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ENERGY SAVING IN MILK PASTERIZATION PROCESS WITH HYDRODYNAMIC HEATER USE

Krasnov I.N., Krasnova A.Yu., Miroschnikova V.V. and Tolstoukhova T.N.

The Azov-Black Sea Engineering Institute is a branch of the Federal State Budget Educational Institution of Higher Education "Don State Agrarian University", Rostov Region, Zernograd, ul. Lenina, 21-Russia

Abstract

They determined the sources of heat loss during milk pasteurization: in the surrounding medium and with the flow of cooling water. They proposed the heat insulation of the milk heater to reduce heat and energy losses in a pasteurization pack by mounting of the holder on its surface and the use of a heat pump during the last stage of pasteurized milk cooling. They obtained the calculated dependences to determine the main parameters of the improved pasteurizer with a hydrodynamic heater.

Key words: milk, pasteurization, heat loss, heat pump.

Introduction

At present, most of the milk is produced by small economic units, its collection and sale is difficult, its storage time and its bacterial contamination are increased [Bredikhin (2011); Bredikhina (2014)]. This causes the need for milk primary processing and pasteurization directly at the site of its production before the delivery to dairy plants.

The existing pasteurization units for indirect heating of milk with an intermediate heat carrier (mainly steam) have a low thermal efficiency and are designed for the pasteurization of a large volume of milk. The known direct milk heating plants are mainly developed on the basis of hydrodynamic heaters (HDH) and also have a number of drawbacks in terms of uneven exposure to milk, an increased force on the cut of milk layers in a heater, a significant heat loss to the environment and with the flow of water used for pasteurized milk cooling. The pasteurizers of direct milk heating have higher efficiency in comparison with indirect heating plants, do not require the presence of boiler rooms, steam lines and automation devices, which makes them more preferable for small dairy farms. However, the process of their work and their parameters are not studied sufficiently.

Flowing cold water is used to cool milk in serial pasteurized direct heating plants - the main source of heat loss in them. It is advisable to use a heat pump with the possibility of cold milk preheating fed for pasteurization to eliminate this during the last stage of heat treatment.

Research methods

The beginning of research on the disinfection of liquids by heating was laid by the pasteurization founder Louis Pasteur more than 100 years ago. After that, scientific activity was mainly aimed to justify the parameters and operating modes of pasteurizers for indirect heating of liquid by steam or hot water [Cook (1955); Mavrin (2015); Plaxin (2005)].

Research methods combined theoretical and experimental studies of an improved pasteurization plant operation with a hydrodynamic milk heater in milk cooling modes after its pasteurization. Theoretical analysis of the apparatus operation was carried out using the laws of classical mechanics, gas dynamics, hydraulics and mathematical analysis. The experimental studies were performed using standard and private techniques, serial devices and equipment, by the processing of their results on a computer with the use of applied statistical program package.

Research results

Hydrodynamic heater is the main thermal apparatus of the pasteurization unit for direct heating of milk [Zaushitsin, *et al.*(1985); Ashuraliev (2002)]. Since the existing HDH have high heat losses to the environment and an uneven load pulsation due to the simultaneous coincidence of cells and their opening during rotor rotation, the heater was used in the experiments. This heater was manufactured according to the Russian Federation patent No. 2398499 (fig. 1) [Krasnov, *et al.* (2010)].

To eliminate these drawbacks in a new heater the cells are arranged in rows along a helical line on the surface of the rotor and the stator. The angle of rotor cell axis inclination differs from the angle of cell axis inclination performed on the stator, but with a different step of cell rows [Krasnov, *et al.* (2010)].

prevents heat loss to the environment.

