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INCREASING THE EFFICIENCY OF HEAT AND MASS EXCHANGE IN AN IMPROVED ROTARY FILM EVAPORATOR FOR CONCENTRATION OF FRUIT-AND-BERRY PUREE

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An improved model of a rotary film evaporator with a cutting blade having a reflective surface and equipped with an autonomous heating system which is fed by a power supply from Peltier elements. The reflective surface of the advanced cutting blade had an area of 0.06 m^2 and was heated by a flexible film resistive electric heater of radiating type with a ~15…20 W power supply. This solution provides additional heating and mixing and helps to capture the cut-off layer of puree while reducing the useful surface of the working chamber by 7 %.

Most evaporators have a low heat transfer coefficient reducing the energy content of the process and final quality of the product. The heat exchange efficiency can be increased by improving the design of the film-forming element of the rotary film evaporator.

The use of the proposed cutting blade with a reflective surface enables an increase in the heat transfer coefficient by approximately 20 % compared to the basic rectangular blade design. When comparing the calculated data, it can be concluded that the main indicator of resource efficiency, namely specific energy consumption for heating a unit volume of product in the RFE amounts to 408 kJ/kg compared to 1,019 kJ/kg with the basic vacuum evaporator which means a 1.97 times consumption reduction. The duration of heat treatment in the RFE is 60 s compared to 1 h in the basic VE which shows a significant reduction of raw material exposure to high temperatures. The obtained data show the effectiveness of engineering and technological solutions. The engineering and technological component of any heat and mass exchange processes, in particular the concentration of fruit-and-berry raw materials, is the main component in the production of semi-finished food products of a high degree of readiness

Keywords: evaporation, rotary film evaporator, heat and mass exchange, heat transfer coefficient, fruit-and-berry raw materials

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1. Introduction

Most of the available food products presented in the markets of European countries contain a certain percentage of concentrated natural products of a high degree of readiness (juices, various confectionery products, etc.) [1]. The efficiency of their use is associated with the maximum preservation of natural properties of raw materials in the form of one-component and multi-component blended systems [2]. Such blended systems improve the physiological and functional properties of food products based on them and the immune component while replacing synthetic dyes and additives with organic ones [3]. Deterioration of the global ecological situation confirms expediency of finding innovative engineering and technological solutions for intensification of heat and mass exchange processes, in particular, concentration to ensure production of high-quality organic products at an affordable price [4]. The use of secondary heat in rotary film evaporators (RFE) is one of the ways to achieve resource efficiency of the process of concentrating organic raw materials based on present-day solutions. This approach minimizes the component of rapid physical and chemical structural change by organic raw material of its initial properties at the important heat exchange stage of its reprocessing [5].

It is the engineering and technological component of any heat and mass exchange processes that affects the final quality of the products obtained from organic raw materials determining a search for ways to raising the heat transfer coefficient and resource efficiency of the concentration process as a whole. The advantages of using rotary film evaporators in the processing and food industries of many countries of the European Union include the following:

– implementation of the heat and mass exchange process in the formation of a film-like flow makes it possible to intensify the concentration process due to the absence of a significant volume of raw materials in the cooking vessel as is the case in vacuum evaporators;

– a high degree of process automation is achieved and therefore simplification of operating conditions and an increase in resource efficiency due to elimination of steam jackets and use of secondary heat.

Development and implementation of present-day engineering and technological solutions in the improvement of RFEs to ensure the replacement of basic designs of vacuum evaporators by these RFEs is an urgent task. Growth of the heat transfer coefficient and the use of secondary energy will improve indicators of resource efficiency, the competitiveness of the resulting quality range of concentrated semi-finished products having a high degree of readiness with the possibility of their further implementation in various food technologies.

2. Literature review and problem statement

Attention is focused in [6] on the needs of consumer communities in food, functional and physiological products of a wide use range based on organic raw materials. However, the need for modernization and technical re-equipment of process equipment to ensure the production of high-quality semi-finished products with a high degree of readiness remains unclear. In most cases, this is explained by objective difficulties in operating obsolete heat and mass exchange units and the units of low resource efficiency [7]. It is also necessary to take into account and implement blending of a variety of organic raw materials in the production of semi-finished products of a high degree of readiness to expand the range of foods with novel taste properties. The need to pay attention to the stages of automated production of plastic containers at all production stages to ensure maximum quality of temporary storage and transportation of concentrated products was considered in [8].

