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IMPROVEMENT OF THE CONTINUOUS "PIPE IN PIPE" PASTEURIZATION UNIT

The result of improving the pasteurizer is a 6-fold decrease in the specific metal consumption by the device, in comparison with the basic design (26 kg/m² versus 160 kg/m²). The duration of heating and pasteurization of drinking milk at a temperature of 73...77 °C while aging over 15...20 s is 27.5 s, which is 1.8 times less. A reduction in the heat consumption for heating the apparatus is achieved, which is 1,372.8 kJ (CPiPPU – Continuous "pipe in pipe" pasteurization unit), in comparison to the consumption by the basic pasteurizer, 8,448 kJ.

The uniformity of flow heating was established when its speed changes from 0.03 to 0.40 m/s for various heat supply techniques; under the condition $v=0.4$ m/s, a temperature drop is ensured: at internal heating – 1.4 °C; in the basic design with external heating by a hot heat carrier – 2.7 °C; and in the proposed CPiPPU with double-sided heating – 0.5 °C. The comparison of heat supply techniques confirms the heat exchange efficiency of raw material processing by CPiPPU while ensuring a minimum temperature drop. The improved continuous pipe-in-pipe pasteurization unit based on the double-sided heating by a flexible film resistive electric heater of the radiating type (FFREHRT) is resource-efficient and can be used to heat food raw materials in the temperature range 15...110 °C

Keywords: pasteurization, milk, pipe-in-pipe heat exchanger, heat supply, flow rate, electric heating

An. Zahorulko

PhD, Associate Professor*

E-mail: zagorulkoAN@hduht.edu.ua

A. Zagorulko

PhD, Associate Professor*

E-mail: zagorulko@hduht.edu.ua

M. Yancheva

Doctor of Technical Sciences, Professor, Head of Department

Department of Meat Technology**

E-mail: ya_marina11@ukr.net

O. Dromenko

PhD

Department of Meat Technology**

E-mail: olena_dromenko@ukr.net

M. Sashnova

PhD, Associate Professor

Department of Software Engineering and Cybersecurity

Kyiv National University of Trade and Economics

Kyoto Str., 19, Kyiv, Ukraine, 02156

E-mail: MV_sashnova@gmail.com

K. Petrova

PhD, Associate Professor

Department of Electrotechnical Systems and Energy Management

Central Ukrainian National Technical University

Universytetskyi ave., 8, Kropyvnytskyi, Ukraine, 25006

E-mail: kate_petrova26@gmail.com

L. Polozhynnikova

PhD, Associate Professor

Department of Food Industry Technologies and Restaurant Industry

Poltava University of Economics and Trade

Kovalia str., 3, Poltava, Ukraine, 36000

E-mail: L_Polozhynnikova@ukr.net

N. Budnyk

PhD, Associate Professor

Department of Food Production

Poltava State Agrarian Academy

Skovorody str., 1/3, Poltava, Ukraine, 36003

E-mail: Budnik.N76@ukr.net

*Department of Processes, Devices and Automation of Food Production**

Kharkiv State University of Food Technology and Trade

Klochivska str., 333, Kharkiv, Ukraine, 61051

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O. Dromenko, M. Sashnova, K. Petrova, L. Polozhynnikova, N. Budnyk

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1. Introduction

Pasteurized milk is one of the types of food that has all the necessary consumer properties for the nation's full-fledged nutrition. In particular, milk contains fats, proteins,

milk sugar, organic acids, immune bodies, vitamins, and other substances that need to be preserved during its processing [1]. Obtaining high-quality dairy products is possible under the conditions of compliance with the technological and structural recommendations directly from the moment

of receiving the raw material from the accepting departments. When processing raw milk into pasteurized milk, the quality of the technological operation of pasteurization plays an important role, which renders a pleasant slightly sweet taste and yellowish-brown color with a water content of about 88 % and 12 % of dry residue. In addition, pasteurization ensures the destruction of vegetative microflora, in particular pathogenic, predetermining the use of innovative technological resource-efficient equipment [2].