The surface of the rotor has oblong cells 9 with the pitch m at the angle β. The inner surface of the stator 1 has the same cells 10 arranged with a different pitch of cell rows, and, thus, their number is smaller, in contrast to the number of rotor cells. The inclination angle â of the cells on the stator is greater than the angle of rotor cell row inclination. The difference in cell slope angles provides a gradual shearing of milk layers, which gives a

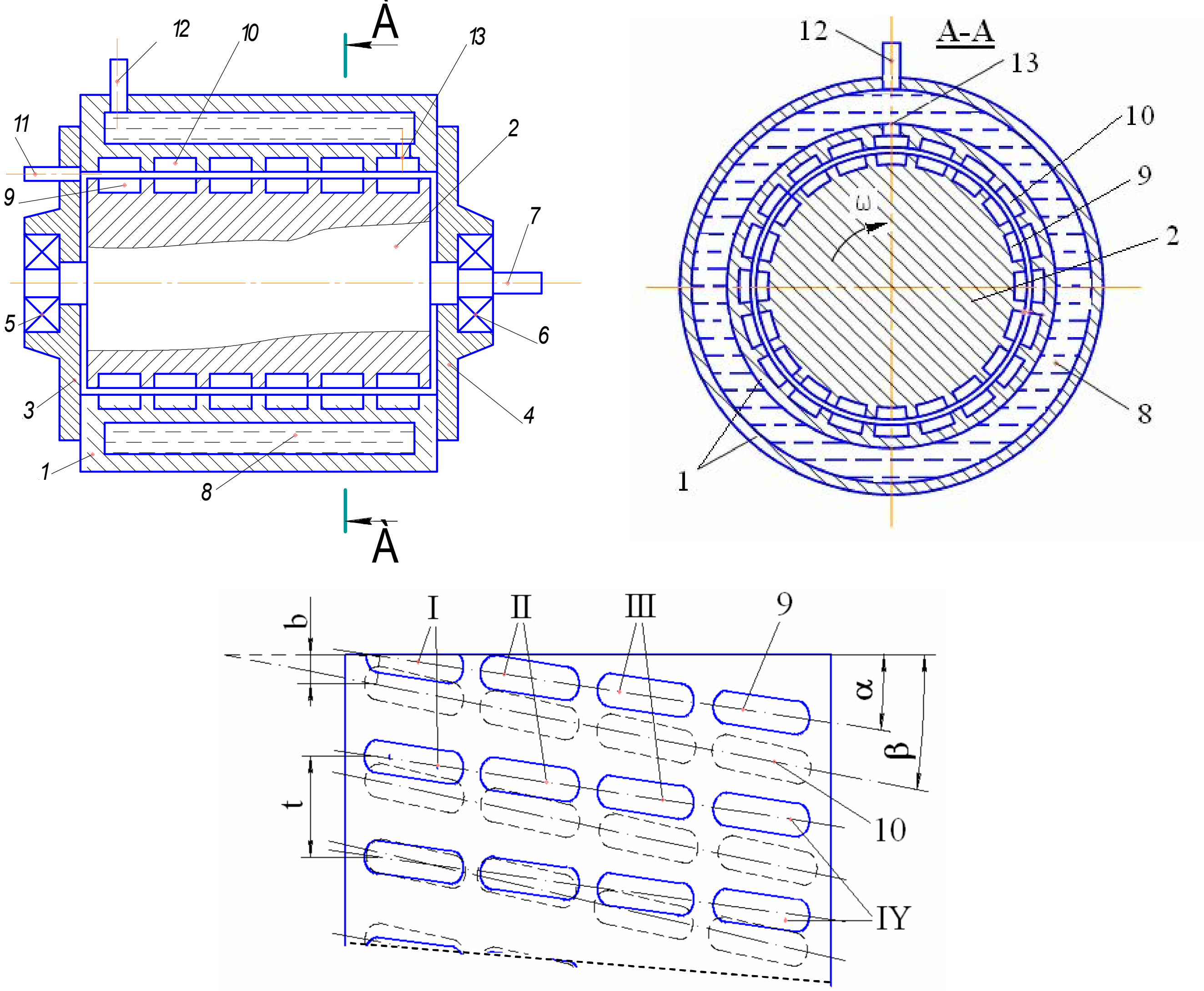

Fig. 1: General view of the hydrodynamic milk heater:
1 - stator; 2 - rotor; 3 and 4 - covers; 5 and 6 - bearings; 7 - shaft; 8 - stator cavity; 9 - rotor cell; 10 - stator cell; 11 and 12 - nozzles, 13 - hole

The hydrodynamic heater consists of a casing 1 made in the form of a hollow cylinder, there is the rotor 2 with a gap inside, there are the cover 3 and 4 on both sides. There is the cavity 8 inside the stator 1 that acts as an endurance holder, its volume corresponds to the pasteurizer productivity. An extender serves as a heat insulator additionally for the working part of HDH, which

more uniform pulsation of load. The heater lids have the pipes for milk feeding 11 and the tap 12 heated to the pasteurization temperature, there is the opening 13 for the introduction of milk into the holder.

