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DETERMINING THE HEAT AND MASS EXCHANGE EFFICIENCY OF A SCRAPER HEAT EXCHANGER FOR HEATING FOOD SEMI-FINISHED PRODUCTS

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This study's object is the process of heating fruit and berry purees made from apple, apricot, and honeysuckle.

This paper reports an improved structure of a scraper heat exchanger for heating viscous liquid food products based on fruit and berry raw materials (purees, pastes). One of the main elements of the modernization is heating with a flexible film resistive electric heater of the radiant type instead of the conventional steam system, which has made it possible to eliminate steam fittings and reduce energy consumption. Additional equipment of the heat exchanger with a hinged blade with a remote plate enables turbulization of the product flow in the heat exchange zone, contributing to the formation of a stable film flow on the heating surface, which significantly improves the efficiency of heat transfer.

The experimental and computational studies revealed the dependence of the heat transfer coefficient on raw material consumption and the frequency of rotation of the apparatus shaft. It was established that the heat transfer coefficient depends on the product flow rate and, after reaching the maximum (13...15) 10^{-3} kg/s, it decreases. The influence of rotor speed is less significant and is manifested mainly during the transition from 1.0 to 1.5 s^{-1}. Comparative analysis revealed that the use of an improved blade with a remote plate makes it possible to increase the heat transfer coefficient by 1.2 times compared to the conventional design. Calculations of specific heat consumption showed its decrease from 250 to 222 kJ/kg, which is a saving of 12.5%.

The proposed structural solutions make it possible to ensure the stability of temperature regimes, reduce energy consumption, improve the quality of heat treatment and process automation. This is especially important for the processing of heat-sensitive and dense products in the food industry

Keywords: scraper heat exchanger, film flow, heat transfer, hinged blade, energy efficiency, fruit and berry puree

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1. Introduction

There is a steady increase in the demand by people for natural products of natural origin that meet safety requirements and have functional properties. This is due to the fact that consumers are aware of the impact of nutrition on the quality of life, which has caused the rapid development of the segment of healthy and functional products, which is possible through the use of plant raw materials that are a source of biologically valuable substances of natural origin, which can provide the human body with necessary nutrients without the use of synthetic additives.

Interest in natural food products covers both children's, therapeutic and preventive and dietary nutrition, and products of everyday consumption, in particular juices, jams, purees, fruit pastes, as well as confectionery, in which plant ingredients not only increase nutritional value but also contribute to the formation of the structure, taste, aroma, and appearance of the finished product [1, 2].

From a technological point of view, plant raw materials are extremely complex, variable in composition and properties. Humidity, density, viscosity, content of dietary fiber, organic acids, polyphenols affect both the course of the technological process and the properties of the finished product. During the production of sweets and muffins, plant raw materials perform not only the function of enriching with functional ingredients but also change the structure of semi-finished products and products, affecting the consistency, moisture-binding capacity, organoleptic characteristics [3, 4].

The thermolabile properties of plant raw materials require the use of gentle processing methods that involve precise control of temperature, duration, pressure, and mechanical impact parameters. The conditions of thermal treatment of plant raw materials must enable the preservation of biologically active substances and natural structure without loss of technological functionality. At the same time, the efficiency of the technological process must be combined with resource efficiency, which determines the relevance of the introduction of innovative equipment and improved technological modes.

Special attention should be paid to the preheating of raw materials before the concentration stage – an important stage that significantly affects the quality of finished pastes and purees. Under certain conditions, outdated equipment (for example, batch heat exchangers) is still used, which is accompanied by difficulties in stabilizing heat transfer, overheating, local burning of raw materials, and losses of valuable compounds. The viscous heterogeneous structure of multicomponent plant raw materials only complicates the heat transfer process, which often leads to quality deterioration and the need for additional energy consumption [5, 6].