A model of studying the relationship between various energy consumption items in boiling out non-Newtonian fluids in the designed model structure was proposed in [9]. However, the issues related to the complexity of implementation of concentration processes in the presence of steam jackets in devices and degradation of resource efficiency because of the complexity of equipment modernization were not identified. One of the solutions is given in [10] with an indication of the heat and mass exchange process during the conversion of pomegranate juice to a concentrate with a 17 % content of dry matter by means of ohmic heating (OVE) in concentration conditions. The presented relationship between heating, consumption of energy for the process and the cutting surface depending on the change of the dry matter content and heat transfer coefficient were presented. However, the authors did not focus on the trajectory of probable movement of the cut layer of juice concentrate and the need for its reflection (settling down) after cutting with emphasizing the need for studies in this direction.

An improved vacuum evaporator with electric heating of the work surface for the production of high quality fruit-and-vegetable pasty semi-finished products was presented in [11]. At the same time, no data were given on determining the heat transfer coefficient of the concentration process for a more detailed visualization of the heat and mass exchange process.

Studies on heat transfer and profiles of velocities of non-Newtonian fluids and their probable paths after collision with blades of various designs were presented in [12, 13] with no taking into account the energy consumed for mixing. However, the possibility of generalized use of hydrodynamic models to create probable ways of improving the processes of mixing food suspensions was not considered which confirmed the relevance of studies in this direction.

The necessity and urgency of presenting hydrodynamic models of non-Newtonian fluids during their mixing in heat exchange processes were confirmed in [14, 15] since their formation has certain technical prerequisites and takes some time. This has substantiated the importance of studying the obtained hydrodynamic models in the improvement of heat and mass exchange processes with various structural elements of stirrers to ensure the rational design and technological parameters of the process. The maximum provision of resource efficiency which is achieved, e.g., when using secondary energy (exhaust air) with a high temperature on the autonomy of certain structural elements of technological devices is an important component of any heat and mass exchange process. Therefore, thermal energy which can be converted, e.g., into electricity due to properties of the Peltier elements with its subsequent use as a power source for heating certain elements of stirrers is the driving energy of heat and mass exchange processes. The efficiency of using these elements in converting the energy of exhaust air into supply voltage for low-inertial electric heaters, in particular, film heaters because they are portable and practical to use was considered in [16, 17].

Most evaporators have a low heat transfer coefficient which reduces the resource efficiency of the process and final quality of the product. The introduction of innovative solutions to improve the film-forming elements in various directions is one of the promising solutions to the above problem. First, providing film-forming elements with reflective surfaces that make it possible to press the cut-off layer of raw materials to the work surface without its possible separation to the rotor due to centrifugal force. Secondly, the use of a reflective surface as a heating surface will provide additional heating of the cut-off layer of raw material during its autonomous heating due to secondary energy and determine the feasibility of studies in this direction.

The above confirms the relevance of the use of rotary film evaporators for the production of concentrated semi-finished products by forming a film-like flow. Issues related to the ways leading to the growth of the heat transfer coefficient from the work surface to the cut-off layer of raw material remain completely unresolved. This provides additional pressing of the cut-off layer of raw material by the reflective surface which is heated autonomously due to the use of a secondary energy source. Such conditions lead to an increase in resource efficiency of the process as a whole when using a flexible film resistive electric heater of radiating type (FFREHRT) [18]. Replacement of steam heating with heating by means of FFREHRT provides elimination of steam generators, technical networks and heating shells and consequently reduction of metal consumption for making evaporators. All the above has a positive impact on the final quality of the resulting concentrated products and ensures their competitiveness.

3. The aim and objectives of the study

The study objective is aimed at increasing the heat and mass exchange efficiency of the improved rotary film evaporator with reduced specific metal quantity by means of changing the heat-removing method and the use of a cutting blade provided with autonomous heating of the reflective surface.

To achieve the objective, the following tasks were solved:

– develop a model design of an advanced rotary film evaporator with a modified method of heat removal and the use of a cutting blade provided with autonomous heating of the reflective surface;

– verify the impact of the proposed design and technological solutions on the efficiency of concentration in comparison with the basic design of the vacuum evaporator by conducting experimental and computational studies.

