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The influence of heat transfer coefficient on moisture evaporation rate during the cooling of fresh baked white pan bread

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Abstract. Cooling rate is a very critical parameter. Low cooling rates can limit production capacity in a bakery, while higher cooling rates can lead to a higher moisture evaporation rate and result in the greater weight loss of the product. The principal objective of this work is to study the effect of heat transfer coefficients on heat and mass transfer processes, which take place in freshly baked white pan bread during its cooling.
The model of bread cooling process is built based on experimental results, Fourier's second law for heat transfer and Fick's second law for mass transfer. The new model allows studying what influence the heat transfer coefficient has on the cooling rate. Several dependencies are revealed and discussed in this article. Several pieces of advice for developing an air distribution system are also provided.

Key words: Bread cooling, heat transfer coefficient.

INTRODUCTION

The increase in the market share of food products, including bakery products, is possible owing to the transition to modern intensive industrial modes of production. Only that way is it possible to ensure the sales of a wide range of quality products in increasing quantities with increasing profitability. Upgrading production with modern technologies and equipment under the conditions of a shortage of resources requires a systematic scientific approach. Attempts of using direct simple solutions are doomed to failure.

Bread production is a laborious and rather time-consuming process, which includes a number of operations. Changing operating parameters takes a long time, which leads to the deterioration of product quality. The cooling of bread to be cut into slices and packaged is an important part of the overall bread making process chain.

In packaging hot products moisture accumulates inside the package, which leads to the wetting of crust, accelerated development of moulds and loss of bread products' appearance and presentation. Moreover, the high-quality cutting of hot bread is associated with certain difficulties. On the other hand, the packaging of entirely cold bread, which has already lost a significant amount of moisture during the cooling process (due to shrinkage), is inappropriate, since in such bread the rate of staling increases significantly. That is why the determination of the optimal cooling period of bakery products could increase the storage time of packaged bread, while the product will maintain good sensory properties and presentation. The following requirements are applied to products to be packaged: in case of products made of rye and rye-wheat flour weighing 0.7–1 kg, the optimal period of cooling prior to packaging is 90–120 minutes for pan bread and 80–100 min for the hearth products; the optimal duration of cooling for bakery products weighing 0.3–0.5 kg is 60–70 minutes.

The problems related to the cooling of bakery products at bakeries are solved in different ways depending on available funds, production facilities, production volumes, and energy requirements. Technically, the process of cooling bread is usually organised in the following ways:

1. In cooling chambers (on fixed pallets or carts). This method requires large areas. The cooling time is over 3 hours.

2. In vacuum systems using evaporative cooling. The cooling time is less than 0.5 hours. In terms of capital and operating costs this method is the most expensive; the performance of facilities is low.

3. On conveyor lines in tunnel or tower installations. The duration of cooling is about 2 hours.

The advantages of applying spiral conveyor systems have been widely discussed for over 5 years (Pastukhov & Danin, 2011). The problem of cooling bread can be solved using a tower conveyor (Fig. 1). This is done in one of the leading St. Petersburg branch enterprises that brings together leading experts in the field of air conditioning and refrigeration equipment from ITMO University and the Bureau for the Equipment of Air Conditioning and Refrigeration Ltd.

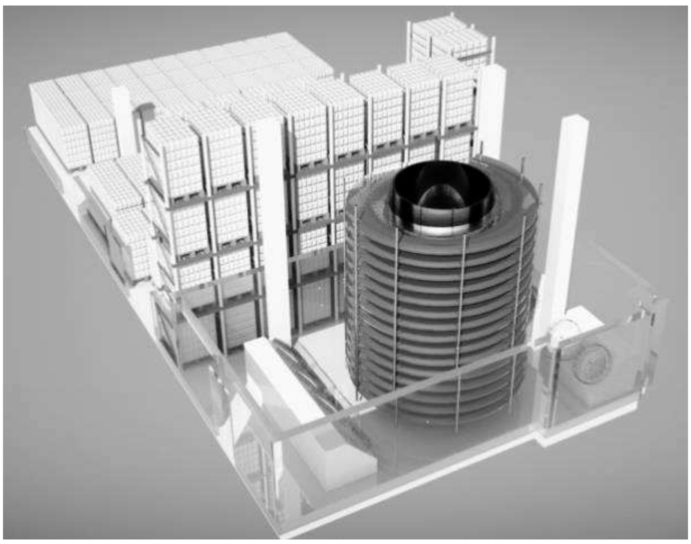

Figure 1. 'Tower' conveyor.

