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HEAT EXCHANGE IN A CHAMBER APPARATUS WITH A CIRCULATION CIRCUIT DURING CHEESE MASSES PRODUCTION

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Summary. *Chamber heat exchangers are used in various branches of the food industry. Different types of stirrers are used in them as the means of intensifying heat transfer. They also give the devices the function of mixing devices. Grinding mechanisms are installed in some designs, which also affect the heat transfer and hydrodynamics of the movement. Grinding and mixing devices are especially widely used in the production of composite products. During heat treatment, uniformity of heating of the whole mass and the same duration of action of the maximum temperature is important for many products. In such cases, it is advisable to use chamber heat exchangers with a circulating circuit for processing thermolabile products. The heat exchange in such a device is complex due to the hydrodynamics of the product. Studies of the heat exchange process in a capacitive device with a circulating circuit are relevant. In particular, the establishment of the criterion equation of heat transfer to determine the heat transfer coefficient from the wall of the device to the product. The article deals with the peculiarities of heat exchange when using chamber heat exchangers with a stirrer and a circulating circuit. The results of research on the heat exchange process at the production of composite products on the basis of cottage cheese are presented. The process of heating the mass is influenced by its movement through the circulating device and in a closed circuit. Therefore, to study the effect of purely mechanical treatment on the heating process of the product, we studied the change in the temperature of the mass at the outlet of the circulation circuit without the supply of a heating agent. According to the results of the research, it was found that the circulation of the product in a closed circuit allows ensuring uniform heating and reduces the duration of the process. And for portions of the product weighing up to 5 kg, the required temperature can be achieved even only through machining. The criterion equation of heat transfer to determine the heat transfer coefficient from the wall to the product was obtained by the method of dimensions. A circulation number is entered, which is the ratio of the volume of the circulating product to the volume mixed by the stirrer.*

Key words*: heat exchange, heat exchanger with a stirrer and circulating circuit, criterion equation of heat exchange.*

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Problem statement. Chamber heat exchangers are used in various branches of the food industry. [1, 2]. Different types of stirrers are used in them as the means of intensifying heat transfer. They also give the devices the function of mixing devices. Grinding mechanisms are installed in some designs, which also affect the heat transfer and hydrodynamics of the movement. [1, 2, 3]. A complex of grinding and mixing devices is especially widely used in the production of composite products. They can be different in value (chamber), means of heat exchange intensifying, and some additional functions.

Under heat treatment conditions, the following parameters are important for a number of products: reaching a certain temperature of heating, uniform heating of the whole mass, and the same period of the maximum temperature action on each volume. In such cases, it is quite reasonable to apply some chamber heat exchangers with a circulation circuit for thermolabile products' treatment [4]. In particular, a chamber heat exchanger with a circulation circuit used in the production of composite milk products, apart from the chamber of a heat exchange shirt and a stirrer, includes a device made as a rotor-vortex apparatus with a pump [1]. An outlet pipe of the device is connected to a circulation pipeline

Corresponding author: Viktor Voroshchuk; e-mail: voroschuk@gmail.com providing the product circulation with its simultaneous emulsification. A scraped-surface mixer constantly mixes the product, cleans the heat exchange surface, and prevents mass local overheating.

Heat exchange in the above-mentioned device is complicated due to the hydrodynamics of a product motion [5, 6].

Nowadays, the study of the heat exchange process in a chamber apparatus with a circulation circuit, namely the determination of the criterion equation of heat exchange taking into account the thermal-physical properties of the product to calculate the heat exchange process, the apparatus design and defining the ways of the process intensification.

Analysis of well-known results of the study. As far as we know, the total amount of heat required for a product to heat to the specified temperature does not depend on the way of heating and can be determined by the formula [7]:

$$Q = c_p m\left(t_2 - t_1\right) \tag{1}$$

where Q – amount of heat required to be delivered to the product, J;

c_p – specific heat capacity of the product, J/kgK;

m – the mass of a product, kg;

t_1, t_2 – initial and final temperature of heating respectively, °C.

