Mathematical model of vacuum cooling process for wheat bread

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Abstract

Introduction. Vacuum cooling is an innovative method that reduces the cooling time of bakery products, improves their structural and mechanical properties, and extends their shelf life.

Materials and methods. A mathematical model of vacuum cooling of bread (loaf) from high-grade wheat flour with weight 0.5 kg was created. The results of experimental studies of the structural and mechanical properties of the crumb, gas permeability of the crust and crumb, and analysis of literature sources were used.

Results and discussion. The crust of the bread formed during the baking process is characterized by low gas permeability ($D = 0.32$ $m^3/m^2 \cdot s$), which significantly hinders the escape of water vapor from the inner layers of the product. Bread crumb has high gas permeability, which contributes to the even evaporation of moisture throughout the product. Its structural and mechanical properties vary with temperature: at high temperatures, the crumb is less durable (1500 Pa at 100 °C, 3600 Pa at 30 °C) and more vulnerable to mechanical stress, which necessitates a controlled pressure drop. In the process of vacuum cooling, phase transitions from liquid to vapor occur adiabatically, which ensures a rapid decrease in product temperature due to internal energy.

A mathematical model of the vacuum cooling process of wheat bread includes calculations of physical and mechanical processes: moisture evaporation, heat and mass transfer, the gas permeability of the crust and structural and mechanical properties of the bread crumb. This makes it possible to predict changes in product quality properties, including its temperature and moisture during cooling after baking.

At the optimal vacuum cooling parameters, the required bread temperature can be reached in just 68 seconds. This is much more efficient than traditional methods that take several hours.

Conclusion. A mathematical model of vacuum cooling of bread from high-grade wheat flour with weight 0.5 kg was created, which helps to optimize the cooling process and improve product quality.

Introduction

Bakery items cooling is an important final stage of the technological process that affects product quality. It is necessary to achieve structural and mechanical properties that allow cutting and packaging without the risk of product deformation, loss of structure or porosity, or condensation inside the package (Everington, 2003; Kozak et al., 2024; Stefanov et al., 2011). The duration of the traditional cooling method depends on the type, size of the product, and the ambient temperature: from 30 minutes for the buns to several hours for the loaves or rye breads (McDonald, 2001).

Traditional cooling methods are characterized by significant energy consumption and duration. In this context, the vacuum cooling process, which is based on adiabatic moisture evaporation, offers significant advantages. It ensures rapid cooling of the product by reducing the pressure in the chamber, which reduces the boiling point of the moisture (Primo-Martín et al., 2008; Zhu et al., 2018). However, excessive pressure reduction can cause undesirable defects, such as cracking of the crust or separation of the crust from the bottom crust (Kozak et al., 2024).

Vacuum cooling is widely used in the food industry to cool vegetables, herbs, and meat products (Ivanov et al., 2021; Peng et al., 2017; Zhang et al., 2014). Studies demonstrate the effectiveness of this method in reducing process time, minimizing energy consumption, and ensuring high product quality (Guo et al., 2018; Wang et al., 2020). However, when cooling bakery products, it is important to take into account the specifics of the product structure, in particular the gas permeability of the crust, and the structural and mechanical properties of the crumb (Kozak et al., 2023; 2024).

Despite significant progress in research, issues remain unresolved regarding the exact determination of the optimal vacuum cooling parameters for bakery products (Everington, 2003; Kinner et al., 2021). A mathematical model is needed that takes into account a complex of physical processes, including the gas permeability of the crust and the structural and mechanical properties of the crumb.

The aim of the study is to create a mathematical model of the process of vacuum cooling of bakery products, which will allow calculating the parameters of the mode taking into account the characteristics of the product.

Materials and methods

Materials

The study was conducted on a 0.5 kg loaf of wheat made from high-grade wheat flour. Important quality characteristics of the finished product of wheat flour products, namely the loaf, are: length – 300 mm, width (product diameter) – 150 mm, height – 80 mm.