There is a computer system for calculating the temperature at the centre of the loaf on the basis of the temperature on its surface (Pastukhov, 2015). The system takes into account the thermal properties (Jarny & Maillet, 1999), shape and mass of the freshly baked product, and can be therefore used for calculating the cooling parameters of various bakery and other food products (Simpson & Cortes, 2004). The calculations are based on experimental studies (choice of initial and boundary conditions for modelling), literature data (Zueco et al., 2004) and mathematical modelling (Van der Sluis, 1993; Zanoni et al., 1994).

MATERIALS AND METHODS

Food materials, including bakery products, are complex heterogeneous objects. Knowledge of the thermal characteristics of a product is required for calculating cooling process kinetics. When using thermal characteristics values provided in literature, large errors are possible because the conditions of determining values are often different from operating conditions. The task of calculating the parameters of bakery products' cooling process is a complex problem involving unsteady heat and mass transfer. This study uses the classical methods of calculating unsteady heat transfer for bodies with limited dimensions (a cylinder and a box), such as the regular mode method and elementary heat balance method (Vanichev, 1946).

The calculation results are shown in Figs 2, 3. They allow judging the theoretically possible cooling rate of bread, as well as the influence of the main factors, such as air temperature and heat transfer coefficient (α), on the intensity of heat transfer.

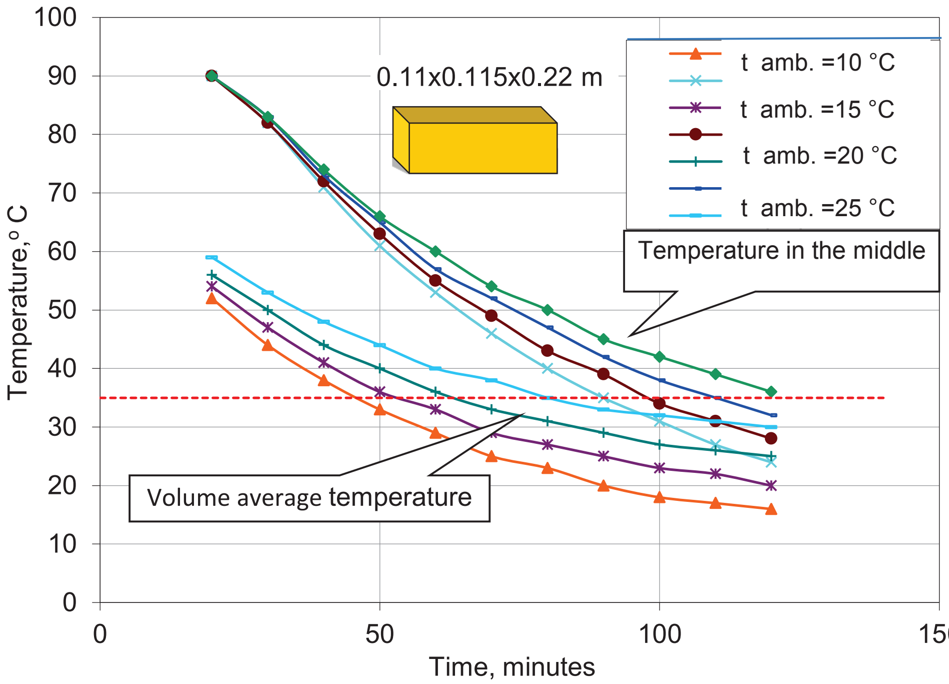

Figure 2. Dependence of bread cooling on ambient temperature (lowest heat transfer coefficient on the surface of the loaf is 15 W (m^2 K)$^{-1}$).

