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THERMOPHYSICAL CALCULATIONS THE PROCESS OF COOLING THE FERMENTED MILK CLOT

Struchaiev N., PhD, ORCID: 0000-0002-8891-4960
Postol Y., PhD, ORCID: 0000-0002-0749-3771
Tarasenko V., PhD, ORCID: 0000-0002-0275-0281
Palianychka N., PhD, ORCID: 0000-0001-8510-7146
Dmytro Motornyi Tavria State Agrotechnological University
Tel. (0619) 42-13-06

Formulation of the problem. Fermented milk drinks are essential for a balanced diet. They are produced in two ways: reservoir and thermostatic. A significant part of the range of fermented milk drinks is produced by the reservoir method [1]. In conditions of energy saving and improving product quality, the requirements for the production of fermented milk drinks, in particular for cooling the fermented milk clot, are increasing and its improvement is currently a very important problem [2].

Analysis of recent studies. The analysis of the most effective methods used to improve the structure of fermented milk drinks notes the extreme importance of the cooling process [2]. There are a number of works on thermophysical calculations taking into account thermal insulation [3-10], which provide general approaches to planning and solving problems of this kind. However, the solution to the problem of increasing the energy efficiency of cooling the fermented milk clot before filling it into consumer containers for further maturation, compensation of the thermal resistance of the mixer gap requires special consideration.

Forming the goals of the article. The aim of the study is to establish the possibility of increasing the energy efficiency of cooling the fermented milk clot before bottling it into consumer containers for further maturation, by reducing energy consumption for maintaining its temperature by installing thermal insulation, determining the optimal location and gap of the mixer to compensate for thermal resistance.

To achieve this goal, the following tasks have been set:

1. To propose a method for calculating heat energy for cooling a fermented milk clot and heat inflows, taking into account the location of the thermal insulation.

2. Check the correspondence of theoretical calculations to the actual value of cooling temperatures of the fermented milk clot.

3. Determine the cooling time of the fermented milk clot.

The research methodology is based on a modified method for studying the heat transfer process.

Main part. To create rational temperature conditions under which it is possible to pour the fermented milk clot into consumer containers for its further maturation, it is necessary to take into account the thermophysical properties of the fermented clot, as well as data on its basic physical and mechanical properties. Calculation of the amount of heat when cooling a fermented milk clot, which is heated to a temperature of 32…34 °C, in a container of complex shape will be performed on the basis of a joint solution of the heat balance and heat transfer equation [3].

The heat balance equation in this case takes the form:

$$Q_{cool.w.} = Q_{cool.f.cl.} + Q_{st.jck.} + Q_{th.in.} + Q_{th.in.}, \qquad (1)$$

where $Q_{cool\ w.}$ – the amount of heat removed by the cooling water, kJ; $Q_{cool\ f.cl.}$ – the amount of heat for cooling the fermented milk clot, kJ; $Q_{st.jck.}$ – the amount of heat for cooling a steel tank with a cooling jacket, kJ; $Q_{th.in.}$ – the amount of heat for cooling the thermal insulation, kJ; $Q_{th.in.}$ – heat inflows of thermal energy from the environment, kJ.

The heat transfer equation during the cooling of the fermented clot [3]. determined by the formula, kJ :

$$Q_{cool.f.cl.} = k_{f.cl.} \cdot F_{tank} \cdot (t_{ht} - t_{col.}) \cdot \tau, \qquad (2)$$

where $k_{f.cl.}$ – is the coefficient of heat transfer from the fermented clot through the walls of the tank to the cooling water, W / (m^2 · K); F_{tank} – is the surface area of the tank, m^2; t_{ht} – is the temperature of the hot medium, °C; $t_{col.}$ – is the temperature of the cold medium; °C, τ – is the operating time of the installation , s.