It is important to determine the duration of the product heating up to the specified temperature [8] and to calculate the area of the heat exchange surface on the basis of the heat transfer equation [1, 2, 3]

$$Q = k \cdot F \Delta t \cdot \tau \tag{2}$$

where k – heat transfer coefficient, W/m^{2}K characterizes the heat exchange process intensity.

F – the surface area of the apparatus heat exchange, m^2;

Δt – the average difference in temperature in the process, K,

τ – duration of product heating, c.

For most heat exchangers, the heat transfer coefficient can be determined by the expression for a flat wall [9]:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2}} \tag{3}$$

where α_1 and α_2 – heat-transfer coefficients from a coolant to the surface, and from the surface to the product respectively, J/(m^2 ·K);

λ – heat conductivity coefficient of the wall, J/(m·K);

δ – the wall thickness, m.

As water here is applied as a coolant, then the well-known criteria dependencies [10] can be used to determine α_1 for convective heat exchange, using average values of temperatures of working environments in the apparatus input-output. The values δ and λ are determined by the apparatus design and the wall material, and at inconsiderable wall thickness, which is a characteristic feature of heat exchangers used in the food industry [1], where thermal resistance of heat conductivity can be neglected. Taking into account, that the temperature on the wall surface will be approximately equal to the temperature of the coolant, then the main fact affecting the heat transfer process will be the heat transfer coefficient from the wall to the product. As for the last one, it depends on a number of facts, namely, on the type of stirrer [11]. Moreover, product circulation has a certain influence as well. Under continuous circulation conditions, certain objects can be mixed and, therefore, can exchange their heat, so, we may speak here about some local heat transfer coefficients from the wall to the product, as well as an average heat transfer coefficient per one cycle of the product motion [11, 12] or an average heat transfer coefficient per one cycle of the product production.

Paper purpose. The aim of the study under discussion is to determine the criteria dependencies of heat exchange in a chamber apparatus equipped with a scraped-surface mixer and a circulation circuit at composite milk-protein products treatment and to define the ways of heat exchange intensification.

Problem setting. To calculate the heat transfer processes the criteria equations are used which are obtained by the dimensional method. For an apparatus with a stirrer and a circulation circuit, the heat transfer coefficient dependence can be presented in the form of variables

$$\alpha = f\left(d, n, \eta, \lambda, c, \gamma, \omega\right), \tag{4}$$

where α – heat transfer coefficient, W/(м^{2}К);
n – the number of revolutions of a stirrer, с$^{-1}$;
η – coefficient of kinematic viscosity, Pa·c;
λ – heat conductivity coefficient, W/(m·K);
c – specific heat capacity, J/(kg·K);
d – chamber diameter (geometrical parameter), m;
γ – product density, kg/m^3
ω – volume speed of mass circulation in the closed circuit, m^3/c.·

Let’s reduce the units of measurement of the specified values to the main ones – a meter, a kilogram, a second, and a Kelvin, (temperature).

$$\alpha - \left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right] = \left[\frac{\mathrm{kg}}{\mathrm{s^3K}}\right];\ \mathrm{n} - \left[\mathrm{s^{-1}}\right],\ \mathrm{d} - [\mathrm{m}],\ \eta - [\mathrm{Pa}\cdot\mathrm{s}] = \left[\frac{\mathrm{kg}}{\mathrm{m^2}\cdot\mathrm{s}}\right],\ \lambda - \left[\frac{\mathrm{W}}{\mathrm{m\ K}}\right] = \left[\frac{\mathrm{kg}\cdot\mathrm{m}}{\mathrm{s^3K}}\right],$$

$$\gamma - \left[\frac{\mathrm{kg}}{\mathrm{m^3}}\right],\ \mathrm{c} - \left[\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}\right] = \left[\frac{\mathrm{m^2}}{\mathrm{s^2}\cdot\mathrm{K}}\right],\ \omega - \left[\frac{\mathrm{m^3}}{\mathrm{s}}\right].$$