4. Materials and methods used in studying the concentration of vegetable raw materials and experimental installation

The technical base of the Research Center "Latest Biotechnologies and Equipment for Producing Food Products with High Health Improving Properties" of Kharkiv State University of Food and Trade (Ukraine) has provided studies in this area. Availability of a model design of a rotary-film evaporator (RFE) has provided a study of ways to improve the heat and mass exchange process in terms of using an improved cutting blade design with autonomous heating of the reflective surface (Fig. 1).

The model design of the RFE makes it possible to determine the heat transfer coefficient α, W/(m^2·K), depending on the rotor speed n, min^{-1} and product flow rate G, kg/s, by experimental determining the temperature difference (Δt) using a measuring device of OVEN Co. (Ukraine) as the difference between the average temperature of the RFE inner surface and the product boiling point at a pressure in the working volume of the apparatus in the range of p=13...15 kPa. The heat transfer coefficient α between the heating wall and the product was determined by the formula:

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

where F is the area of the heat transfer surface, m^2; Q is the amount of heat transferred (Table 1), W; Δt is the temperature difference, °C

Implementation of resource efficiency in conditions of use of secondary steam energy intensifies the heat and mass transfer process when using the proposed design of the cutting blade with an autonomous system for heating the reflective surface. This solution will improve the quality of the heat and mass exchange process due to the additional contact of the raw material layer with the heated surface of the reflector after cutting it with a blade with ensuring its purposeful impact on the working surface.

5. Determining the efficiency of heat and mass transfer of an advanced rotary film evaporator

5. 1. Development of an improved model of a rotary film evaporator

An improved model of a rotary film evaporator with the proposed cutting blade equipped with an autonomous system for heating the reflective surface is presented in Fig. 1, *a*. The use of a flexible film resistive electric heater of radiating type (FFRENRT) 2 as a heater of the vertical working chamber 1 instead of a steam jacket and the corresponding technical lines to it will ensure the energy efficiency of the design and process. To increase the heat transfer coefficient of the concentration process, it is proposed to use an advanced cutting blade equipped with an autonomous system for heating the reflective surface (*II*, Fig. 1, *b*) due to the use of secondary steam formed during concentration. The secondary steam comes from the inner space of the heated vertical working chamber 1 to the separating space 6 with an internal structural narrowing to accommodate Peltier elements 9. The Peltier elements convert the heat of the secondary steam into a low voltage supply for its further use in autonomous heating the reflective surface of the proposed hinged blade 3 under conditions of using the FFRENRT 2.

Generation of supply voltage by Peltier elements when secondary energy temperature reaches 30 °C was revealed by research and development means. The effective area of the reflective surface of the developed hinged blade has also been established to ensure a rational heat transfer coefficient (0.06 m^2, with a ~15...20 W power supply of FFRENRT). In this case, the cutting blade is hinged on rotor 4 rotated by the V-belt transmission 8 and provides the driving centrifugal force of the film flow of raw materials. The film layer of raw material is formed by injecting it through pipe 10 to the distribution mechanism 5 to form the required thickness of the blended puree layer. The puree is concentrated at a pressure of 12...15 kPa in a heated vertical working chamber followed by concentrate discharge through pipe 1. Remnants of secondary steam enter the condensate discharge line 7.

The heat and mass exchange process is controlled by control unit 12 ensuring strict control of the rotor speed (— · · —), pressure (····) and temperature (– –) during concentration with the use of Oven automatic control means.

