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Methodology to Calculate Design Parameters of Screw Heat Exchanger for Vat Pasteurizer

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Abstract: The study describes methods of calculating the design parameters of screw heat exchanger for vat pasteurizer on the example of vat type VDP-300 (300 L). Patent search showed that the authors proposed a new design of screw heat exchanger for vat pasteurizer. There is a patent for utility model "Vat pasteurizer". The use of developed equipment would reduce production costs by reducing energy consumption and time spent on production. Production of dairy products directly on the basis of farms and using the developed equipment will improve the efficiency of milk production. Also it will create a good business struggle between the milk processing enterprises and decrease the price for products. The proposed methodology of calculating the design parameters of screw heat exchanger is based on the common methods of calculation of heat transfer processes.

Key words: Screw heat exchanger, heat transfer, vat pasteurizer, heat transfer coefficient, efficiency, patent

INTRODUCTION

An important task at all stages of the food industry has always been and remains the production of food products, that meet established quality standards. The dairy industry is no exception. Milk and dairy products-high-value food ingredients, nearly unparalleled on food properties. Concerning the recommendation of the Institute of Nutrition intake of milk and dairy products in terms of milk is 392 kg per person per year including 116 kg of whole milk (nearly 30% of the total) butter: 6.1 kg, sour cream: 6.5 kg, cottage cheese: 8.8 kg and the cheese: 6.1 kg (Mukhametgaliyev *et al*., 2011). Low consumer demand for milk and dairy products due to high retail prices and low incomes of the population which hinders the growth of agricultural production. One of the ways to overcome this contradiction is the development of the free market competition. Implementing practice of agribusiness natural (drinking) milk to the population shows its high efficiency. Processing milk into dairy products and their implementation at times to increase the profitability of production of milk and dairy products but consumers will have a fresh product from the manufacturer at a price with no extra charge dealers. However not every farmer can afford to set up the production of dairy products on the basis of his farm because of the high cost of processing equipment and the large area occupied by the equipment as well as low-skilled processing technology or lack thereof. Use of continuous in operation equipment is not acceptable to farmers, because incoming milk for processing is not constant. Using batch equipment is also associated with certain difficulties. Existing equipment with water jacket are highly inert. Use known equipment for the production of dairy products after pasteurization of milk in the same bath takes a lot of time spent on replacement coolant refrigerant. Such devices cost-effectively used only for pasteurization or only for the production of dairy products (fermentation and aging). There is a need to

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build the technology and equipment that meet the requirements of the modern village which do not require high energy consumption and allows to produce dairy products as soon as possible. The solution may be a combination of the advantages of a batch equipment with the benefits of continuous in operation equipment. In connection with the above-described problem set objective of the study: develop equipment allows to carry out the heat treatment and processing of milk into dairy products with minimal downtime. To achieve this goal have been formulated objectives of the study:

- Analyze existing technologies and means of mechanization of heat treatment and processing of milk
- Conduct theoretical justification parameters of developed equipment
- Test the hypothesis experimentally

MATERILAS AND METHODS

Theory: We propose to replace the water jacket of classic long pasteurized bath formed from two baths to the screw heat exchanger (Fig. 1). The main advantages of the screw heat exchanger: a small amount of heat used by the agent that is in constant motion, i.e., who gave (accepted) heat exchanger agent flow out of the space and drive into, where it would be re-heated (cooled) or simply replaced with a new one. This arrangement of the equipment reduces the time of heating (cooling) of the product which affects the total time of production of dairy products. However, in the analyzed literature, we were not able to find method for calculating the proposed scheme of heat exchanger, so we made methodology for calculating the design parameters of the proposed heat exchanger ourselves, based on the common method of calculation of heat transfer processes (Fig. 2). It has required to find the geometric parameters of the screw heat exchanger: the heat exchange area, the length of the helix, the number of turns of the heat exchanger; with the following preset parameters: initial and final temperature of the water: t_{wi} = 100°C and t_{wf} = 73°C; the initial and final temperature of the milk: t_{mi} = 37°C and t_{mf} = 68°C; the velocity of the water in the heat exchanger: ω_w = 0.5 m sec^{-1}; speed of milk in the bath: ω_m = 0.5 m sec^{-1}; the volume of processed milk: V_{bath} = 300 l = 0.3 m^3.

