

VACUUM COOLING OF BAKERY PRODUCTS: PARAMETERS AND FEATURES IN CONTINUOUS PRODUCTION

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ABSTRACT: This article examines the features of the vacuum cooling process of bakery products in continuous production conditions. It has been established that the critical parameters limiting the rate of pressure reduction in the vacuum chamber are the crust gas permeability (0.32–0.42 m³/(m²·s)) and the structural-mechanical properties of the crumb. Experimental studies showed that the crust acts as the main barrier for vapor release, while the crumb has practically no effect on the process. A dependence of crumb strength on temperature was revealed: as temperature increases, the strength limit decreases, which should be taken into account when determining cooling regimes. For a 0.5 kg wheat bread, the optimal process parameters were determined: the pressure reduction rate in the vacuum chamber does not exceed 4.5 kPa/s, and the cooling time is 66 s, allowing the traditional cooling time of 1–2 hours to be reduced to 66 s. The obtained results allow assessing the impact of vacuum cooling on the physico-mechanical properties of products and provide a basis for improving existing equipment and developing new ones, increasing the efficiency and energy saving of bakery production. The practical application of these results contributes to improving product quality and reducing technological time at enterprises.

KEYWORDS: vacuum cooling, bakery products, crust gas permeability, structural-mechanical properties, cooling in continuous production.

1. INTRODUCTION (HEADING 1)

Cooling bakery products is an important stage in the technological process, as it ensures the formation of the structural and mechanical properties necessary for further cutting and packaging. Mechanical impact on freshly baked hot products leads to their crushing, loss of shape, structure, and porosity.

Three main cooling methods are used in production: natural (convective), using conditioned air, and vacuum. The disadvantages of the first two methods are [5]:

- significant duration of the process;
- large size and weight of equipment;
- complex conveyor system;
- high requirements for working air conditions;
- uneven cooling;
- increased bacterial contamination of products.

The use of traditional equipment does not allow for a significant reduction in cooling time, which can take several hours. This raises the question of creating vacuum cooling devices capable of reducing the duration of the process to a few minutes [7].

The principle of vacuum cooling is based on heat removal through adiabatic boiling of moisture inside the product. The advantages of this method are:

increased product volume, extended shelf life, and improved structural and mechanical properties. The disadvantages are considered to be: increased percentage of drying and crust hardening.

Research on vacuum cooling has been conducted for a long time by many scientists, including employees of the National University of Food Technologies. However, the implementation of this technology in flow production requires improvement of both the theoretical foundations and the process parameters. In particular, an overly intense reduction in pressure in the vacuum chamber creates a sharp pressure gradient between the steam in the product and the surrounding environment, which leads to cracking of the bread crust (Figure. 1) and separation of the crumb from the bottom crust (Figure. 2) [6].

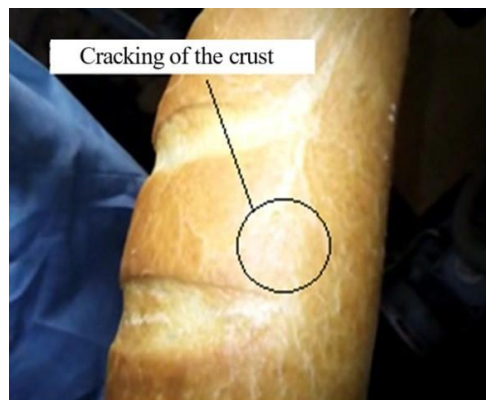


Figure 1. Cracking of the crust as a result of too intense pressure reduction in the vacuum chamber



Figure 2. Destruction of wheat bread:

- 1 – sample with correctly selected vacuum cooling mode; 2, 3 – samples with too intense vacuum cooling mode

In order to determine the operating parameters of vacuum cooling, this study investigated the cooling process of wheat bread and determined the gas permeability of the crust and the structural and mechanical properties of the crumb [6].

2. MATERIALS AND METHODS

We studied the cooling of bread made from premium wheat flour weighing 0.5 kg.

To conduct research on the vacuum cooling process, we created an experimental setup (Figure. 3).

Freshly baked bread (at a temperature of 98–100 °C) is placed in vacuum chamber 1 after measuring its weight, temperature in the center, and geometric dimensions. The chamber is covered with a lid 2 and the vacuum pump is turned on. Video recording is used to record changes in time and pressure in vacuum chamber 1 [7].