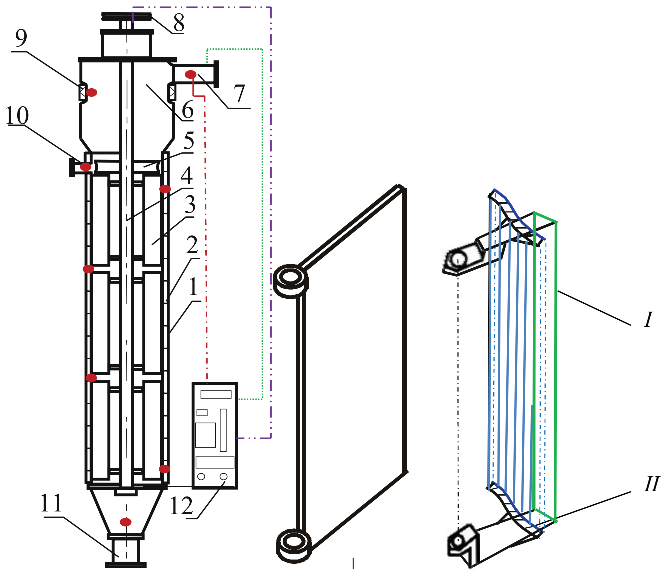

Fig. 1. Visualization of the improvement: *a* — the diagram of the improved model design of the rotary film evaporator with a cutting blade provided with an autonomous system for heating the reflective surface: 1 — vertical working chamber; 2 — flexible film resistive electric heater of radiating type with heat-insulating external surface (FFRENRT); 3 — hinged blade equipped with an autonomous system for heating the reflective surface; 4 — rotor; 5 — distribution mechanism; 6 — separating space; 7 — condensate drain line; 8 — V-belt transmission; 9 — Peltier elements; 10 — branch pipe for the blended puree injection; 11 — branch pipe for concentrate removal; 12 — a device for controlling technological parameters of the device; *b* — the basic design of a rectangular blade; *c* — cutting blade provided with an autonomous system for heating the reflective surface: *I* — cutting edge; *II* — autonomously heated reflective surface *II*

5. 2. Experimental and computational studies of the impact of the proposed engineering and technological solutions on the process efficiency

The second task of the study implied determining the coefficient of heat transfer from the working surface of the rotary film evaporator to the experimental blended raw material depending on its flow rate and rotor speed (Fig. 2, 3).

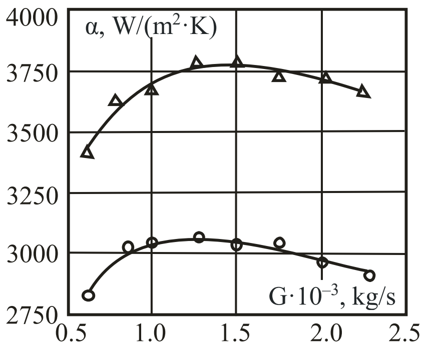

Fig. 2. Dependence of the heat transfer coefficient on the flow rate of the experimental raw material: the ○ curve for the basic design of the rectangular blade; the Δ curve for the cutting blade provided with an autonomous system for heating the reflective surface

At a low feed of raw material, the working surface of the blades is wetted with a thin layer of raw material ensuring sliding of the blades on the working surface since the centrifugal force pressing the blades exceeds hydrodynamic resistance of the raw material providing an insignificant mixing. As the thickness of the raw material layer on the blade surface increases, heat exchange gets more intensive under conditions of uniform wetting of the surface of rotation, thereby providing pressing of the blade to the working surface with a minimum gap and uniform mixing.

The maximum value of the heat transfer coefficient was observed in the area with a mass flow rate of raw material within G=(1.3...1.5)·10^{-3} kg/s. With a further increase in the flow rate, the heat transfer coefficient α begins to decrease. Growth of the film thickness reduces the duration of retention of raw materials on the working surface and its rapid removal from the working chamber. The use of an improved design of the cutting blade with an autonomous system for heating the reflective surface will increase the degree of mixing of the raw material by undercutting the raw material and changing the direction of its movement by the heated reflective surface. Such movement of raw material leads to an increase in the heat transfer coefficient α, which in comparison with the basic design of a rectangular blade will grow by about 20 % confirming intensification of the concentration process.

The frequency of rotation of the rotor with advanced cutting blades equipped with an autonomous system for heating the reflective surface affects the change of the heat transfer coefficient α to a certain time point. Namely, during the transition from the minimum to the maximum speed, the turbulence of the raw material flow is ensured, thus α increases, and when the rotation speed n=1.1...1.35 s^{-1} is reached, the influence of this parameter on α is stopped. This phenomenon is explained by the stable formation of a film of the moving layer of raw material which is mixed not only with blades but also by intense vaporization in the process of concentration.