Let’s write equation (4) using only the main values:

$$\frac{\mathrm{kg}}{\mathrm{s^3K}} = \left(\frac{1}{\mathrm{c}}\right)^{a} \cdot (\mathrm{m})^{b} \cdot \left(\frac{\mathrm{kg}}{\mathrm{m}\cdot\mathrm{s}}\right)^{c} \cdot \left(\frac{\mathrm{kg}\cdot\mathrm{m}}{\mathrm{s^3}\cdot\mathrm{K}}\right)^{k} \cdot \left(\frac{\mathrm{m^2}}{\mathrm{s^2}\cdot\mathrm{K}}\right)^{f} \cdot \left(\frac{\mathrm{kg}}{\mathrm{m^3}}\right)^{i} \cdot \left(\frac{\mathrm{m^3}}{\mathrm{s}}\right)^{g} \tag{5}$$

Let’s make a relativity equation of the exponents at the same values:
for a kilogram [kg]

$$1 = c + k + i\ ; \tag{6}$$

for a meter [m]

$$0 = b - c + k + 2f + 3g - 3i\,; \tag{7}$$

for a Kelvin [K];

$$-1 = -k - f \tag{8}$$

for a second [c];

$$-3 = -a - c - 3k - 2f - g \tag{9}$$

We determine k from the equation (3) and substitute in the equation (5) (7).

We have obtained:

$$0 = -a - c + f - g, \tag{10}$$

$$0 = c - f + i, \tag{11}$$

$$-1 = b - c + f + 3g - 3i, \tag{12}$$

We have assumed g, f, i as known values.

Having solved the system of equations, we have obtained: $c = f - i$, $a = i - g$, $b = -1 - 3g + 2i$.

We have substituted the obtained values in the equation (4).

We have obtained:

$$a = n^{i-g} \cdot d^{-1-3g+2i} \cdot \eta^{f-i} \cdot \lambda^{1-f} \cdot c^{f}. \tag{13}$$

Let’s group the values with the same exponents:

$$\frac{a \cdot d}{\lambda} = \left(\frac{d^2 n \cdot \gamma}{\eta}\right)^{i} \cdot \left(\frac{\eta \cdot c}{\lambda}\right)^{f} \cdot \left(\frac{\omega}{d^3 n}\right)^{g}. \tag{14}$$

Let’s analyze the obtained complexes:

$\frac{a \cdot d}{\lambda}$ – Nusselt number – it characterizes the heat exchange in a wall layer,

$\frac{d^2 n \cdot \gamma}{\eta}$ – Reynolds number for mixing processes. It characterizes the hydrodynamics of the product movement caused by a stirrer.

$\frac{\eta \cdot c}{\lambda}$ – Prandtl number. It characterizes the thermal-physical parameters of the product.

$\frac{\omega}{d^3 n}$ – the number that characterizes the hydrodynamics at simultaneous action of circulation and mixing.

The criteria equation can be presented as follows:

$$Nu = C_1 Re^{n} Pr^{m} K^{z}. \tag{15}$$

The obtained equation, taking into account the first two members, is typical for heat exchange apparatuses with a mixer.

For the scraped-surface heat exchangers, Skeland, Oliver and Tuke [14] have proposed the following dependence:

$$\frac{a \cdot d}{\lambda} = C \cdot \Pr^{3}\left(\frac{(D-d)\cdot\omega\cdot\gamma}{\eta}\right)\cdot\left(\frac{d\cdot n}{\omega}\right)\cdot\left(\frac{d}{D}\right)\cdot n_z^{0,53}, \qquad (16)$$

where D – internal diameter of the pipe of a scraped-surface heat exchanger, m;
d – diameter of привідного валу, m;
ω – speed of the fluid main flow, m\c;
n_z – the number of scrapes, c^{-1}.

Whereas in the equation (16) the complex $\frac{D\cdot n}{\omega}$ characterizes the relationships between circular and axial velocity of the product, then the complex $\frac{\omega}{d^3 n}$ characterizes the relationships between the volume of the circulating product and the product which is in the chamber and is being mixed by a stirrer.

The coefficient C_1 takes into account the design solution of certain elements of a rotor-vortex emulsifier.

The invariants of geometrical and design similarity have to be added to the equation (14), such as the ratio of maximal and minimal diameters of the chamber h_1, the length of the stirrer to the width h_2, the number of blades of the stirrer n_1. Then the obtained criteria equation will look like this:

$$Nu = C_1 Re^{n} Pr^{m} K^{z} h_1 h_2 n_1 . \qquad (17)$$

During composite products production it is important to calculate thermal and physical characteristics which will depend on the product constituents and on the degree of mechanical and heat treatment.