Thermal and physical parameters for wheat bread varieties were as follows: humidity, 38–45%; thermal conductivity (λ), 0.2–0.3 W/m·K; heat capacity (c), 2.5–3.0 kJ/kg·K; density (ρ), 200–300 kg/m³; porosity of the crumb, 68 %.

Important quality indicators for wheat flour products are their sensory characteristics: appearance, cut, texture, color, smell, and taste of the finished product.

Requirements for the sensory characteristics of the product were as follows: appearance corresponds to the mold in which it was baked, without side spills. A mold in the form of a product or part of it cut into slices is allowed.

Surface (crust): light yellow to brown, without burning. Slight wrinkling is allowed for packaged products; for sliced products with traces of cuts.

Crumb condition: baked, elastic, not wet to the touch, no traces of unleavened bread.

Taste: typical for this type of product, without off-flavors.

Methods

To create a mathematical model for vacuum cooling of a 0.5 kg loaf from high-grade wheat flour, an integrated approach was used including a literature review and experimental studies. The research covers the parameters of vacuum cooling, as well as the structural and mechanical properties of the crumb and the gas permeability of the crust and crumb of the loaf. The results were the basis for building a mathematical model that takes into account key aspects of the process.

Results and discussion

Influence of product structural properties on vacuum cooling

During the study of the operating parameters of the vacuum cooling process of a loaf, it was found that the crust formed during baking has significant resistance (low gas permeability). This significantly hinders the escape of water vapor from the inner layers of the loaf to the environment of the vacuum chamber, which affects the cooling efficiency (Kozak et al., 2023). It has been found that the cooling intensity is determined by the gas permeability of the crust and the structural and mechanical properties of the crumb, which vary depending on the product temperature (Kozak et al., 2023).

To determine the operating parameters of the vacuum cooling process, studies were conducted that allowed us to establish the following indicators. The throughput of the loaf crust is D = 0.32 $m^3/m^2 \cdot s$, area of loaf crust, F = 0.091 m^2, and the volume of steam formed during vacuum cooling is equal to V = 0.444 m^3 (Kozak et al., 2023).

The study of the structural and mechanical properties of the loaf crumb showed a linear dependence of the tensile strength on temperature, as shown by equation (Kozak et al., 2024):

$$\sigma = -30 \cdot t + 4500; \quad (1)$$

where: σ is the tensile strength of the loaf crumb (Pa);
t is the temperature of the loaf crumb (˚C).

At a temperature of 100 °C, the tensile strength of the crumb is 1500 Pa, and at 30 °C it is 3600 Pa (Kozak et al., 2024).

Scheme of vacuum cooling of bread on the example of loaf

Based on the analysis of literature sources (Everington, 2003; Kinner et al., 2021) and the results of experimental studies of vacuum cooling of the loaf, as well as the determination of the structural and mechanical properties of the crumb and gas permeability of the loaf crust, a scheme for vacuum cooling of the loaf was created (Figure 1) (Kozak et al., 2023; 2024).

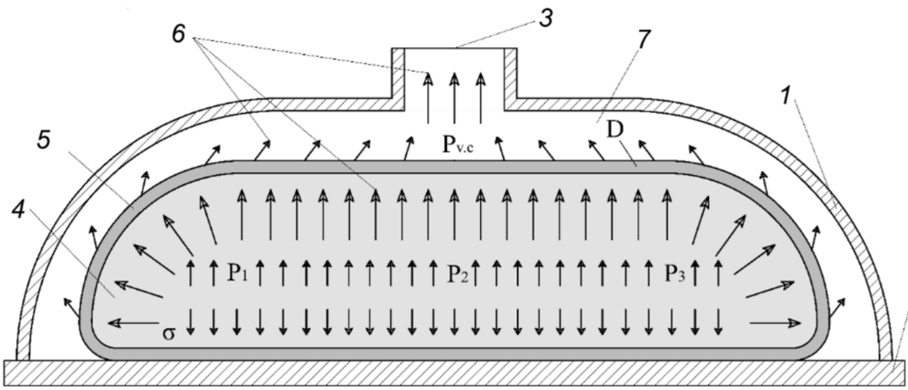

Figure 1. Scheme of vacuum cooling of loaf:
1 – vacuum chamber; 2 – vacuuming table; 3 – vacuum supply; 4 – loaf crumb; 5 – loaf crust; 6 – visualization of steam movement during the process; 7 – vacuum chamber environment.

