The object of study is the milk pasteurization by way of improving construction parameters. Main target experimental substantiation of the design and technological parameters of an improved heater based on the use of an induction heater and conducting production tests of an experimental pasteurizer, evaluating its performance and quality indicators. This study is in the nature of a search for a method to preserve the milk quality.

The study consists of the direction of improving the flow-through and parallel-cumulative induction pasteurizer, the design of the continuous-acting induction milk pasteurizer, the substantiated mathematical dependences of the interrelationships of its effective design and operating parameters, as well as the method of technical parameter reporting and evaluation of the effect of the improved experimental pasteurizer on the basic milk properties.

The bactericidal phase before and after milk pasteurization in an experimental heater is as follows: for fresh milk (t=300 °C), the duration of the bactericidal phase is 2 hours, with self-cooling of fresh milk from 370 °C to 200 °C, the duration of the bactericidal phase is 3 hours, and when cooling milk to 8...100 °C – 8 hours. For pasteurized milk (t=300 °C), the duration of the bactericidal phase is 17 hours, and when the milk is cooled to 8–100 °C, the duration of the bactericidal phase is 30 hours. The proposed induction pasteurizer ensures efficient milk pasteurization produced on dairy farms, ensuring the possibility of direct delivery of the product to a retail chain or delivery to a processing plant without damage, which provides economic benefits to the farm.

The proposed induction pasteurization unit is recommended for use not only in small and medium-sized farms, but also in centralized district milk collection points

Keywords: animal husbandry, pasteurization, electric pasteurization, induction heater, bactericidal cycle, induction energy

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DEVELOPMENT OF AN ELECTRIC MILK PASTEURIZER FOR FARMING

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1. Introduction

The main indicators of milk are its chemical composition, degree of purity, organoleptic, biochemical, physico-mechanical properties, the presence of toxic substances and the presence of substances that neutralize them.

Milk contains more than a hundred organic (fats, proteins, carbohydrates, enzymes, vitamins, hormones) and inorganic (water, minerals, salts, pigments, gases) substances.

Milk is a complex polydisperse system. Milk sugar is soluble in the dispersed medium of milk (85–89 % in water). The size of its molecule is 1–1.5 nm. Milk salts are in the form of colloidal particles, and protein substances form a colloidal solution. Milk fat forms an emulsion in warm milk and a suspension in cold milk [1].

The milk composition is variable. The absence of any substance or its amount slightly exceeding the norm indicates that the animal is in a painful condition or the food ration (feed) is not fully adequate. When heating milk for a long time at a temperature of 100 °C its color changes. This is due to the formation of melanoidins as a result of the reaction between lactose and proteins. Lactose can also react with other free amino acids. Melaoids have a brown color and a caramel flavor. This reaction occurs during the preparation of warmed milk, fermented baked milk, yoghurt and canned milk.

In modern production, economic and organizational forms, the farmer has the opportunity to sell its products not at the factory, but in a wholesale network through its store. The milk offered for sale must be pasteurized [2].

However, it should be noted that the well-known industrial devices for heat treatment of milk are mainly intended for use in processing plants and do not meet modern production requirements in family farms. They are characterized by high metal consumption, high maintenance complexity and high productivity. In this regard, the improvement of the design and technological scheme of the device for the heat treatment of raw milk in family farms is of great scientific and practical importance.

Well-known industrial devices for heat treatment of milk are mainly intended for use in processing plants and do not meet modern production requirements in family farms. They are characterized by high metal consumption, high maintenance complexity and high productivity. In this regard, a number of questions remain open on improving the design and technological scheme of the device for heat treatment of raw milk in private farms, determining rational parameters and operating modes.

As mentioned above, well-known industrial devices for heat treatment of milk are mainly intended for use in processing plants and do not meet modern production requirements in family farms. They are characterized by high metal consumption, high maintenance complexity and high productivity. Therefore, in this regard, a number of questions remain open on improving the design and technological scheme of the device for heat treatment of raw milk in conditions of personal subsidiary farms, determining rational parameters and operating modes [3].

2. Literature review and problem statement

Commercial dairy farms use stationary milking machines that collect milk into milking buckets, or milking machines that can be moved around the cowshed. Recently, the use of devices for milk transportation has also been observed. At that time, there was a high level of contamination and increased acidity of the milk, and therefore the milk was sold at a reduced price [4].

One of the most labor-intensive operations in milk production is its heat treatment. However, the use of steam pasteurizers in farms and other forms of farms requires additional costs for steam-generating equipment, ventilation systems and complex automation [5]. In this regard, the issue arose of increasing efficiency and reducing operating costs during the heat treatment of milk.

The current technical regulations for milk and dairy products have been further tightened in terms of the safety of raw materials [6]. First of all, necessary focused on microbiological indicators: the number of mesophilic aerobic microorganisms and facultative anaerobic microorganisms (MAM and FAnMS, no more than 1×10^5) and the number of somatic cells per 1 cm^3 (no more than 4×10^5). In this regard, producers are faced with a difficult situation: although the bacteriological contamination of the milk produced has remained the same, the requirements for milk quality have increased.

Among the known methods of reducing bacterial contamination in processing plants, the most effective way to preserve the properties of raw milk is to heat it to 72–76 °C keep it for minutes 15...20 seconds and subsequently cool to 40 °C. Adding such a technological operation to primary milk processing allows producers to solve the quality problem associated with high bacterial contamination of milk.

At the same time, transportation costs can be reduced by collecting milk from family farms and farms located far from the dairy in order to fully load the dairy and transport it to the factory once every two days without losing the assortment [7]. At the stage of primary processing, milk is subjected to heat treatment to reduce bacterial contamination. The product is heated indirectly in heating devices using various heat carriers: steam, boiling water, exhaust gases, heated air, and electric current. Saturated water vapor is more widely used for this purpose. Thus, when it is condensed, a large amount of heat is obtained at a relatively low cost [8].

