

MODEL DEVELOPMENT FOR FRESH BAKED BREAD NATURAL AND FORCED COOLING

Artem Pastukhov^{1*}, Vladimir Danin²

¹*Department of Food and Nutritional Sciences, University of Reading, Reading, RG6 6AP, UK,
e-mail: artem.pastukhov1984@gmail.com

²*State University of Low Temperatures and Food Technologies, Saint-Petersburg, 191002, Russia*

Abstract

Industrial production of bakery products allows consumers to get fresh bread at any time of the day. However, there are many problems connected with storage and cooling of bread before distributing it to the trading network. Microbiological safety requirements and marketing necessitates the packaging of bread into films after baking. However, this is only possible when the baked bread has cooled. Rate of cooling is, therefore, very critical parameter. Low cooling rates can limit production capacity in a bakery, while higher cooling rates can lead to higher moisture evaporation rate and result in greater weight loss of the product. The moisture distribution in bread at the end of cooling can also result in water condensation on the film, which can accelerate fungal growth. The principal objective of this work is to study the effect of cooling conditions on heat and mass transfer in bread, and assess their influence on product quality. Experiments were carried out with white pan bread which was prepared in a laboratory. Cooling was undertaken in ambient environment (26 ± 2 °C, RH 50 %) by placing the hot product on a rack, as well as in a climatic cabinet with controlled temperature, humidity and level of convection. A mathematical model based on Fourier's second law for heat transfer and the Fick's second law for the mass transfer was developed to simulate heat and mass transfer processes in the bread during cooling, and validated using experimental data. The model is able to predict mass and volume changes during the „cooling” time.

Key words: Bread cooling, model development, heat and mass transfer.

Introduction

Heat and mass transfer in bakery products production occurs during proofing, baking and post-baking cooling. Several works are available in the literature on the modelling of heat transfer during baking, for example, DeVries et al. developed a quantitative model for heat transport in dough and crumb during baking (deVries, 1988).

Modelling of simultaneous heat and water transport in the baking process can be also found in Sablani (1988) work. Zanoni (1993) represented results of thorough study on the baking process modelling (Zanoni, 1994). In 2007 Wagner published an article concerning water transport in bread during baking (Wagner, 2007).

In the other words there is a lot of information available in literature, which describes heat and mass transfer in bread during baking, but there is a lack of knowledge in the modelling of the bakery products cooling. In 1993 van Sluis used a finite element computer program designed for the simulation of the cooling of bovines carcasses, and adapted his model to bakery products (van der Sluis, 1993).

Heat and mass transfers are taken into account, and chilling and freezing can be simulated. The heat transfer on the surface takes into account the convection and the radiation, but not the evaporation. N. Hamdami in this paper determined, thermo-physical properties, including apparent and true densities, specific heat, enthalpy and effective thermal conductivity separately for crumb and crust of partly baked bread (Hamdami, 2004).

This study is an attempt to develop a mathematical two dimensional model which takes into account thermo-physical properties of fresh baked bread and heat and mass transfer by convection, radiation and evaporation in order to predict mass loss and time of cooling, and to show the influence of each kinds of heat transfer on the duration of cooling process.

Materials and Methods

Experiments were carried out with white pan bread which was baked from scratch in a laboratory and then cooled by natural and forced convections.

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Dough was prepared based on the straight-dough bread making recipe (Finney, 1984) which is given in Table 1.

Table 1

Bread formula

Baker's, %	Ingredients	Weight, g
100	Bread flour	1160
62	Water	742
2	Yeast (fresh)	24
3	NFDM	35
3	A.P. Shortening	35
6	Gran. sugar	70
2	Salt	23
Total Weight		~2085

Mixing was done in VMI spiral mixer (France). Dough was rounded and left for rest for 7 minute at ambient temperature and final moulded using a Sorensen 'New Universal. Mark 2' moulder (England) and then loaded into slightly greazed unlidded rectangular tins (100x100x300 mm). Tins were placed in an Acrivan Proving Cabinets (UK) for final proofing (40 °C, 70% RH) for 1 hour. Baking was performed in a Frederick Bone gas-fired reel oven (UK) set at 244 °C for 30 min without steam injection with leads covered tins to achieve rectangular shape of final loaf.

Cooling of bread was considered as finished when the temperature at the bread geometrical centre reached 25 °C.

Temperature measurements in the middle of the crumb, at the crust surface and air near the surface were made by thermocouples connected to a Grant data-acquisition system (UK) each second during 12000 seconds.