The specific coefficient of heat capacity and the heat transfer coefficient can be determined by the adaptivity method taking into account the composition of separate components [14] or by the well-known experimental formulae.

It is necessary to determine the coefficient of kinematic viscosity for non-Newton fluids taking into account its dependence on the speed of stirring during the process of treatment. In these cases, the concept of kinematic viscosity is used:

$$\eta_e = k^{l}\left(\frac{dw}{dx}\right)^{m} . \qquad (18)$$

For dilatant fluids (cottage cheese) at $m \geq 1$ we can assume, that the change of coefficient of kinematic viscosity is taking place on the width of the stirrer scraper. To determine η_e, the dependencies [15] were used.

The obtained criteria equation will look like this:

$$Nu = 0,4 Re^{0,67} Pr^{0,3} K^{0,2} n_1^{0,4} . \qquad (19)$$

At $0,03 < \mathrm{Re} < 4,0$, $0,1\cdot 10^{-3} < \Pr < 0,2\cdot 10^{-3}$, $2 < n_1 < 6$.

As it is very difficult to determine the heat emission coefficient immediately, we have decided to calculate the heat transfer coefficient by the formula (2):

$$k = \frac{Q}{\left(t_n - t_p\right)F}, \tag{20}$$

where t_n, t_p – the temperature of the product and the working environment respectively, the temperature of the product was measured on the output from the emulsifying device.

Results of the study. Taking into account a great variety of milk protein-based composite products, the composition of well-known recipes of cheese masses has been analyzed. The main constituents of the recipes under consideration are cottage cheese, water, food additives where the content of gelling substances is from 1% to 5% of the mixture total mass. To summarize rheological characteristics a complex coefficient K proposed by A. V. Horbatov [13] was used to estimate the mass composition.

The product «Yahidka» (TU 49 832-81 «Fermented milk product with fruit and berry and flavor fillers»), whose deviation from the averaged complex coefficient of the mass composition K of well-known products based on cottage cheese was the lowest one and was equal to 5,28%, was chosen for the study as the most typical regarding the ratio of main components.

An experimental plant (fig. 1) was presented by a model of a rotor-vortex emulsifier.

