic acids, aldehydes) occurs. The collected aromatic fraction can be reintegrated into the finished semi-finished product or used as a separate food ingredient with high value, which increases the quality characteristics of the product and creates an additional by-product for commercialization.

The speed of the mixer is regulated by a thyristor converter installed in control unit 13 and makes it possible to change rotation frequency in the range of 10...60 rpm depending on the viscosity of the raw material. To control the process, online sensors of the concentration of dry substances (refractometer) and product temperature are provided, which are integrated into the SCADA control system. The thermal insulation of the housing is made of basalt wool 25 mm thick with an external stainless steel casing.

Thus, the fans perform a dual function: in the upper part of the system, they increase the efficiency of condensation, and in the lower part they provide targeted removal and utilization of spent gas-vapor mixtures, integrating the device into the overall energy management of production.

The main advantages of the improved model are:

– absence of steam losses and condensate lines;

– stabilization of the temperature regime, which ensures the preservation of vitamins and aromatic substances;

– possibility of mobile operation of the apparatus in conditions of limited access to centralized steam supply;

– recovery of secondary heat and selection of volatile aromatic fractions.

Thus, the introduction of flexible film-like electric heaters into the design of the vacuum evaporator makes it possible to increase the resource efficiency of the concentration process. This, in turn, provides a qualitatively new level of control over heat flows, which is critically important for the production of pasty semi-finished products of high biological value.

5. 2. Experimental verification of the effectiveness of the device design and assessment of its competitiveness

In the process of experimental and practical studies on the improved structure of the vacuum evaporation device, the structural and mechanical characteristics of the fruit and berry semi-finished product (puree, paste) were determined. The need to determine the structural and mechanical characteristics of the product is determined by their significant impact on the heat-technical and energy performance of the equipment and its use in calculating its main structural units.

The device was tested in the process of boiling fruit and berry puree, prepared according to the recipe for making paste based on apples, jujube, and blueberries designed at DBTU. During the concentration of the blended fruit and berry puree in the improved vacuum evaporation device, gentle temperature conditions are observed when using a periodic mode with forced mixing with a unified mixer. For adequate modeling of the evaporation process, it is necessary to establish the viscosity indicators of fruit masses at temperatures of real boiling conditions in the apparatus and corresponding shear rates. We determined the structural and mechanical properties in the temperature range of 25...55°C and at the shear rate value of 1 s^{-1} (Fig. 2).

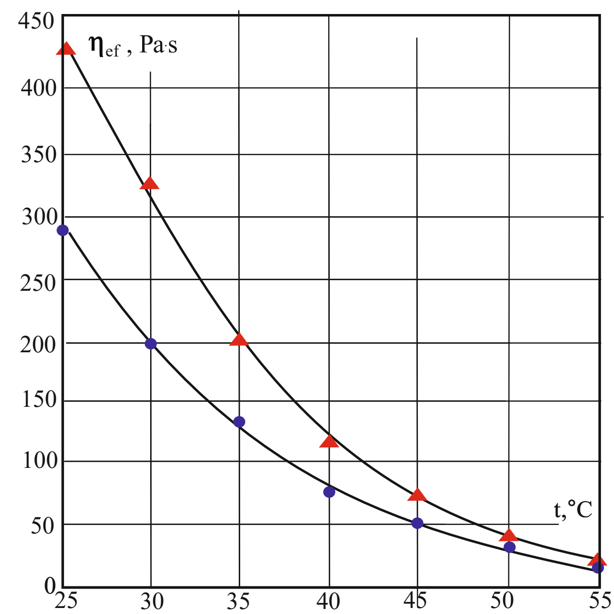

Fig. 2. Structural and mechanical indicators of fruit and berry mass depending on temperature at a shear deformation rate of 1 s^{-1}: ● – 15% dry matter; ▲ – 30% dry matter

It was found that with increasing temperature, the structural and mechanical indicators of the studied samples of puree and paste naturally decrease. At a temperature of 25°C, the paste with a mass fraction of dry matter of 30% has a viscosity of 428 Pa·s, which is 1.5 times higher than that of puree with 15% dry matter (290 Pa·s).

For a stationary evaporation regime at temperatures of 52...55°C at a residual pressure of 13...16 kPa, the effective viscosity of the product with a dry matter content of 15 to 30% is within 12...28 Pa·s (shear rate 1 s^{-1}).