Most devices for milk pasteurization employ an indirect technique of heat supply using a variety of substances as heat carriers, including steam, hot liquid, and air, and even electric current [3, 4]. However, the use of these carriers has operational difficulties associated with the additional costs of heating, transportation, automation, and the stabilization of a temperature field for the uniform heat treatment. In addition, pasteurization devices with indirect heat supply possess the artificially lowered efficiency, high energy consumption, and, therefore, low resource efficiency, thereby requiring scientific and practical research on how to eliminate the above shortcomings. Possible innovative advancements in the process of improving the pasteurization pipe-in-pipe equipment should provide for the resource efficiency of the structural-technological component given the relevance of the set task, which implies the reduction of metal consumption, the elimination of the additional networks of pipes for heat carriers, a clearly-defined stabilizing temperature effect when using an advanced continuous "pipe-in-pipe" pasteurization unit.

2. Literature review and problem statement

Work [5] analytically confirms the impact exerted on the environment and human health by the raw milk pasteurization processes, which requires the presence of heat exchangers that consume large amounts of energy and fuel at enterprises. This predetermines the need to implement solutions to reduce their application through the introduction of non-traditional energy sources such as wind, biomass, solar energy, and so on. Paper [6] noted that solar pasteurization systems are a promising alternative to solve these problems by providing thermal disinfection of raw materials by solar energy without the use of fuel and electricity. The pre-installed systems in Brazil and Italy are both environmentally friendly in terms of the geographical location when comparing the eco-profiles of two solar pasteurization technologies: natural circulation and a thermostatic valve system. The use of solar energy in pasteurization avoids direct emissions and reduces the global environmental impact associated with thermal energy generation. However, for most territories, the fully-fledged implementation of non-traditional sources is difficult from a natural point of view, and costly, allowing, at present, only the implementation of energy-saving solutions at enterprises. At the same time, for most territories, the fully-fledged implementation of non-traditional sources is a complex and costly process from a natural point of view; thus, it is an open question on how to implement comprehensive resource-efficient solutions at enterprises.

The heat-and-mass exchange pasteurization processes are currently implemented by the plate, casing-pipe, and pipe-in-pipe pasteurizers, the first of which is expensive to maintain, the second is characterized by high metal consumption. The process of pasteurization in most cases is implemented at metal- and energy-intensive equipment, emphasizing the need for

its improvement for the technological implementation of the set goal in terms of maximum resource efficiency.

In paper [7], the authors determined the average weight of plate pasteurizers, which exceeds 2,000 kg, casing-pipe pasteurizers – 500 kg, and "pipe-in-pipe" pasteurizers – about 350 kg. That predetermines the prospects of improving "pipe-in-pipe" units in terms of increasing the heat transfer surface while reducing metal consumption and simplifying the structural, operational, and practical features of their use.

Works [8, 9] noted the efficiency of the non-thermal technology of pasteurization of food raw materials when supplying high, medium, and low voltages to the working chamber of the devices, ensuring the microbiological safety of a received product. But there are issues to be solved related to the practical operational safety of these devices under voltage, the cost of equipment, and maintenance in general, as these are the crucial factors for entrepreneurs.

In [10], the process of coconut milk heating at temperatures (50...54.5 °C, 60...64.5 °C, and 70...74.5 °C) in volume flows in an experimental section equipped with four flat plates is shown. The results illustrate an increase in pollution when the temperature is reduced due to the chemical reaction, which is formed due to the impossibility of achieving a uniform temperature effect when heat is supplied. Emphasizing thus the need to create a stabilized temperature effect from a heat carrier under conditions of change in the hydrodynamic properties of raw materials.

Paper [11] reports the evaluation of the effect of thermal processes using an example of liquid food products of low viscosity (milk and juices) under conditions of continuous pasteurization (70...85 °C, during 10...60 s) to ensure the safety and quality of food products, which could create the optimized hardware-technological components of the pasteurization process, leaving to be established the impact of a technique of heat supply and the design features depending on technological needs.

Work [12] gives a general computational physical model of tunnels for beer pasteurization in the food industry, which combines fundamental and empirical correlations, the principles of thermodynamics and heat transfer, etc. Its drawback is the failure to initially take into consideration the optimal geometry for the minimum energy consumption by the tunnel, defining, as a physical constraint, the total volume of the tunnel. This emphasizes the need for the implementation of engineering and technical solutions to ensure a fully controlled interaction between the hardware support to the pasteurization process and the achievement of technological needs in terms of resource efficiency.