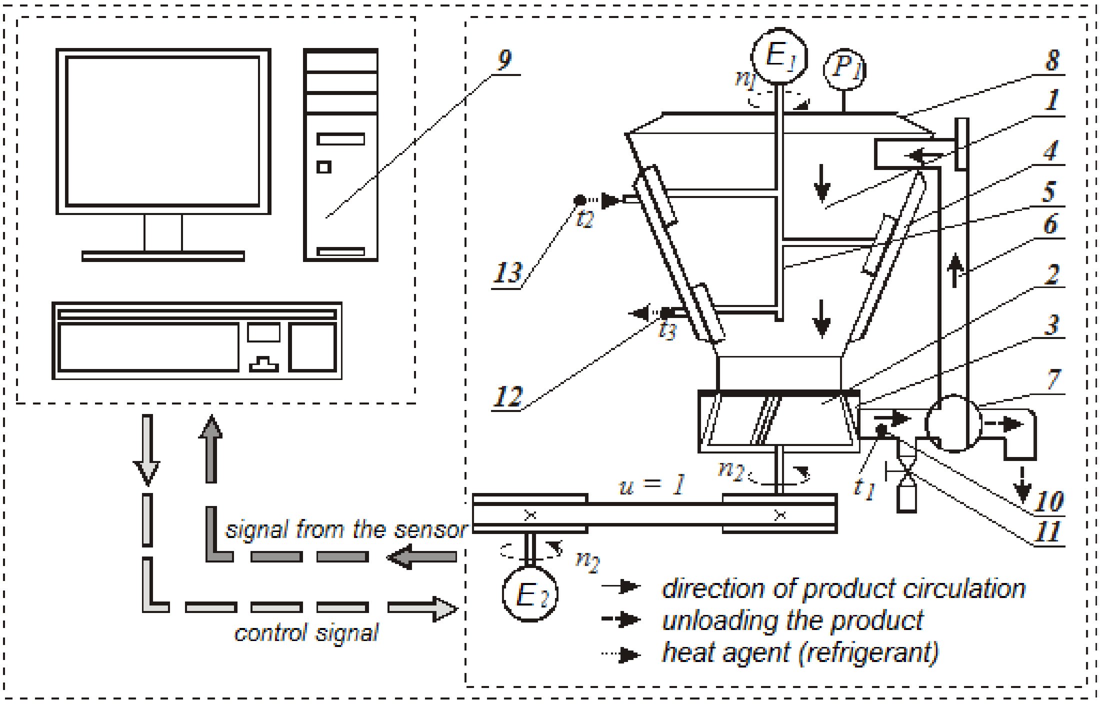


Figure 1. Experimental plant:
1 – working chamber; 2 – rotor; 3 – stator; 4 – circulation circuit; 5 – scraped-surface mixer; 6 – circulation pipeline; 7 – three-way valve; 8 – cover; 9 – computer control system; 10, 12, 13 – thermocouple; 11– sampling; E_1, E_2 – electric motors; P_1 – compound pressure and vacuum gauge.

The basic elements of the plant include working chamber 1 with a shirt 4, a circulation pipeline 6 and a two-bladed scraped-surface mixer 5, a device for the product circulation consisting of a couple rotor-stator 2–3, that also provided the product emulsifying. The working clearance value can be adjusted from 0,22 to 3 mm by a spacer nut.

The rotor was driven by an electrical motor D1 with the regulated number of revolutions within the limits of 0...4000 r/min, enabling to change the efficiency.

Heat treatment of the product was carried out in a working chamber 1 through a heat exchange shirt 4 due to the supply either heating – or cooling agent depending on the stage of heat treatment. The chamber was made in the form of a with the maximum diameter 0,26 m and the minimal one 0,09 m, with the 0,014 m width of the mixer blade. The method of contact measurement was used to measure the temperature by means of chromel kopel thermocouples ХК (L) -50÷0÷800 C connected to a digital potentiometer.

A thermocouple 10 was used to control the working mixture temperature at the exit from the circulation circuit. The product temperature was measured near the chamber surface, in the middle of the chamber radius and in the chamber center in tree points by height and at the input of the circulation circuit when the scraped-surface stirrer was stopped every three minutes of the treatment. For this purpose, a special cover was designed which excluded any contact of the thermocouples with other products [16]. Rotation frequency of the scraped-surface stirrer varied within the limits of 0...30 r/min.

The duration of the loaded mass passing through the rotor-vortex device with an open valve 7 to the outside, which was equal to 5–6 c within the number of rotor revolutions 2500 – 3000 r/min was assumed as one cycle of circulation.