Milk enters the nozzle 11 into the gap between the working elements and fills the cell 9 and 10. When the rotor rotates, it is captured by the rows of cells, the inclination angle of cells allows the product self-suck in the device. The milk is subjected to intense hydrodynamic action, as well as vortex formation, the friction of product layers among themselves and the surface of the working organs in the gap between the working bodies, due to the acceleration of the rotor 2 and a sharp stop of the stator 1 by cells. Thus, the milk is heated to the pasteurization temperature. At this temperature, the heated milk enters the stator cavity 8 through the aperture 13 to hold it, then it is discharged through the branch pipe 12 of HDH to further processing LINE: regeneration, cooling and storage in accordance with the scheme shown on fig. 2.

According to this scheme, the pasteurization plant is additionally equipped with a heat pump (HP). It consists of the hydrodynamic heater 1, the regenerator 2, the receiving tank 3, the holder 4, the cooler 6, the tank for pasteurized milk collection 7, the compressor 8, the condenser 9, the heat exchanger 10 and, if necessary, the pump 14.

During the operation of such a pasteurizer, the milk is supplied from the tank 3 by the pump 14 to the plate condenser 9 where it is preheated by the refrigerant vapor coming from the compressor 8, eliminating the heat loss in the serial pasteurizers. Then the milk is fed to the plate regenerator 2, in which it is washed through the plate walls by a counterflow of hot milk from the holder.

Then, the milk, which is additionally heated in the regenerator, enters the hydrodynamic heater 1, where it is heated to the pasteurization temperature. At the outlet from HDH, milk can not be heated to the pasteurization temperature, so an automatic valve 5 is installed here, which can direct the milk for reheating to the desired temperature. After that, it enters the holder 4 and is sent to the regenerator 2 to meet the flow of milk heated for pasteurization.

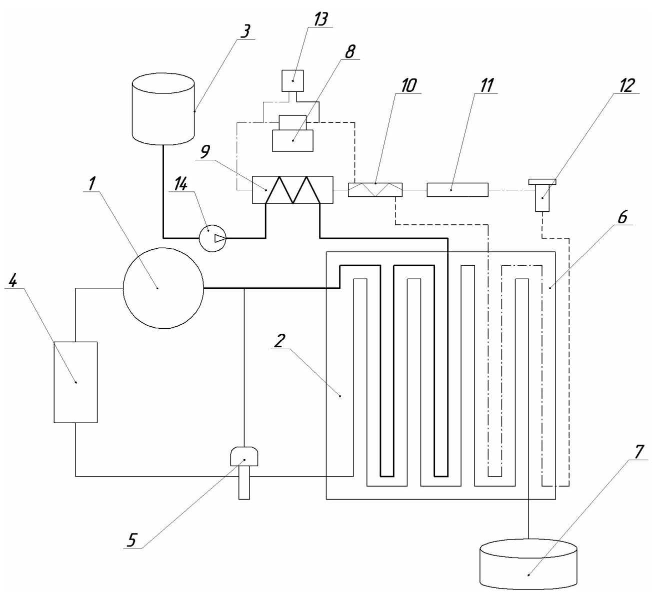

Fig. 2: General scheme of the pasteurization plant

1 - hydrodynamic heater; 2 - regenerator; 3 - receiving tank; 4 - holder; 5 - automatic valve; 6 - cooler; 7 - the tank for pasteurized milk collection; 8 - compressor; 9 - condenser; 10 - heat exchanger; 11 - filter drier; 12 - heat crane; 13 - pressure sensor

From the regeneration section, the pasteurized milk flows into the plate cooler 6 for final cooling with halocarbon and is collected in the tank 7 for its storage in a cooled state.