These problems can be solved by improving and implementing heat exchange systems that can provide a stable, controlled, uniform heating mode with minimal thermal damage to the raw materials. This approach could make it possible to obtain high-quality multicomponent plant pastes suitable for further use as universal products (pastes, purees, baby food) and semi-finished products, in particular in functional confectionery formulations. Therefore, research into the development of efficient and energy-saving technologies for processing plant raw materials, in particular the improvement of heat exchange equipment, is extremely relevant. It will contribute to making high-quality functional products with maximum preservation of biologically active substances, which meets modern requirements for healthy nutrition and technological efficiency of production in the food industry.

2. Literature review and problem statement

The expansion of the range of "healthy food products" based on plant raw materials is directly related to the use of technological operations based on resource-efficient, gentle, and functionally adapted equipment. Currently, there is a rapidly growing interest in improving heat treatment processes, in particular heating and concentration, which are key to obtaining stable multicomponent pastes of plant origin. Particular attention is paid to minimizing the thermal effect on biologically active substances, in particular polyphenols, vitamins, organic acids, and pectic substances, which determine the quality of final products. Modern approaches to the design of technological equipment are focused on creating conditions for uniform heat transfer, avoiding local overheating, and preserving the structural and functional characteristics of raw materials [7]. This makes it possible not only to reduce nutrient losses and preserve the natural structure but also to ensure the consistency and organoleptic quality of the finished product.

In work [6], the heat supply system to the heating tanks was replaced and the results prove a reduction in heat consumption for the process. However, changes in heat transfer coefficients in the presence of such structural solutions, in contrast to conventional ones, have not been fully studied.

The innovative solution considered in [5] to improve the scraper heat exchanger equipped with a reflective heating design of the mixing device is to improve the hydrodynamic flow of the product. The disadvantage is the lack of data on cleaning the reflective plate during operation from sticking and burning of particles of the processed raw material. Of particular importance during the heat treatment of plant raw materials, which is in a thin layer, is the method of its application to the heating surface and the design features of the mixing device. These structural solutions make it possible not only to prevent burning of the raw material but also promote its thorough mixing for uniform heat treatment [8].

In [9], a model of the flow pattern of a scraper heat exchanger for the production of ice cream is described. It was found that the speed of the product layer close to the surface is less than the main flow; this is explained by the difference in the viscous characteristics of the wall layers. Therefore, it is important to take into account the structure of the fluid flow, taking into account the structural and mechanical properties. The results of experimental studies reported in [10] on a heat exchanger with a cleanable surface established the dependence of the heat transfer coefficient on the speed of rotation of the scrapers, the width of the gap between the blades and walls, and the type of gaseous working fluid. However, the effect of changes in raw material consumption on the heat exchange process was not taken into account.

The positive effect of using scraper heat exchangers for non-Newtonian pseudoplastic liquids, which was demonstrated in [11], allows us to make an assumption about the prospects of developing and implementing such solutions for various branches of food production. Thus, the energy consumption for the rotation of the rotor shaft with scrapers is sufficiently repaid due to the speed of the process and its high-quality indicators. Special attention during the research of the operation of scraper heat exchangers [12] is paid to the study of the velocity profile for different areas of the flow of the processed product, its velocities, and the corresponding flow functions. However, the issues remain unresolved on the example of comparative characteristics and resource saving indicators compared to conventional heat exchangers.

The results of work [13] relate to the movement of suspensions in an isometric field with the appropriate definition of vortex flow profiles from cleaning elements; however, there are no indicators of experimental studies that would indicate the degree of uniformity of product movement.

An important point is noted in [14], in which the modeling of fluid flow hydrodynamics and heat exchange in a heat exchanger with scraper elements is considered. Namely, the influence of various forces on the edges of a rigidly mounted scraper was taken into account, with the results justified by changes in the Reynolds and Nusselt numbers. However, this model cannot be fully used for surface cleaning processes with full scraper contact.

In [15], a hydrodynamic model of raw material movement is reported, which takes into account theoretical aspects and experimental developments [16]. The model reflects the relationship between the film flow of the liquid flow, the properties of the heat-transfer surface and the structural characteristics of the raw material.