The pasteurization process is the milk heating to a temperature of 63...90 °C to neutralize it. At this time, the taste, smell and consistency of milk remain unchanged, and the bacteria that cause brucellosis, tuberculosis and other diseases are destroyed [9].

The main goal of pasteurization is the destruction of vegetative forms of microorganisms in milk (pathogens of intestinal diseases, brucellosis, tuberculosis, dysentery, etc.). At the same time, it is necessary to preserve the biological nutritional value and quality of milk [10].

The data in article [11] mainly shows problems with milk sterilization. The equipment used is metal-intensive. They are characterized by high labor intensity and high maintenance productivity, but the main reasons for increasing productivity and product quality are not specified.

In [12], the authors analyzed the milk indicators – its chemical composition, degree of purity, organoleptic, biochemical and physico-mechanical properties, the presence of toxic substances and the presence of substances that neutralize them. Milk contains more than a hundred organic (fats, proteins, carbohydrates, enzymes, vitamins, hormones) and inorganic (water, minerals, salts, pigments, gases) substances Milk is a complex polydisperse system. Milk sugar is soluble in the dispersed medium of milk (85...89 % in water). The size of its molecule is 1...1.5 nm. Milk salts are in the form of colloidal particles, and protein substances form a colloidal solution. Milk fat forms an emulsion in warm milk and a suspension in cold milk. In this work [13], the milk composition varies. The absence of any substance or its amount slightly exceeding the norm indicates that the animal is in a painful condition or the diet (feed) is not fully adequate. Water is an important component of milk and determines its physical condition; its content in milk averages 87.5 %. The paper does not specify the reasons for improving the milk quality, as well as the technical means that are the basis for improving quality. According to the author's research [14], the basis of butter is esters and triglycerides, which consist of triatomic alcohol, glycerol and fatty acids. In milk processing, milk fat plays a more important role than its other components. Milk fat contains more than 140 fatty acids. Only 20 of them are significant (1.5 %) and consist mainly of three carbon atoms C4–C20. As in the previous study, the authors mainly explore the technology, but did not specify the technical means.

As indicated in the article [15], palmitic, myristic and stearic acids account for 60...75 % saturated acids, while oleic acid accounts for 30 % unsaturated acids. In winter, milk fat is characterized by a high content of myristic, lauric and palmitic acids. Oleic acid and stearic acid predominate in summer. In addition to oleic acid, it contains a small amount of essential unsaturated acids – linoleic acid, linolenic acid and arachidonic acid (3...5 %). They provide a high biological value of the oil. The density of milk fat is lower than that of water and other milk components. Therefore, fat globules can always float to the surface of the milk. To prevent this property of milk, it is homogenized. When heating milk for a long time at a temperature of 100 °C with its color changing. This is due to the formation of melanoidins as a result of the reaction between lactose and proteins. Lactose can also react with other free amino acids. Melaoids have a brown color and a caramel flavor. This reaction occurs when cooking warmed milk, fermented baked milk, yogurt, and canned milk. When conducting a commodity examination of milk, not only the conformity of products with established requirements is revealed, but also various types of falsification. This study mainly focuses on the milk product, but not on the installation and its design.

In the course of study [15], which is mainly devoted to the milk storage, the number of microorganisms contained in it and the ratio between different groups of bacteria changes. The nature of these changes depends on the temperature, the duration of milk storage, as well as the degree of contamination and the composition of the microflora. The microflora that increases during milk storage is called secondary microflora. The secondary microflora changes according to certain patterns. In other words, it goes through a certain natural phase of development. Milk neutralization when heated to a temperature of 63...90 °C is considered a pasteurization process. In this case, the bacteria that cause brucellosis, tuberculosis and other pathogens are destroyed, while the taste, smell and consistency of milk do not noticeably change. At this time, it is necessary to preserve the biological nutritional value and quality of milk. As in the previous study, the authors do not analyze the installation or its design. The article [16] is in the field of substantiating the parameters and operating modes of pasteurizers that indirectly heat milk. The role of a heat carrier in them is performed by steam or boiling water. The authors of this study did not take into account the design of the sterilizers. The authors of [17] consider well-known industrial installations for the heat treatment of milk, mainly designed for use in technological enterprises and not meeting modern production requirements in a family farm. In this study, despite the broad perspective of the analysis, the authors do not specify a structural analysis. In that article[18], researchers are distinguished by their high metal content, high labor intensity of maintenance and high productivity. In this regard, many issues on improving the constructive and technological scheme of the device for heat treatment of raw milk in the conditions of family farm farms, determining the rational parameters and operating modes remained open, however the problem of the milk pasteurization quality was not studied.

3. The aim and objectives of the study

The aim of this study is to develop the design of the pasteurizer parameter. A patent was obtained for this development and improved design and technological parameters of heat treatment for milk in a farming environment.

To achieve this aim, the following objectives are accomplished:

– to conduct a theoretical study of the basic process of milk pasteurization using an induction heater;

– to develop a block diagram of the pasteurizer.

4. Materials and method

The object of study is the milk pasteurization by way of improving construction parameters. Main target experimental substantiation of the design and technological parameters of an improved heater based on the use of an induction heater and conducting production tests of an experimental pasteurizer, evaluating its performance and quality indicators. The working hypothesis chosen for the purposes of the study is that the efficiency of the process is ensured by ensuring that the milk heated by induction energy is maintained at a temperature above the pasteurization temperature for the required period of time in accordance with the technological requirements of milk pasteurization. The main assumption of this study was effective modes of operation of the device, ensuring parallel operation of the milking parlor, improving the microbiological parameters of milk produced on a dairy farm with low energy consumption. The results presented in this paper are confirmed by theoretical and experimental studies. Theoretical studies were conducted using the basic laws of mechanics, electrical engineering, thermal engineering, hydraulics and mathematical analysis methods. Experimental studies have been conducted on induction heating prototypes using standard methods, and the operation of the developed experimental milk pasteurizer in industrial conditions has been verified.