In [13], the authors investigated the characteristics of a heat exchanger with two pipes with separated longitudinal fins, which make it possible to interrupt the liquid's surface at the boundary layer to ensure the turbulence of the flow along its length. The results obtained in the cited work confirm the need to consider the hydrodynamic and heat and mass transfer properties in the interaction with the hardware-technological component, leaving undefined the resulting resource efficiency and ways to ensure and increase it. One of the ways to ensure the resource efficiency of the structural part of the "pipe-in-pipe" units and additional equipment to ensure the production of a hot heat carrier, proposed in [14], is to use recuperators. This, in turn, while providing for some savings would also increase the metal consumption of the pasteurized complex in general, its cost,

and complexity of maintenance, which is impractical from a structural point of view.

Papers [15, 16] describe the growing need for the development of and increase in the efficiency of heat exchangers, which led to a wide range of studies to increase the rate of heat transfer along with reducing the size and cost of industrial equipment, respectively. One of such numerous devices used in various industries is a two-pipe heat exchanger, which attracts attention due to its simplicity and a wide range of application. This, in turn, confirms the importance of scientific and practical research into improving pasteurizers of the “pipe-in-pipe” system with a stabilized uniform temperature effect under conditions of the increased heat transfer surface.

Therefore, the pre-established problematic components in the implementation of a milk pasteurization process in the “pipe-in-pipe” unit imply the difficulty of stabilizing and ensuring the uniformity of a heat flow considering the hydrodynamic model and the raw materials’ properties. To solve the specified structural and technological shortcomings, it is proposed to explore the ways to eliminate them by improving the basic design of the “pipe-in-pipe” pasteurizer.

3. The aim and objectives of the study

The aim of this study is to improve a continuous “pipe-in-pipe” pasteurization unit (CPiPPU) by using a flexible film resistive electric heater of the radiating type (FFREHRT) as a heater.

To achieve this aim, the following tasks were set:

- to improve the model structure of the continuous “pipe-in-pipe” pasteurization unit (CPiPPU) by using FFREHRT as a heater;
- to study experimentally and computationally the model structure of a continuous “pipe-in-pipe” pasteurization unit to confirm its effectiveness.

4. Materials, methods of studying the improved continuous “pipe-in-pipe” pasteurization unit

The pre-defined innovative engineering solutions aimed at accomplishing the aim of this work were implemented at the Scientific Research Center “Latest Biotechnologies and Equipment for Food Products with High Health Properties”, the Kharkiv State University of Food and Trade (Ukraine). To implement the main task of improving the model structure of a continuous “pipe-in-pipe” pasteurization unit (CPiPPU) using FFREHRT as a heater [17]. It was proposed to compile a detailed description of the structural-technological component of the improved model structure of a continuous CPiPPU and to perform calculations to confirm the effectiveness of engineering solutions.

The model structure of a continuous CPiPPU based on FFREHRT with automatic control of a temperature field was verified by using a temperature regulator made by “OVEN” (Ukraine) in a combination with thermocouples (8 pieces, the admissible deviation limit of measurements is ± 1.0 °C). We studied milk pasteurization at the raw material’s flow rate in the range of 0.03...0.4 m/s with tempera-

ture stabilization at 75 °C and by using standard calculation and experimental procedures.

5. A continuous “pipe-in-pipe” pasteurization unit

5.1. Development of the improved model structure of a continuous “pipe-in-pipe” pasteurization unit using FFREHRT as a heater

The pasteurization “pipe-in-pipe” units represented in the market of Ukraine have certain structural and technological shortcomings associated with the increased metal and energy consumption of technical networks, the presence of shells and heat generators to maintain the properties of heat carriers. This, in turn, allows us to identify innovative resource-efficient preconditions for their improvement by eliminating heat carriers with the subsequent use of temperature-stable FFREHRT with and without thermal insulation surface.

The first task is implemented by creating an advanced model pasteurization unit, of the “pipe-in-pipe” type, using FFREHRT as heating surfaces and the increased heat transfer surface. CPiPPU is intended for pasteurization treatment of any raw material, in particular, dairy (Fig. 1); it has the horizontally arranged cylindrical pipes 1, whose external surface is heated by FFREHRT 2 with a heat-insulating surface. In the CPiPPU, to increase the heat transfer surface and improve the quality of the process, the inner part of the horizontal pipes is additionally equipped with hollow pipes 3, whose inner surface is additionally heated by FFREHRT 4 without insulation. The connection of horizontal sections 1 is enabled by elbows 5 with rubber seals and bolts 6.

CPiPPU is equipped with technical holders of sections 11 and has nozzles to supply 7 and remove 9 food raw materials, thus forming the continuity and direct flow of processed products. For fixing and centering, inner hollow tube 3 is arranged on holders 8, which are equipped with a liquid flow separator, thereby ensuring the additional turbulence of the flows.

