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Development of the mathematical model of the electric resistance baking process

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Abstract. The work is dedicated to the development of the mathematical model of the electric resistance baking process for the purpose of predicting temperature changes during baking of dough pieces of arbitrary sizes. The equation for the non-stationary thermal regime of a body with an internal heat source was used with a number of assumptions. The dynamics of the dough temperature changes was determined by numerical solution of the equation in Comsol Multiphysics.
Due to the complexity of the dough baking process and the impossibility of solving the equation by analytical method only, a number of values included in the energy balance of ER baking were determined experimentally. A dough piece with dimensions of 100×50×80 mm was baked during the experiment. After the adjustment, the adequacy of the model was checked by comparing the data on the dough temperature changes during baking dough pieces of the same recipe, but of different sizes (150×49×80, 80×62×80, and 65×75×80). Statistical analysis using Fisher's criterion confirmed the adequacy of the model.

Key words: bread, electric resistance baking, mathematical modeling.

INTRODUCTION

Currently, the process of electric resistance baking (ER baking) of bread is becoming the subject of an increasing number of studies due to its advantages over convective baking. Electric resistance baking is energy-efficient; no ovens in the conventional sense are required for ER baking, since heating occurs due to the release of heat directly inside the dough piece itself in accordance with Joule's law. In this regard the duration of the electric resistance baking process is several times shorter than that of convective baking. It must be noted that the duration of ER baking process depends significantly on the shape of the dough piece, namely, on the ratio of the distance between the electrodes and the height and width of the dough piece. Also, the dough formula, moisture and salt content of the dough play an important role. Therefore, convective and ER baking should be compared taking into consideration all these factors. In particular, in the work (Kulishov et al., 2020) bread of the same weight was baked by two methods: convective and ER baking, wherein the duration of convective baking was 25 minutes, ER baking - 2 minutes maximum. In work (Kulishov et al., 2021) the duration of baking of toast bread by the ER method was 5 minutes, by convective method - 25 minutes.

Direct comparison of baking times using different reference sources is often difficult because ER heating is rarely used directly for baking bread. Usually, this is a tool for uniform and controlled heating of the dough in order to study its properties, as, for example, in works (Luyts et al., 2013; Masure et al., 2019).

For the practical application of the electric resistance baking process, reliable prediction of the temperature regime of baking is of great importance. The dynamics of temperature change during baking, as well as its distribution over the volume of the dough piece, depends on a number of parameters. Among these are the power of heat release, the formula of the dough piece and its thermophysical properties, the conditions of heat exchange with the surrounding objects and the walls of the container in which baking is carried out, as well as the physicochemical processes intrinsic to the baking process. To ensure the necessary behavior of the temperature of the dough piece, it is important to have a methodology for calculating and choosing the electric capacity, time of baking, formula of the dough piece, and the design of the installation.

There are a number of publications on the mathematical modeling of electrical resistance heating. In particular, estimation of the temperature distribution over the volume of the dough piece, the influence of external conditions, the designs of experimental installations and measurement techniques for various types of dough pieces and liquids are presented in works (Sastry & Palaniappan, 1992; Fryer & Li, 1993; Fu & Hsieh, 2006; Ghnimi et al., 2008; Marra et al., 2009; Gally et al., 2016; Gally et al., 2017). In the work (Gally et al., 2016) much attention is paid to the influence of the dough formula on its thermophysical properties and electrical conductivity, their dependence on temperature; a thermal model of the baking process has been developed. The key drawback of the presented materials is the absence of parameters that would make allowance for the processes of moisture evaporation during baking and the corresponding physicochemical transformations in the dough piece. These processes have a significant effect on the temperature regime of baking and electricity consumption. In addition, it is not clear from the published materials how the proposed calculation models can be applied to objects with other geometric relationships.

Thus, the purpose of this work is to develop the mathematical model (MM) of the ER baking process for the correct prediction of the temperature of the dough piece during its baking by the electric resistance method. Adequate mm will allow to determine the duration and dynamics of bread baking for various process parameters and arbitrary sizes of the dough piece.