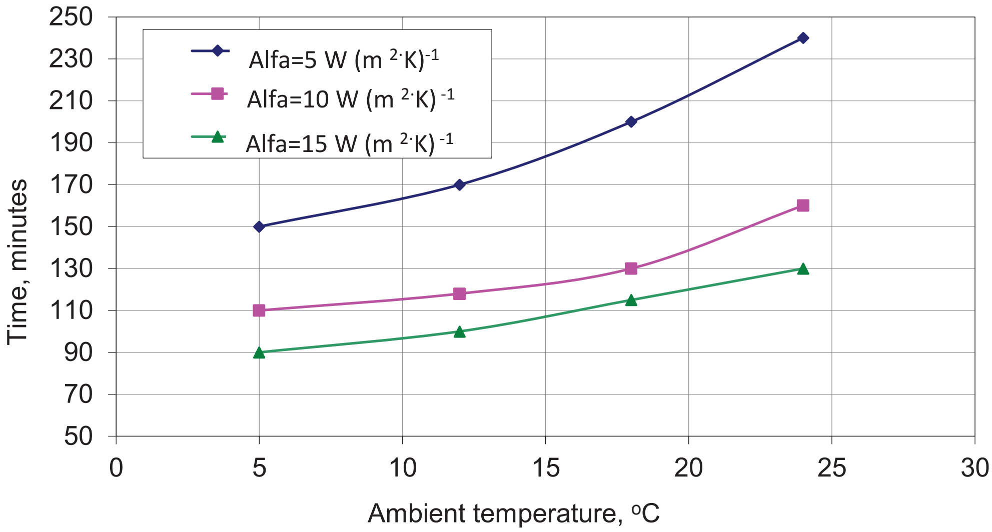

Figure 3. Dependence of cooling time on ambient temperature and heat transfer coefficient.

The discrepancies between the cooling time calculations carried out independently with different methods are no more than 10–15%. However, the theoretical data require validation through experiments in all cases.

RESULTS AND DISCUSSION

It is important to limit the cooling temperature range with the maximal values of heat transfer coefficient on the surface of the bread to achieve minimal temperatures in the cooling tower. The value of the first parameter directly depends on the mobility of ambient air near the bread crust surface. Values of $\alpha = 5;\ 10;\ 15;\ 20$ W (m^2 K)$^{-1}$ correspond to the air speed $\omega = 0.5;\ 1.5;\ 2.5;\ 3$ m s^{-1}. The minimum level of air temperature at the exit of air coolers in the standard air handling units of air conditioning systems is 8–10 °C. A further decrease in temperature is problematic due to the necessity to maintain negative temperatures on the heat exchange surface and to organise periodic defrosting. In real conditions currently used at bakery products' production plants the average value of the heat transfer coefficient is no more than 12–15 W (m^2 K)$^{-1}$. In order to increase the value of this parameter it is necessary to develop an air distribution system based on experiments and mathematical simulations.

1. As a result of the preceding discussion, the following conclusions can be drawn: 1. The minimum time of cooling the centre of the bread from 90 °C to 35 °C with an average air temperature of 5 °CC; 10 °CC; 15 °CC; 20 °CC; 25 °CC and an air velocity of $\omega = 1.5$ m s^{-1} ($\alpha = 10$ W (m^2 K)$^{-1}$) near the surface of the bread will be approximately 95; 105; 110; 125; 140 minutes respectively. In this case the mean bulk temperature of 35 °CC may be achieved in 50; 58; 68; 80; 100 minutes respectively.

2. The minimal time of cooling the centre of the bread from 90 °CC to 35 °CC with an average air temperature of 10 °CC; 15 °C; 20 °C; 25 °C and an air velocity of $\omega = 2.5$ m s^{-1} ($\alpha = 15$ W (m^2 K)$^{-1}$) near the surface of the bread will be approximately 90; 98; 110; 125 minutes respectively. In this case the mean bulk temperature of 35 °C can be achieved in 46; 50; 60; 80 minutes respectively.

Obtaining a temperature of 35 °C in the centre of the bread after 1 hour is problematic in the considered conditions.

The actual cooling rate with optimum air distribution is 100 and 110 minutes when the average air temperature in the tower is 10 °C and 15 °C respectively ($\alpha = 10$ W (m^2 K)$^{-1}$). In these cases, the maximum output of bread will decrease from 2,715 kg h^{-1} to 1,629; 1,480 kg h^{-1}, and heat generation will be 95; 81 kW (considering shrinkage) respectively.