To assess the efficiency of the improved structure of the vacuum evaporation apparatus with a mixer equipped with heating blades, a comparative determination of its heating was carried out relative to the base apparatus of the MZS-320 type (Fig. 3).

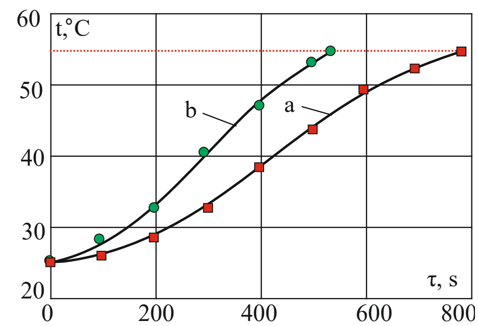

Fig. 3. Transient characteristic of heating fruit and berry puree: *a* – basic apparatus; *b* – improved apparatus

Our results showed a reduction in the duration of the temperature regime of boiling at the level of 550 s for the model improved apparatus in contrast to the basic apparatus, 790 s. The established reduction in the duration of heating of the modernized design at the level of 30% indicates an increase in the thermal efficiency of the structure.

The improvement in indicators is due to a decrease in the specific metal capacity of the apparatus due to the structural solution of excluding the steam-water jacket and shut-off valves, as well as the use of a unified mixer with a film electric heater. Such conditions for conducting the evaporation process provide a more intensive and uniform distribution of the thermal field throughout the entire volume of the product.

A comparison of the characteristics of the basic evaporator (MZS-320) and the improved model structure of the vacuum evaporator with heating blades is given in Table 1. The calculations were performed without taking into account heat losses to the environment. The estimation makes it possible to objectively establish the influence of the proposed heat supply system and mixer design on the thermal performance of the equipment.

The data given in Table 1 show that the improved vacuum evaporation apparatus with an improved heating system and a unified mixer with heating blades provides a reduction in the metal consumption of the structure by 45%. In general, this solution makes it possible to reduce the total mass of the apparatus from 1700 to 1105 kg.

The heating time of the equipment during the boiling of fruit and berry puree (from 15% to 30% of dry matter) is reduced by approximately 16%. The reduction is explained by the increase in the heating surface to a value of 4.4 m^2.

The specific heat consumption for heating the apparatus decreased from 134.5 to 119 kJ/kg in the basic and improved ones, respectively. This effect occurs due to the removal of the steam shell (outer bowl) from the heat supply system. Also, the use of a flexible film-like electric heater of the radiant type improves the stability of the temperature regime, preventing the burning of concentrated masses and increasing the quality of the final product. The results of the technical assessment of the modernized structure are given in Table 2.

Table 1

Comparing the operational and technological characteristics of the basic and improved vacuum evaporator

Indicator	Basic apparatus	Improved apparatus
Heating surface area, m^2	$F = 3.7\ m^2$	$F_m = F + F_{\text{mixers}} = 3.7 + 0.7 = 4.4\ mm^2$
Total mass of the device, kg	$m = 1700$ kg	$m_m = m - m_{ob} + m_h = 1700–620 + 25 = 1105$ kg
Specific metal content, kg/m^2	$M = m / F = 1700 / 3.7 = 459.5$ kg/m^2	$M = m_m / F = 1105 / 4.4 = 251$ kg/m^2
Boil time, s	$T = Q_b / F \cdot k \cdot \Delta t = 2097362 / 3.7 \cdot 1454 \cdot 88 = 4430$ s	$T = Q_b / F \cdot k \cdot \Delta t = 2\,715\,279.45 /4.4 \cdot 1454 \cdot 88 = 3725$ s
Heat of heating the product, kJ	$Q_1 = m_{pr} \cdot c \cdot (t_k - t_i) = 1600 \cdot 3.7 \cdot (55 - 25) = 177\,600$ kJ	$Q_1 = m_{pr} \cdot c \cdot (t_k - t_i) = 1600 \cdot 3.7 \cdot (55 - 25) = 177\,600$ kJ
Heat of heating the outer bowl, kJ	$Q_2 = m_{ob} \cdot c_c \cdot (t_2 – t_1) = 620 \cdot 0.48 \cdot (143–60) = 24\,700.8$ kJ	–
Heat of heating the inner bowl, kJ	$Q_3 = m_{ib} \cdot c_c \cdot (t_k - t_i) = 900 \cdot 0.48 \cdot (55 - 25) = 12\,960$ kJ	$Q_3 = m_{ib} \cdot c_c \cdot (t_k - t_i) = 900 \cdot 0.48 \cdot (55 - 25) = 12\,960$ kJ
Specific heat consumption for heating the apparatus and product, kJ/kg	$q_s = Q_h / m = 215260.8 / 1600 = 134.5$ kJ/kg	$q_s = Q_h / m = 190560 / 1600 = 119$ kJ/kg

Note: Data on the basic device MZS-320 are taken from [26].