The amount of heat required to cool the fermented milk clot:

$$Q_{cool.f.cl.} = m_{f.cl.} \cdot c_{f.cl.} \cdot (t_{init} - t_{fin}), \qquad (3)$$

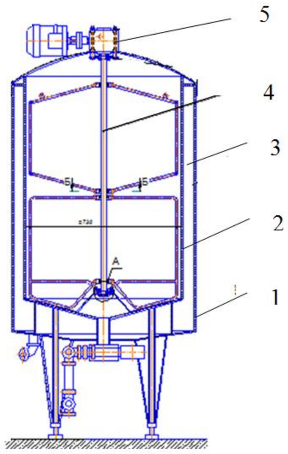
where $Q_{cool\ f.cl.}$ – is the amount of heat for cooling the fermented milk clot, kJ; $m_{f.cl.}$ – is the mass of the fermented milk clot, kg; $c_{f.cl.}$ – the heat capacity of the fermented milk clot, kJ / (kg·°C); t_{init} – is the initial temperature of the fermented milk clot, °C; t_{fin} – is the final temperature of the fermented milk clot, °C.

Mass of fermented milk clot:

$$m_{f.cl} = \rho_{f.cl.} \cdot V_{f.cl.}, \qquad (4)$$

where $\rho_{f.cl.}$ – is the density of the fermented milk clot, kg / m^3; $V_{f.cl.}$ – is the volume of the fermented milk clot, m^3.

The amount of heat for cooling a steel tank with a cooling jacket (Fig. 1).



1 – thermal insulation of the tank; 2 – tank; 3 – cooling jacket; 4 – mixer; 5 – mixer drive.

Fig. 1. Scheme of the tank for cooling the fermented milk clot.

$$Q_{st.jac.} = m_{st.jac.} \cdot c_{ct.} \cdot (t_{init} - t_{fin}), \quad (5)$$

where $\boldsymbol{Q_{st.jac.}}$ – amount of heat for cooling a steel tank with a cooling jacket, kJ; $\boldsymbol{m_{st.jac.}}$ – mass of a steel tank with a cooling jacket, kg; $\boldsymbol{c_{St.}}$ – heat capacity of steel, kJ / (kg deg); $\boldsymbol{t_{init}}$ – initial steel temperature, °C; $\boldsymbol{t_{fin}}$ – final steel temperature, °C.

Mass of a steel tank with a cooling jacket, kg:

$$m_{st} = \rho_{st.} \cdot V_{st.} , \quad (6)$$

where $\boldsymbol{\rho_{st.}}$ – density of steel, kg / m^3; $\boldsymbol{V_{st.}}$ – volume of steel, m^3.

The amount of heat removed by the cooling water required to cool the steel tank and fermented milk clot is equal to the total amount of heat removed according to formula (1).

On the other hand, the amount of heat removed by the cooling water can be determined by the formula:

$$Q_{cool.water} = m_{cool.water} \cdot c_{cool.water} \cdot (t_{init.water} - t_{fin.water}), \quad (7)$$

where $\boldsymbol{Q_{cool.\ water}}$ – the amount of heat removed by the cooling water for cooling the fermented milk clot, kJ; $\boldsymbol{m_{cool.\ water}}$ – the mass of the cooling water, kg; $\boldsymbol{c_{cool.\ water}}$ – the heat capacity of the cooling water, kJ / (kg · deg); $\boldsymbol{t_{init\ water}}$ – initial temperature of the cooling water, °C; $\boldsymbol{t_{final\ water}}$ – final temperature of the cooling water, °C.

Having solved the equations (1) and (7) together, we determine the amount of cooling water required to cool the steel and the fermented clot.