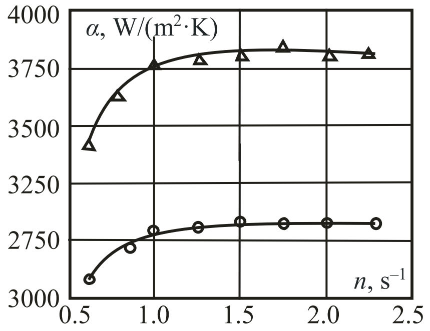

Fig. 3. Dependence of the heat transfer coefficient on the rotor speed: ○ — with the basic structure of a rectangular blade; Δ — with an advanced blade equipped with an autonomous system for heating the reflective surface

Thus, the heat transfer coefficient in the rotary film evaporator is influenced by the mass flow rate, heat flux density, rotor speed, design of the film-forming element of the rotor. The presence of a heated reflective surface makes it possible to reduce the useful surface of the working chamber by 7 % due to additional heating, partial mixing, and capture of the layer of raw material being undercut.

To determine the efficiency of the improved rotary film evaporator, a comparative analysis of energy consumption for concentrating a blended apple, blueberry and Cornelian cherry puree mixture based on (Table 1) with an initial dry matter content of 12 % to final content of 30 %. The product flow rate, the specific heat of raw materials and the working surface of the device (stainless steel), as well as the design parameters of the basic vacuum evaporator (VE) and RFE (weight, heating surface area) were used in calculations as input data. Calculations were made without taking into account losses in the environment.

It was established that the main indicator of resource efficiency, namely the specific energy consumption for heating a unit volume of product in the RFE amounts 408 kJ/kg (Table 1). In comparison with the basic VE (1019 kJ/kg), the obtained indicator shows a 1.97 times reduction of consumption by the improved RFE.

This provides a heat treatment duration of 60 s in the RFE compared to 1 hour in the base VE which results in a significant reduction of raw material exposure to high temperatures.

Basic technical and operational indicators of the improved rotary film evaporator equipped with a cutting blade with an autonomous system for heating the reflective surface were obtained in experimental and practical studies (Table 2).

The obtained data confirm the efficiency of its further introduction into the process lines for producing fruit and vegetable semi-finished products.

6. Discussion of the results obtained in the concentration of fruit-and-berry puree in the improved rotary film evaporator

The experimental and practical results obtained in the study of using the improved RFE for the concentration of fruit-and-berry puree are explained by the use of the present-day FFRENRT as a heater of the working surface and a reflective surface of the cutting blade. The use of FFRENRT ensures removal of the steam jacket from evaporators, technical lines of coolants, and improves the energy efficiency of the process as a whole. Conversion of secondary energy into the supply voltage for the FFRENRT by means of Peltier elements provides autonomy of heating the reflective surface with a simultaneous intensification of the degree of mixing the cut-off raw material layer. At the same time, additional heating, partial mixing and capture of the cut-off raw material layer result in a 7 % reduction of the useful surface of the working chamber.

The use of the RFE design and technological solutions in practice leads to the reduction of inertia and specific metal content in basic structures of similar devices with ensuring uniformity of the heat transfer surface, partial use of secondary energy for autonomous operation of some important technological and structural elements. A significant reduction in overall resource-efficient parameters in the improved RFE including reduction of the duration of heat and mass exchange processing to 60 s instead of 1 hour will ensure production of concentrated semi-finished food products of a high degree of readiness. Instead, most studies on the concentration of vegetable raw materials are implemented in conditions of using inertial and metal-intensive steam jackets and even with the heating of the mixing device [20]. This leads to a significant complication of implementation of the process of rel-

Table 1

Comparative characteristics of the advanced rotary film evaporator in comparison with the vacuum evaporator

