Modeling and study of cheese cooling

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Abstract. After the end of the fermentation process, which results in a curd clot, the resulting product is sent for cooling. This process directly determines the quality of the resulting curd. The cooling rate and accuracy of maintaining the temperature affect the cessation of lactic acid fermentation and the increase in acidity – one of the main qualitative indicators of cottage cheese. The use of different types of existing coolers does not fully meet the requirements of the technological regulations for the conduct of the process. The reason lies in the need to take into account not only the design features of the device, but also the knowledge of its dynamic properties, as well as in identifying a number of constantly changing production factors that have a significant impact on the flow of the cooling process. Using the mathematical modeling method allows you to reduce the costs and time required to solve the tasks. The conducted research allowed us to identify the parameters that most affect the cooling temperature and develop ways to eliminate them. The performed calculations allowed us to determine the laws of regulation that ensure high cooling speed and sufficient accuracy of maintaining the set temperature. The results obtained confirmed the effectiveness of the combined control system in comparison with the commonly used standard single-circuit control systems.

1. Introduction
In the production of cottage cheese, one of the most important is the cooling process, the temperature regime of which affects the cessation of lactic acid fermentation and the increase in acidity, that is, the quality of the finished product.

Among the devices for cooling, the most perfect is the screw cooler [1-2]. After production, the curd is fed to the loading bin and moved using a screw. Here, the curd is cooled by its contact with the surface of the shirt, inside which the refrigerant flows – ice water.

The transport system is additionally equipped with cutting scrapers installed on the bushing between the auger turns, which remove the layer of frozen curd to the surface of the side jacket.

2. The purpose of the study
An important task in the production of cottage cheese is to accurately maintain the temperature of the regime during cooling. Deviation from the required nominal value leads to changes in lactic acid fermentation and acidity of cottage cheese. The purpose of the study is to study the dynamic properties of the curd cooling process, the factors that affect its flow, and to develop a control system that ensures accurate temperature maintenance.
3. The object of the study
The object of the study is the cooling process of cottage cheese, which takes place in a screw cooler. The curd arrives at a certain initial temperature and is moved by a screw through the cooler. The coolant is ice water with a variable flow rate.

4. Materials and methods

4.1 Mathematical description of the cottage cheese cooling process
The diagram of the screw cooler is shown in figure 1.

![Diagram of the screw cooler and the main material flows](image)

**Figure 1.** Diagram of the screw cooler and the main material flows

When developing a dynamic model of the cottage cheese cooling process, assumptions are made:
- screw cooler with separated spaces for cold water and cottage cheese without phase transformations with perfect mixing in both spaces has concentrated parameters;
- the refrigerant is only supplied to the cooler jacket;
- the temperature of the heat transfer walls is the same at all points (the thermal resistance is negligible);
- the coefficient of heat transfer between the media and the surface of the metal walls, the specific heat capacity of water, cottage cheese and the wall material are constant over time;
- the heat of the cottage cheese is spent on heating the heat transfer walls and the refrigerant.

A dynamic model of the cooling process that links the main characteristics of material flows (consumption, initial and final values of the cottage cheese and coolant temperatures) is obtained by composing the heat balance equations for the product, the refrigerant, and the heat transfer wall for a small time interval $\Delta \tau$:

\[
G_v \cdot cv \cdot T_{vn} \cdot \Delta \tau + Sr \cdot \alpha_{vr} \cdot (Tr - T_{vk}) \cdot \Delta \tau = G_v \cdot cv \cdot T_{vk} \cdot \Delta \tau + M_v \cdot cv \cdot \Delta T_{vk},
\]

\[
G_t \cdot ct \cdot T_{tn} \cdot \Delta \tau = Sr \cdot \alpha_{tr} \cdot (Tk - Tr) \cdot \Delta \tau + G_t \cdot ct \cdot Tk \cdot \Delta \tau + M_t \cdot ct \cdot \Delta T_{tk},
\]

\[
Sr \cdot \alpha_{tr} \cdot (Tk - Tr) \cdot \Delta \tau = Sr \cdot \alpha_{vr} \cdot (Tr - T_{vk}) \cdot \Delta \tau + M_r \cdot cr \cdot \Delta Tr,
\]