From the energy conservation equation, we write that the amount of heat removed from the fermented milk clot is equal to the amount of heat supplied to the cooling water:

$$Q_{cool.f.cl.} = Q_{cool.water.} \tag{8}$$

Then the amount of cooling water will be equal to:

$$m_{cool.water.} = Q_{cool.f.cl.} / (c_{cool.water.} \cdot (t_{init.water.} - t_{fin..water.})), \tag{9}$$

Final cooling water temperature:

$$t_{fin.water.} = t_{init.water.} + Q_{cool.f.cl.} / (m \cdot c_{cool.water.}), \tag{10}$$

Cooling jacket rectangular tube length:

$$l = (H_{\tan k} - b \cdot n) / (a \cdot \pi \cdot D_{\tan k}), \tag{11}$$

where ***l*** – is the length of the rectangular tube of the cooling jacket, m; $\boldsymbol{H_{tank}}$ – is the height of the tank shell, m; ***a*** – is the width of the rectangular tube of the cooling jacket, m; ***b*** – is the gap between the turns of the rectangular tube of the cooling jacket, m; ***n* –** is the number of turns, $\boldsymbol{D_{tank}}$ is the diameter tank, m.

Speed of water movement in a rectangular pipe of the cooling jacket:

$$v = 4 \cdot Q_{cool.water.} / (a \cdot h), \tag{12}$$

where ***v*** – is the speed of water movement in a rectangular pipe of the cooling jacket, m / s.

The residence time of water in a rectangular pipe of the cooling jacket:

$$\tau_{water} = l / v\,. \tag{13}$$

The mode of water movement in a rectangular pipe of the cooling jacket is determined using the Reynolds criterion:

$$\mathrm{Re} = \frac{V \cdot D_{eq.}}{\nu}, \tag{14}$$

where ***Re* –** is the general Reynolds criterion; ***V*** – is the speed of water movement in a rectangular pipe of the cooling jacket, m / s; $\boldsymbol{D_{eq}}$ – is the equivalent pipe diameter, m; ***ν*** – is the coefficient of kinematic viscosity of water, m^2 / s.

Equivalent pipe diameter:

$$D_{eq.} = 4F/P = a*h/(2(a+h)), \tag{15}$$

For a rectangular fully filled pipe, the Reynolds criterion takes the form:

$$\mathrm{Re} = \frac{V \cdot \dfrac{4 \cdot a \cdot h}{2 \cdot (a+h)}}{\nu}, \tag{16}$$

The calculated Reynolds criterion for the cooling jacket pipe (see table 2) is greater than the critical one:

$$Re = 43338{,}5 > Re_{cr.} = 2320$$

That is, the regime of movement of water in the pipe is turbulent.

Nusselt criterion for turbulent regime:

$$Nu = 0{,}021 \cdot \mathrm{Re}_{w.}^{\;0{,}8} \cdot \mathrm{Pr}_{w.}^{\;0{,}43} \cdot \left(\frac{\mathrm{Pr}_{w.}}{\mathrm{Pr}_{st.}}\right)^{0{,}25}, \tag{17}$$

where $\boldsymbol{Pr_w}$ – is the value of the Prandtl criterion for water at 2 °C; $\boldsymbol{Pr_{st}}$ – is the value of the Prandtl criterion for a steel wall.

Heat transfer coefficient during the movement of cooling water in pipes:

$$\alpha_{w.} = \frac{Nu \cdot \lambda_{w.}}{D_{eq.}}, \tag{18}$$

where $\boldsymbol{\alpha_w}$ – is the heat transfer coefficient of the cooling water, W / (m^2 · K); $\boldsymbol{Nu}$ – is the Nusselt criterion; $\boldsymbol{\lambda_w}$ – is the thermal conductivity of the cooling water, W / (m · K); $\boldsymbol{D_{eq}}$ – is the equivalent pipe diameter, m.

Mixer circumferential speed:

$$\omega = \pi \cdot d_{m.} \cdot n_{m.}, \tag{19}$$

where $\boldsymbol{\omega}$ – is the circumferential speed of the mixer, m / s; $\boldsymbol{d_m}$ **–** is the mixer diameter, m; $\boldsymbol{n_m}$ – is the mixer rotation frequency, 1 / s.