The steam-air mixture pumped out of vacuum chamber 1 enters condenser 5, into which cold water is fed in a counterflow. Most of the steam formed during vacuuming condenses in condenser 5, and the condensate flows into condensate collector 4.

Once the required vacuum has been achieved, vacuum pump 3 is switched off and the pressure is equalized with atmospheric pressure using a tap located on the lid of vacuum chamber 2. We measure the temperature, mass, and geometric dimensions of the bread [9].

An experimental setup (Figure. 4) was created to determine the gas permeability of the crust and crumb.

Cut a sample of crust or crumb with a diameter of 25 mm and a thickness of 5 mm from freshly baked or cooled bread, weigh it, place it in clamp 3, and turn on the vacuum pump [8].

Using video recording, record the air consumption over time on the gas consumption meter 4 and the pressure change over time on the digitally connected manometer to the tees with fittings for differential connection of the manometer 5 [10].

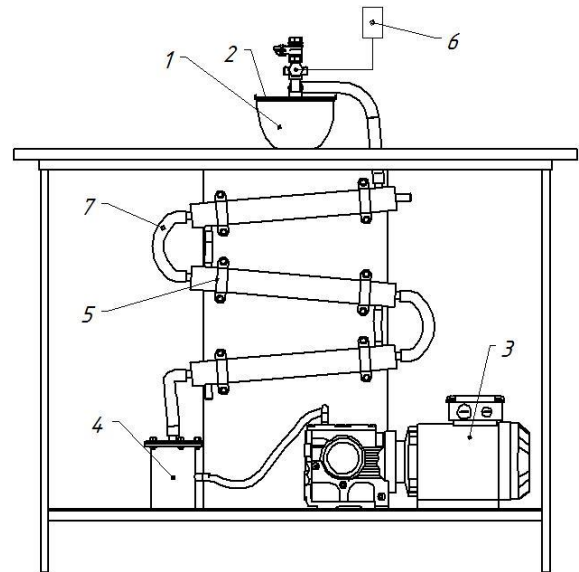


Figure 3. Vacuum experimental setup:

- 1 – vacuum chamber; 2 – vacuum chamber cover; 3 – vacuum pump; 4 – condensate collector; 5 – condenser; 6 – pressure gauge; 7 – pipeline.

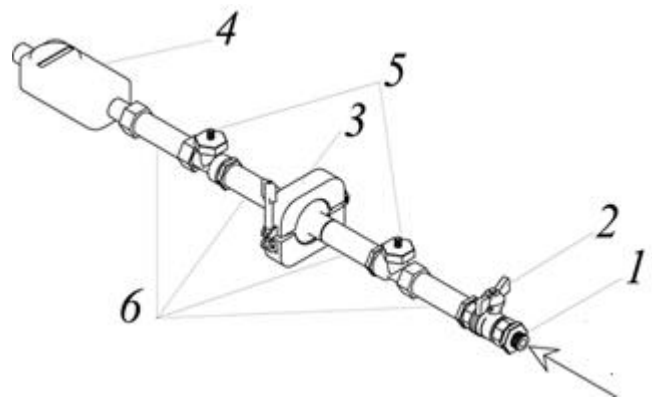


Figure 4. Apparatus for determining the gas permeability of bread crust and crumb

- 1 – connector for attaching a vacuum pump; 2 – tap for regulating the vacuum creation rate; 3 – clamp; 4 – gas flow meter; 5 – tees with fittings for differential connection of a pressure gauge; 6 – pipeline

Gas permeability (specific throughput) is an indicator of the volume of gas passing through a unit of surface area per unit of time [6].

To determine the rheological properties of the crumb, we used a semi-automatic penetrometer of the AP 4/1 brand with a flat indenter (Figure. 5).

The research was conducted in production conditions with freshly baked wheat bread weighing 0.5 kg, taken from the oven, following these steps: using a knife, a crumb sample measuring 30 mm in height, width, and length was cut from the bread. This sample was placed on a platform and lifted to the surface of the indenter using a lifting screw [5]. During the studies, it became clear that the rheological characteristics of the crumb depend largely on temperature. For each crumb temperature value, three samples were taken, and a new sample was used for each experiment [10].