Vacuum cooling of the loaf occurs as follows (Figure 1): a vacuum is created in the vacuum chamber Pv.c. (1) through the vacuum inlet (3). Because of the pressure decrease, adiabatic boiling of moisture begins in the entire volume of the loaf due to the fact that $P_1 = P_2 = P_3 = P_l$ (crumb 4). The main obstacle to the escape of steam (6) from the loaf is the crust (5) with gas permeability G. In order to avoid product destruction, the process should be carried out in such a way that the pressure gradient between the vacuum chamber environment (7) and the environment inside the loaf (crumb 4) does not exceed the tensile strength of the crumb $\Delta P < \sigma$.

Determination of operating parameters of vacuum cooling process of loaf

Based on the scheme for determining the operating parameters of the loaf vacuum cooling process (Figure 2), the following provisions were formulated:

Structural characteristics of the loaf:

A loaf after baking is considered as a capillary-porous body (Everington, 2003; McDonald, 2001).

The porosity of the loaf is 68%, which indicates a significant number of small pores in its structure (Kinner et al., 2021).

The crust of the loaf has low gas permeability, i.e., it does not allow moisture evaporating during the process to pass through (Kozak et al., 2023).

The crumb of the loaf is characterized by high gas permeability, which facilitates easy evaporation of moisture, allowing the cooling process to occur simultaneously throughout the entire volume (Kozak et al., 2023).

Structurally, the mechanical properties of the crumb vary linearly with temperature: the higher the temperature, the lower the tensile strength. This means that a loaf at high temperatures is softer and less resistant to mechanical stress (Kozak et al., 2024).