5. Results of research of the continuous technological process of milk pasteurization

5. 1. Theoretical study of the milk pasteurization process using an induction heater

A vortex induction heater is known [19]. This device consists of a magnetically conductive cylindrical container, pipes for supplying and discharging coolant, an induction coil made of copper wire and a toroidal cylindrical housing made of insulating material enclosing it. Inside said container, metal pipes are attached to the outer walls, arranged concentrically concerning each other, with the same distance between them. This formed a labyrinthine passage for the coolant from the inlet pipe to the outlet pipe. An induction coil is placed inside the specified pipe.

The main disadvantage of this heater is the inefficiency of lengthening the selected travel path to maintain heated milk at a certain temperature for a specified period of time, by the technological requirements of milk pasteurization.

Another vortex induction heater for liquids consists of inlet and outlet pipes, upper and lower covers, an induction coil, double-walled cups and an annular bottom [20]. Here, the vortex heater is equipped with an air vent and a magnetic washer, and the air vent is mounted on the top cover using fasteners connecting the top cover to the magnetic washer, and a vertical hole is drilled in the fastener. with two open sides. This article's author [21] points out that Environmental concerns and consumer demand necessitate alternative pasteurization techniques that sustainably produce safe and high-quality milk. To this end, a new non-thermal (<42 °C) moderate electric field (MEF) system was developed with elongated electrodes and a reduced electrode gap. Response surface methodology optimized technical and thermo-physical attributes, including viscosity, density, freezing point, solid non-fat (SNF), temperature, power usage, and specific energy consumption (SEC), by altering electrical field intensities (EFI) and mass flow rates ($\dot{m}$) from 25 to 30 V/cm and from 0.017 to 0.033 kg/s, respectively. The results were then compared with the conventional thermal pasteurization (CP, 63 °C for 30 min). Besides, process cost analysis in terms of electricity consumption was performed to identify cost reduction opportunities for the industry, and milk samples were analyzed by scanning electron microscopy to elaborate on the mechanisms involved. MEF optimal processing conditions were 29.8 V/cm EFI and 0.018 kg/s $\dot{m}$, which reduced 98.58 % of energy consumption, 98.51 % of SEC, and 99.09 % of processing time in comparison with CP. Also, MEF possessed higher productivity than CP. D-value for total count bacteria (TCB) in MEF was significantly lower than CP (0.06 vs. 14.80 min), and MEF and CP reduced TCB by 99 % and 88.61 %, respectively. Compared with the previously reported MEF milk pasteurizer, the MEF system developed in this study saved energy, cost, and time by 99.2 %, 99.0 %, and 78.4 %; therefore, this emerging technology could further contribute to the sustainable manufacturing of foods, however not analyzed of construction of equipment for pasteurization. This article's author [22] points study presents a new non-thermal moderate electric field (MEF) process for milk pasteurization. To evaluate the applicability of this process, fresh milk was treated by MEF at electrical field strength (EFS) of 8.33, 14.58, and 20.80 V/cm and mass flow rates (MFR) of 0.018, 0.042 and 0.077 kg/s to compare the microbiological quality, alkaline phosphatase activity, chemical composition, and some physical properties of the product with those of conventionally pasteurized (15 s at 72 °C) and raw milk. The changes in the total count of bacteria (TCB) and titratable acidity of samples were observed during 18 days of storage at 5 °C for shelf life estimation. The results showed that MEF reduced energy consumption by 63 % in comparison with thermal pasteurization. Also, MEF treatment inactivated coliforms (100 %), Staphylococcus aureus (100 %), psychrophiles (100 %), yeasts and molds (100 %), and alkaline phosphatase (100 %) while keeping the processing temperature below 22 °C. Also, TCB of the sample was reduced by increasing the EFS from 8.33 to 20.8 V/cm and decreasing the MFR from 0.0774 to 0.0185 kg/s. The longest shelf life of MEF samples, i.e., 15 days, was observed at EFS of 20.80 V/cm and MFR of 0.018 kg/s which was better than that of thermal pasteurization samples, i. e., 9 days. This article's author [23] points study of pulsed electric field processing. Pulsed electric field (PEF) processing was investigated as an alternative dairy preservation technology that would not compromise quality yet maintain safety. PEF processing of raw whole milk (4 % fat) was conducted at two processing conditions (30 kV/cm, 22 μs, at either 53 or 63 °C outlet temperature) and compared with two thermal treatments (15 s, at either 63 or 72 °C) and a raw milk control and replicated twice. Milk bottles (2 L) from each treatment were incubated for two weeks, at 4 and 8 °C, and assessed for total plate count, pH, color, rennetability, plasmin activity and lipid oxidation. The microbial quality of the thermal (72 °C/15 s) and PEF (63 °C) were similar. A drop in pH occurred after a change in counts was observed. Rennetability was not different between the treatments. Short-chain acids dominated the volatile profile of the milk samples. The concentration of volatiles derived from microbial activity, namely 2,3-butanedione, acetic acid and other milk lipid-derived short-chain free fatty acids (e. g. butanoic and hexanoic acids), followed the trend of microbial activity in milk samples, similar as above authors, not analyzed of construction of equipment for pasteurization. This article's author [24] points study of the heat treatment of milk. It is well understood that heat treatment of milk, such as pasteurization, allows its safe consumption in terms of foodborne illness, while failure in adequate heat treatment has resulted in both product recalls and also foodborne disease outbreaks. Aspects of different heat treatments within the dairy industry that affect relevant microorganisms, with an emphasis on bacteria, are discussed in this review. These include a description of D- and Z-values as measures of heat resistance, the factors that affect D-values, such as different dairy matrices, a discussion of some of the mechanisms associated with heat resistance of bacteria important for dairy products, different types of heating effects on microorganisms present in various dairy products, and recommendations for the most appropriate experimental design for understanding how heat affects microorganisms. The milk processing technology is specified, but the technology and technical means are not specified. This article's author [25] points study of the milk serum. Milk serum contains many immune active proteins that are sensitive to heat treatment. This study compared the effects of thermal (63 °C, 30 min; 72 °C, 15 s; 85 °C, 5 min) and non-thermal (ultra-violet-C, UV-C; thermoultrasonication, TUS) treatments on bovine milk serum proteins by using label-free LC-MS/MS-based proteomics. UV-C (4500 J/L) and TUS (60 W, 6 min) treatments achieved a 5log microbial reduction as determined by plate counting. Proteomics showed that e.g., complement proteins, xanthine dehydrogenase /oxidase, and fatty acid-binding protein decreased significantly ($p<0.05$, |fold change|>1) after thermal treatments, and almost no lactoferrin, immunoglobulin, and lactoperoxidase was retained after heating at 85 °C for 5 min, whereas these proteins were mostly retained after non-thermal treatments. Most of these heat-sensitive proteins were located in membrane and extracellular regions and were involved in cellular and metabolic processes, response to stimulus, binding, immune process and catalytic functions. Finally, part of the proteomics results was verified by ELISA. This study provided insights for the development of optimized thermal and novel non-thermal treatments for dairy processing. This article describes the technology of milk processing, but does not specify the technical means and design. The author of this research [26] points electric field (PEF) processing was investigated as an alternative dairy preservation technology that would not compromise quality yet maintain safety. PEF processing of raw whole milk (4 % fat) was conducted at two processing conditions (30 kV/cm, 22 μs, at either 53 or 63 °C outlet temperature) and compared with two thermal treatments (15 s, at either 63 or 72 °C) and a raw milk control and replicated twice. Milk bottles (2 l) from each treatment were incubated for two weeks, at 4 and 8 °C, and assessed for total plate count, pH, color, rennetability, plasmin activity and lipid oxidation. The microbial quality of the thermal (72 °C/15 s) and PEF (63 °C) were similar. A drop in pH occurred after a change in counts was observed. Rennetability was not different between the treatments. Short-chain acids dominated the volatile profile of the milk samples. The concentration of volatiles derived from microbial activity, namely 2,3-butanedione, acetic acid and other milk lipid-derived short-chain free fatty acids (e.g. butanoic and hexanoic acids), followed the trend of microbial activity in milk samples. This article describes the technology of milk processing, but does not specify the technical means and design. In article [27], the effect of high-intensity pulsed electric fields (HI-PEF) processing (35.5 kV/cm for 1,000 or 300 μ with bipolar 7-μs pulses at 111 Hz; the temperature outside the chamber was always <40 °C) on microbial shelf life and quality-related parameters of whole milk were investigated and compared with traditional heat pasteurization (75 °C for 15 s), and to raw milk during storage at 4 °C. A HIPEF treatment of 1,000 μ ensured the microbiological stability of whole milk stored for 5 d under refrigeration. Initial acidity values, pH, and free fatty acid content were not affected by the treatments; and no proteolysis and lipolysis were observed during