As was noted earlier, the rotor and the stator have cells. The partitions between the cells are the blades, and the flow part is formed by the cells and the gap between the rotor and the stator. The thickness of the flowing layer of milk constantly changes from the maximum when the cells coincide to the minimum, corresponding to the gap between the working bodies. Such HDH design resembles a centrifugal pump and allows to exclude the installation of an additional pump in a pasteurization unit. The relative milk velocity ω_1 is determined by the difference between the angular velocity of the rotor ωo and the averaged milk velocity ω (fig. 3):

$$\omega_1 = \omega_o - \omega \quad (1)$$

The centrifugal force acts on the inner surface of the stator and it is caused by the angular velocity of the liquid:

$$P = mR\omega^2 \quad (2)$$

where m is the mass of the pasteurized liquid in the

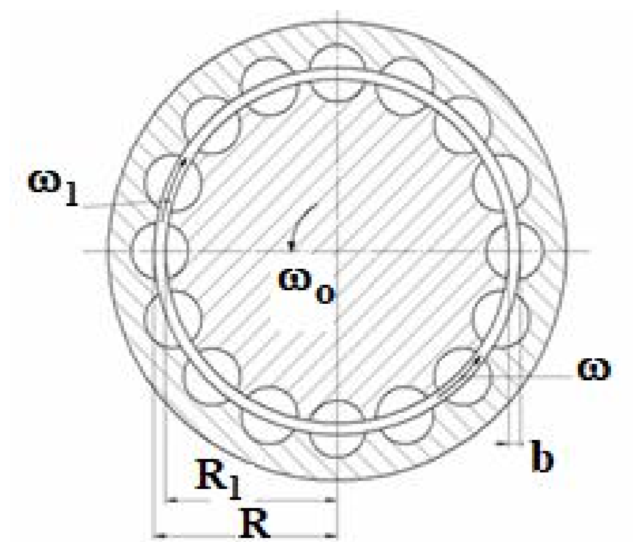

Fig. 3: The scheme of fluid flow in the flowing part of HDH:

1 - rotor; 2 - stator; 3 - cells

flowing part of HDH, kg;

R is the radius of the stator inner groove, m.

The volume of the HDH flowing part is the sum of the gap between the working bodies with the thickness b and the volume of rotor and stator cells:

$$V = V_з + V_я = \pi(R^2 - R_1^2)\cdot B + \pi r^2 \cdot B \cdot n \qquad (3)$$

where R_1 is the outer radius of the rotor, m;

B is the width of the HDH, m;

r and n are the radius (m) and the number of cells in HDH, made in the form of holes in the area of the stator-rotor gap.

The mass of the product in the flowing part of HDH is the following one:

$$m = V \cdot \gamma = \left[\pi(R^2 - R_1^2)B + \pi r^2 Bn\right]\gamma \qquad (4)$$

where γ is the specific gravity of the liquid, kg / m².

Then the pressure of the pasteurized liquid on the internal walls of the stator will be the following:

$$p = \frac{P}{F} = \frac{\left[\pi(R^2 - R_1^2)B + \pi r^2 Bn\right]\gamma \cdot R \cdot \omega^2}{\pi RB}$$

$$= (R^2 - R_1^2 + r^2 n)\gamma \cdot \omega^2 \qquad (5)$$

where F is the area of ??the stator internal boring for the rotor, m².

The pressure caused by fluid friction on the stator will be the following one [Alexopolsky, *et al.* (1963); Cook (1955)]:

$$\tau_o = \varepsilon\rho\frac{\omega^2}{8}, \text{H}; \qquad (6)$$

where ε – the coefficient of resistance to flow;

ρ – fluid density, $\rho = \gamma/g$ kg/m³;

The force $F\tau_o$ will act on the entire surface of the stator $F = \pi R \cdot B$

$$F\tau_o = \varepsilon\rho\frac{\omega^2 R^2}{8}F \qquad (7)$$

Under the action of this force, the torque appears across the entire width of the rotor B:

$$M = \varepsilon\rho\frac{\omega^2 R^4}{8}\pi \cdot B \qquad (8)$$

which in principle is equal to the moment of the forces applied to the rotor blades, since each of them permeates the layer of liquid of the height r with the relative angular velocity (fluid lagging velocity is less than the cell velocity) ω1. At that, the rotor blade of a front surface with the height r and the length B overcomes the hydraulic pressure of the pasteurized liquid:

$$p_1 = \frac{\rho\omega_1^2}{2}R_x^2 \cdot B \qquad (9)$$

where R_x is the radius of the elementary area along the rotor blade height, m.