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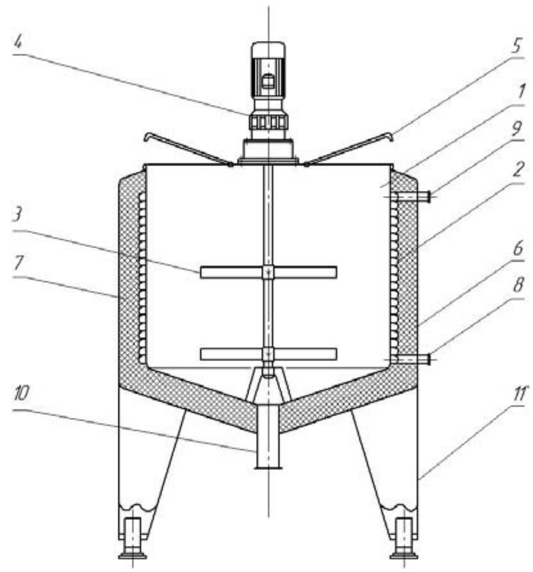

Fig. 1: Long pasteurized bath with screw heat exchange: 1) Bath for product; 2) screw heat exchanger; 3) stirrer; 4) the electric motor with reduction gear; 5) cover; 6) casing; 7) insulating layer; 8) inlet; 9) outlet; 10) branch tube for draining the product; 11) feet

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RESULTS AND DISCUSSION

Any heat exchange process is characterized primarily by the amount of heat transmitted from one body to another. Patterns of heat is the essence of all thermal processes taking place without change and with changes in the aggregate state of substances. The amount of heat transferred to the heat transfer process in the presence of significant surface contact between the heating and cooling medium, taking into account the driving force of heat exchange processes is determined by the basic equation of heat transfer (Smith, 2011):