The results of scientific research [17] on the improvement of product processing technologies using thin films indicate that one of the important effective characteristics is the shape of the scraped element. Thus, in [17], various blade geometries and their influence on the performance of the scraped surface heat exchanger are considered. However, it is necessary to use more accurate methods for calculating heat flow and energy consumption. This necessitates research on determining and correlating heat transfer characteristics with the subsequent establishment of flow regime parameters. It is also important to use the conservation of latent heat energy to create an optimal configuration of the thermal system [18].

The use of scrape heat exchangers for freeze-drying processes has been shown to reduce energy consumption by a factor of seven compared to evaporation-based processes, as well as to reduce corrosion and scaling problems [19]. This effect is possible due to self-cleaning surfaces, with studies of the impact of performance under different operating conditions.

The results of paper [20] also show that improving the design of rotary blades contributes to the uniformity of the fluid flow in the channel, thereby improving the heat transfer of the structure as a whole. In the context of the development of high-tech equipment for the food industry, it is advisable to consider approaches to digital stability, risk management and adaptive information transmission systems. In particular, in [21], methods for reliable transmission of permutations in short-packet communication systems are considered, which is an example of highly reliable information architecture. This can be applied in the design of controlled electrothermal systems of heat and mass exchange equipment with autonomous temperature control in real time – as in the case of modernized heat exchangers with electric heating. Adaptation of modern technological processes requires direct process control, suspending the autonomy of the production cycle and production safety. However, when analyzing the concept of implementing innovative functional equipment for the production of products from plant raw materials, it is important to consider sustainable business models in the digital environment. Thus, in [22], IT innovation tools were investigated in the context of the REMIT model, focusing on transparency and stability in energy and production systems. This approach is relevant for thermal process control systems that provide for flexible resource regulation at small and mobile food production facilities.

Thus, it is possible to state significant advantages of heat exchangers with a cleanable surface for processing various liquid food products. The main advantages of their use are a higher degree of mixing, reduced heat treatment time, thorough cleaning of the heating surface, as well as increased heat transfer rates. The identified ways of improvement should be directed to the structural elements of scrapers made on a hinged support. It is the hinged support during processing that facilitates the possibility of the blade sliding along the heating surface, increasing the heat transfer coefficient, and facilitating surface cleaning. It is also necessary to take into account the optimal heat supply system to replace steam heating systems with electric ones with more accurate temperature stabilization. Such implementation of the heating scheme could simplify the operation of the equipment to facilitate its implementation at low-power workshops near the collection of plant raw materials. To determine the optimal structural elements of the designed hinged blade, it is necessary to conduct computational and experimental studies to determine rational operating modes by optimizing raw material consumption and blade rotation frequency. There is also a need to conduct comparative calculations of the specific heat consumption by the proposed structural solutions and conventional devices.

3. The aim and objectives of the study

The aim of our work is to determine the heat transfer efficiency of an improved scraper heat exchanger equipped with a film-type electric heater and a stirrer in the form of a hinged blade with a remote plate for the heating process of liquid food products. This will make it possible to improve the quality of heat treatment, preserve valuable raw material components, and reduce energy consumption in food production.

To achieve this aim, the following objectives were accomplished:

– to improve the design of a scraper heat exchanger with a heating system using a flexible film resistive electric heater of the radiant type and a hinged blade with a remote plate;

– to investigate the heat transfer characteristics of an improved scraper heat exchanger

4. The study materials and methods

The object of our study is the process of heating fruit and berry puree made from apple, apricot, and honeysuckle.

The hypothesis of the study assumes the possibility of increasing the efficiency of the scraper heat exchanger design by equipping it with a flexible film resistive electric heater of the radiant type and a stirring device in the form of a hinged blade with a remote plate for carrying out the process of heating liquid food products. The use of an improved structure of the scraper heat exchanger will make it possible to increase the heat transfer coefficient and reduce the specific heat consumption for heating the food product.

The model structure of the scraper heat exchanger, taking into account the use of a hinged blade with a remote plate and a flexible film resistive electric heater of the radiant type equipped with a heating system, makes it possible to investigate ways to increase heat transfer. Our work describes a model experimental design of an improved heat exchanger, the materials used, and methods for studying the heat exchange process. To test the heat exchange device, fruit and berry puree was used, made according to the recipe content of raw materials: apple 50%, apricot 35%, rosehip 15%.