1 week of storage in milk treated by HIPEF for 1,000 μ. The whey proteins (serum albumin, β-lactoglobulin, and α-lactalbumin) in HIPEF-treated milk were retained at 75.5, 79.9, and 60 %, respectively, similar to values for milk treated by traditional heat pasteurization. Initial acidity values, pH, and free fatty acid content were not affected by the treatments; and no proteolysis and lipolysis were observed during 1 week of storage in milk treated by HIPEF for 1,000 μ. The whey proteins (serum albumin, β-lactoglobulin, and α-lactalbumin) in HIPEF-treated milk were retained at 75.5, 79.9, and 60 %, respectively, similar to values for milk treated by traditional heat pasteurization.

The main disadvantage of this heater is the inability to keep the heated milk at a certain temperature for the time required for pasteurization.

As our research has shown, this device also involves lengthening the milk flow path to ensure that the heated milk is maintained at the pasteurization temperature, so its main disadvantage is considered to be the lack of efficiency of the process. The elements added to the structure serve to solve the problem. Thus, dividing the flow of liquid heated by induction energy into two for simultaneous processing as water and milk by wing-shaped stem plates located in the center of the housing allows pasteurized milk to be stored for the required time in a container with a water jacket outside the device, which increases the pasteurization effect. The proposed induction pasteurizer ensures efficient milk pasteurization produced on dairy farms, ensuring the possibility of direct delivery of the product to a retail chain or delivery to a processing plant without damage, which provides economic benefits to the farm. The initial data are during the research, the installation indicator was 5.56 m^3/s, where the initial temperature of the milk was 20 °C, and the final temperature of the milk was 90 °C, the mains voltage was 380 V, and the frequency was 5 Hz.

The connection of the phases of the first winding is a "triangle". The first winding's material is copper, the second winding is a stainless pipe, the magnetic circuit is electrical steel 3414, and the sheet thickness is 0.35 mm. The study was conducted in the sequence of determining the mathematical dependencies of the following factors.

After analyzing the authors working in this direction, it is possible to find these data as initial data, and our research was conducted to determine to determine the mathematical dependencies of the following factors.

Let's use extreme experimental planning to optimize the operating and design parameters of an experimental heating device. Here, the minimum temperature difference (T, °C) and power consumption (P, kW) is assumed as the optimization criterion (objective function φ) at the input and output of the device. The optimization parameters were taken as follows: x_1 (heater length L, mm), x_2 (external flow gap, mm), x_3 (internal gap aitch, mm), x_4 (capacity – M, kg/h).