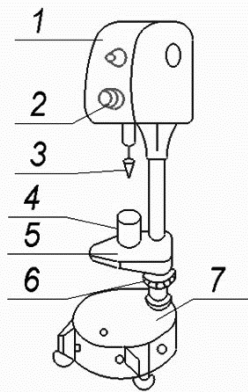


Figure 5. Penetrometer model AP-4/1:

- 1 - measuring head; 2 - scale indicator;
- 3 - indenter; 4 - sample; 5 - platform for the sample;
- 6 - nut for bringing the platform with the sample to the indenter; 7 - base

The analysis of the obtained experimental data was performed based on the scientific works of P. A. Rebinder and other researchers who studied the rheological properties of low-modulus materials using the compression method. On the OA segment (Figure. 6), the material obeys Hooke's law, which means that the deformation of the material is proportional to the applied stress [2].

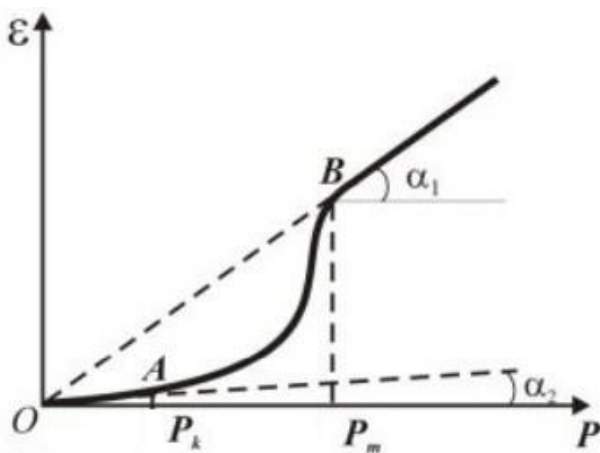


Figure 6. Generalized graph of deformation of low-modulus materials during compression studies of rheological properties.

The stress P_k indicates the beginning of structural failure. With further increase in stress, section AB (Figure. 6), the curve loses its linear character, indicating partial structural failure and the appearance of plastic deformation. At point B of the deformation curve, the structure of the system is almost completely destroyed. The stress corresponding to this point is called the limit shear stress P_m (the strength limit of the material). Above P_m , when the structure breaks down, the material deforms according to Hooke's law [9].

3. RESULTS AND DISCUSSION

As a result of studies conducted on a vacuum experimental setup (Figure. 3), we established a rational cooling regime for the baton to a temperature of 30 °C, which is shown in the graph in Figure. Curves 2 and 3 in Figure. 7 correspond to samples 2 and 3 in Figure. 2, and under these modes, it was found that the crumb of the tested sample breaks, which does not meet the established requirements.

At the mode shown by curve 1 in Figure. 7, the cooling time of a 0.5 kg loaf is 2 minutes, and the maximum rate of vacuum formation does not exceed 4.5 kPa/s.

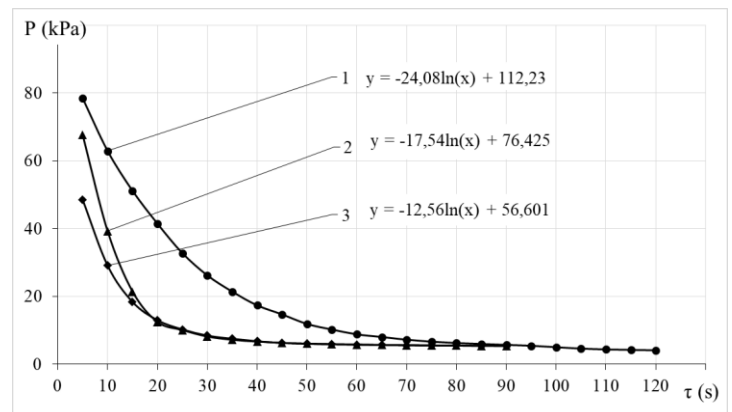


Figure 7. Curves of vacuum creation in a vacuum chamber:

- 1 – vacuum cooling mode in which the baton is not destroyed and the maximum vacuum creation rate in the vacuum chamber is 4.5 kPa/s;
- 2,3 – modes in which the baton is destroyed and the maximum rate of vacuum creation in the vacuum chamber is 5.5 kPa/s (2) and 8.8 kPa/s (3)

In order to optimize the operating parameters of the vacuum cooling process for bread loaves (Figure. 7, curve 1), we conducted research to determine the gas permeability of the crust and crumb of bread loaves, as well as research on the structural and mechanical properties of the crumb [8].

As a result of studies on the cooling of bread in a vacuum experimental setup, it was found that the rate of pressure reduction in the vacuum chamber affects

not only the duration of the process, but also the quality of the products. Excessively intense pressure reduction leads to the destruction of the loaf, in particular, the separation of the crumb from the bottom crust and cracking of the surface. This is due to the emergence of a significant pressure gradient between the steam formed inside the loaf and the environment in the chamber, caused by the low gas permeability of the crust [7].