The regime of movement of the fermented clot in the gap between the tank and the mixer is determined using the Reynolds criterion:

$$\mathrm{Re}_{f.cl} = \frac{V_{f.cl.} \cdot D_{gap.}}{\nu_{f.cl.}}, \tag{20}$$

where $\boldsymbol{Re_{f.cl.}}$ – Reynolds criterion for a fermented clot; $\boldsymbol{V_{f.cl.}}$ – the speed of the fermented clot movement in the gap, m / s; $\boldsymbol{D_{gap}}$ – the equivalent diameter of the gap, m; $\boldsymbol{\nu_{f.cl.}}$ – coefficient of the kinematic viscosity of the fermented clot, m^2 / s.

The equivalent diameter of the gap is calculated by the formula (15). The Reynolds criterion for the motion of the clot in the gap calculated by formula (20) is less than the critical one:

$$Re_{gap} = 726{,}8 < Re_{\text{cr}} = 2320,$$

in this way the regime of movement of the clot in the gap is laminar.

The Nusselt criterion for laminar viscosity-gravitational motion will be:

$$Nu_{f.cl.gap.} = 0{,}15 \cdot \mathrm{Re}_{f.cl.}^{\;0{,}33} \cdot \mathrm{Pr}_{f.cl.}^{\;0{,}43} \cdot Gr_{f.cl.}^{0{,}1} \left(\frac{\mathrm{Pr}_{f.cl.}}{\mathrm{Pr}_{st.}} \right)^{0{,}25}, \qquad (21)$$

where $\boldsymbol{Pr_{f.cl.}}$ – value of the Prandtl criterion for fermented milk clot; $\boldsymbol{Pr_{st}}$ – value of the Prandtl criterion for the steel wall; $\boldsymbol{Gr_{f.cl.}}$ – Grashoff criterion for a clot.

The heat transfer coefficient when the fermented clot moves along the tank wall is determined by the formula (18).

Heat transfer coefficient from the fermented clot through the walls of tank to the cooling water:

$$k_{f.cl.} = \frac{1}{\dfrac{1}{\alpha_{f.cl.}} + \dfrac{\delta_{st..}}{\lambda_{st.}} + \dfrac{1}{\alpha_{w..}}}, \qquad (22)$$

where $\boldsymbol{k_{f.cl.}}$ – coefficient of heat transfer when moving from the fermented clot through the walls of the tank to the cooling water, W / (m^2·K); $\boldsymbol{\alpha_{f.cl.}}$ – coefficient of heat transfer of the fermented clot to the wall of the tank, W / (m^2·K); $\boldsymbol{\delta_{st}}$ – thickness of the steel wall, m; $\boldsymbol{\lambda_{st}}$ – coefficient of thermal conductivity of steel, W / (m·K); $\boldsymbol{\alpha_{w}}$ – coefficient of heat transfer from the wall to water, W / (m^2·K).

From the heat transfer equation (2), we determine the cooling time of the fermented milk clot:

$$\tau = \frac{Q}{k \cdot F \cdot \Delta t_{m.l.}}, \qquad (23)$$

where $\boldsymbol{\Delta t_{m.l.}}$ – is the mean logarithmic temperature difference, °C.

The mean logarithmic temperature difference is determined by the formula:

$$\Delta t_{m.l.} = \frac{\Delta t_{l.t.d.} - \Delta t_{s.t.d.}}{\ln \dfrac{\Delta t_{l.t.d.}}{\Delta t_{s.t.d.}}}. \qquad (24)$$

Conclusions. A method of thermophysical calculation is proposed to increase the efficiency of cooling the fermented milk clot taking into account the location of the thermal insulation, by reducing heat inflows and increasing the rate of temperature decrease. The correspondence of theoretical calculations to the actual value of the cooling temperatures of the fermented milk clot has been checked. The cooling time of the fermented milk clot was determined. The proposed method of thermophysical calculation can be used when designing tank of complex shape for cooling a fermented milk clot.