The variable parameters of the four-factor experiment are as follows (Table 1).

Table 1

Variable parameters of the four-factor experiment

No.	Parameter	Indicators of parameters and measures	Code	Border of variation		
				–1	0	+1
1	Heater length	L, mm	x_1	1,000	1,200	1,400
2	External intermediate space	a_{xar}	x_2	3	5	7
3	Internal intermediate space	$a_{iç}$	x_3	3	5	7
4	Productivity	M, kg/hour	x_4	290	340	390

After excluding the insignificant coefficients of the planning of the four-factor experiment, the regression equation is as follows:

$$Y_1 = b_0 + b_2 a_{xar} + b_2 a_{iç} + b_5 L^2 + \\ + b_6 a_{xar}^2 + b_{13} a_{xar} M + b_{14} a_{iç} M. \quad (1)$$

The equation with the number values of the coefficients is written as follows:

$$\Delta T = -9.614 - 28.7331 a_{xar} + 16.698 a_{iç} - \\ -5.994 L^2 + 7.997 a_{xar}^2 - 1.967 a_{xar} M \cdot 1.969 a_{iç}. \quad (2)$$

Optimum values of parameters:
1. a_{xar}, $a_{iç}$ – 4...6 mm.
2. L=1250 mm.
3. M=400 kg/hour.

The input factors of the three-factor experiment were:
– the number of indicator coils – x_1, (ω-units);
– the outer diameter of the pipe – x_2 (d_{xar}, mm);
– the length of the indicator –x_3 (l_{ind}, m);
– the output factor (target function active power);
– the active thermal power (P, W).

The optimal values of input factors are determined in relation to the maximum of P.

The variational parameters of the factors are as shown in Table 2.

Table 2

Variational parameters of a three-factor experiment

No.	Parameter	Indicators of parameters and measures	Code	Border of variation		
				–1	0	+1
1	Number of inductor coils	ω, piece	x_1	720	870	1,020
2	The outer diameter of the pipe	d_{xar}, mm	x_2	0.021	0.025	0.029
3	Indicator length	l_{ind}, m	x_3	0.9	1.0	1.1

After excluding the insignificant coefficients of the planning of the three-factor experiment, the regression equation is as follows:

$$Y_2 = b_0 + b_1\omega + b_7\omega^2 + b_8 d_{xar}^2 + b_9 l_{ind}^2, \quad (3)$$

$$P = 0 - 16.3\omega + 139.9\omega^2 + 159.9 d_{xar}^2 + 128.8 l_{ind}^2. \quad (4)$$

Optimum values of parameters:
1. Outer diameter of pipe – d_{xar}=0.029 m.
2. Number of indicator winding – ω=900.
3. The length of indicator l_{ind}=1 m.

At the productivity of the experimental installation of 200–400 kg/h, the heating time of milk does not exceed 2 seconds. In a number of studies, for milk pasteurization at a temperature of 67 °C, this time should be 30 seconds.

5. 2. Development of a block diagram of the pasteurizer

This device also involves lengthening the milk flow path to ensure that the heated milk is maintained at the pasteurization temperature, so its main disadvantage is considered to be the lack of efficiency of the process.

As a working hypothesis, the design improvement aims to increase the efficiency of pasteurization by ensuring that the heated milk is kept at the pasteurization temperature for a specified period under the technological requirements of milk pasteurization. This goal is achieved by the fact that the induction heating pasteurizer consists of a housing made of food-grade plastic, two lower inlet chambers (right and left) and two upper outlet chambers (right and left), inlet and outlet pipes, respectively, arranged coaxially. pipes inside the housing, and a central heating element in the housing. It is equipped with a stainless-steel rod with wing-shaped plates on both sides, an indicator coil on the outside of the housing, a thermal insulation layer surrounding the housing, a water tank, a water pump, water pipes, milk pipes and a water jacket. The tank consists of a milk pump, a milk tank and taps. According to the working hypothesis, the liquid flow is divided into two parts by a core plate located in the center of the body, one of which supplies the water jacket of the tank with heated water, and the second for milk processing. The elements added to the structure serve to solve the problem. Thus, dividing the flow of liquid heated by induction energy into two for simultaneous processing of both water and milk using wing-shaped rod plates located in the center of the housing allows pasteurized milk to be stored for the required period in a container with a water jacket outside the device, which enhances the pasteurization effect.

The closest technical solution to the idea as a working hypothesis is an induction heater with a liquid reservoir. This device consists of a housing, a lower input chamber and an upper output chamber, as well as their corresponding input and output pipes. The movement of the heated liquid is carried out in a gap formed between coaxially arranged pipes and a stainless-steel rod inside a housing made of food-grade plastic. An inductor coil is located outside the housing, and an annular volumetric storage device is installed on it. The liquid from the heater is fed through a circulation pipe into the storage tank. The product is discharged through the exhaust pipe. The device is protected from above by a layer of thermal insulation. Since this device involves lengthening the milk flow path to ensure that the heated milk is maintained at the pasteurization temperature, its main disadvantage is the lack of efficiency of the process.

A pasteurizer with an induction heater is schematically shown in Fig. 1.

The induction heating pasteurizer consists of a housing made of food-grade plastic 1, two lower inlet chambers 2, 3, two upper outlet chambers 4, 5, and inlet and outlet pipes 6, 7. Accordingly, the housing 1 with coaxially arranged pipes 8 inside and stainless steel rod 10 located in the center of the housing 1 and provided on both sides diametrically with a wing-shaped plate 9, with gaps 11 formed between them, and an indicator coil 12 outside the housing 1, thermal insulation layer 13, covering body 1, water tank 14, water pump 15, water pipes 16, milk pipes 17, holder 19, equipped with a water jacket 18, milk pump 20, milk tank 21 and consisting of taps 22.