The temperature of the device wall was determined as the average value from thermocouples located on the model body. The rotor rotation frequency was changed using a DC motor and measured with a tachometer.

The heat transfer coefficient between the heating wall and the product was determined using the following formula:

$$\alpha = \frac{Q}{F\Delta t}, \quad (1)$$

$$Q_p = Gc(t_k - t_i), \quad (2)$$

where c is the specific heat capacity of the product J/kg·K; G – device productivity by product, kg/s; t_i – product temperature at the inlet to the device; t_k – product temperature at the outlet from the device.

The temperature difference was calculated as the difference between the average temperature of the inner surface of the device and the heating temperature of the product.

The research results were obtained by conventional experimental and appropriate calculation methods using a set of measuring instruments manufactured by the company "OWEN" (Ukraine), as well as Mathcad software (USA).

5. Results of determining the efficiency of the improved scraper heat exchanger

5. 1. Improving the scraper heat exchanger

According to the above hypothesis, the structure of the scraper heat exchanger for the heating process of liquid food semi-finished products has been improved. Fig. 1 shows a schematic diagram of the improved model structure of the scraper heat exchanger, which provides for the use of a hinged blade with a remote plate. In order to increase resource efficiency and uniformity of heat supply, a flexible film resistive electric heater of the radiant type (FFREhRT) 2 covered with an additional heat-insulating outer surface was used as a heating element instead of a conventional steam-water jacket.

The heat exchange scraper apparatus consists of working body 1, equipped with pipes for feeding and discharging raw materials, electric heater (FFREhRT) 2, rotating shaft sealing system 4, and rotor 5. Support disks 3 are mounted on rotor 5, equipped with a system of hinged blades with removable plates 6.

To intensify heat exchange, a new film-forming element in the form of a blade with a remote plate is proposed. The structure of this element is depicted in Fig. 1, *d*, which shows a cross-section of hinged blade 6 with remote consoles and rods 7, on which remote plate 8 is fixed. The design provides a constant gap, both between the remote plate and the front surface of the blade, and between the blade itself and the inner cylindrical surface of the device. The size of this gap is equal to half the width of the remote plate. Also, the main condition is that the plate is oriented at an angle of 30° at the point of its contact with the heating surface, which contributes to the formation of a uniform layer of the product film. The operation of the improved heat exchange device is based on the following principle. The product (for example, fruit and berry puree, paste) is fed tangentially into the fitting located in the upper part of housing 1, and is immediately formed by a blade with a remote plate on the inner surface of the device in the form of a thin liquid film. The geometry of this film of the product is determined by the contours of the cylindrical shell of the housing. Heating is carried out by a heating element located outside the cylindrical surface (FFREhRT) 2.