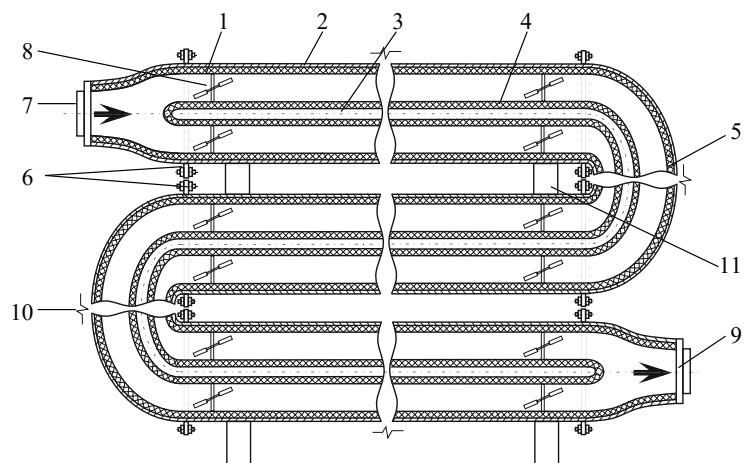


Fig. 1. Schematic of the improved model “pipe-in-pipe” pasteurization unit: 1 – horizontal cylindrical pipes; 2, 4 – flexible film resistive electric heater of radiating type with the thermal and non-insulating surface (FFREHRT); 3 – internal hollow tube; 5 – connecting elbows of horizontal sections with rubber seals; 6 – bolted clamps of flanges; 7, 9 – branch pipes to supply and remove raw materials; 8 – holder of the inner tube (3) with liquid flow separators; 10 – symbol of the cross-section of the elbows and cylindrical pipes (as there could be a different number of sections, which are not marked in this figure, depending on the desired efficiency of the pasteurizer); 11 – technical holder of sections

By repeating the geometric shape of cylindrical surfaces 1, 3, FFREHRT (2, 4) enables an accurate stabilized and uniform heat removal for a high-quality process of the pasteurization of raw milk when reducing metal consumption and increasing the heat transfer surface, also reducing the cost of heating, transportation, and maintenance.

5. 2. Experimental and estimation studies of the model structure of a “pipe-in-pipe” pasteurizer to confirm its efficiency

Comparing the structural and technological characteristics of the improved design of CPiPPU to those of the basic structure of a “pipe-in-pipe” heater with steam heating during milk pasteurization (Table 1) could determine and confirm the effectiveness of the proposed engineering solutions for improvement.

It was calculated that the specific metal consumption of the advanced pasteurizer is 6 times lower compared to the basic design. The duration of heating and pasteurizing drinking milk at a temperature of 73...77 °C, when aged for 15...20 s, is 27.5 s, while it is 50 s in the basic unit, which is 1.8 times less. Such a duration of processing is explained by the reduction of the technical parameter (the length of the unit), from 20 m at external heating, and 11 m in the advanced unit (Table 1), thereby reducing the duration of heating the flow at the same heat exchange areas. This provides for the reduced heat consumption for heating the structure of the unit, 1,372.8 kJ, in comparison with the basic device (8,448 kJ, Table 1).

The implementation of the pasteurization process of milk in the improved CPiPPU could significantly reduce the dimensional and weight characteristics of devices of this type, which is favorable for its further operation not only at dairy enterprises. The use of heat supply based on FFREHRT simplifies operational conditions due to the elimination of steam heating and the maintenance of technical networks of carriers and shells, significantly reducing metal costs while heating the connecting tubes.

The dependences of a temperature difference of the flow were experimentally determined using an example of a rectilinear section of the horizontal section of CPiPPU when changing the rate of a raw material’s flow ($v=0.03...0.40$ m/s). The derived graphical dependences (Fig. 2), when comparing different structural solutions of heat supply, are acceptable for all proposed techniques at a flow rate of 0.4 m/s, because, under conditions of heating the inner cylindrical channel FFREHRT, the value is $\Delta t=1.4$ °C, the external one (by a hot heat carrier) – $\Delta t= 2.7$ °C, and, in the proposed design of FFREHRT, with heating the annular gap on both sides, is $\Delta t=0.5$ °C.