Within the height and length B of the blade, the elementary moment of this pressure is the following one:

$$dM = \frac{\rho}{2}\omega_1 BR_x^2 \cdot dR_x \cdot R_x$$

The fluid pressure p_1 in relative motion depends on the blade shape, which is taken into account by the coefficient $c = B/r$ for flat blades. In HDH, the blades are made with a spherical surface which allows the slipping of milk layers directly over them, which can be taken into account by an additional coefficient C_1, then

$$C = C_1\frac{B}{r} \qquad (10)$$

Given the number of blades on the rotor z and this correction factor for the moment applied to the rotor axis, we get the following:

$$M = c_1\frac{B^2}{r}\cdot z\rho\frac{\omega_1^2}{8}\left(R_1^4 - R_2^4\right) \qquad (11)$$

Equating (11) to (8) and taking into account that ω_o-ω_1 we get the following:

$$\left(\frac{\omega_o - \omega_1}{\omega_1}\right)^2 = \frac{C_1 zB}{\pi\varepsilon r}\cdot\frac{R_1^4 - R_2^4}{R^4},$$

Thus the expression for ω_1 will be the following one:

$$\omega_1 = \frac{\omega_o}{1 + \sqrt{\frac{C_1 zB}{\pi\varepsilon r}\cdot\frac{R_1^4 - R_2^4}{R^4}}} \qquad (12)$$

Then we can determine the angular velocity of the liquid via $\omega = \omega_o$-ω_1:

$$\omega = \omega_0 = \left(\frac{1}{1+\sqrt{\frac{C_1 zB}{\pi\varepsilon r}\frac{R_1^4 - R_2^4}{R^4}}}\right). \qquad (13)$$

The analysis of the obtained dependences shows that the power of the motor for HDH drive can be determined from the following expression:

$$N = M \cdot \omega_o = \frac{c_1 B^2 z \rho \omega_1^2 \cdot \omega_o}{8r}\left(R_1^4 - R_2^4\right) \quad (14)$$

In accordance with (14), the reduction of power is possible by the reduction of blade number and the various steps of their placement on the working bodies, as well as by their alternate opening during HDH operation.

The maximum performance of the HDH will be the following one:

$G_T = \delta \cdot B \cdot \upsilon$, m^3/s

where b is the radial clearance of the rotor-stator, m;

υ – the circumferential velocity of milk in the gap, m/s.

But υ=ωR, then $G_T \approx 6R^2\delta B\omega$ (15)

Since heat losses in the serial pasteurization units take place due to fluid and air cooling, it is advisable to use a heat pump at this stage of milk cooling (fig. 4). According to this scheme, the cooler also performs the evaporator role. The freon with the temperature txx is throttled through the heating crane, which takes heat away from the milk, boiling at low pressure and at a negative temperature. Evaporating and cooling the milk, freon vapors are sucked off by a heat pump compressor into a heat exchanger at the temperature t_{xo}, increasing the temperature at the compressor inlet to t_{xt} in contact with the liquid coolant passing through its coil.

The compressor in a circular cycle compresses them to the pressure of 1500 ... 1800 kPa and with the temperature of t_x = 80 ... 90°C feeds the vapor into the condenser, through its coil cold milk is supplied by a countercurrent from the tank on the way to pasteurization. The milk is heated to the temperature t_{mc}, and the refrigerant vapor is cooled to the temperature t_{xk}, thereby ensuring that the milk heat is "transferred" from the coolant to the cold milk fed for pasteurization.

Further, the condensate of the refrigerant in the heat exchanger is washed with coolant vapors from the cooler, it is additionally cooled to the temperature t_{xTo}, passes through the heat-tap in the cooler, and the operation of the unit is repeated.