where $G_v$, $G_t$ – mass consumption of cold water and cottage cheese, kg/s; $T_{vn}$, $T_{tn}$, $T_{vk}$, $T_{tk}$ – temperatures of cold water and cottage cheese at the inlet and outlet of the cooler, °C; $cv$, $ct$, $cr$ – heat capacity of cold water, cottage cheese and shirt, J/(kg·°C); $M_v$, $M_t$, $M_r$ – masses of cold water and cottage cheese in the cooler, as well as the jacket between cold water and cottage cheese, kg; $Tr$ – the average temperature of the jacket wall between cold water and cottage cheese, °C; $Sr$ – the surface area of the shirt between cold water and cottage cheese, m²; $\alpha_{vr}$, $\alpha_{tr}$ – heat transfer coefficients from cold water to jacket and from jacket to cottage cheese, W/(m²·°C); $\tau$ – time, s.

Dividing the left and right parts of equations (1) by $\Delta \tau$ and moving to the limit at $\Delta \tau \to 0$, we obtain a system of nonlinear differential equations:
\[
M \cdot cv \cdot \left( \frac{d}{d\tau} T_{vk} \right) + (Gv \cdot cv + Sr \cdot aov \cdot ct) \cdot T_{vk} = Gv \cdot cv \cdot T_{vn} + Sr \cdot aov \cdot Tr,
\]
\[
M \cdot ct \cdot \left( \frac{d}{d\tau} T_{tk} \right) + (Gt \cdot ct + Sr \cdot atr \cdot ct) \cdot T_{tk} = Gt \cdot ct \cdot T_{tn} + Sr \cdot atr \cdot Tr,
\]
\[
Mr \cdot cr \cdot \left( \frac{d}{d\tau} Tr \right) + Sr \cdot (aov \cdot atr) \cdot Tr = Sr \cdot (atr \cdot T_{tk} + aov \cdot T_{vk}).
\]

By presenting the variable parameters as a sum of equilibrium values and increments:
\[
Gv = Gv_0 + \Delta Gv, \quad Tvn = Tvn_0 + \Delta Tvn, \quad Tvk = Tvk_0 + \Delta Tvk, \quad Gt = Gt_0 + \Delta Gt, \quad Tn = Tn_0 + \Delta Tn, \quad Tr = Tr_0 + \Delta Tr, \quad Ttk = Ttk_0 + \Delta Ttk,
\]

opening parenthesis and taking into account the heat balance equations in statics:
\[
(-Gv_0 \cdot cv - Sr \cdot aov) \cdot T_{vk0} + Gv_0 \cdot cv \cdot T_{vn0} + Sr \cdot aov \cdot Tr_0 = 0,
\]
\[
(-Gt_0 \cdot ct - Sr \cdot atr) \cdot T_{tk0} + Gt_0 \cdot ct \cdot T_{tn0} + Sr \cdot atr \cdot Tr_0 = 0, \tag{2}
\]
and discarding the second-order terms of smallness (products of increments of variables), we get a system of linearized differential equations for the cooling process of cottage cheese:
\[
\frac{d\Delta T_{vk}}{d\tau} = -\frac{Gv_0 \cdot cv + Sr \cdot aov}{Mv \cdot cv} \cdot \Delta T_{vk} + \frac{Sr \cdot aov}{Mv \cdot cv} \cdot \Delta T_{vn} + \frac{cv \cdot (T_{vn0} - T_{vk})}{Mv \cdot cv} \cdot Gv_0 \cdot cv \cdot \Delta T_{vn} - Gv_0 \cdot cv \cdot \Delta T_{vn}
\]
\[
\frac{d\Delta T_{tk}}{d\tau} = -\frac{Gt_0 \cdot ct + Sr \cdot atr}{Mt \cdot ct} \cdot \Delta T_{tk} + \frac{Sr \cdot atr}{Mt \cdot ct} \cdot \Delta T_{tn} + \frac{Gt_0 \cdot ct \cdot (T_{tn0} - T_{tk})}{Mt \cdot ct} \cdot \Delta Gt + \frac{ct \cdot (T_{tn0} - T_{tk})}{Mt \cdot ct} \cdot \Delta Gt
\]
\[
\frac{d\Delta Tr}{d\tau} = \frac{Sr \cdot aov}{Mr \cdot cr} \cdot \Delta T_{vk} + \frac{Sr \cdot atr}{Mr \cdot cr} \cdot \Delta T_{tk} - \frac{Sr \cdot (atr - aov)}{Mr \cdot cr} \cdot \Delta Tr
\]