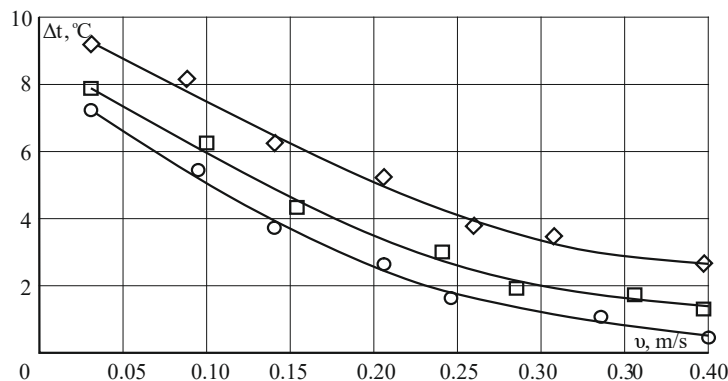


Fig. 2. Dependence of the temperature difference of flow along the rectilinear section of the CPiPPU horizontal section at a rate of the raw material’s flow ($v=0.03...0.40$ m/s) when heated: ○ two-way FFREHRT heating; □ internal FFREHRT heating; ◇ external heating (by a hot heat carrier)

An analysis of the obtained data confirms ensuring the most uniform heating of the entire layer of milk when increasing the speed of milk movement up to 0.4 m/s with non-uniform heating of 0.5 °C.

The main technical parameters of the improved CPiPPU based on FFREHRT are given in Table 2.

Table 1

Comparison of the structural and technological characteristics of the improved CPiPPU with the basic “pipe-in-pipe” structure of the heater with steam heating

Indicator	Basic «pipe-in-pipe» heater with steam heating	Pasteurization «pipe-in-pipe» unit based on FFREHRT
Weight of the unit	$m^*=320$ kg	$m=52$ kg
Time of heating and pasteurization	$\tau=L/v=20/0.4=50$ s	$\tau=L_T/v=11/0.4=27.5$ s
Area of heat transfer surface	$F^*=2.0$ m ²	$F=2.0$ m ²
Unit heating	$Q_{heat}=m_1 \cdot c_{st} \cdot (t_k - t_n) = 320 \cdot 0.48 \cdot (75 - 20) = 8.448$ kJ	$Q_{heat}=m_T \cdot c_{st} \cdot (t_k - t_n) = 52 \cdot 0.48 \cdot (75 - 20) = 1.372.8$ kJ
Product heating	$Q_{pr}=G \cdot c \cdot (t_k - t_n) = 0.32 \cdot 3.969 \cdot (75 - 20) = 69.854$ kJ/s	$Q_{pr}=G \cdot c \cdot (t_k - t_n) = 0.32 \cdot 3.969 \cdot (75 - 20) = 69.854$ kJ/s
Specific metal consumption of the unit	$m=M/F=320/2.0=160$ kg/m ²	$m=M/F=52/2.0=26$ kg/m ²

Note: *Data to compare data the basic structure of a “pipe-in-pipe” heater with steam heating are borrowed from paper [18]

Table 2

Technical parameters of the improved continuous “pipe-in-pipe” pasteurization unit

Technical parameter	Value
Heating surface area, m ²	2.0
Productivity, kg/s	0.024...0.32
Temperature range of the heat transfer surface with FFREHRT, °C	from 15...110
Rate of a raw material’s flow, v, m/s	0.03...0.40
Weight (without loading), kg	52

The obtained scientific and practical results of the research allow us to give the main technical and operational indicators of the improved continuous “pipe-in-pipe” pasteurization unit on the basis of two-way heating by FFREHRT that confirm the effectiveness of the proposed engineering solutions with a guaranteed possibility of the further implementation of the design not only in the dairy industry but also in other sectors of food and pharmaceutical industries. It should be noted that a given design could be used as a heater of liquid phases within the temperature range – 15...110 °C, ensuring the rate of the processed flow

in the range 0.03...0.40 m/s. The use of the tested structure of the improved continuous “pipe-in-pipe” pasteurization unit by the double-sided heating by FFREHRT would provide for the resource-efficient structural and technological re-equipment of many enterprises for achieving a stable and uniform pasteurization process. This, in turn, would allow enterprises to obtain high-quality products to maintain the competitiveness of market relations.