A pasteurizer with an induction heater works as follows [28]. The water and milk pump 15, and 20 are switched on, and the indicator coil 12 is connected to the current source. At this time, the tap 22 on the water supply 16 and the tap 22 connecting the milk tank 20 to the milk pump are open. Water enters the left inlet chamber 3 from the left inlet pipe 6, passes through the left-hand gaps 11, separated by coaxial cylinders 8 and wings 9 of the centrally located rod 10, and the induction energy received by the indicator coil 12 is heated, enters the upper outlet chamber 5, and from there enters the water jacket 18 with a left outlet pipe 7 and a water pipe 16, in which the tank is located 19, from below, and exits from above, and circulates by pouring into a water tank 14 through a water pipe, in a water jacket 18 allows the temperature of the storage unit located at 19 to remain constant. At this time, milk supplied from the milk container using a pump passes through the lower right inlet pipe 6 into the right inlet chamber 2, and from there through the gaps 11 on the right side, separated by wings 9 from the coaxially arranged cylinders and centrally located rod 10, and enters the indicator circuit. It is heated by the induction energy received by 12 and transferred to the upper outlet chamber 4, and from there to the holder 19 through the right outlet pipe 7 and milk line 17. The milk collected in the storage tank 21 at the pasteurization temperature (depending on the adopted technology) is stored with the support of a water jacket for as long as required by technological necessity.

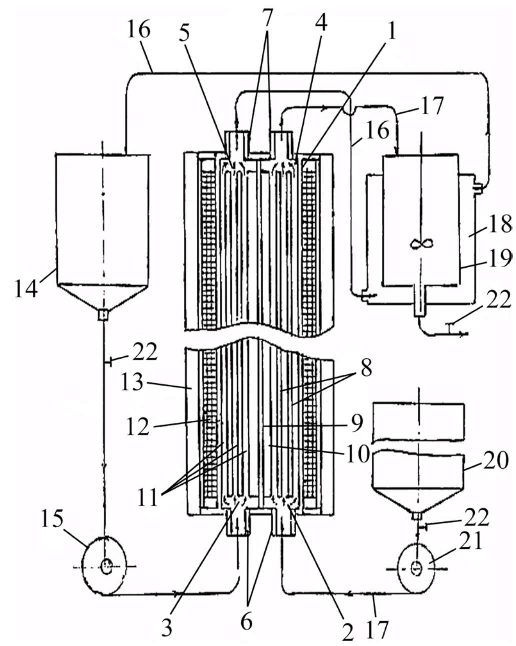

Fig. 1. Block diagram of the pasteurizer: 1 — barrel; 2, 3 — lower right and left inlet chambers; 4, 5 — two upper outlet chambers, right and left; 6, 7 — inlet and outlet pipes; 8 — coaxially arranged pipes; 9 — wing-shaped plate; 10 — rod; 11 — intermediate gap; 12 — indicator coil; 13 — insulation layer; 14 — water tank; 15 — water pump; 16 — water pipe; 17 — milk pipes; 18 — water jacket; 19 — holder; 20 — milk pump; 21 — milk tank; 22 — taps

The proposed induction pasteurizer ensures efficient milk pasteurization produced on dairy farms, ensuring that it can be directly sold in a retail chain or delivered to a processing plant without damage, which provides economic benefits to the farm.

Fresh milk was used in experimental studies. The main components of milk are characterized as follows. The water in milk is predominantly in a free state. The average water content in the milk taken for analysis was 87.0 %. When heated to 1000 °C, water turns into steam. The remaining 13.0 % is called the dry residue. The most volatile part of the dry residue is milk fat (butter). Therefore, fatness indicators are used more in research. The fat content in the sample taken for analysis was 3.9 %. Milk fat is an ester of glycerol and alcohols of saturated and unsaturated fatty acids (oleic, caproic, caprylic, capric, lauric, myristic, palmitic, stearic, dioxysterine, oleic) [29].

Carbohydrates in milk are represented by milk sugar. In the sample, its number was 4.6 %. Lactose is dissolved in milk, and 90 % of it is converted into whey during cheese production.

Fat is distributed in milk in the form of numerous balls. Their number is not constant, but variable. The literature [30] shows that their number ranges from 739 thousand to 4.8 million per 1 ml of milk. On average, the number of fat globules per ml ranges from 1.6 to 5 ml. Under a microscope, the diameter of the oil droplet in the material sample was determined to be 0.1…10 microns, and the density was 1,029 kg/m^3 at a temperature of 300 °C. As the heating temperature increased, the density and viscosity of the milk decreased. If the viscosity at 60 °C was 0.060 m^2/s, then at 76 °C it was 0.052 m^2/s. During this time, the milk density decreased by 14.2 %. Thermophysical properties of milk at heating temperatures in the range of 60…80 °C was:

– heat capacity is 3900 J/kg·K;
– coefficient of thermal conductivity is 0.513 W/m·K;
– thermal conductivity is $0.098 \cdot 10^{-6}$ m^2/s.

The obtained values show that within a more reliable range (70…80 °C) of the pasteurization temperature (60 °C), certain changes in the properties of milk are possible before processing, which should be taken into account when designing options for constructive improvements to heating devices. In general, it is known from studies conducted during reconnaissance experiments [31] that heating milk causes changes not only in its composition, but also in its properties. However, these results were obtained indirectly in the study of devices powered by heating. In these devices, heat is applied to the milk container from the outside to the center, as a result of which the layers of material located closer to the walls of the container heat up more intensively. The influence of various temperature effects on milk has also been recorded on its bactericidal properties. During induction pasteurization, the milk is heated in stages. First, the milk supplied to the plant is heated to the pasteurization temperature (60 °C), then kept at this temperature for a certain time in a storage tank, and then cooled in a regenerator to a temperature at which the destruction of microorganisms occurs.