The amount of heat taken away from the milk in the cooler is transferred to the refrigerant vapor through its walls

$$Q_{ox} = G_x c_x \left(t_{xo} - t_{xx}\right) \quad (16)$$

where G_x is the mass of the refrigerant supplied to the cooler, kg/s;

C_x – the heat capacity of the refrigerant, J/kg·K;

t_{xo} and t_{xx}– the refrigerant temperatures at the cooler outlet and inlet, °C.

The ratio of the refrigerant flow rate will be the following one:

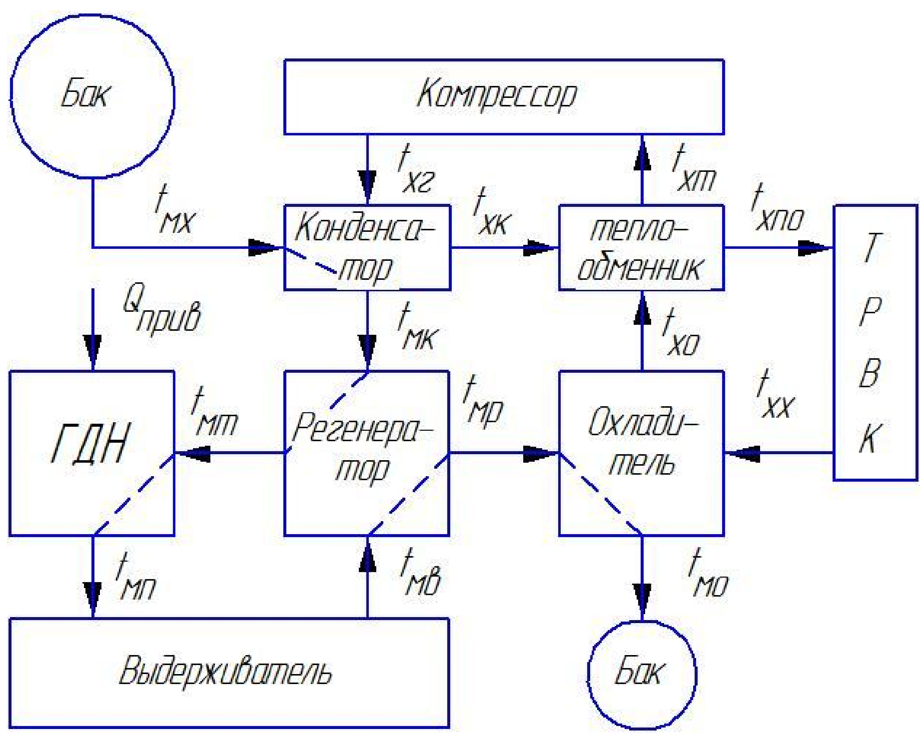

Fig. 4: Technological interaction scheme for the heat units of a pasteurized plant using a heat pump

$$K_k = \frac{c_м(t_{мр} - t_{мо})}{c_x(t_{xo} - t_{xx})} \tag{17}$$

In order to cool down the milk to the set temperature, it must be located in the cooler for a certain time T_0. The same amount of heat can be imagined as necessary for milk cooling that is in the cooler simultaneously:

$$Q = f_{пл} \cdot l \cdot \left(\frac{z_{пл}}{2}\right) \cdot \rho \cdot c \cdot \left(t_{мр} - t_{мо}\right) \text{Дж/с}. \tag{18}$$

Then the duration of the milk presence in the cooler is the following one:

$$T_o = \frac{f_{пл} \cdot l \cdot z_{пл} \cdot \rho_м \cdot c_м \left(t_{мр} - t_{мо}\right)}{2 \cdot k \cdot F \cdot \Delta t_{ср}} \tag{19}$$

The condenser of the heat pump can also be designed as a flat plate unit. One side of such unit plates contains hot steams of freon with the temperature t_{hg} coming from the compressor, and the other side contains the milk supplied from a tank at the temperature t_{mh}. Cooled steam of freon exit from the condenser up to t_{hk} temperature, and the milk is heated to the temperature t_{mk}. The amount of heat taken from the milk by the refrigerant:

$$Q = G_м C_м (t_{мх} - t_{мк}),$$

where t_{mx} and t_{mk}– the initial and the final milk temperature, °C.