where \(Gv_0, Gt_0\) – mass consumption of cold water and cottage cheese in static (equilibrium), kg/s; \(Tvn_0, Tm_0, Ttk_0\) – temperatures of cold water and cottage cheese at the inlet and outlet of the cooler in static, \(^\circ\)C; \(Tr_0\) – average wall temperature of the cooler jacket in static, \(^\circ\)C; \(\Delta Gv, \Delta Gt\) – increments in mass consumption of cold water and cottage cheese, kg/s; \(\Delta Tvn, \Delta Tm, \Delta Ttk, \Delta Tr\) – temperature increments of cold water and cottage cheese at the inlet and outlet of the cooler, \(^\circ\)C; \(\Delta Ttk\) – increment of the average wall temperature of the cooler jacket, \(^\circ\)C.

By setting the equilibrium values of flow rates \((Gv_0, Gt_0)\) and temperatures \((Tvn_0, Tm_0)\) of cold water and cottage cheese at the inlet of the cooler, we find the equilibrium values of temperatures \((Tr_0, Tvk_0, Ttk_0)\) of the jacket wall, cottage cheese and cold water at the outlet of the cooler, as a solution of the system (2).

Mathematical description (3) in vector-matrix form:
\[
\frac{dX(t)}{dt} = A \cdot X(t) + B \cdot U(t) + C \cdot Z(t), \tag{4}
\]

where \(X(t) = [\Delta T_{vk}(t), \Delta T_{tk}(t), \Delta Tr(t)]^T, U(t) = \Delta Gv(t), Z(t) = [\Delta Tvn(t), \Delta Tm(t), \Delta Gt(t)]^T\) – vectors of state, control, and perturbation variables; \(A, B, C\) – coefficient matrices of the form:
\[
A = \begin{bmatrix}
\frac{Gv \cdot cv + Sr \cdot atr}{Mv \cdot cv} & 0 & \frac{Sr \cdot atr}{Mv \cdot cv} \\
0 & \frac{Gt_0 \cdot ct}{Mt \cdot ct} & 0 \\
\frac{Sr \cdot atr}{Mr \cdot cr} & \frac{Sr \cdot atr}{Sr \cdot atr} & \frac{Sr \cdot (atr + atr)}{Mr \cdot cr}
\end{bmatrix},
\]
\[
B = \begin{bmatrix}
\frac{cv \cdot (Tvn_0 - Tvk_0)}{Mv \cdot cv} \\
0 \\
0
\end{bmatrix},
\]
\[
C = \begin{bmatrix}
\frac{Gv \cdot cv}{Mv \cdot cv} & 0 & 0 \\
0 & \frac{Gt_0 \cdot ct}{Mt \cdot ct} & 0 \\
0 & 0 & \frac{ct \cdot (Tvn_0 - Ttk_0)}{Mt \cdot ct}
\end{bmatrix}.
\]

To analyze the impact of key factors (consumption and initial temperatures of curd and ice water) in the cooling process (temperature of curd at the outlet of the cooler) will move from descriptions of state variables to describe the transfer functions by applying Laplace transformation to the expression (4):
\[
s \cdot X(s) = A \cdot X(s) + B \cdot U(s) + C \cdot Z(s),
\]
\[
X(s) = (sI - A)^{-1} \cdot (B \cdot U(s) + C \cdot Z(s))
\]
where \(X(s) = \{\Delta Tvk(s), \Delta Ttk(s), \Delta Tr(s)\}^T\), \(U(s) = \Delta Gv(s),\ Z(s) = \{\Delta Tvn(s), \Delta Tm(s), \Delta Gt(s)\}^T\) – Laplace images of state, control, and perturbation variables; \(s\) - Laplace operator.