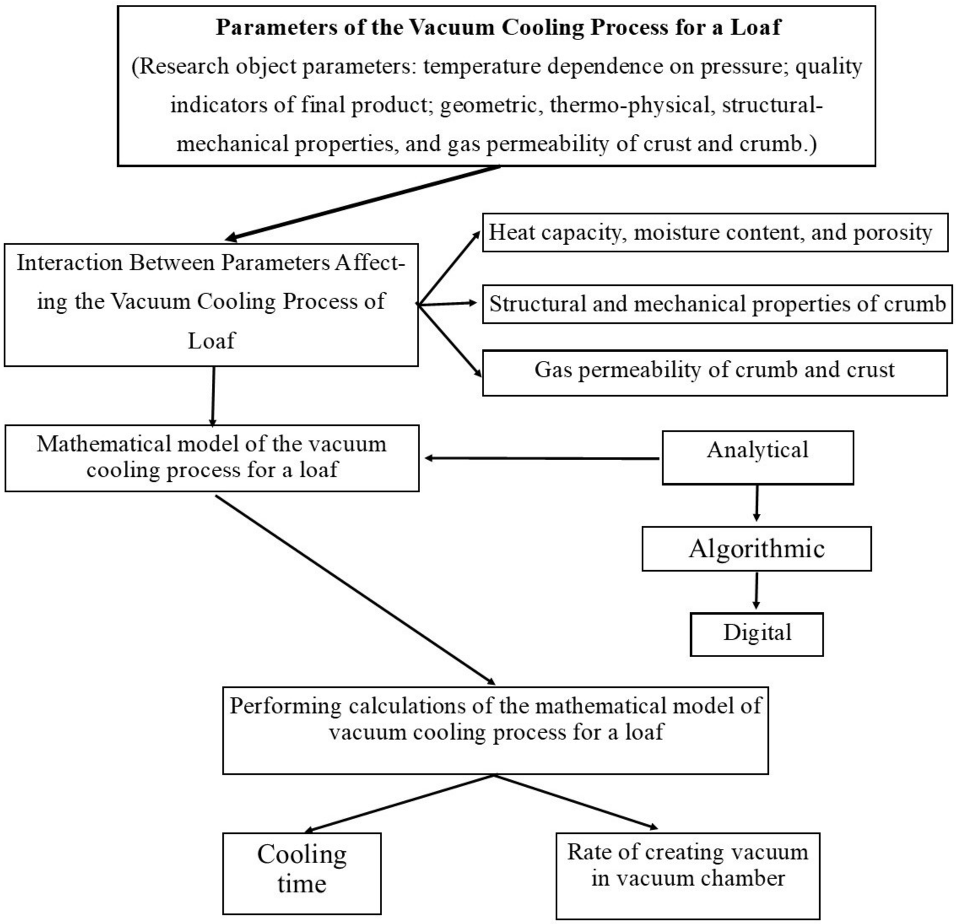

Figure 2. Scheme for determining operating parameters of loaf vacuum cooling process

Phase transitions:

The liquid-to-vapor phase transitions occur evenly throughout the loaf, which guarantees uniform moisture evaporation and ensures uniform cooling of the product (McDonald, 2001; Kozak et al., 2023).

Energy balance:

The phase transition occurs without additional heat input from the outside, due to a decrease in the internal energy of the product. This means that the loaf is cooled by its own energy, which is spent on moisture evaporation. As a result, the temperature of the product decreases, which ensures fast and efficient cooling (Ajani et al., 2022; Peng et al., 2017)

Thus, vacuum cooling of the loaf effectively reduces the temperature of the product by evaporating moisture, distributing it evenly throughout the volume, and reducing the internal energy of the product (Wang et al., 2020; Zhang et al., 2014).

Based on the above provisions, a mathematical model of the process of vacuum cooling of bakery products has been developed on the example of a loaf.

Analytical model of loaf vacuum cooling process

The analytical model, based on calculations of moisture evaporation, heat transfer, mass transfer, and mechanical strength of the bread crumb, allows you to assess the dynamics of changes in product quality, in particular during cooling after baking.

Structural and mechanical properties.

From the study of the structural and mechanical properties of the loaf crumb, we obtained a linear dependence of the tensile strength on temperature (Kozak et al., 2024):

$$\sigma = -30\,t + 4500; \qquad (2)$$

where σ is a tensile strength of bread crumb (Pa);
t is a temperature (˚C).

Pressure drop between the media.

The Boyle-Mariotte gas law was used to calculate the pressure generated inside the loaf during the vacuum cooling process. This law states that for a constant amount of gas, its pressure and volume are inversely proportional to (Kozak et al., 2023):

$$P_1 \cdot V_1 = P_2 \cdot V_2 \qquad (3)$$

where: P_1 is an initial pressure inside the loaf (Pa);
V_1 is an initial gas volume inside the loaf (m^3);
P_2 is a pressure inside the loaf during vacuum cooling (Pa);
V_2 is a gas volume inside the loaf during vacuum cooling (m^3);.

The gas flow through the crust of the loaf is described by the equation (Kozak et al., 2023):

$$J = \frac{P \cdot D}{L} \qquad (4)$$

where J is gas flow through the loaf crust (m^3/s);
P is pressure difference between the internal and external environments (i.e. P= P1-P2),
D is gas permeability of the loaf crust ($m^3/(m^2 \cdot s)$),
L is thickness of the loaf crust (m).