The same amount of heat are gained by refrigerant steams:

$$Q = G_м C_м (t_{мх} - t_{мк}),$$

where t_{xz} and t_{xk}–the initial and the final refrigerant temperature, °C.

Since the heating plate in the plate devices is continuous, the refrigerant flow multiplicity coefficient will be the following one:

$$K_k = \frac{c_м(t_{мх} - t_{мк})}{c_x(t_{хг} - t_{хк})} \tag{20}$$

The efficiency of a heat pump operation shows heat k_x and cold k_T conversion coefficients interconnected by the dependence [Zaushitsin, *et al.*(1985); Buzoverov (2012)]:

$$k_m = k_x + 1$$

The following expressions for heat and cold coefficient determination are obtained by the Carnot cycle:

$$k_т = \frac{t_{хг}}{t_{хг} - t_{хк}} \tag{21}$$

$$k_х = \frac{t_{хк}}{t_{хг} - t_{хк}} \tag{22}$$

The application of a heat pump (HP) excludes the loss of heat with the coolant flow which about 70 mJ for the pasteurizer with the capacity of 600 kg/hr, which is equivalent to almost 19 kWh of energy and exceeds HDH drive power 2 times.

The experiments have shown that the temperature difference at the outlet of the cooled milk and inlet refrigerant flow Ät ranges from 6 to 8°C. Since the temperature of the coolant after pasteurization should be about 4°C, the refrigerant temperature should not be below + 3°C, due to the fact that the wall temperature of the coolant milk ducts can be reduced to less than 0.5°C, which may be the cause of its freezing.

Therefore, the refrigerant temperature supplied to the cooler is equal to 2°C. When the capacity of the refrigerant heat pump receiver makes 12 l the multiplicity of its circulation in the system will be about 15 times per hour.

In the temperature range of milk cooling 35 ... 4°C the heat conversion ratio made 5.96, and cold conversion ratio made 5.4, which corresponds to the known data on heat pump use effectiveness in utilities [Buzoverov (2012); Bredikhina (2014)]. The heat capacity of the cooled pasteurized milk in a test device may be used to heat cold milk supplied for pasteurization in the volume of up to 70% of the HP thermal power. The rest of the HP energy costs are spent on its idle operation, and the losses into the environment. The refrigerant of the grade R410 A provides a safe temperature in the cooler - about 270 °T. At that the refrigerant condensation and evaporation temperature difference is 28o, and their ratio is 0.906. This operation mode of a heat pump under the studied conditions of milk cooling is the limiting one, further reduction of Txx entails the freezing of the milk layer on the inner surfaces of the cooler [Buzoverov (2012)].

With a pasteurization plant milk container volume of about 5 liters (table), the duration of heat treatment does not exceed 30 seconds and it decreases with the productivity increase.

According to the experimental data, the capacity of HDH regenerator with the rotor diameter of 150 mm is 0.2 liters, the holder capacity makes 0.5 liters. The table shows the time of milk stay in these devices within the

Table 1: The indicators of pasteurization unit heater participation with HDH in the pasteurization effect of milk treatment (G = 600 kg/h)

List of devices for pasteurizing plants	Device volume V, 10^{-3} m^3	Heat processing period, s	The fraction delivered by the device in the pasteurization criterion *Pa*
Hydrodynamic heater	0,2	1,2	0,17
Regenerator	4	12,2	0,20
Holder	0,5	3,0	0,63

same cycle of milk processing and the fraction they contribute to the criterion Pa.

Only a part of the regenerator plate area participates in the pasteurization of milk within its cooling range from 75°C to 60°C. The processing time of milk in it does not exceed 12.2 s, and the fraction contributed to Pa makes 0.2.

In HDH, the milk is heated sharply from 60 to 75°C and it provides the share of 0.17 in Pa at a pasteurization plant capacity of 600 kg/h, which is not enough to suppress microflora completely.

Summary

Thus, the hydrodynamic heater and the regenerator do not provide together the degree of heat treatment sufficient to suppress microflora. A holder of 0.5 liter provides the share introduced into the pasteurization criterion which makes more than 60% in Pa, which allows it to be mounted into the heater directly.

Conflict fo interest

The author confirms that the presented data do not contain a conflict of interests.

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