Weight loss measurements were carried out using a Mettler PE 3600 precision scale; the volume of bread was measured by using of a laser volumeter. Such system allows to determinate the bread volume without any contact such as in the case of rapeseed displacement methods. The volume of the breads was measured just after baking, and in 3 hours after baking. Each bread sample was placed on a rotating plateau (60 rpm). A laser beam installed on a rotating arm was then used to measure the volume of the bread without contact. The accuracy of volume measurement using this equipment was estimated to $\pm 0.4\%$ according to 3 repetitions with the same loaf.

Bread moisture during chilling is determined gravimetrically by taking samples from the crumb and heating them for 1.5 hours at 130 °C.

Results and Discussion

Modelling is based on the Fourier's second law for heat transfer and the Fick's second law for the mass transfer.

Rectangular shaped bread loaf with dimensions 100 mm x 100 mm x 300 mm was chosen for model development. Two dimension geometry along x-y axis is shown on a Figure 1.

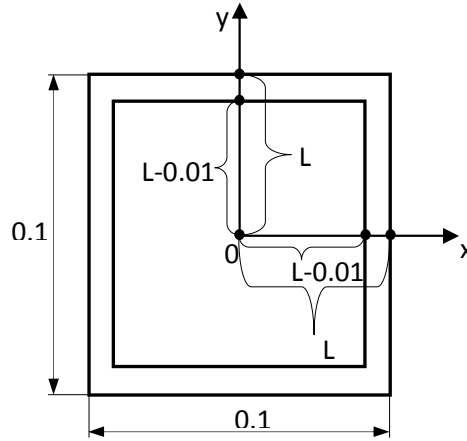


Figure 1. Cross-section dimensions

For modelling the grid containing 20 points in x and y coordinates, and the time step for 30 seconds are used.

The heat diffusion equation (1):

$$\frac{\partial T}{\partial t} = \frac{\lambda(T)}{\rho_b c_{p_b}(T, W)} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \quad (1)$$

where:

$\lambda(T)$ – is the thermal conductivity, $W (m K)^{-1}$;

ρ_b – is the density of bread, $kg m^{-3}$;

c_{p_b} – is the specific heat of bread, $J (kg K)^{-1}$.

As a boundary condition $\lambda(T)$ is defined taking into account heat transfer by convection, radiation and evaporation.

$$-\lambda(T) \left(\frac{\partial T}{\partial x} \right)_{x=L} = -\lambda(T) \left(\frac{\partial T}{\partial y} \right)_{y=L} = \alpha (T_s - T_{air}) + \varepsilon \sigma (T_s^4 - T_{air}^4) + \beta H_{lg}(W) (p_s(T, W) - p_{ext}(T, W)), \quad (2)$$

where:

α – is the heat transfer coefficient, $W (m^2 K)^{-1}$;

ε – is the emissivity of bread surface;

σ – is the Stefan–Boltzmann constant;

T_{air} – is the air temperature near the bread surface, K;

T_s – is the temperature of bread surface, K;

β – is the mass transfer coefficient, $m s^{-1}$;

p_s, p_{ext} – are the partial vapour pressure on bread surface and near the bread surface, Pa.

$$p_s = a_{ws} p_s^g, \quad (3)$$

where:

a_{ws} – is the water activity at the surface;

p_s^g – is the saturating vapour pressure at the bread surface and can be found from

Antoine's law as
$$p_s^g = 133.3 e^{\left(\frac{18.3036 - \frac{3816.44}{T_s - 46.13}}{T_s - 46.13} \right)} \quad (4)$$

Partial vapour pressure in the air near the bread surface p_{ext} depends on relative humidity of the ambient air H_{ext} :

$$p_{ext} = H_{ext} p_{ext}^g, \quad (5)$$

where:

p_{ext}^g – is the saturating vapour pressure in the ambient air

$$p_{ext}^g = 133.3 e^{\left(\frac{18.3036 - \frac{3816.44}{T_{ext} - 46.13}}{T_{ext} - 46.13} \right)}, \quad (6)$$

The mass transfer equation:

$$\frac{\partial W}{\partial t} = D(W) \left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} \right), \quad (7)$$

where:

W – is local moisture content, W surface = 0.1;

$D(W)$ – is mass diffusion coefficient, $m^2 s^{-1}$.

$$-D(W) \left(\frac{\partial W}{\partial x} \right)_{x=L} = -D(W) \left(\frac{\partial W}{\partial y} \right)_{y=L} = \beta(p_s(T, W) - p_{ext}(T, W)), \quad (8)$$

The initial condition concerned mainly the temperature distribution in the crumb at the end of baking. The experimental temperature distribution was implemented in the code.