Then the pressure P_2 inside the loaf:

From the permeability-concentration equation, we can express the pressure difference P (Kozak et al., 2023):

$$P = \frac{J \cdot L}{D} \qquad (5)$$

Substituting this value of the pressure difference P into the Boyle-Mariotte law, we obtain (Kozak et al., 2023):

$$P_1 \cdot V_1 = (P_1 - P) \cdot V_2 \quad (6)$$

Where we get it:

$$P_1 \cdot V_1 = \left(P_1 - \frac{J \cdot L}{D} \right) \cdot V_2 \quad (7)$$

Given that the volume of gas inside the loaf does not change during vacuum cooling, we can assume that $V_1 \approx V_2$. In this case, the equation is simplified to (Kozak et al., 2023):

$$P_1 \approx P_2 + \frac{J \cdot L}{D} \quad (8)$$

Hence, we can derive the value of the pressure in the loaf P2 that occurs during vacuum cooling (Kozak et al., 2023):

$$P_2 = P_1 - \frac{J \cdot L}{D} \quad (9)$$

Evaporation of moisture.

In order for the moisture in the middle of the loaf to turn into steam, a certain amount of heat must be consumed, which is determined by the heat of phase transition. To estimate the amount of evaporated moisture W(τ) per unit mass of product, we use the equation (Everington, 2003; McDonald, 2001):

$$W(\tau) = \frac{q(\tau) \cdot g_p}{r} \quad (10)$$

where: τ – time, sec

q(τ) is amount of heat consumed for the phase transition of water to steam (J/kg);

r – heat of phase transition (J/kg);

g_p is weight of the product (kg).

The amount of heat used to cool the product (Everington, 2003; McDonald, 2001):

$$q(\tau) = (c_{d.m.} g_{d.m.} + c_m g_m)(t_l - t_{c.l.}) \quad (11)$$

where: $q(\tau)$ is the amount of heat consumed for cooling a unit mass of loaf (J/kg);;

$c_{d.m.}$ is a specific heat capacity of the loaf dry matter (J/(kg °C));

t_l is a temperature of the loaf after leaving the oven (°C);

$t_{c.l.}$ is an emperature of the cooled loaf (°C).

$g_{d.m.}$ is a dry matter content in the loaf determined by the formula (Everington, 2003; McDonald, 2001).

$$g_{d.m.} = \frac{100 - W_l}{100} \quad (12)$$

where W_l is a moisture content in the hot loaf.

Moisture content in the loaf (kg):

$$g_m = \frac{W_l}{100}. \quad (13)$$

Because 1 kg of steam at different pressures occupies a different volume, it is necessary to calculate the volume of steam generated as a result of cooling (Kozak et al., 2023):

$$V = V^{`} \cdot W. \quad (14)$$

where: V`is a volume occupied by 1 kg of steam at the corresponding pressure (Figure 3).
W is a mass of moisture evaporated because of cooling.

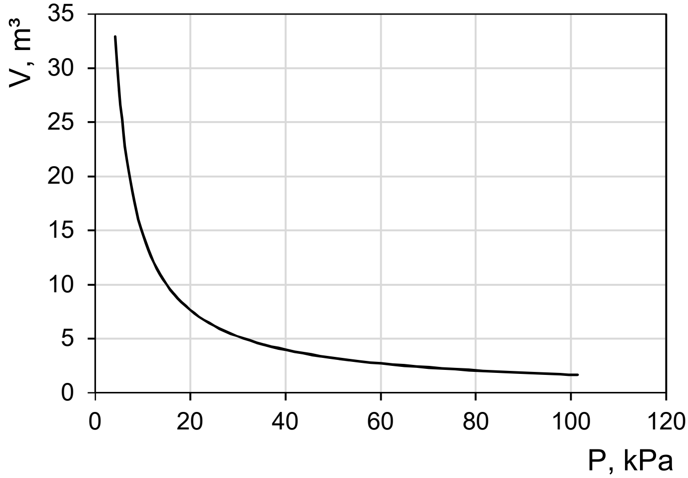

Figure 3. Dependence of steam volume on pressure

Mass transfer.