The effect of temperature on the microflora at these stages is different. This makes it important to determine the operating mode of the pasteurizer and the parameters of the heater. Experiments conducted with the aim of completely destroying the microflora yielded almost similar results. In the course of our research, let's study the dependence of the bactericidal phase of milk on its shelf life. The bactericidal phase of milk before pasteurization and after pasteurization in the experimental heater is as follows: For freshly milked milk (t=30 °C), the duration of the bactericidal phase is 2 hours; When fresh milk is selfcooled from 37 °C to 20 °C, the bactericidal phase lasts 3 hours, and when milk is cooled to 8…10 °C – 8 hours. For pasteurized milk (t=30 °C), the duration of the bactericidal phase is 17 hours, and when the milk is cooled to 8…10 °C, the duration of the bactericidal phase is 30 hours. It was found that in an experimental installation for long-term storage of pasteurized milk (2 days) without spoilage (at 4 °C), the temperature difference at the inlet and outlet increases. Therefore, the optimization of inlet and outlet temperatures should be determined by minimizing this difference. After heat treatment of milk, its organoleptic properties practically do not change in the presence of indirect heating devices. The fat content remains almost constant. The density is slightly lower compared to natural milk. The acidity depends on the time elapsed from the moment of milking to sending the milk for processing. In the experimental induction pasteurizer, some protein coagulation occurs, from which ammonia and sulfur hydrate are separated.

However, due to the action of yeast enzymes, it is difficult to coagulate. This happens because part of the calcium salts contained in it passes into an undissolved precipitate. In the experimental setup, pasteurized milk does not require sterilization before coagulation of albumin and globulin. Thus, in the experimental setup, their interaction with sugar in the carbonate group is very small. The release of carboxylic acid from milk can lead to a slight decrease in the acidity of even pasteurized milk. There are some changes in the salt content of milk. Their number decreases slightly, and the variance increases. Some of the salts become sediments. The above-mentioned changes in the composition and properties of milk are also observed in indirect heating pasteurizers. But the level of change here is deeper. The effect on milk fat content in the induction pasteurization method is more specific. Milk contains 150 fatty acids. It is found in milk in a coarse form. Only the amount of lipids is very small (0.06 %). Fat is distributed in milk in the form of small particles. The particle size in unpasteurized milk is 0.5…10 microns. The smaller they are, the more resistant the milk is to coagulation.

On an experimental installation with a capacity of 200…400 kg/hour milk heating time does not exceed 2 seconds. In a number of studies, this time should be 30 seconds for milk pasteurization at a temperature of 67 °C. When observing the flow of milk in the heating zone through the viewing window, the flow is quite chaotic, even with low pump efficiency. The colored jet instantly dissipates and enters a swirling turbulent motion. In this zone, the milk flow rate slows down from the speed of rotation of the pump impeller and heats up to a temperature corresponding to the required temperature regime. The flow in the pipe gaps exerts pressure on the working organs of the pump, making a complex vortex motion with different speeds. This leads to the retention of some of the milk. When adjusting the capacity and temperature of milk heating by the outlet tap (increasing T), the time of milk in the heating zone and the time of transition to the working area can be delayed by half a second for every 40 °C. by temperature. The milk flow rate in the heating zone varies exponentially depending on productivity. If the flow rate in the heating zone is 0.17 m/s with a capacity of 300 kg/hour, then with an increase in productivity to 400 kg/hour and 600 kg/hour, the milk flow rate will be 0.24 m/s. It was noted that the subsequent increase in productivity led to a multiple increase in the flow rate in the milk processing area. Using the method of planning extreme experiments, the total power (N, W) is determined by the diameter of the indicator (D, mm) and length (lind, m); productivity (M, kg/hour); dependences on the number of turns of the indicator (ω, number) and the length of the indicator tube (lind, m) are determined. The specified optimization criteria are based on the objective function (minimum full power, active heat output P, W) and maximum efficiency M. The diameter of the indicator tube satisfying the above conditions is D=25 mm, and the length of the indicator tube is L=1.1

m. The number of indicator coils corresponding to the minimum of full power is determined to be ω=2050. The number of turns corresponding to the maximum capacity of the experimental installation is 900, and the pipe length is 1.08 m. The optimal values of the gaps between the pipes are the parameters that ensure the maximum active heat output (*P*, *W*) and the temperature difference at the inlet and outlet of the device (*T* °*C*), namely the external flow and internal gaps aitch: flow=3 mm, aitch=6 mm. Part of the pasteurization process takes place in a container and largely depends on the volume of the container and the heating temperature of the milk. In the case of an increase in the pasteurization temperature of milk, while maintaining a constant volume according to the *Fa* criterion, a decrease in the volume of the retainer helps to reduce it to zero at t>76 °C (Fig. 2).

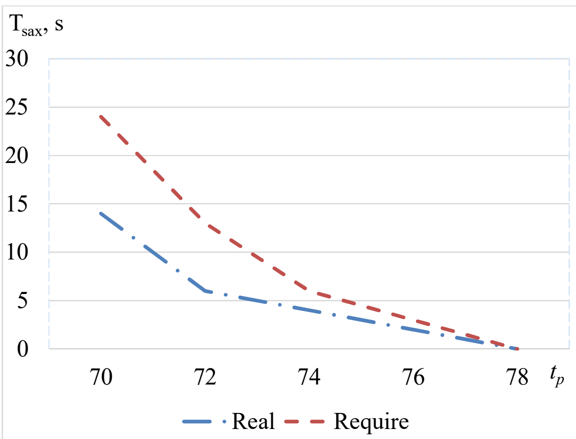

Fig. 2. Graph of the dependence of milk shelf life on pasteurization temperature: 1 – real; 2 – required

The time spent by the milk in the heating device is sufficient to destroy the microflora. The *Fa* criterion requires an increase in the required storage volume at a constant pasteurization temperature t_p=76 °C (Fig. 3).