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ТЕПЛОФИЗИЧЕСКИЕ РАСЧЕТЫ ПРОЦЕССА ОХЛАЖДЕНИЯ СКВАШЕННОГО СГУСТКА МОЛОКА

Стручаев Н. И., Постол Ю. А., Тарасенко В. Г., Паляничка Н. А.

Аннотация

Статья посвящена повышению энергоэффективности охлаждения сквашенного сгустка молока перед розливом его в потребительскую тару для дальнейшего созревания, путем снижения энергозатрат на поддержание его температуры, установкой теплоизоляции, определения оптимального расположения и зазора мешалки для компенсации термического сопротивления пристенного ламинарного слоя. Предложенная методика теплофизического расчета может быть использована при проектировании ёмкостей сложной формы для охлаждения сквашенного сгустка молока.

Ключевые слова: энергосбережение, теплоизоляция, потери энергии, тепловые притоки, компактные ёмкости сложной формы охлаждение, сквашенный сгусток молока.

ТЕПЛОФІЗИЧНІ РОЗРАХУНКИ ПРОЦЕСУ ОХОЛОДЖЕННЯ СКВАШЕНОГО ЗГУСТКА МОЛОКА

Стручаєв М. І., Постол Ю. О., Тарасенко В. Г., Паляничка Н. О.

Анотація

Стаття присвячена підвищенню енергоефективності охолодження сквашеного згустку молока перед розливом його в споживчу тару для подальшого дозрівання, шляхом зниження енерговитрат на підтримку його температури, установкою теплоізоляції та визначенням оптимального розташування і зазору мішалки для компенсації термічного опору пристінного ламінарного шару. Проведений аналіз найбільш ефективних методів покращення структури кисломолочних напоїв, відзначено важливість процесу охолодження при виробництві молочних продуктів. Запропоновано методику теплофізичного розрахунку для підвищення ефективності охолодження сквашеного згустку молока з урахуванням розташування теплоізоляції, шляхом зменшення притоків теплоти і збільшення темпу зниження температури, перевірено відповідність теоретичних розрахунків фактичним значенням температур охолодження сквашеного згустку молока, визначено час охолодження сквашеного згустку молока. Виконано розрахунок кількості теплоти при охолодженні збродженого кисломолочного згустку на основі вирішення рівняння теплового балансу та тепловіддачі. Режим руху води в прямокутній трубі охолоджувальної сорочки визначався за допомогою критерію Рейнольдса. Визначено еквівалентний діаметр зазору між змішувачем і стінкою резервуару та критерій Рейнольдса для руху згустку в зазорі, який виявився менше критичного, в цьому випадку режим руху згустку є ламінарним. Коефіцієнт тепловіддачі під час руху охолоджуючої води в трубах та згустку в зазорі визначали за допомогою критерію рівнянь Нуссельта. Запропонована методика теплофізичного розрахунку може бути використана при проектуванні ємностей для охолодження сквашеного згустку молока.

***Ключові слова*:** енергозбереження, теплоізоляція, втрати енергії, теплові притоки, компактні ємності складної форми для охолодження, сквашений згусток молока.

THERMOPHYSICAL CALCULATIONS
THE PROCESS OF COOLING THE FERMENTED MILK CLOT

N. Struchaiev, Y. Postol, V. Tarasenko, N. Palyanichka

Summary

The article is devoted to increasing the energy efficiency of cooling the fermented milk clot before filling it into consumer containers for further maturation, by reducing energy consumption to maintain its temperature, by installing thermal insulation and determining the optimal location and gap of the mixer to compensate for the thermal resistance of the walls laminar layer. The proposed method of thermophysical calculation can be used when designing containers of complex shape for cooling a fermented milk clot.

Key words: energy saving, thermal insulation, energy losses, heat inflows, compact containers of complex shape, cooling, fermented milk clot.