The amount of moisture that evaporates depends on the amount of heat removed from the bread to cool the product. The process of mass transfer due to moisture evaporation is described by the equation (Ajani et al., 2022):

$$\frac{dW(\tau)}{d\tau} = \frac{q_{v(\tau)}}{r}. \quad (14)$$

where W(τ) –is a change in moisture mass in the product.

Heat transfer.

The temperature depends on the amount of heat transferred, the heat capacity of the product, and its density (Gao et al., 2018; Guo et al., 2018):

$$\frac{dt(\tau)}{d\tau} = -\frac{q_v(\tau)}{c_p \cdot \rho}. \qquad (15)$$

where:

q_v is an intensity of internal heat flow (W);

c_p is a specific heat capacity (J/kg·°C);

ρ is a density of the product (kg/m^3).

There is no heat flux on the surface of the loaf, so there are no boundary conditions for heat flux:

$$q(0,\tau) = q(L,\tau) = 0. \qquad (16)$$

Determine the pressure inside the vacuum chamber.

According to the temperature of product, the pressure is determined at which the moisture boils in the center of bread (Figure 4) (Everington, 2003; McDonald, 2001):

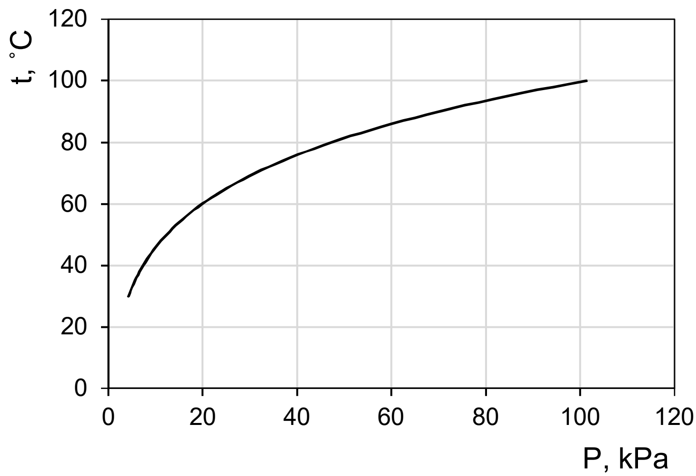

Figure. 4. Dependence of the boiling point of moisture on pressure

Boundary conditions.

For heat transfer:

$$t(0, \tau)=t(L, \tau)=t_f, \qquad (17)$$

where T_f is a temperature of the medium.

For pressure:

$$P(0, \tau)=P(L, \tau)=P_k \qquad (18)$$

For the strength of the crumb:

$$\sigma(\tau) \geq \Delta P(\tau) \qquad (19)$$

Algorithmic model for calculating process of vacuum cooling of loaf

Initial data: Temperature after baking t_0; initial moisture content of the product W_0; initial pressure P_0.

Material properties: specific heat capacity c_p; density ρ; heat of phase transition r; gas permeability of the crust G; crust area F, tensile strength of the crumb.

Algorithm steps.

Initialization of parameters: temperature 100 °C, humidity 42%, pressure 101.325 kPa. We set the time step Δ τ (1 s) and the total simulation time τ_{fin}.

Strength calculation (Kozak et al., 2024):

$$\sigma = -30t + 4500;. \quad (20)$$

Determine the pressure drop between media (Kozak et al., 2023):

$$P_2 = P_1 - \frac{J \cdot L}{D}. \quad (21)$$

$$\Delta P = P_1 - P_2. \quad (22)$$

Calculation of mass transfer.

Determine the weight and volume of evaporated moisture at each step (Ajani et al., 2022):

$$W(\tau + \Delta\tau) = W(\tau) - \frac{q_v \cdot \Delta\tau}{r}. \quad (23)$$

$$V = V` \cdot W \quad (24)$$

Calculation of heat transfer.