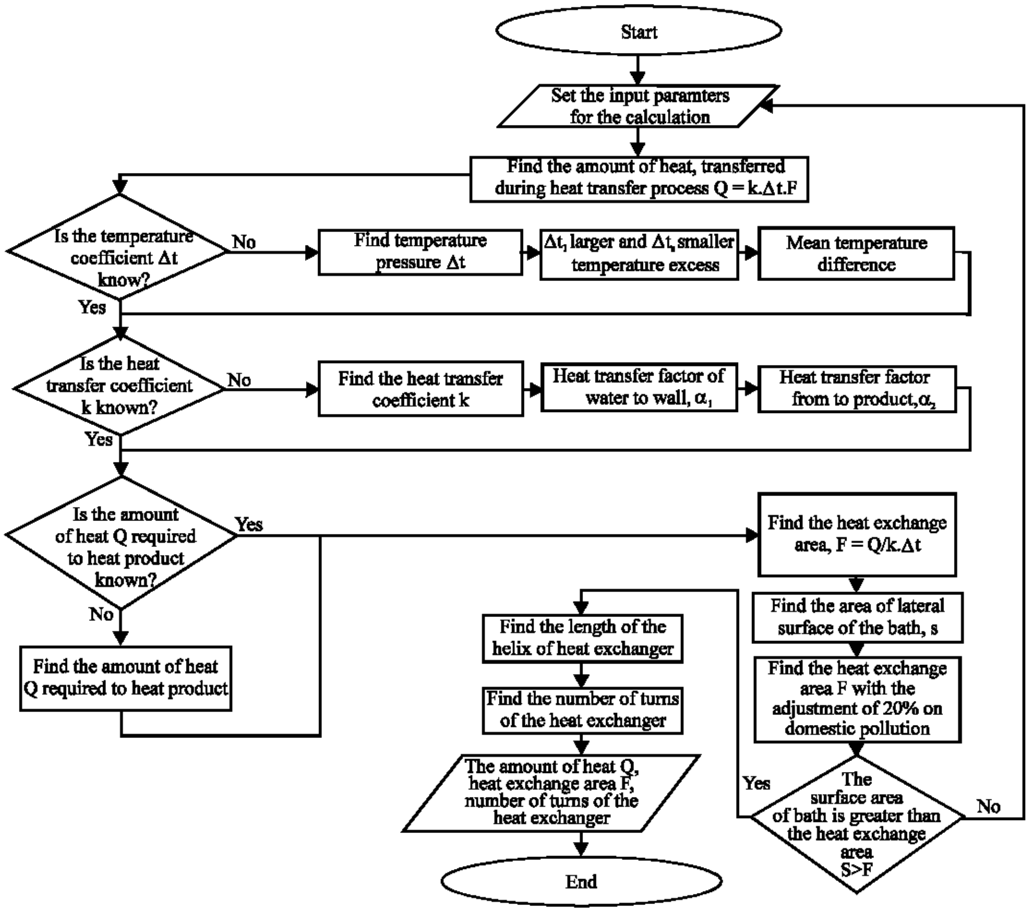

Fig. 2: The flow chart of calculating the screw heat exchanger

$$Q = k \cdot \Delta t \cdot F \tag{1}$$

Where:

- Q = Amount of heat spent on heating of the milk (kJ)
- k = Coefficient of heat transfer
- Δt = Temperature difference (°C)
- F = Heat exchange area (m^2)

We should use the Eq. 1 to find the surface area of heat transfer. To do this, first we should find the amount of heat Q, the heat transfer coefficient k and the temperature difference Δt. The temperature conditions of the process. Determine the average temperature difference between the heated milk and the cooling water in the heating process. A large temperature difference Δt_l = 100°-37°C = 63°C; the smaller temperature difference Δt_s = 73°- 68°C = 5°C. Given that the ratio $\Delta t_l/\Delta t_s$ = 63/5 = 12, 6>2, temperature pressure would be defined as the average logarithmic temperature difference:

$$\Delta t = \frac{\Delta t_l - \Delta t_s}{\ln\frac{\Delta t_l}{\Delta t_s}} = \frac{63-5}{\ln\frac{63}{5}} = 22.89°?$$

The heat transfer coefficient can be found with:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta}{\lambda_{wall}} + \frac{1}{\alpha_2}} \tag{2}$$

Where:

- α_1 = Coefficient of heat transfer out of the water to the wall
- α_2 = coefficient of heat transfer from the wall to the product
- δ = thickness of heat transfer wall (m)
- λ_{wall} = thermal conductivity of stainless food steel. λ_{wall} = 16 W/m.°C

To find the values of the coefficient of heat transfer out of the water to the wall we should use the formula of Nusselt number:

$$Nu = 0.03 \cdot Re_w^{0.8} \cdot Pr_w^{0.43}\left(\frac{Pr_w}{Pr_{wall}}\right)^{0.25} \tag{3}$$

Where:

- Nu = Nusselt number, dimensionless heat transfer coefficient
- Re_w = Reynolds number, fluid motion criterion regime
- Pr_w = Prandtl number for water, dimensionless characteristic of thermal properties of the fluid
- Pr_{wall} = Prandtl number for water in the boundary layer

The Reynolds number is given by:

$$Re_w = \frac{\omega \cdot d_t}{\upsilon_w} \quad (4)$$

Where:

- Re_w = Reynolds number for water in the tube
- υ_w = Water velocity in the tube of the heat exchanger (m sec^{-1})
- d_t = The heat exchanger tube diameter (m)
- v_w = The kinematic viscosity of water (m^2 sec^{-1})

To improve the heat transfer from the water to the walls of the heat exchanger need to create a turbulent flow of fluid motion (Fellows, 2000). The velocity of water in the heat exchanger tube we will mark as υ_w = 0.5 m sec^{-1}. To analyze the calculation we will take three tubes with different diameters of the heat exchanger:

- d_{t1} = 30, MM = 0.03 M
- d_{t2} = 50, MM = 0.05 M
- d_{t3} = 70, MM = 0.07 M

Inlet water temperature in heat exchanger 100°C but output temperature is 73°C. This means that average water temperature in heat exchanger:

$$t_{a.w.} = \frac{100+73}{2} = 86,5 \approx 87°?$$

Kinematic viscosity of water at average temperature of 87°C would be interpolated with v_w= 0.3377. $10^{-6}M^2/C$. According to Eq. 4, we can find the Reynolds number for tube with diameter of 30 mm:

$$Re_w = \frac{0.5 \cdot 0.03}{0.3377 \cdot 10^{-6}} = 44418.123$$

According to Smith (2011) while Re>10.000 the movement of water in the tube is considered to be turbulent. Prandtl number for water in the heat exchanger with an average temperature of 87°C would be interpolated with Pr_w = 2.028. In the boundary layer water temperature would be 2°C below than in exiting the heat exchanger (Fellows, 2000). Prandtl number for water in the boundary layer at a temperature of 71°C would be interpolated like Pr_{wall} = 2. 516. Using the Eq. 3, we can find Nusselt number for a tube with diameter of 30 mm:

$$Nu = 0.03 \cdot 44418.123^{0.8} \cdot 2.028^{0.43} \left(\frac{2.028}{2.516}\right)^{0.25} = 201.334$$

From the equation Nu = α . d/λ, we should find the coefficient of heat transfer of water to the wall α_1:

$$\alpha_1 = \frac{Nu \cdot \lambda_w}{d_t} \quad (5)$$

where, λ_w = thermal conductivity of water. Thermal conductivity of water depends on water temperature. Based on tabulated data (Singh and Heldman, 2013) by interpolation we should find the coefficient of thermal conductivity of water at 87°C temperature:

$$\lambda_w = 0.6782 \text{ W/m} \cdot \text{K}$$

According to the Eq. 5, we find the heat transfer coefficient from water in the tube to the wall α_1:

$$\alpha_1 = \frac{201.334 \cdot 0.6782}{0.03} = 4551.49 \text{ W/m}^2 \cdot \text{K}$$

According to the above mentioned algorithm we can find coefficient of heat transfer from water in the heat exchanger to the wall with 50 and 70 mm diameter tubes. The results are summarized in Table 1.

Table 1 shows that with increasing the size of tube, heat transfer coefficient decreases. To find the heat transfer coefficient from wall to the milk α_2 we should use method described above. We should find Reynolds number. For this purpose we choose bath with diameter D_b = 0.7 m = 700 mm. The Reynolds number is given by Eq. 4. The movement speed of milk in the bath, we will mark like υ = 0.5 m sec^{-1}. The bath would be filled with fresh milk but temperature of this milk suppose to be 37°C. For pasteurization the milk should be heated until temperature of milk is 68°C. Hence, the average temperature of the milk in the bath:

$$t_{a.m.} = \frac{37+68}{2} = 52.5 \approx 53°C$$

According to the data in table (Ginzburg *et al*., 1980) by interpolation, we should calculate kinematic viscosity of milk at 53°C: v_m = 0.7968 .10^{-6} m^2 sec^{-1}. Reynolds number should be found to determine the movement nature of milk in the bath.

Table 1: Calculation data of heat transfer coefficient for different types of pipes with different diameters

Pipe diameter (m)	v_w at 87°C ($m^2\ sec^{-1}$)	Re_w	Pr_w at 87°C	Pr_{wall} at 71°C	Nu	λ_w at 87°C	α_2
0.03	$0.3377.10^{-6}$	44418,123	2.028	2.516	201,334	0.6782	4551,490
0.05	$0.3377.10^{-6}$	74030,204	2.028	2.516	302,968	0.6782	4109,458
0.07	$0.3377.10^{-6}$	103642,286	2.028	2.516	396,550	0.6782	3842,008