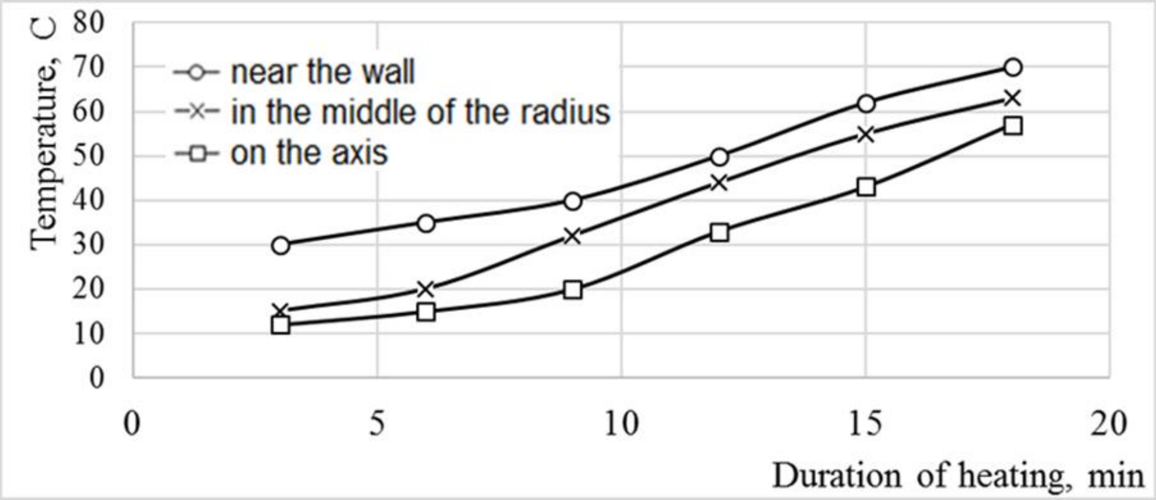


Figure 2. Product temperature change during heating at 0.1 m height

The rotor rotation frequency was set up before the start of the work by means of a controls system «Lenze», after that the recipe mixture of 5 kg weight was loaded into the chamber. When the product was loaded, a heat agent was supplied into the steamed shirt to heat the cheese mass to the temperature of pasteurization.

Under its own weight action, the cheese mass was supplied to the circulation device. While passing the clearance between the rotor and the stator, the product was crushed, mixed and through the circulation pipeline was sent to the chamber again. A two-blade scraped-surface stirrer has provided both the heat exchange surface renovation and the products mixing in the working chamber.

To determine the impact of circulation on the mass heating, first of all, the study of heating in the chamber was conducted, excluding its circulation only under the stirrer operation conditions. It was found, that the product was heated nonuniformly, the maximum temperature was in the product layers which were the closest ones to the apparatus wall (fig. 2).

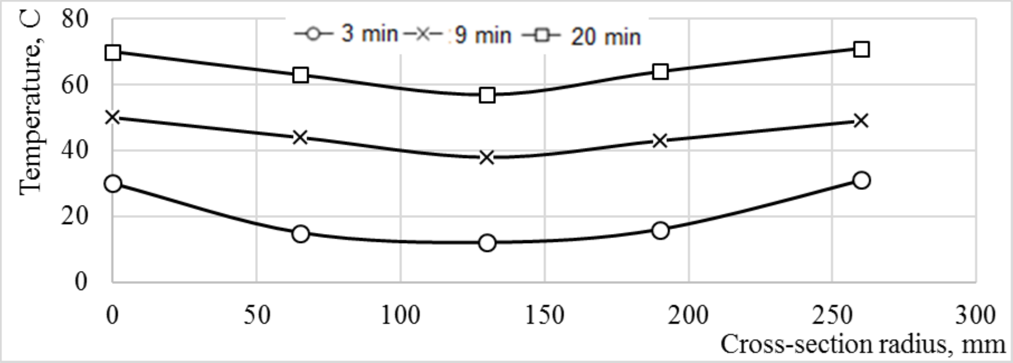


Figure 3. Product temperature change in the apparatus at 100 mm height during the treatment

The next task was to determine the required duration of treatment to reach the operating temperature of the product (64℃) in the farthest section from the apparatus wall – in its center. The obtained results have proved, that for a product of 5 kg weight the specified temperature in the center can be reached in 20 minutes of the treatment duration (fig. 3).