Based on the expression (5), the change in the temperature of the cottage cheese at the outlet of the cooler is described by the dependence:
\[
\Delta Tvk(s) = \frac{k_{11}}{d_3 \cdot s^3 + d_2 \cdot s^2 + d_1 \cdot s + 1} \cdot \Delta Gv(s) + \frac{k_{21}}{d_3 \cdot s^3 + d_2 \cdot s^2 + d_1 \cdot s + 1} \cdot \Delta Tvn(s) + \frac{k_{31} \cdot s^2 + k_{32} \cdot s + k_{33}}{d_3 \cdot s^3 + d_2 \cdot s^2 + d_1 \cdot s + 1} \cdot \Delta Tm(s) + \frac{k_{41} \cdot s^2 + k_{42} \cdot s + k_{43}}{d_3 \cdot s^3 + d_2 \cdot s^2 + d_1 \cdot s + 1} \cdot \Delta Gt(s)
\]
(6)

where \(k_{11}, k_{21}, k_{31}, k_{32}, k_{33}, k_{41}, k_{42}, k_{43}, d_1, d_2, d_3\) – coefficients formed from elements of matrices A, B, C as a result of matrix transformations in (5) and bringing to the canonical form.

Analysis of expression (6) shows that the temperature of the cottage cheese at the outlet of the cooler depends on consumption and initial temperatures of the refrigerator and the cottage cheese.

It is recommended to stabilize the initial temperature of water and cottage cheese at the entrance to the cooler. This can be achieved with high accuracy by using single-circuit control systems for these parameters. Then taking the corresponding terms (second and third) equal to zero in expression (6), we get:
\[
Tvk(s) = Wo(s) \cdot \Delta Gv(s) + W_o^f(s) \cdot \Delta Gt(s),
\]
where \(Wo(s) = \frac{k_{11}}{d_3 \cdot s^3 + d_2 \cdot s^2 + d_1 \cdot s + 1}, W_o^f(s) = \frac{k_{41} \cdot s^2 + k_{42} \cdot s + k_{43}}{d_3 \cdot s^3 + d_2 \cdot s^2 + d_1 \cdot s + 1}\) – transfer functions for the control channel (cold water consumption) and perturbation channel (cottage cheese consumption), respectively.
Based on the obtained mathematical description of the cottage cheese cooling process, it is proposed to use a combined [3] control system (Figure 2), ensuring the most accurate maintenance of the temperature regime.

**Figure 2.** Structural block diagram of the combined cottage cheese temperature control system at the outlet of the screw cooler

$W_p(s)$, $W_k(s)$, $W_0(s)$, $W_f(s)$, $W_{ad}(s)$, $W_d(s)$ - transfer functions of the regulator, compensator, control and disturbance channels, actuator and sensor, respectively; $y_1$, $y_2$ - outputs of the control and disturbance channel; $y$ - the measured output of the object (the final temperature of the cottage cheese); $u_{ad}$, $y_3$ - outputs of the actuator (cold water flow rate) and of the temperature sensor; $u$, $u_k$ - control actions from the regulator and compensator; $u_s$ - the summary control action; $y'$ - setpoint; $f$ - controlled disturbance (consumption of cottage cheese); $e$ - the magnitude of the error.

The operation of the control system is affected by the dynamic characteristics of the sensor and actuator, so it is necessary to take them into account during calculations.

A modular resistance thermometer is selected as the sensor and actuator iTHERM™401 and a control-shut-off valve with an electric drive AUMATIC, the transfer functions of which have the form:

$$W_d(s) = \frac{k_d}{T_d \cdot s + 1}, \quad W_{ad}(s) = \frac{k_{IM}}{T_{IM} \cdot s + 1},$$

where $k_d$, $k_{IM}$ - proportional coefficients of the sensor and actuator; $T_d$, $T_{IM}$ (=5 s) - time constants of the sensor and actuator, respectively, $s$.