Calculate the temperature field of the product at the next time step (Gao et al., 2018; Guo et al., 2018):

$$t(\tau + \Delta\tau) = t(\tau) - \frac{q_v}{c_p \cdot \rho} \cdot \Delta\tau \quad (25)$$

$$q_v = \frac{r \cdot \Delta W}{\Delta \tau} \quad (26)$$

According to the temperature of the product, we determine the pressure at which the roll in the middle of the product will boil

Moving to the next time step.

– Increase the time τ by Δ τ.
– $\tau < \tau_{fin}$, return to step 2 to calculate the parameters at a new time step.

End of modelling.

– When the time reaches τ_{fin}, the model is complete.
– It is analysed the results: temperature field, moisture evaporation dynamics, product strength, and other parameters.

Results of calculations

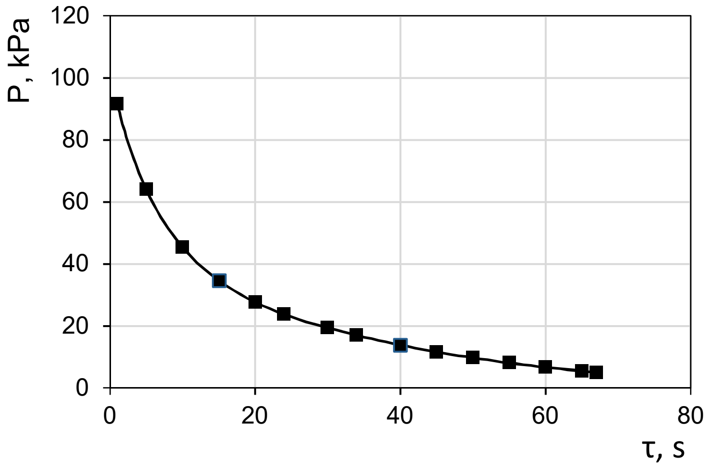

Figure 5. Calculated mode of vacuum creation in a vacuum chamber

As a result of calculations of the mathematical model of the process of vacuum cooling of a loaf of high-grade wheat flour weighing 0.5 kg, it is recommended to reduce the pressure of the vacuum chamber according to the dependence shown in Figure 5. Under these conditions, the cooling time is 68 seconds.

Summarizing and comparing the results

During the study of the operating parameters of vacuum cooling of the loaf, it was found that the crust formed during baking has a high resistance, which prevents the diffusion of water vapor from the middle of the loaf to the environment (Kozak et al., 2023). Therefore, the cooling rate is limited by the gas permeability of the crust and the structural and mechanical properties of the loaf crumb (Kozak et al., 2024).

If not properly adjusted, the pressure reduction in the vacuum chamber causes a pressure gradient between the vapor in the cooled product and the environment. This leads to cracking of the loaf crust (Figure 6) and detachment of the crumb from the bottom crust (Figure 7) (Kozak et al., 2023; 2024).

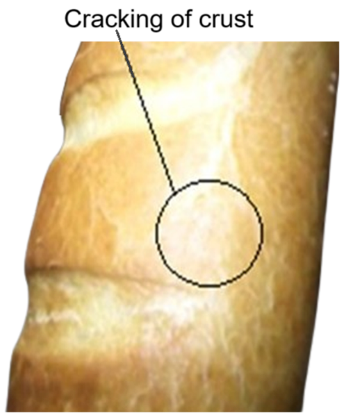

Figure 6. Loaf crust cracking as result of too much pressure reduction in vacuum chamber

In the experimental setup, we established the optimal mode of cooling the loaf to a temperature of 30 °C, which is shown in the graph in curve 1 (Figure 8). Curves 2 and 3 in Figure 8 correspond to samples 2 and 3 in Figure 7, and under such conditions, it was found that the crumb of the test sample was ruptured, which does not meet the established quality requirements (Kozak et al., 2023; 2024).