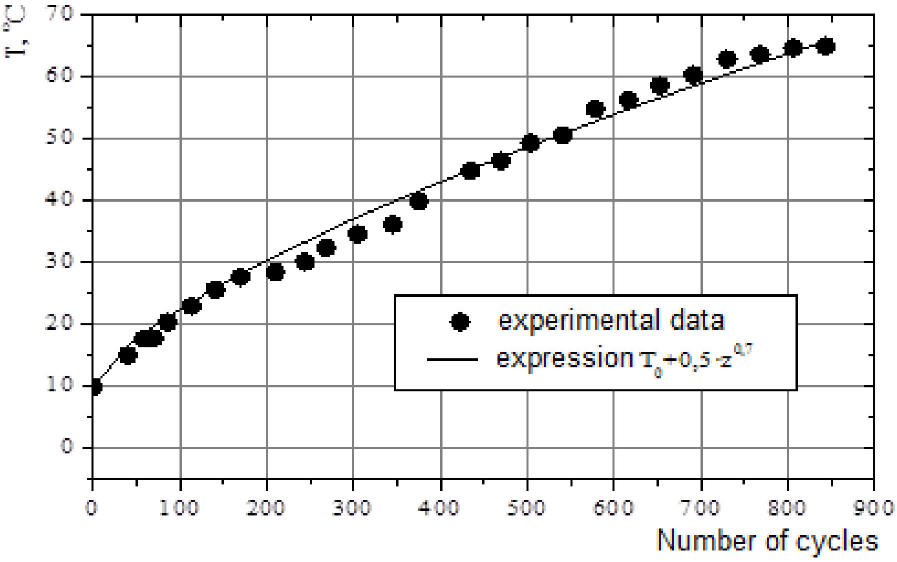
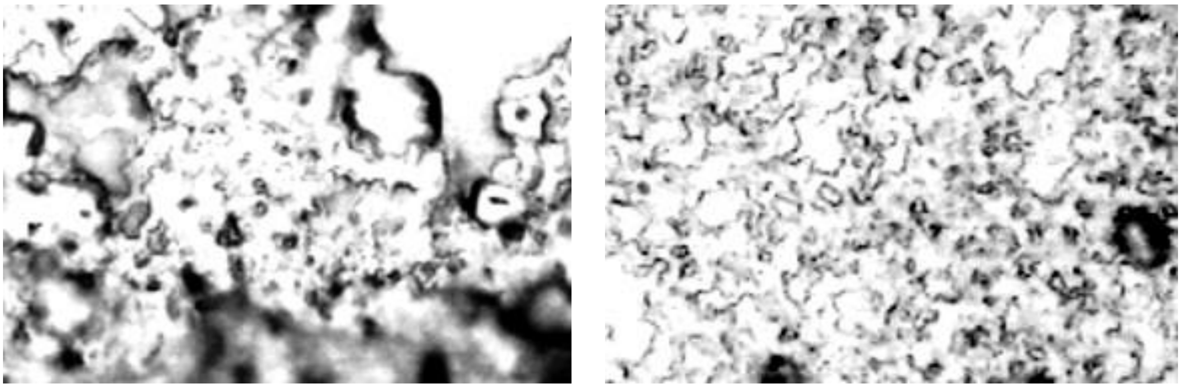


Figure 4. Product temperature change at the exit from the circulation circuit caused by mechanical treatment (the stirrer was turned off)

The mass heating is affected by its motion through the circulation device and along the closed circuit. The investigation of the mass temperature change at the exit from the circulation circuit without a heat agent supply to a shirt was conducted to study the impact only mechanical treatment on the product heating (fig. 4). It was found, that, in general, the product temperature has 0,8–1,2 C increase per each cycle of circulation and can be represented by the following dependence:

$$T = T_0 + 0,5z^{0,7}, \tag{21}$$

where T – product temperature, ℃;
T_0 – initial temperature of the product, ℃;
z – number of circulation cycles.



а   б

Figure 5. Change of mass microstructure during the treatment:
a) the first stage of the treatment; b) the second stage of the treatment

It was found, that for a product of 5 kg weight, not more than 850 cycles of treatment are required to achieve the necessary temperature of the treatment. It means that any additional heating is not necessary for small portions of the product.

The well-known criteria equations were used to determine the heat transfer coefficient from the working environment (water) to the wall [2, 4, 5]. The deviation in experimentally and theoretically found heat transfer coefficient at different stages of the treatment was within the limits of 20%, that can apparently be caused by the mass structural changes (fig. 5).

At the first stage of stirring and thermal treatment with the homogeneous structure development, at the second one – with the mass gelling.