The sensor proportionality coefficient is defined as the ratio of the output signal range $\Delta R$ (4-20 mA) to the scale range of the measured value (temperature) $\Delta Y$:

$$k_d = \frac{\Delta R}{\Delta Y} = \frac{20 - 4}{200 - (-50)} = 0,064.$$

The transmission coefficient of the actuator is defined as the ratio of the output (ice water flow rate) to the input (change in the input signal 4-20 mA):

$$k_{IM} = \frac{y_3}{u} = \frac{-3 \cdot Gv_0}{-3 \cdot 0.121} = -0,023.$$

Calculation of the compensator (Figure 2) carried out on the basis of the invariance principle:

$$W_e(s) = -\frac{W_f(s)}{W_o(s) \cdot W_{ad}(s)}.$$  \hspace{1cm} (7)
The controller settings are determined as a result of numerical optimization using the gradient method [5]. In this case, finite difference equations are used to describe the combined system (moving from differential equations):

\[ u_i = u_{i-1} + q_0 (y^i_i - y_d^i) + q_1 (y_{i-1}^i - y_{d-1}^i), \]

\[ u_{k_i} = k_{0m} f_i + k_{1m} f_{i-1} + k_{2m} f_{i-2} + k_{3m} f_{i-3}, \]

\[ u_{s_i} = u_i + u_{k_i}, \]

\[ u_{\text{M}_{i+1}} = a_{d_0} u_{\text{M}_{i+2}} + b_{d_0} y_{i+1}, \]

\[ y_{2_{i+1}} = a_{1}^2 y_{2_{i+1}} + a_{2}^2 y_{2_{i+1}} + a_{3}^2 y_{2_{i+1}} + y_{0} f_{i} + y_{0} f_{i-1} + y_{0} f_{i-2} + b u_{\text{M}_{i+1}}, \]

\[ y_{1_{i+1}} = a_{1}^2 y_{1_{i+1}} + a_{2}^2 y_{1_{i+1}} + a_{3}^2 y_{1_{i+1}} + b u_{\text{M}_{i+1}}, \]

\[ y_{d_{i+1}} = a_{d} y_{d_{i+1}} + b_{d} y_{i}, i = mc/N. \]

(8)

where \( q_0, q_1, q_2, k_{0m}, k_{1m}, k_{2m}, k_{3m} \) - tuning parameters of the digital controller and compensator; \( a_{d_0}, b_{d_0}, a_{1}, a_{2}, a_{3}, v_0, v_2, v_2, a_{1}, a_{2}, a_{3}, b, a_{d}, b_{d} \) - the model parameters of the actuator, channels disturbance and management of the object and sensor; \( d_{a}, d_{f}, d_{v}, d_{d} \) - the number of quantization cycles of control channels and perturbation, the actuator and the sensor; \( i \) - the index of the quantization cycle; \( mc \) - the highest value from the orders of object, regulator, and compensator models; \( N \) - the number of quantization cycles corresponding to the controls time.

The use of the invariance principle makes it possible to optimize the regulator without taking into account the equations of the compensator and the perturbation channel [4-5]. Then the system (8) will take the form:

\[ u_i = u_{i-1} + q_0 (y^i_i - y_d^i) + q_1 (y_{i-1}^i - y_{d-1}^i), \]

\[ u_{s_i} = u_i, \]

\[ u_{\text{M}_{i+1}} = a_{d_0} u_{\text{M}_{i+2}} + b_{d_0} u_{s_i}, \]

\[ y_{1_{i+1}} = a_{1} y_{1_{i+1}} + a_{2} y_{1_{i+1}} + a_{3} y_{1_{i+1}} + b u_{\text{M}_{i+1}}, \]

\[ y_{d_{i+1}} = a_{d} y_{d_{i+1}} + b_{d} y_{i}, i = mc/N. \]

(9)