Table 2: Results of heat transfer coefficient calculation

Heat exchanger's tube diameter (d_t, m)	Heat transfer coefficient from the water to the wall (α_1)	Heat transfer coefficient from the wall to the milk (α_2)	The wall thickness of the heat transfer (δ, m)	The thermal conductivity of the wall (λ_{wall}, W/(m.K))	The heat transfer coefficient (k)
0.03	4551,490	1819,185	0.003	16	1041,667
0.05	4109,458	1819,185	0.003	16	1020,408
0.07	3842,008	1819,185	0.003	16	1000

$$Re_m = \frac{0.5 \cdot 0.7}{0.7968 \cdot 10^{-6}} = 439257.028$$

According to Singh and Heldman (2013) at Re>100.000, the movement of milk in flow plate is considered to be turbulent. Prandtl number for the milk depends on its temperature. Therefore, in accordance with tabulated data (Ginzburg *et al*., 1980) Prandtl number at 53°C should be interpolated like $Pr_m = 5.547$. The boundary layer temperature of the milk is 2°C higher than the temperature required for pasteurization. Prandtl number for milk in the boundary layer at temperature of 70°C would be calculated with data in table (Ginzburg *et al*., 1980). $Pr_{wall} = 4.14$ to find Nusselt number for bath with diameter 700 we use Eq. 3:

$$Nu = 0.03 \cdot 439257.028^{0.8} \cdot 5.547^{0.43}\left(\frac{5.547}{4.14}\right)^{0.25} = 2203.165$$

From formula Nu = α . d /λ, we find heat transfer coefficient from the wall to the milk α_2:

$$\alpha_2 = \frac{Nu \cdot \lambda_M}{D_B} \quad (6)$$

where, λ_m = thermal conductivity of the milk. Thermal conductivity of the milk depends on its temperature. Drawing on data in table (Ginzburg *et al*., 1980) by interpolation find the coefficient of thermal conductivity of milk at temperature 53°C λ_m = 0. 578 W/m·K. According to Eq. 6, we find heat transfer coefficient from wall of the bath to the milk α_2:

$$\alpha_2 = \frac{2203.165 \cdot 0.578}{0.7} = 1819.185\ W/m^2 \cdot K$$

According to Eq. 2, we find the heat transfer coefficient for the system with 30 mm diameter tube:

$$k = \frac{1}{\frac{1}{4551.49} + \frac{0.003}{16} + \frac{1}{1819.185}} = 1041.667$$

Heat transfer coefficient data calculation depending on tube's diameter has summarized in Table 2. With the increase diameter of the tube of heat transfer, coefficient of heat exchanger decreases, there is an inverse relationship. The amount of heat spent for heating milk, can be found in Eq. 7:

$$Q = G_? \cdot C_? \cdot (t_1 - t_0) \quad (7)$$

Where:

G_M = The mass of heated milk (kg)
C_M = milk heat capacity (kJ/(kg · K))
t_0 = Fresh milk temperature (°C)
t_1 = Milk pasteurisation temperature (°C)

Specific heat of milk the value which depends on temperature. Therefore, according to the data in table (Ginzburg *et al*., 1980) we find heat capacity of milk at 53°C temperature by interpolation C_m = 3.973 kJ/(kg · K). Mass of G_m milk can be found across its density. Density of fresh milk 1027 kg/m³ (Charrondiere *et al*., 2012). Bath volume 300 L = 0.3 m³:

$$G_m = \rho \cdot V = 1027 \cdot 0.3 = 308.1\ N \quad (8)$$

According to Eq. 7, we find the quantity of heat spent to heat milk till the temperature to able to pasteurize:

$$Q = 308.1 \cdot 3.973 \cdot (68 - 37) = 37946.52\ N$$

From Eq. 1 we, find necessary heat transfer area:

$$F = \frac{Q}{k \cdot \Delta t} = \frac{37946.52}{1014{,}199 \cdot 31} = 1.21\ N$$

Lateral surface area of the bath can be found by formula to find lateral surface of cylinder:

$$S = 2 \cdot \pi \cdot r \cdot h = 2 \cdot 3.14 \cdot 0.35 \cdot 0.75 = 1.65 \text{ m}^2$$

When comparing the heat transfer area F and lateral surface area S of bath, we obtain that S > F, consequently, heating milk in bath with right selected heat exchanger is possible. The best heat transfer coefficient according to the studied variants is heat exchanger when the tube diameter is 30 mm (0.03 m) but in order to save material and minimize labor costs to produce equipment, we propose to adopt heat exchanger with tube which diameter is 50 mm (0.05 m). The number of turns of heat exchanger will be assumed for the version with tube 50 mm diameter.