In the regime represented by curve 1 in Figure 3, the cooling time for a 0.5 kg loaf is 2 minutes, and the maximum rate of rarefaction does not exceed 4.5 kPa/s.

Figure 7. Destruction of loaf:
1 – specimen with a properly selected vacuum cooling mode;
2, 3 – samples with too intensive vacuum cooling mode

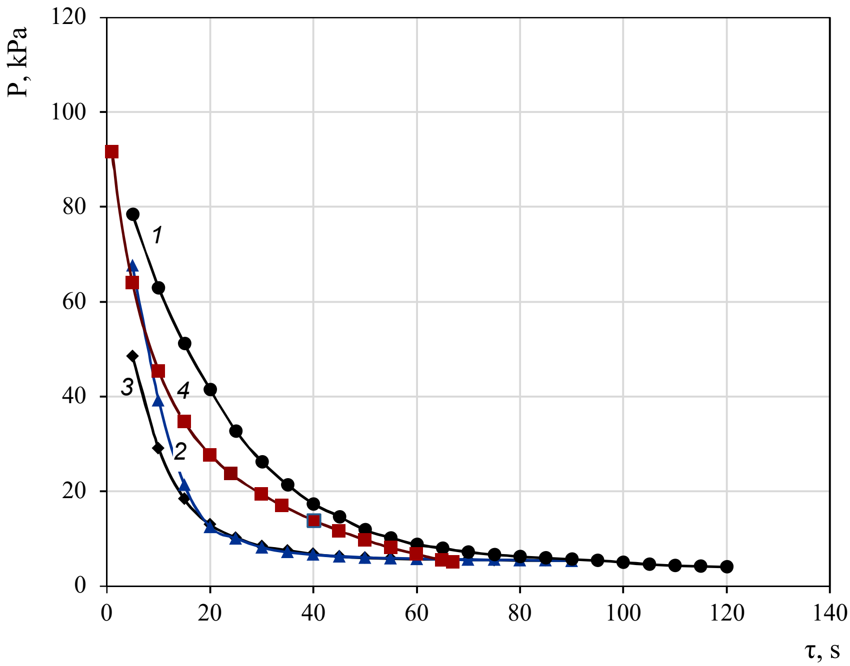

Figure 8. Curves of vacuum generation in vacuum chamber:
1 – experimentally found regime parameters of pressure change over time in a vacuum chamber at which no loaf destruction occurs;
2, 3 – experimentally found regime parameters of pressure change over time in a vacuum chamber at which the destruction of the loaf occurs;
4 – calculated mode of creating a vacuum in a vacuum chamber

Because of the studies, literature review, and mathematical model calculations, the regime parameters of pressure changes in the vacuum chamber were obtained, under which no loaf destruction occurs and the cooling time is 68 s.

Conclusions

1. The crust of the loaf formed during the baking process is characterized by low gas permeability (D = 0.32 $m^3/m^2 \cdot s$), which significantly hinders the escape of water vapor from the inner layers of the product.
2. The loaf crumb has high gas permeability, which contributes to the even evaporation of moisture throughout the product. Its structural and mechanical properties vary with temperature: at high temperatures, the crumb is less durable (1500 Pa at 100 °C, 3600 Pa at 30 °C) and more vulnerable to mechanical stress, which necessitates a controlled pressure drop.
3. In the process of vacuum cooling, phase transitions from liquid to vapor occur adiabatically, which ensures a rapid decrease in product temperature due to internal energy.
4. A mathematical model of the vacuum cooling process has been developed, which makes it possible to calculate the operating parameters under which crust cracking or detachment of the crumb from the lower crust does not occur. In particular, the model takes into account the structural and mechanical properties of the crumb, the gas permeability of the crust, heat and mass transfer processes during vacuum cooling.
5. According to the calculations of the mathematical model, a graph of pressure changes in the vacuum chamber as a function of time was constructed. According to the results of the calculations, the cooling time is 68 s instead of several hours when using traditional methods of cooling the loaf.

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