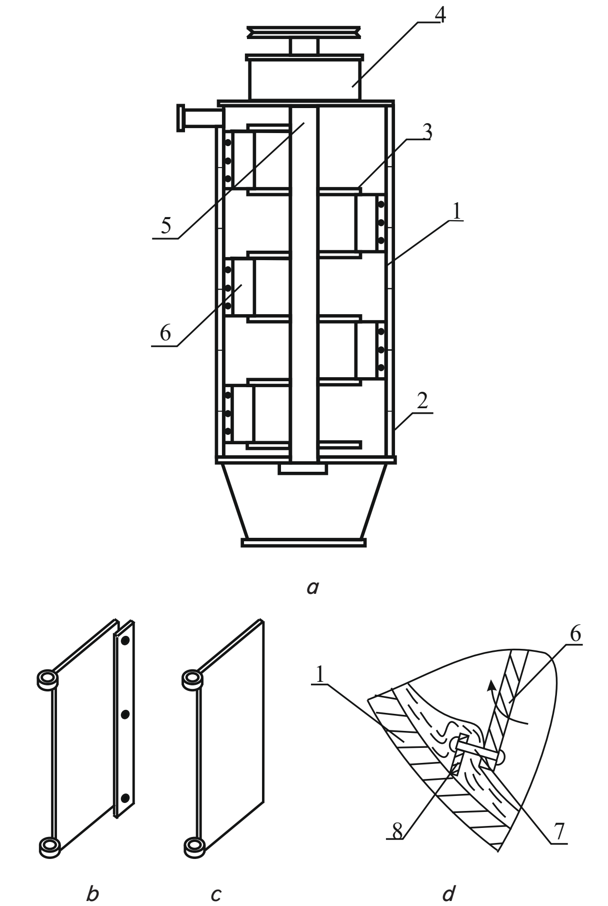

Fig. 1. Schematic diagram of the improved model of a scraper heat exchanger: *a* – longitudinal section of the device; *b* – hinged blade with a remote plate; *c* – standard hinged blade; *d* – fragment of the cross-section of the blade with a remote plate: 1 – working cylindrical chamber; 2 – flexible film resistive electric heater of the radiant type (FFREhRT) covered with an additional heat-insulating outer surface; 3 – support discs; 4 – rotating shaft sealing system; 5 – shaft; 6 – hinged blade with a remote plate; 7 – console (rods); 8 – remote plate

Control over the heat exchange apparatus operation is executed by the measuring device "OWEN", which makes it possible to stabilize the required shaft rotation frequency and product heating temperature.

On rotating shaft 5, support disks 3 are mounted (Fig. 1, *a*); in these disks blades 6 with remote plate 8 are attached with hinges. During the rotation of the shaft, the processed product (fruit and berry purees, pastes), moving in the form of a film under the action of centrifugal force and gravity, interacts with hinged blade 6 and remote plate 8. In front of the remote plate, a nose wave of reduced height is formed (unlike the conventional blade Fig. 1, *c*), through which the product flows, and enters the space in front of the blade plane and the plate itself. Under the action of centrifugal force, it enters the gap between the blade edge and the heat exchange surface.

The structural feature of the proposed hinged blade with a remote plate is the constancy of its deflection angle when changing the productivity of the device for the product. This design of the blade enables an increase in the relative speed of movement of the product in the gaps. At the same time, internal mixing in the film is activated, caused by the transition of the flow direction from helical along the body to radial in the gap zone. As a result, the movement of the proposed blade structure forms a significant number of turbulent micro vortices, which intensify the heat exchange process between the heating surface and the product in the film state.

5. 2. Results of research into the heat transfer characteristics of the improved scraper heat exchanger

The heat transfer coefficient from the heating surface to fruit and berry puree (based on apples, apricots, and rose hips) was determined depending on the change in heat exchanger performance (Fig. 2) and shaft rotation frequency (Fig. 3).

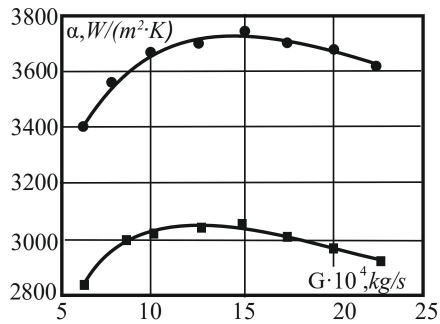

Fig. 2. Heat transfer coefficient depending on the change in heat exchanger performance by product: ■ — hinged blade; ● — hinged blade with a remote plate

When using low raw material consumption, the working surface of the blades is covered with a thin layer of product, which allows the blades to slide along the working surface. Such conditions of low product productivity cause centrifugal force, which presses the blades to the heating surface, exceeding the hydrodynamic resistance from the product side, which leads to minimal mixing. With an increase in product productivity, heat exchange intensifies on the blade surface, since the heating surface is completely wetted, which enables maximum pressing of the blade to the working surface with a minimum gap and uniform mixing.

The maximum values of the heat transfer coefficient are observed when the device's productivity for fruit and berry puree is in the range of (13...15) 10^{-3} kg/s. With a further increase in raw material consumption, the heat transfer coefficient begins to decrease slightly. This is due to the formation of a thicker film, which reduces the time the raw material remains on the heating surface until its separation after cutting with a blade. To eliminate this effect, an improved blade structure with a remote plate is used, which provides an increase in the heat transfer coefficient compared to the basic structure of the hinged blade (Fig. 1, *c*) at a value that is 1.2 times greater, which indicates an intensification of the heat exchange process.