However, it would be more correct to take the average bulk temperature as a determined value. In this case, it is possible to get the actual cooling time of 70; 80 minutes. In this case the maximum output of bread will decrease from 2,715 kg h^{-1} to 2,327; 2,036 kg h^{-1}, and heat generation will be 148; 120 kW (considering shrinkage) respectively. It is necessary to consider heat loss through the protecting constructions of the cooling tower, electric drives, and other unaccounted heat input in the amount of at least 25–30 kW in calculations and the design of the cooling towers.

The above calculations are applied to the most massive volume, and, as a result, the most ‘unfavourable’ shape (in terms of heat mass transfer) of loaf can be said to be that of the pan bread ‘Stolichniy’. The actual cooling rate of hearth loaves can be significantly higher than that of ‘Stolichniy’ due to their lower weight and size.

An important factor limiting the intensity of heat and mass transfer, and, consequently, the cooling rate of bread, is the optimization of air distribution in the working zone of the cooling tower. The determining factors that influence the rate of heat transfer on the surface of the bread are the velocity of the air coming from the air distributors, angle-of-attack of air flow relative to the axis of the conveyor, air temperature, temperature of the loaf, tightness of the jet by the conveyor elements, etc. The computing package STAR-CD—a specialized complex high-level program certified in accordance with ISO 9001 available from Computational Dynamics Ltd—was used for solving mathematical problems. Efficient algorithm parallelization decisions based on the finite volume method combined with the unique methods of automated partitioning of the flow region can simulate computational fluid dynamics tasks with any degree of complexity. The model of the bread cooling process was built based on experimental results, Fourier’s second law for heat transfer and Fick’s second law for mass transfer. The model is also based on the relationship between the Biot number and cooling rate during natural or forced cooling that was discussed before (Pastukhov & Danin, 2012). Results of the computational experiment for the determination of the optimum angle-of-attack of air flow by ITMO University, Institute of Refrigeration and Biotechnologies are shown in Fig. 4 and Table 1.

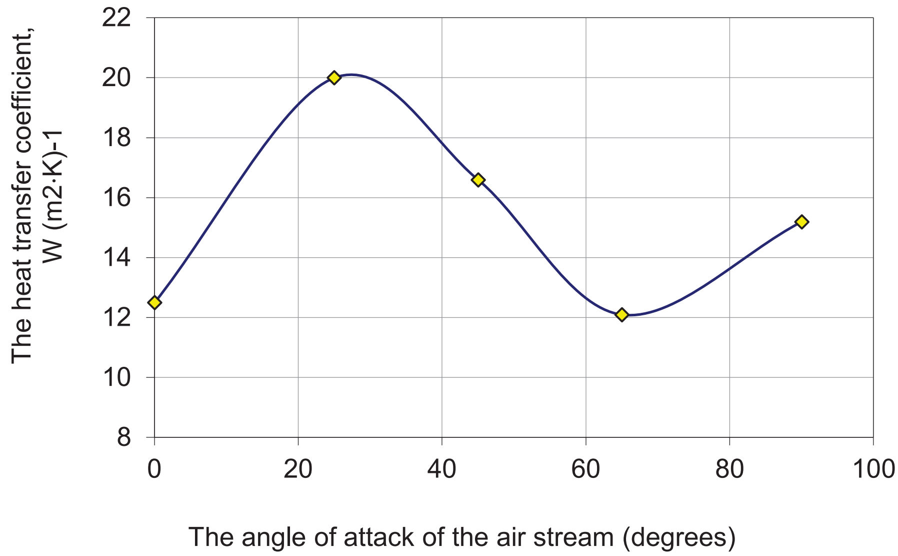

Figure 4. Dependence of the effective heat transfer coefficient on the surface of the loaf on the angle-of-attack of the air stream.

Table 1. Heat transfer coefficient on the surface of the loaf

Parameter					
angle °	0	25	45	65	90
air flow rate, m s^{-1}	2	2	2	2	2
air temperature, °C	7	7	7	7	7
heat transfer coefficient, W $(m^2 \cdot K)^{-1}$	12.5	20	16.6	12.1	15.2

CONCLUSIONS

Results of the theoretical and pilot researches conducted allow drawing the following conclusions:

The maximum heat transfer coefficient (about 20 W $(m^2\ K)^{-1}$) was observed at the angle of 25 (air flow rate 2 m s^{-1}). Thus, an adequate air distribution system should be developed to ensure these parameters.

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