Table 2

Technical characteristics of the improved model of vacuum evaporator with unified stirrer

Technical characteristics	Indicator
Heating area ((including agitator with film heater), m^2	4.4
Temperature of the heating surface with agitator, °C	to 120
Volume of the working chamber for concentrating puree masses, m^3	1.0
Drive power (geared type electric motor), kW	2.0
Agitator speed, min^{-1}	30...50
Weight (including 25 mm thick basalt wool insulation and stainless steel outer casing, kg	1105

The overall result of our experimental and computational studies has confirmed the increase in the efficiency of the apparatus due to the rational organization of heat transfer and reduction of the product boiling time. The use of an improved structure of the vacuum evaporator during testing in production for the manufacture of fruit and berry concentrates will increase the resource efficiency of the process, may contribute to improving the quality of the finished product, as well as reduce its cost.

6. Results of improving the vacuum evaporator with a mixer that has heating blades: discussion

One of the main problems of conventional vacuum evaporators is their limited mobility and the difficulty of using them directly at the places of raw material procurement. This situation is associated with the need to use intermediate heat carriers, which increase the energy and metal consumption of the structure, complicate the regulation of temperature parameters, and reduce the stability of the thermal regime. The result is a deterioration in the quality of finished vegetable paste-like semi-finished products because of local overheating or uneven heating of the product. To eliminate these shortcomings, experimental and computational studies were conducted aimed at improving the process of boiling vegetable puree-like raw materials by modernizing the heat supply and mixing system. The main idea was to use a mixer with internal heating, namely, the internal hollow space of the shaft of which the heat carrier is supplied [27]. This solution allows for a more uniform distribution of thermal energy across the product volume and reduces the duration of the concentration process.

However, the use of conventional steam or liquid heating systems remains impractical because of their high mass, complexity of maintenance, and uneven heat transfer. Therefore, this work proposes eliminating intermediate heat carriers and switching to an electrical technique of heat supply based on surface flat resistive elements of a new type, which are built directly into the mixer blades.

The basis of the innovation is the replacement of the conventional steam jacket with flexible film-like electric heaters of the radiant type to enable uniform and controlled heat supply. The structure includes a unified mixer with heating blades, which stabilizes the concentration process and prevents the burning of thick masses. Heat recovery from spent steam-air mixtures and the selection of aromatic substances are also provided, which contributes to the preservation of the nutritional and organoleptic value of the finished product.

Retrofitting the basic design of the MZS-320 apparatus makes it possible to increase the useful heat exchange surface by 0.7 m^2 due to additional heating of the mixing elements. This ensured a reduction in the heating duration to 550 s, compared to the conventional apparatus, 790 s, which led to a decrease in the thermal load on the product. The secondary heat utilization system was also improved, which increases the energy efficiency of the concentration process. Owing to the Peltier elements mounted on the condenser-collector, part of the thermal energy of the secondary steam is converted into low-voltage electricity, which is used to power autonomous fans (Fig. 1). Such implementation creates a closed energy system that does not require an external power source and provides cooling autonomy.

The operating parameters are controlled using a thyristor converter, which makes it possible to adjust the speed of the mixer in the range of 10...60 rpm depending on the viscosity of the product. To increase the accuracy of control, the system has online sensors for the concentration of dry substances and temperature, connected to the SCADA control system, which provides automatic monitoring, parameter fixation, and prompt adjustment of operating modes. Thermal insulation of the body made of basalt wool 25 mm thick with an external stainless casing minimizes heat losses and supports resource-saving design.

Our results confirm the technological efficiency and advantages of the improved vacuum evaporator. In particular, it was possible to eliminate losses through steam and condensate pipes, stabilize the temperature regime, ensure the autonomy of the cooling system, implement secondary heat recovery, and improve the controllability of heat flows, as well as the overall energy balance.