The rotation frequency of the rotor with improved hinged blades with external plates also affects the change in the heat transfer coefficient up to a certain point when it increases. Thus, when moving from minimum to maximum speeds, the layer of fruit and berry raw materials becomes turbulent, which leads to an increase in the value of the heat transfer coefficient. However, at a rotation frequency within 1.0...1.5 s^{-1}, the influence of this parameter ceases, which is explained by the formation of a stable film flow.

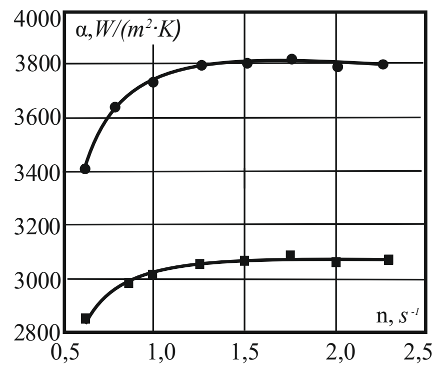

Fig. 3. Heat transfer coefficient depending on the change in the number of shaft revolutions: ■ — hinged blade; ● — hinged blade with a remote plate

The established dependences indicate that the heat transfer coefficient in a scraper heat exchanger is influenced by the following key parameters, such as productivity, shaft rotation frequency, and structural elements of the hinged blade. Productivity determines the thickness of the raw material film that contacts the heating surface and intensifies heat exchange when raw material consumption increases, but an excessive increase in consumption leads to a decrease in the heat transfer coefficient due to the formation of a too thick film layer. Changing the shaft rotation frequency affects the level of turbulence in the film. When the speed increases, the intensity of movement and heat transfer increases but an excessive increase in turbulence leads to a gradual stabilization of the heat exchange characteristics. The structure of the hinged blade with a remote plate enables constant contact between the product and the heat exchange surface, reducing the resistance to movement and increasing the heating efficiency. Taking these parameters into account in the proposed structure makes it possible to increase the heat transfer coefficient and heat exchange efficiency in the system.

A comparison of energy costs for heating fruit and berry purees made from apples and apricots was carried out (Table 1). The following input data were used in the calculations: puree consumption, specific heat capacity of the product, and the material of the working surface of the apparatus (stainless steel), as well as the structure parameters of the basic heater and the improved heat exchanger, including the mass and area of the heating surface. Heat losses to the environment were not taken into account during our calculations.

Table 1

Comparing the characteristics of an improved scraper heat exchanger and a heater

Value	Heater (MZS-320)	Scraper heat exchanger
Specific costs	$q_{sp} = Q/m = 375\,508 / 1500 = = 250$ kJ/kg	$q_{sp} = Q/m = 6216 / 0.028 = = 222$ kJ/kg
Mass of the device	$M_{MZS} = 1520$ kg	$M_{SH} = 74$ kg
Heat costs for heating the device body	$Q_h = m_1 c_s (t_4 - t_3) + m_2 c_s (t_2 - t_1) = = 620 \cdot 0.48 \cdot (143 - 80) + + 900 \cdot 0.48 \cdot (65 - 25) = = 18748 + 23760 = 42508$ kJ	$Q_h = M_{SH} c_s (t_k - t_i) = = 74 \cdot 0.48(80 - 20) = 2131.2$ kJ
Heat costs for heating fruit and berry puree	$Q_p = mc(t_k - t_i) = 1500 \cdot 3.7 \times \times (80 - 20) = 333000$ kJ	$Q_p = Gc(t_k - t_i) = 3700 \times \times 0.028\ (80 - 20) = 6\,216$ J/s
Total costs	$Q = 375\,508$ kJ	$Q = 6\,216$ J/s

Note: characteristics of the MZS-320 basic structure are taken from [23].