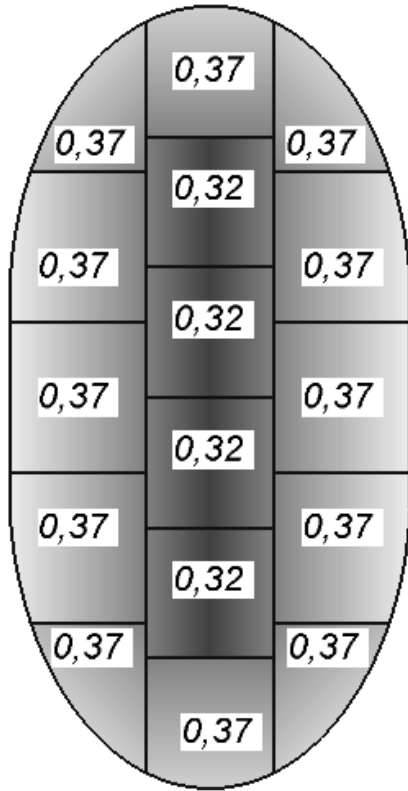


Figure 8. Distribution of gas permeability of the upper crust of the loaf ($\text{m}^3/(\text{m}^2 \cdot \text{s})$)

The intensity of vacuum cooling is limited by the gas permeability of the crust and the strength of the crumb. For wheat bread weighing 0.5 kg, the rate of pressure reduction should not exceed 4.5 kPa/s, which prevents the crust from cracking and the crumb from breaking off, ensuring the proper quality of the product. Studies have shown (Figure. 8) that the central part of the crust has lower gas permeability compared to the side areas, which is due to more intense thermal exposure during baking. Visually, this is manifested in a darker color of the crust: the darker it is, the lower the gas permeability due to the compaction of the structure and intense caramelization processes [8].

Gas permeability of the lower crust: $G1 = 0.42$ ($\text{m}^3/(\text{m}^2 \cdot \text{s})$).

Gas permeability of the central part of the upper crust: $G2 = 0.32$ ($\text{m}^3/(\text{m}^2 \cdot \text{s})$).

Gas permeability of the side part of the upper crust of the loaf: $G3 = 0.37$ ($\text{m}^3/(\text{m}^2 \cdot \text{s})$).

The average gas permeability of the loaf is $G = 0.37$ ($\text{m}^3/(\text{m}^2 \cdot \text{s})$).

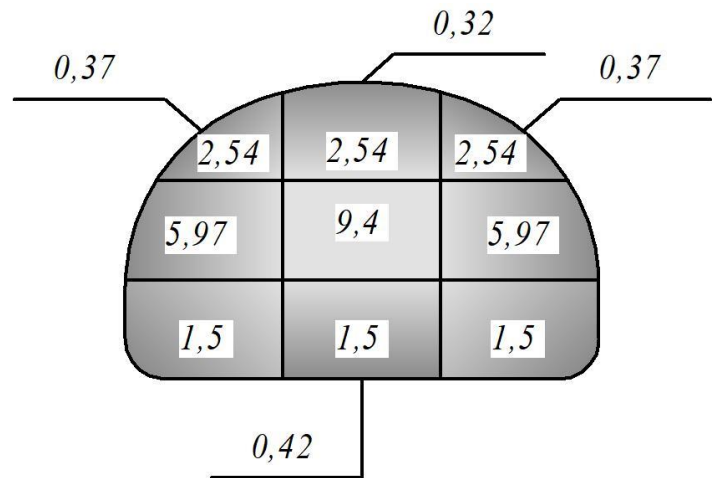


Figure 9. Distribution of gas permeability values in the crumb in a cross-section of the loaf ($\text{m}^3/(\text{m}^2 \cdot \text{s})$)

During the research, it was found that the gas permeability of the crumb in the cross section of the loaf (Figure. 9) significantly exceeds the gas permeability of the crust. This allows us to conclude that the gas permeability of the crumb has practically no effect on the vacuum cooling process of wheat bread, since the restriction of gas exchange between the media is due to the properties of the crust.

As a result of studies to determine the structural and mechanical properties of the crumb of a loaf of bread, typical curves of the dependence of the deformation of the sample on the applied stress were obtained when determining the rheological properties of materials by the compression method [9].