4.2 Numerical simulation of cottage cheese cooling process

The following values are used as initial data for numerical simulation of the process of cooling cottage cheese on a PC: the equilibrium temperature of cottage cheese at the entrance to the cooler \( (T_{\text{in}}) \) 24 °C; equilibrium temperature of cottage cheese at the outlet \( (T_{\text{out}}) \) 18 °C; equilibrium temperature of cold water at the inlet \( (T_{\text{W}}} \) 2 °C; equilibrium temperature of cold water at the outlet \( (T_{\text{Wout}}) \) 9,487 °C; the temperature of the jacket wall in the equilibrium state \( (T_{\text{r}}) \) 11,313 °C; equilibrium consumption of cottage cheese through the cooler \( (G_{\text{c}}) \) 0,215 kg/s; the equilibrium flow of refrigerant \( (G_{\text{r}}) \) 0,121 kg/s; the heat capacity of cold water \( (c_{v}) \) 4187 J/(kg·°C); heat capacity of cottage cheese \( (c_{t}) \) 2930 J/(kg·°C); heat capacity of the jacket wall \( (c_{r}) \) 462 J/(kg·°C); heat transfer coefficient from cold water to the jacket \( (c_{av}) \) 824 W/(m²·°C); the coefficient of heat transfer from the jacket to the cottage cheese \( (c_{a}) \) 225 W/(m²·°C); the surface area of the jacket between cold water and cottage cheese \( (S_{r}) \) 2,512 m²; mass of cold water in the cooler \( (M_{w}) \) 110 kg; mass of cottage cheese in the cooler \( (M_{c}) \) 265 kg; mass of the jacket between the cold water and cottage cheese \( (M_{r}) \) 39,7 kg; the gain of the sensor \( (k_{d}) \)
0.064 mA/°C; coefficient of gain of the actuator \((k_{M})\) -0.023 kg/(s·mA); the time constant of the sensor \((T_d)\) and actuator \((T_{IM})\) 5 s.

On the basis of a dynamic model of the cottage cheese cooling process, an invariant compensator for disturbances is calculated according to the dependence (7). The settings of three control laws were optimized: proportional, proportional-differential, and proportional-differential-integral (P, PD, PID) using dependencies (9). The optimization results are represented by graphs of transients (figure 3) and setting values (table 1).

![Figure 3](image.png)

**Figure 3.** Graphs of changes in the temperature of cottage cheese when using: a) P or PD of the law of regulation; b) PID of the law of regulation

| Settings, criterion | P-regulator | PD-regulator | PID-regulator |
|---------------------|-------------|--------------|---------------|
| \(q_0\)             | 1112.88     | 771.33       | 0.092         |
| \(q_1\)             | -           | 337.16       | -0.108        |
| \(q_2\)             | -           | -            | 0.02          |
| Integral-quadratic error | 267.56 | 267.73 | 1599.5 |

Table 1. Values of settings and optimization criteria for regulators

At the end, the simulation of cooling of cottage cheese in single-circuit (without compensator) and combined (figure 2) the systems of regulation. The perturbation (consumption of cottage cheese) changed stepwise by 0.2 kg/s. The simulation results are represented by a graph of the transition process in a single-circuit system (figure 4) and the values of quality indicators (table 2). The transition process schedule in the combined system is not given because the temperature did not change.
Figure 4. Graphs of changes in the curd temperature in a single-circuit system when the cottage cheese consumption changes

Table 2. Values in a single-circuit system and a combined system

| Settings, criterion        | Single circuit system | Combined system |
|----------------------------|-----------------------|-----------------|
| Integral-quadratic error   | 62.95                 | 0               |
| Static error               | -0.14                 | 0               |
| Control time, s            | 3535.8                | 0               |
| Overshoot, %               | 303.4                 | 0               |
| Attenuation, %             | 61                    | -               |

5. Discussion of the results
Analysis of the values of the optimization criterion (table 1) shows that the best quality of regulation is achieved when using P and PD laws. This is explained by the high inertia of the cooling process, which is why the presence of an integral component leads to a significant increase in the transition time (figure 3) and a decrease in the quality of regulation.

In the case of a sharp change in the consumption of cottage cheese (perturbation) in a single-circuit control system, the high inertia of the cooling process leads to a long transition process that ends with the setting of a temperature different from the set one. This may result in the quality of the resulting product not meeting the requirements. When using a combined invariant system, the change in the consumption of cottage cheese does not cause any change in its temperature, that is, there is a complete elimination of the influence of the disturbance on the cooling process.

6. Conclusion
Modeling and research of the combined control system for the cooling process of cottage cheese in a screw cooler was carried out. The use of P or PD laws provides a high cooling rate and sufficient accuracy to maintain the temperature of the cottage cheese. The main advantage of the proposed combined control scheme in comparison with the typical single-circuit is the complete independence of the cottage cheese temperature from its consumption and the possibility of using the system in conditions of constantly changing load of the screw cooler. The reason lies in the presence of an invariant compensator that ensures the timely formation of a control effect when a disturbance occurs. It is assumed that the use of a combined system will optimize the consumption of refrigerant and improve the quality of the resulting products.

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