It was established that under boiling conditions at temperatures of 52...55°C at a residual pressure of 13...16 kPa, the effective viscosity of the product with a dry matter content of 15 to 30% has the limits of 12...28 Pa·s (shear rate 1 s^{-1}) (Fig. 2). Analysis of the transient characteristics during heating of the product revealed that the use of an apparatus with heating blades reduces the duration of thermal exposure to the product by 30% compared to the basic version (Fig. 3). In addition, a decrease in the specific heat energy consumption by 11.5% and an increase in the total heat exchange area by 19% was observed, which indicates an increase in resource efficiency of the process (Table 1).

The improvements made to the design of the vacuum evaporator equipped with a unified mixer with heating blades provide a comprehensive technological advantage: reducing boiling time, preserving biologically active substances, reducing energy consumption, and increasing the stability of the thermal regime.

The implementation of the proposed structure at processing complexes equipped directly at the places of raw material collection is especially relevant in regions with seasonal availability of fruit and berry products. The improved apparatus will make it possible to produce plant-based pastes with a reduced time of thermal impact on the product, which will contribute to the preservation of physiologically functional components. Such pastes are in demand for the production of healthy confectionery products, in particular pastille and marmalade [28].

The recommended operating temperature range of the apparatus is 40...65°C, which provides an optimal combination of resource saving and preservation of quality indicators of concentrated semi-finished products. Failure to comply with the recommended modes may lead to excess temperature load, destruction of the structure of the raw material, and a decrease in its nutritional value, which could negatively affect the competitiveness of the processing complex and finished products. Further research will aim to determine the preservation of color, aroma, and chemical composition of fruit and berry pastes when manufactured in an improved vacuum evaporation apparatus.

7. Conclusions

1. An improved heat supply system for a vacuum evaporator equipped with a unified mixer has been proposed. Instead of conventional techniques for heating the steam-water shell, a flexible film-like electric heater of the radiant type is introduced. The heater is evenly located on the outer surface of the working container. The device also uses a unified mixer with heating blades with built-in electric heating elements, the total area of the heating surface of which is 0.7 m^2. This solution not only provides a stable thermal field throughout the volume of the device but reduces the time for the system to enter the operating mode. In addition, this solution makes it possible to reduce the inertia of the heating process, increase resource efficiency, and avoid local overheating of the product, which is especially important when boiling thermolabile fruit and berry masses.

2. The process of boiling a semi-finished product from apples, jujube, and blueberries was tested in the improved apparatus. It was found that the structural changes of the product naturally decrease with increasing temperature. At a temperature of 25°C, a paste with a mass fraction of dry matter of 30% has a dynamic viscosity coefficient of 428 Pa·s, which is 1.5 times higher than that of a puree with 15% dry matter (290 Pa·s). It was determined that for the evaporation mode under boiling conditions at temperatures of 52...55°C with a residual pressure of 13...16 kPa, the effective viscosity of the product with a dry matter content of 15 to 30% has the limits of 12...28 Pa·s (shear rate of 1 s^{-1}). The transient characteristic during heating in the improved apparatus, compared to basic MZS-320, when brought to the boiling temperature, has a heating duration shorter by 30%. The metal consumption of the improved structure has been reduced by 45%. The duration of boiling fruit and berry puree (from 15% to 30% of dry matter) was reduced by approximately 16%, which is explained by the increase in the heating surface to a value of 4.4 m^2. The specific heat consumption for heating the system decreased from 134.5 to 119 kJ/kg, which confirms the positive effect of the structural solution proposed in our work.

Conflicts of interest

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

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Data availability

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

Use of artificial intelligence

The authors 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 generate, process, or interpret scientific data, form conclusions or other elements related to the scientific results of this paper.

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

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

Author`s contribution

Oleksiy Zagorulko: conceptualization, methodology, design of the experimental setup, analysis of results; **Valeriy Mykhaylov**: scientific supervision, statement of the research hypothesis, review and editing of the manuscript; **Andriy Pak**: design of the structure of the mixer with heating blades, modeling of heat and mass transfer processes, preparation of graphic materials; **Oleksiy Gromov**: conducting experimental studies, data processing, participation in the preparation of conclusions; **Natalya Fedak**: selection and analysis of methods for measuring rheological characteristics, generalization of experimental results, participation in writing the "Discussion" section; **Andriy Pugach**: formulation of practical recommendations, assessment of the innovative component and competitiveness of the technological advancement, editorial revision; **Myushfik Bakirov**: participation in the technical design of the apparatus, adaptation of the structure to industrial conditions, consultations on technological efficiency; **Kyrylo Pavlyuchenko**: participation in research, statistical processing of experimental data, design of graphs and tables.

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