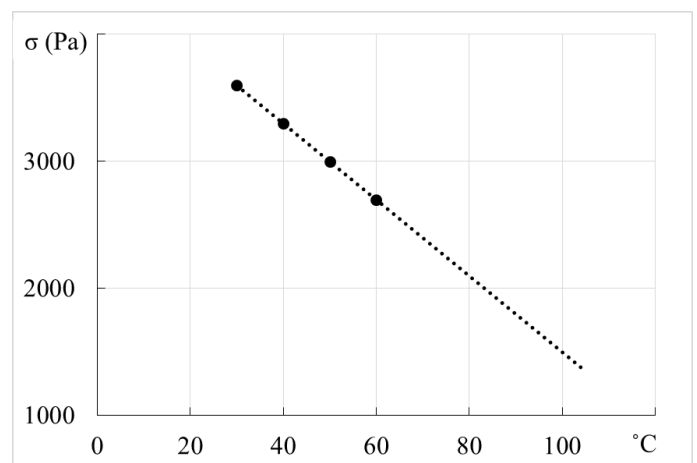


Figure 10. Graph showing the dependence of the strength limit on temperature

During further analysis of the experimental data based on the preliminary results, we constructed a graph showing the dependence of the strength limit

on temperature and identified a corresponding pattern (Figure. 10).

Analyzing the graph obtained during the analysis (Figure. 10), it can be stated that the strength limit of the bread crumb is directly proportional to temperature.

At 100 °C, the strength limit is 1500 Pa, while at 30 °C it is 3600 Pa. This relationship can be expressed as an equation:

$$\sigma = 30 \cdot t + 4500;$$

where: t - temperature in (°C);

σ - strength limit of the bread crumb in (Pa).

Based on the results of the study of the structural and mechanical properties of the crumb and gas permeability of the crust of wheat bread weighing 0.5 kg, the vacuum cooling mode was calculated. It was established that the pressure gradient between the environment inside the product and the vacuum chamber should not exceed the strength limit of the bread crumb (Figure. 11) [8].

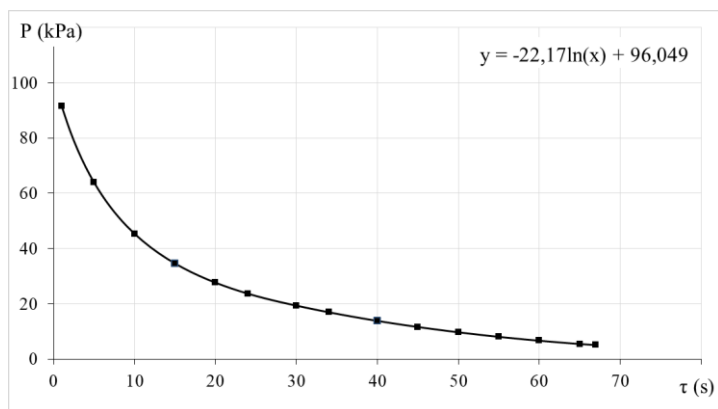


Figure 11. Calculated operating parameters for creating a vacuum in a vacuum chamber

Experimental data confirmed that a maximum pressure reduction rate of 4.5 kPa/s is optimal. At the same time, the gas permeability value of the crust (0.32 m³/(m²·s)) ensures intensive mass transfer, which reduces the cooling time of the product from several hours to 66 s (Figure. 11) [7].

Further increasing the air pumping rate is impractical, as it creates an excessive pressure gradient that exceeds the strength limit of the crumb. As a result, the crumb separates from the bottom crust, which leads to a deterioration in product quality and does not meet the requirements.

4. CONCLUSIONS

1. It has been established that the cooling rate of bakery products in a vacuum chamber is limited by

the gas permeability of the crust and the structural and mechanical properties of the crumb.

2. It has been proven that the crust is the main barrier to vapor escape ($G = 0.32\text{--}0.42 \text{ m}^3/(\text{m}^2\cdot\text{s})$), while the crumb has almost no effect on the process.

3. The dependence of crumb strength on temperature has been revealed: the higher the temperature, the lower the strength limit ($\sigma=30\cdot t+4500$), which must be taken into account when determining cooling modes.

4. For wheat bread weighing 0.5 kg, the optimal parameters for vacuum cooling have been determined: the rate of pressure reduction in the chamber does not exceed 4.5 kPa/s, and the cooling time is 66 s.

5. The use of the optimal mode allows reducing the cooling time from 1–2 hours to 66 s without losing product quality.

6. The results obtained can be used to improve the design of vacuum devices and introduce energy-saving technologies in bread baking.

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