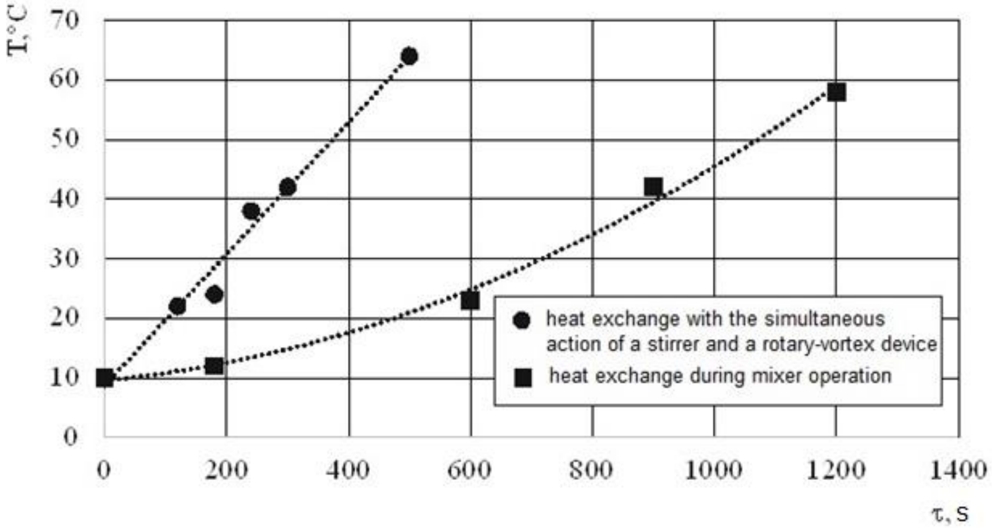


Figure 5. Temperature change in the apparatus working chamber during the stirrer operation and during simultaneous action of the stirrer and the rotor-vortex device

Conclusions. The product circulation along the closed circuit with the simultaneous mechanical treatment of the product has made possible to intensify the heat exchange considerably, provide the uniform heating and reduce the process duration.

The criteria equation obtained by the dimensional method has allowed us to determine the heat transfer coefficient for a chamber heat exchanger with a stirrer and a circulation circuit.

In engineering calculations, the coefficient of heat transmission can be identified as the heat transfer coefficient with sufficient accuracy.

For small portions of the product of 5–10 kg weight the required temperature can be reached only due to the mechanical treatment.

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ТЕПЛООБМІН У ЄМКІСНОМУ АПАРАТІ З ЦИРКУЛЯЦІЙНИМ КОНТУРОМ ПРИ ВИРОБНИЦТВІ СИРКОВИХ МАС

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Резюме. *Ємкісні теплообмінні апарати використовують у різних галузях харчової промисловості. Як засоби інтенсифікації теплообміну в них використовуються різного типу мішалки, які надають апаратам також функцію перемішуючих пристроїв. У деяких конструкціях встановлюються подрібнювальні механізми, які також впливають на теплообмін та гідродинаміку руху. Комплекс подрібнювальних і перемішуючих пристроїв особливо широко використовується при виробництві композиційних продуктів. При термічній обробці для багатьох продуктів важливим є рівномірність нагрівання всієї маси та незначна дія максимальної температури. У таких випадках для обробки термолабільних продуктів доцільно використовувати ємкісні теплообмінники з циркуляційним контуром. Теплообмін у такому апараті складний, що пов'язано з гідродинамікою руху продукту. Є актуальними дослідження процесу теплообміну в ємкісному апараті з циркуляційним контуром, зокрема встановлення критеріального рівняння теплообміну для визначення коефіцієнта тепловіддачі від стінки апарата до продукту. Розглянуто особливості теплообміну при використанні ємкісних теплообмінних апаратів з мішалкою та циркуляційним контуром. Представлено результати досліджень процесу теплообміну при виробництві композиційних продуктів на основі сиру кисломолочного. Для вивчення впливу виключно механічної обробки на процес нагрівання продукту проведено дослідження зміни температури маси на виході з циркуляційного контуру без подачі теплового агента. За результатами досліджень встановили, що циркуляція продукту по замкненому контуру дозволяє забезпечити рівномірне нагрівання і зменшити тривалість процесу, а для порцій продукту масою 5–10 кг досягнути необхідної температури можна виключно за рахунок механічної обробки. Методом розмірностей отримали критеріальне рівняння теплообміну для визначення коефіцієнта тепловіддачі від стінки до продукту. Введено число циркуляції, яке являє собою відношення об'єму продукту, що циркулює, до об'єму, який перемішується мішалкою. Показано, що циркуляція продукту значно інтенсифікує процес теплообміну.*

Ключові слова: *теплообмін, теплообмінний апарат з мішалкою і циркуляційним контуром, критеріальне рівняння теплообміну.*

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