Analyzing our calculation data, we can conclude that the improved scraper heat exchanger has significant advantages compared to the basic heater in terms of the main indicator of resource efficiency – specific energy consumption for heating the product (fruit and berry puree). In particular, the specific heat consumption in the improved heat exchanger is 222 kJ/kg (Table 1), which is 12.5% less than in the basic heater where this indicator is 250 kJ/kg. This indicates a significant reduction in energy consumption in the improved structure, which can lead to a decrease in operating costs for production.

6. Discussion of results related to the process of heating fruit and berry puree in the improved scraper heat exchanger

The structure of a scraper heat exchanger has been improved for the implementation of heat treatment processes of liquid food semi-finished products using the example of fruit and berry puree. The modernization involves equipping the internal mixing unit with a hinged blade with a remote plate, which contributes to the intensification of heat and mass transfer by improving contact interaction with the heat exchange surface. Also, to increase energy efficiency and ensure uniform distribution of the heat flow, instead of the conventional steam-water shell, a flexible film resistive electric heater of the radiant type (FFREhRT) was used as a heating element (Fig. 1).

The result of our research is the confirmed increase in heat transfer efficiency in the improved scraper heat exchanger due to the use of new structural solutions. Unlike the approaches described in [15–19], which mostly use conventional heat exchangers with massive heat jackets operating with the help of intermediate heat carriers, the improved heat exchanger does not require a significant metal structure, complex shut-off valves and piping. In addition, such conventional designs have a limited level of mixing intensity in the area of action of the scraper elements, which leads to less efficient heat transfer and an increased risk of local overheating of the product.

To confirm the effectiveness of the proposed structural solutions, the heat transfer coefficient depending on the heating surface to the fruit and berry puree was determined depending on the change in productivity (Fig. 2) and the shaft rotation frequency (Fig. 3). In the presence of low productivity, the working surface of the blades is covered with a small layer of product, which enables the movement of the blades along the heating surface with minimal mixing. Such process conditions lead to the fact that the centrifugal force pressing the blade to the heating surface exceeds the hydrodynamic resistance of the fruit and berry puree, which causes limited mixing. As the layer of fruit and berry puree grows, the heat exchange process intensifies due to greater wetting of the heating surface. As a result, maximum pressing of the blade to the heating surface of the apparatus with a minimum gap and ensuring uniform mixing of the puree is ensured.

Thus, the maximum values of the heat transfer coefficient, which are observed at the productivity of raw materials in the interval of (13...15) 10^{-3} kg/s, have been established. With a further increase in raw material consumption after passing this interval, the value of the heat transfer coefficient gradually decreases. Such a decrease can be explained by the formation of an increased thickness of the product film, which leads to a decrease in the time of the raw material on the heating surface and, in turn, reduces the efficiency of the heat transfer process. To solve this problem, an improved structure of the blade with a remote plate was used, which makes it possible to increase the heat transfer coefficient by 1.2 times compared to the basic structure of the hinged blade. Our data indicate an increase in the heat transfer process, which in turn leads to an increase in energy efficiency.

Our studies on the dependence of heat transfer coefficient on rotor speed have established that when moving from the minimum values of the shaft speed to the maximum, the degree of movement of the fruit and berry puree increases. This effect leads to an increase in the heat transfer coefficient due to better mixing and uniform temperature distribution in the product layer. A further increase in the number of revolutions to values within 1.0...1.5 s^{-1} leads to that the effect of this parameter on heat transfer ceases since a stable film flow of raw materials is formed, which stabilizes the heat exchange process and reduces the effectiveness of the influence of the rotation frequency on the overall heating process.

Comparative calculations of the specific energy consumption for heating a unit of product volume showed that the proposed structural solution of the improved heat exchanger leads to a decrease in the specified indicator by 12.5% compared to the basic heater. Thus, the specific energy consumption in the improved scraper heat exchanger is 222 kJ/kg, while for the basic structure this indicator is 250 kJ/kg (Table 1). These values illustrate an increase in the efficiency of heat transfer in the improved heat exchanger.