Indicator	Vacuum evaporator (MZS-320)	Rotary film evaporator
Apparatus weight	m^*=1,520 kg	m=43 kg
Energy consumed for the apparatus heating	$Q_{heat}=m_1c_c\left(t_2'-t_1'\right)+m_2c_c\left(t_2''-t_1''\right)=620\cdot 0.48\times$ $\times(143-80)+900\cdot 0.48\cdot(65-25)=18{,}748+$ $+17{,}280=36{,}028$ kJ	$Q_{heat}=m_1c_c(t_k'-t_1')=$ $=43\cdot 0.48(65-20)=$ $=930$ kJ
Energy consumed for product heating and boiling out	$Q_{pr}=mc(t_k-t_n)+rm_{\text{cond}}=$ $=1500\cdot 3.7\cdot(65-50)+2350\cdot 600=$ $=1493250$ kJ	$Q_{pr}=Gc(t_k-t_n)+rG_{\text{cond}}=$ $=3{,}700\times 0.028(65-50)+2{,}350\times 10^3\times$ $\times 0.0052=13{,}539$ J/s $Q_{pr}\ Gc(t_k-t_n)+rG_{\text{cond}}=3{,}700\times 0.028\times$ $\times(65-50)+2{,}350\times 10^3\times 0.0052=13{,}539$ $3{,}600=48{,}740$ kJ
Total energy consumed	Q=1,529,278 kJ	Q=14,470 J/s Q=14,470·3,600=52,092 kJ
Specific consumption	$q_{pr=}\dfrac{Q}{m}=\dfrac{1{,}529{,}278}{1{,}500}=1{,}019$ kJ/kg	$q_{pr}\dfrac{Q}{G}=\dfrac{14{,}470}{0.028}=517$ kJ/kg
Treatment time	$T_{VE}=Q/F\cdot k\cdot\Delta t=15{,}10530/3.7\cdot 1{,}454\cdot 78=3{,}600$ s	$T_{RFE}=L_{an}/\upsilon_{nl}=1.2/0.02=60$ s

Note: Comparative data of the basic MZS-320 design were taken from [19]*

Table 2

Main technical characteristics and engineering-and-economic performance of the RFE

Output of the product, kg/hour	100
Area of the heat exchange surface, m^2	0.82
Internal diameter, m	0.2
Pressure in the apparatus, kPa	12...15
Working medium temperature in the apparatus, °C, not more than	63...68
The apparatus rotor speed, min^{-1}	180...200
Voltage, V	220±10 %
Power control of electric heaters	continuous
Overall dimensions: $L\times W\times H$, mm	330×280×1,680
Weight, kg, not more than	43
Performance	0.85
Specific quantity of metal, m_{ap}, kg/m^2	52.5
Specific heat rate, q_s, kJ/kg	517

atively stable gentle mode of heat treatment in the automated mode when concentrating vegetable raw materials. A rational approach to the choice of heat supply methods confirms the importance of implementing the resource-efficient technologies with ensuring optimal conditions of heat and mass exchange processing of vegetable raw materials.

The task of stabilizing the number of revolutions, especially when changing the product flow rate, was one of the limitations in the study of change of the heat transfer coefficient with a change in the rotor speed. Speed stabilization is possible by using various V-belt transmission pulleys for the DC motor or installing an automatic frequency regulator for the AC motor. It is recommended to use the improved RFE design within the rational pressure of 12…15 kPa for ensuring the production of concentrated semi-finished food products of a high degree of readiness.

Further studies can be aimed at improving the implementation of concentration processes in the proposed heat and mass exchange equipment by determining ways of agitation of the film flow, as well as the use of secondary energy to heat the raw material before its concentration. It is also planned to establish changes in colorizing the fruit-and-berry raw materials in the process of their processing and hence determine the final quality of the obtained concentrated semi-finished food products of a high degree of readiness.

7. Conclusions

1. An improved model of a rotary film evaporator with a proposed cutting blade provided with an autonomous system for heating the reflective surface by converting the energy of the secondary steam into the supply voltage for the heaters by means of Peltier elements. The area of the reflective surface of the advanced cutting blade is 0.06 m^2 and requires ~15…20 W power supply for autonomous FFRENRT operation. This, in turn, will provide additional heating, mixing, and capture of the layer of the cut-off raw material and reduces the useful surface of the working chamber by 7 %.

2. It was established that the use of the proposed cutting blade with a reflective surface leads to an increase in heat transfer coefficient by approximately 20 % compared to the basic design of a rectangular blade. Calculated resource efficiency indicators were obtained: specific energy consumption for heating a unit volume of the product in the RFE amounts 408 kJ/kg in comparison with 1019 kJ/kg for the basic VE showing a 1.97 times reduction of consumption in the improved RFE. This provides a 60 s duration of heat treatment in RFE compared to 1 hour in the base VE which means a significant reduction of the raw material exposure to high temperatures.

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