The initial temperature was constant and equal to T_0 in the sample, except close to surface where it was decreasing from T_{s0} to T_0 with a linear relationship through a 1 cm thickness layer.

The local water content was decreasing with a linear evolution from W_{max} in the center to W_0 at 1 cm under the surface, and then from W_0 to W_{min} until the surface.

The initial conditions parameters given in table 2.

Table 2

Parameters of initial conditions

Parameter	Value	Units
T_0	372.00	K
T_{s0}	415.00	K
W_0	0.70	g water / g dry matter
W_{max}	0.78	g water / g dry matter
W_{min}	0.10	g water / g dry matter

The solution of equations (1) and (2) based on the boundary and initial conditions derived from field experiments have allowed us to obtain a mathematical model of convective bread cooling.

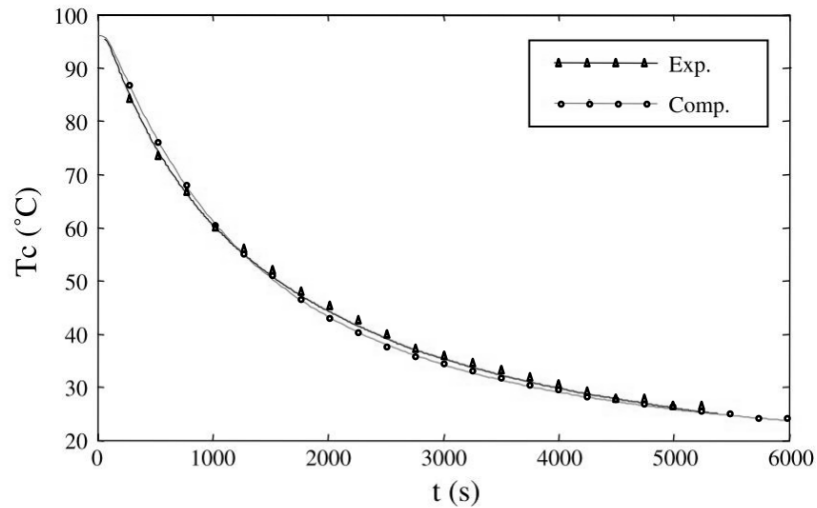


Figure 2. Comparison between calculated and measured data of the temperature in the middle of the crumb

The two curves have some distinction; this indicates a lack of precision in the physical parameters of heat transfer. The quadratic average of the difference between the measured and calculated values was used to quantify the discrepancy between model and experiment (9).

$$m = \sqrt{\frac{1}{N} \sum_{j=1}^N (T_{\text{exp}} - T_{\text{cal}})^2} = 2.87, \tag{9}$$

where:

N – is the number of measured points at the centre and on the surface.

Future work with the model will include improving of several physical parameters, such as thermal conductivity and mass diffusion coefficient of the bread, and also it is necessary to carried out modeling with a 3-D geometry.

Received model was used for studying the effect of mass transfer coefficient on the time of cooling and mass changing. The influence of different heat transfer coefficient value on the calculated duration of cooling 1kg bread loaf with the two modes: with evaporation, convection and radiation, without evaporation (convection and radiation only), the mass of evaporated moisture, and duration of evaporation are given in Table.3.

Table 3

Calculated duration of cooling 1kg loaf

Parameter	Value				
Heat transfer coefficient α , $W (m^2 K)^{-1}$	10.0	15.0	20.0	25.0	30.0
Time of cooling, min	139.0	106.0	89.0	80.0	73.0
Time of cooling (excluding evaporation), min	83.0	73.0	68.0	65.0	64.0
Mass loss, g	33.7	26.7	21.3	17.0	13.7
Time of mass changing, min	69.0	47.0	35.0	27.0	21.0

Conclusions

1. During the cooling process at low heat transfer coefficients the evaporation of moisture has a significant effect on the duration of cooling (40%). At high heat transfer coefficients the same effect on the duration of the process is small – only 12%. Number of evaporated moisture is low (1 to 3 percent of the mass loaf), and at high heat transfer

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coefficients the moisture is evaporated during the first third of the process only, because of the rapid cooling of the surface. At low heat transfer coefficients the moisture is evaporated during almost the entire process.

2. The model showed good agreement with experimental data of the temperature changing during cooling process. For high cooling rates the heat evaporates the moisture only during the first third of the process, because of the rapid cooling of the surface. At low heat transfer coefficients the moisture is evaporated during almost the entire process.

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