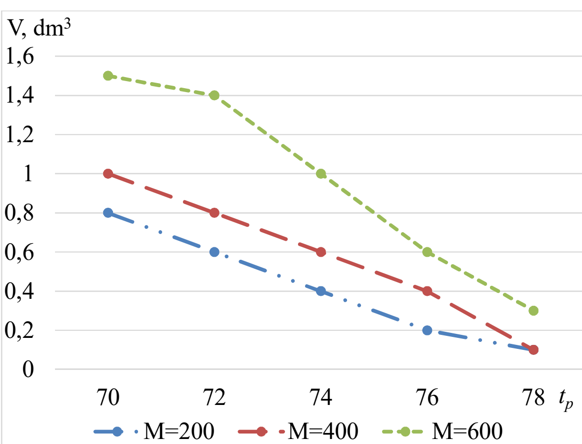

Fig. 3. Graph showing the required volume of the storage tank at different plant capacities: 1 – *M*=200 kg/h; 2 – *M*=400 kg/h; 3 – *M*=600 kg/h

Experiments with a pasteurizer at a constant temperature (t_p=76 °C) show that at low values of the Pasteur criterion $\left(F_a^3\right)$ in the regenerator (0.2...0.5), the keeper Pasteur criterion changes by 70...80 %. At F_a^3 = 0.8...1.0, it is slightly less. The residence time in the container as a function of temperature and its pasteurizing effect (*Fa* – Pasteur criterion) are shown in Fig. 2, and the graph showing the required volume of the container for different device performance is shown in Fig. 3.

When the milk enters the heating device with a temperature of 60 °C at the outlet of the regenerator, it heats up to a temperature of 76–78 °C, the storage time of the material in the storage tank is 30 seconds, and the volume used is no more than 2 liters. liters. As productivity and temperature increase, this volume can be further reduced. As a result of the calculation based on experimental values, the heat transfer surface should be 0.93 m^2.

The working hypothesis chosen for the purposes of the study is that the efficiency of the process is ensured by ensuring that the milk heated by induction energy is maintained at a temperature above the pasteurization temperature for the required time in accordance with the technological requirements of milk pasteurization.

6. Discussion of the results of developing the design of the pasteurizer parameter

The introduction of farm-based pasteurizers requires additional costs for steam generation equipment, ventilation systems, and sophisticated automation. In this regard, there is a great need for the use of devices and devices that directly heat milk. The working hypothesis chosen for the purposes of the study is that the efficiency of the process is ensured by ensuring that the milk heated by induction energy is maintained at a temperature above the pasteurization temperature for the required time in accordance with the technological requirements of milk pasteurization. Analytical dependences have been obtained for the method of describing the operating and design parameters of an induction heater, which was chosen as a working hypothesis through theoretical research. At the same time, it was found that a double-row PB2 wire was used in the transformer-type heater, the cross-sectional area of the wire was 58.8 mm^2. 86 winding points were identified, arranged in two rows. The remaining parameters of the heater are similar to those indicated in the report for a conventional transformer. The distribution of energy flows in the inner and outer cylinders of the inductor is investigated. It is established that the density of the heat flow from the outer walls of the inner cylinder interacts with the coolant. This is confirmed by the heat flow in the cylinder itself. The temperature distribution over the cylinder thickness remains constant over time at constant power $\left(E_\sigma^\varepsilon\right)$. These are the flows from the cylinder to the inductor and from the cylinder to the coolant. When heating milk in an induction heater and subsequent storage in a container, changes in the physico-mechanical and some thermophysical properties of milk, as well as the cessation of the vital activity of microorganisms, have been studied. As the heating temperature increased, the density and viscosity of the milk decreased. If the viscosity at 60 °C is 0.060 m^2/s. If it were 10^{-6}, then at 76 °C it would be 0.052 m^2/s 10^{-6} milk density decreased by 14.2 %. The thermophysical properties were as follows:

– heat capacity is 3900 C/kg·K;
– thermal conductivity coefficient is 0.513 W/m·K;
– thermal conductivity is 0.098×10^{-6} m^2/s.

They should be taken into account when designing options for constructive improvements to the heater. This is confirmed by the heat flow in the cylinder itself. The proposed induction pasteurizer ensures efficient milk pasteurization produced on dairy farms, ensuring the possibility of direct delivery of the product to a retail chain or delivery to a processing plant without damage, which provides economic benefits to the farm. The proposed induction pasteurization unit is recommended for use not only in small and medium-sized farms, but also in centralized district milk reception points.

7. Conclusions

1. Based on theoretical studies, analytical dependencies have been obtained for the method of describing the operating and design parameters of an induction heater, which was chosen as a working hypothesis. At the same time, it has been found that a double-row PB 2 wire was used in transformer-type heaters, the cross-sectional area of the wire was 58.8 mm^2. The remaining parameters of the heater are similar to those indicated in the report for a conventional transformer.

2. The efficiency of the process is ensured by ensuring that the milk heated by induction energy is maintained at a temperature above the pasteurization temperature for the required time under the technological requirements of milk pasteurization. If the viscosity at 60 °C is 0.060 m^2/s. If it were 10^{-6}, then at 76 °C it would be 0.052 m^2/s 10^{-6} milk density decreased by 14.2 %. The thermophysical properties were as follows: heat capacity – 3900 J/kg K; thermal conductivity coefficient – 0.513 W/m. K; thermal conductivity 0.098.10^{-6} m^2/s. They should be taken into account when designing options for constructive improvements to the heater.

Conflict of interest

The authors have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

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

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