The accomplished level of indicators is attributed to the proposed structure features of the new model of scraper heat exchanger, in particular, the use of a hinged blade with a remote plate, which provides more effective wetting of the working surface and improved heat exchange. Also, replacing steam heating with heating (FFREhRT) will increase the energy efficiency of the heat exchanger, creating a more uniform temperature distribution over a thin layer of the product, reduce heat consumption, and improve equipment operating conditions. Thus, the use of FFREhRT helps reduce maintenance and repair costs and also makes it possible to eliminate bulky pipeline equipment, typical of conventional steam systems. In general, such solutions make the system more flexible, reliable, and suitable for automated control over heating processes.

Our computational and experimental results allow us to conclude that the improved scraper heat exchanger provides not only a reduction in energy costs but also improves the quality of the processed product due to rapid uniform heating and intensive mixing of raw materials. The introduction of the proposed structure of the scraper heat exchanger into industrial processes for fruit and berry raw materials could significantly improve the structure and technological parameters of production, ensuring high quality of liquid food products of plant origin (puree, paste) and reducing their cost.

Our results related to increasing the heat transfer efficiency of a scraper heat exchanger when implemented in the practical activities of food production have limitations only from the point of view of rational use of operating parameters and strict adherence to the rules of operational equipment. These structural solutions can be used to improve devices of this type using appropriate techniques. It is also necessary to note the necessity of studying the structural and mechanical characteristics of the processed product at all stages of its production since it is known that changes in temperature and particle size of the dispersed phase significantly affect viscosity. Failure to take these parameters into account may become one of the shortcomings and affect our experimental results.

Thus, our study confirms the feasibility of using improved scraper heat exchangers in the production of fruit and berry purees and pastes, both from the point of view of energy efficiency and from the point of view of the resulting cost of the product. The results also indicate the prospects for further developments for improving the designs of heat exchangers for wider use in the food industry.

The limitations of the current research are the selected parameters within which the process was studied (puree consumption and shaft rotation frequency), which does not make it possible to fully assess the effectiveness of the improved structure under wider production conditions. Our study focused exclusively on fruit and berry purees and pastes of plant origin, which limits the possibility of generalizing the results to other types of viscous products, in particular protein or dairy systems, which may have other rheological and thermal properties.

Further research may address the implementation of improved scraper heat exchangers for other types of food products, such as dairy products, sauces, jams, broths, as well as for the implementation of sterilization and pasteurization processes in the flow. Such implementations could significantly expand the range of applications of heat exchange equipment in the food industry. It is also promising to study the possibility of implementing the proposed heating technique in automated control and management systems, which would improve the accuracy and stability of the temperature regime, reduce energy costs, and increase the efficiency of processes.

7. Conclusions

1. We have improved a model of the scraper heat exchanger equipped with FFREhRT and a hinged blade with a remote plate for heating liquid food products from fruit and berry raw materials (puree, paste). Replacing the steam heating system with FFREhRT makes it possible to reduce the energy efficiency of the structure by eliminating the corresponding steam fittings while simultaneously improving operational characteristics. Installing a film-forming element in the form of a hinged blade with a remote plate leads to an increase in the intensity of the movement of raw materials when passing through the structural elements of the blade plate mounted on consoles (rods) and leads to an increase in heat transfer efficiency.

2. It has been established that the heat transfer coefficient significantly depends on the product flow rate and after reaching the maximum value within (13...15) 10^{-3} kg/s has a tendency to decrease. The influence of rotor speed on the value of heat transfer coefficient is not significant and is mainly due to the transition from low to high speeds of 1.0...1.5 s^{-1} and after further increase tends to gradually stabilize. We have conducted comparative analysis using the conventional hinged blade and the improved one with a remote plate, which reveals an increase in the heat transfer coefficient by 1.2 times for the latter. The specific heat consumption in the improved heat exchanger is 222 kJ/kg, in contrast to the conventional heater, 250 kJ/kg. The resulting values show a decrease in the specific heat consumption by the improved structure by 12.5%.

Conflicts of interest

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

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Data availability

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

Use of artificial intelligence

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

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