6. Discussion of the results of milk pasteurization in the improved pasteurization unit

The implementation of the improved CPiPPU based on the bilateral heating by FFREHRT with the improved operational parameters and the optimal dimensions and weight, which could provide for the most effective temperature-uniform effect as evidenced by our calculations, has the following benefits, specifically regarding the decrease in the main structural and technological parameters:

- the specific metal consumption, by more than 6 times (26 kg/m² – CPiPPU, Table 1), in comparison with the basic design (160 kg/m²);
- the duration of heat treatment of drinking milk at a temperature of 73...77 °C, when aged for 15... 20 s, is 27.5 s (Table 1), by 1.8 times, compared with the basic design – 50 s, respectively;
- the CPiPPU heat consumption is equal to 1,372.8 kJ, which is 6.2 times less than the consumption by the basic structure – 8,448 kJ (Table 1).

We have determined experimentally the dependences of the temperature difference using an example of a rectilinear section of the horizontal section of CPiPPU when changing the rate of a raw material's flow in the range $v=0.03...0.40$ m/s. The obtained dependences, when compared, prove the efficiency of the two-way heating in CPiPPU (a temperature difference is 0.5 °C) at a speed of 0.4 m/s with the obtained control data: internal by FFREHRT (1.4 °C) and external (by a hot heat carrier – 2.7 °C) for heating by FFREHRT, respectively (Fig. 2).

The proposed modern engineering structural and technological solutions for improving the continuous “pipe-in-pipe” pasteurization unit are characterized by the following benefits: reduced metal consumption while eliminating the need to use heat carriers and the improved conditions of technical operation (Table 1, Fig. 2). Ensuring a uniform heat and mass transfer process of pasteurization of the entire layer of a food raw material in the flow, which, in turn, would increase the competitiveness of these devices while reducing their cost and ensuring the guaranteed quality of the products.

The improved design of the continuous “pipe-in-pipe” pasteurization unit is recommended for performing high-quality heat and mass exchange processes in the food industry (in the range of heat treatment 15...110 °C, Table 2), as well as heaters. For example, for the flow pasteurization of raw milk, wine, juices, and beer for reasonable technological needs with maximum preservation of the original properties

at important stages of functional product manufacturing. At the same time, attempts to violate the technological and structural recommended parameters could lead to a guaranteed reduction in the quality of the process and would reduce the consumer properties of the products in general. The limitations of the experimental part are due to the approbation of the pasteurization “pipe-in-pipe” unit using raw milk in certain speed streams. That is, there is a need for more detailed testing involving other food raw materials, to be followed by the appropriate preparation of recommended conditions for a flow rate, the number of sections, temperature parameters, taking into consideration the obtained physical and chemical properties of the raw materials.

At present, further scientific and practical research is underway to determine ways to increase the turbulence of a raw material's flow when using secondary thermal energy generated by the improved continuous pasteurization “pipe-in-pipe” unit. Involving modern energy-saving complexes and converters of thermal energy, in particular to electricity, by using Peltier elements, which, in turn, could significantly improve the resource-efficient properties for the preservation of the environment.

7. Conclusions

1. The improved design of the continuous pasteurization “pipe-in-pipe” unit based on the bilateral heating by FFREHRT makes it possible to eliminate a structural component of the necessary existence of liquid and steam heat carriers in the conditions of providing the stabilized and uniform heating of the entire volume of the raw materials. The device could be used as a heater to enable a temperature range of the heat and mass exchange processing of food raw materials within the temperature range of 15...110 °C.

2. The improved CPiPPU is characterized by a decrease in the technical and technological indicators, namely, the specific metal consumption, by 6 times, compared to the basic design (26 kg/m², respectively, up to 160 kg/m²). The duration of heating and pasteurization of drinking milk at a temperature of 73...77 °C, aged for 15...20 s, is 27.5 s, which is 1.8 times less. This provides for a reduction in heat consumption to heat the device, which is 1,372.8 kJ (CPiPPU), compared with the consumption by the basic pasteurizer, 8,448 kJ.

The uniformity of heating by the improved design of the continuous pasteurization “pipe-in-pipe” unit based on the two-side heating of the annular space by means of FFREHRT when changing the rate of flow ($v=0.03...0.40$ m/s) has been established by the comparative-experimental way. When using various design solutions of heat supply, the optimal flow rate is 0.4 m/s with a temperature difference under the conditions of internal heating by FFREHRT of 1.4 °C, external (by a hot heat carrier, 2.7 °C), and the two-way heating (CPiPPU), 0.5 °C, respectively. These results confirm the efficiency of the uniform heat treatment of raw materials by the proposed design solution of CPiPPU.

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