When calculating the geometric parameters of heat exchanger it is necessary to consider the effect of contamination, by choosing surface to exchange heat so that heat output of equipment should be 10-20% higher than calculated in equation (Shah and Sekulic, 2003). Q_{est} = 37946.52 kJ, therefore for calculation we should take the value of consumed heat with the adjustment of + 20%: Q_{corr} = 45535.82 kJ. So, the real heat exchange area with regard to pollution would be F = 1.45 M^2. Heat exchange area for screw heat exchanger after scanner would have rectangular shape, the length of screw can be found from the formula for finding the area of rectangle:

$$a = \frac{S}{b} \quad (9)$$

Where:

a = The length of rectangle and the length of screw heat exchanger (m)
S = The area of rectangle (m^2)
b = The width of rectangle but the heat exchanger's tube diameter (m)

From the Eq. 9, the length of the screw heat exchanger coil is a = 29 m. The length of the outer circumference of the bath is equal to L = 2.2 m. This means that the number of turns is found from the expression:

$$n = \frac{a}{l} = \frac{29}{2.2} = 13.2 \approx 13.5 \text{ N}$$

This quantity of turns of the pipe with diameter of 50 mm can be placed at height of 700 mm which is sufficient for our bathtubs with wall which height is 750 mm.

CONCLUSION

Studies have shown that the proposed methodology can be used to calculate the design parameters of heat exchangers baths of any volume. The proposed design of the heat exchanger for bath with prolonged pasteurization can reduce time for pasteurize milk due to the smaller displacement and constant turbulent flow of coolant. In such bath, you can process milk into dairy products without draining it. Thus, for the preparation of fermented dairy products such as yogurt, pickled cheese it requires less equipment. This reduces the initial financial costs of agricultural producers, as well as reduced energy costs for production. Cost of production is greatly reduced. It is possible an increase in flow of funds through the sale of high-quality product at discounted price. To automate the calculation of the proposed method, you can use the Microsoft Office Excel Software application, using the standard formulas of software.

NOMENCLATURE

Q = Heat quantity spent in heating the milk (kJ)
k = Coefficient of heat transfer
Δt = Temperature pressure (°C)
F = Heat exchange area (m^2)
Δt_l = Larger temperature excess
Δt_s = Smaller temperature excess
α_1 = Heat transfer factor of water to wall
α_2 = Heat transfer factor from wall to product
δ = Thickness of heat-transfer wall (M)
λ_{wall} = Heat transfer coefficient of wall (stainless food steel)
Nu = Nusselt number, the dimensionless heat transfer coefficient
Re_w = Reynolds number, dimensionless quantity, used to check whether the flow is laminar or turbulent, (water)
Pr_{wall} = Prandtl number for water in the boundary layer
υ_w = Water velocity in the pipe of heat exchanger (m sec^{-1})
d_t = Diameter of heat exchanger tube (m)
v_w = The kinematic viscosity of water (m^2 sec^{-1})
λ_w = Heat transfer coefficient of water
λ_m = Heat transfer coefficient of milk
G_m = Weight of heated milk (kg)
C_m = Heat capacitance of milk (kJ/(kg·K))
t_0 = Temperature of fresh milk (°C)
t_1 = Pasteurized milk temperature (°C)
a = The length of the rectangle and screw line of heat exchanger (m)
S = Area of a rectangle (m^2)
b = The width of the rectangle and diameter of heat exchanger tube (m)

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