To achieve this goal, it is necessary to solve the following tasks:

• to assess the factors affecting this thermal process, to develop physical and mathematical models of this process on the basis of the well-known literature data on the ER heating of dough pieces, as well as the results of our own experimental studies on this problem;

• to carry out numerical modeling of ER baking and provide recommendations for the optimal process parameters.

MATHERIALS AND METHODS

Development of the physical model of ER baking

The heat transfer processes in the considered device are complex, therefore it is necessary to make a number of assumptions that simplify the solution of the problem and increase the reliability of the calculation results. In this case, the mechanism of heat transfer in the dough mass is a non-stationary thermal regime of a body with an internal heat source.

The proposed physical model is based on the following assumptions:

1. All the ingredients of the dough formula are evenly distributed throughout its volume, therefore, its thermophysical properties such as density, heat capacity and thermal conductivity are identical throughout the volume of the dough piece;
2. The temperature field of the dough piece is uniform and characterized by one volume average temperature;
3. Heat exchange with the cell walls is neglected due to the low thermal conductivity of the wall material and the relatively short baking time;
4. Heat exchange of the dough piece with the environment is carried out by means of free convection and radiation through the open surface of the piece, while the coefficient of convective-radiant heat transfer and the ambient temperature are considered constant;
5. Heat exchange surface area and the total specific heat of the dough piece are considered constant;
6. The voltage of the alternating current supplied to the electrodes is constant and equal to 220 V;
7. Resistance to the flow of electric current passing through the dough piece depends on the electrophysical properties of the dough pieces and their geometrical dimensions.

Assumption 2 is justified by the fact that the heat release, when the structure of the prepared dough piece is homogeneous, will be even throughout its volume.

Assumption 5 is justified by the fact that changes in surface area and weight of the dough piece due to the moisture evaporation during baking are insignificant in relation to the initial values before baking.

Mathematical description of the physical model of ER baking

The task is to predict the temperature of the dough piece at any given time.

For the case of a non-stationary thermal regime of a body with an internal heat source, the differential equation will have the form:

$$\nabla^2 t + \frac{W(t)}{\lambda} = \frac{c\rho}{\lambda}\frac{dt}{d\tau}; \quad (1)$$

where c – specific heat capacity, $J\,(kg\cdot K)^{-1}$; ρ – density, $kg\cdot(m^3)^{-1}$; λ – thermal conductivity of the dough piece, $W\cdot(m\cdot K)^{-1}$; W – power density of heat release in the dough piece, $W\cdot(m^3)^{-1}$.

For the case of a uniform temperature field in the body and the conditions of heat exchange with the environment, corresponding to the Newton-Richmann law, Eq. (1) will take the form:

$$\frac{dt}{d\tau} + m(t - t_c) = \frac{W(t)\cdot V}{C}; \quad (2)$$

where C – total specific heat of the dough piece, $J\cdot K^{-1}$; $m = \alpha S\cdot C^{-1}$ – heating rate, s^{-1}; α – coefficient of convective-radiant heat transfer with the environment, $W\cdot(m^2)^{-1}\cdot K$; S – heat exchange surface area, m^2; V – volume of the dough piece, m^3; t_c – ambient temperature.

During baking, the energy supplied to the electrodes is consumed in several processes:

1. Heating the dough mass from the initial temperature to the temperature of 98–99 °C (W_C);
2. Partial evaporation of water that is present in the dough (W_{ev});
3. Physicochemical processes taking place during baking, such as protein denaturation, starch gelatinization, etc. (W_{phc});
4. Irreversible heat loss to the environment (W_{hl});
5. Heat loss due to heating of the electrodes (W_{elh});
6. Heat loss due to electrochemical reactions, which are inevitable when using stainless steel electrodes at a current frequency of 50 Hz ($W_{el/ch}$).

The heat dissipation power density W undergoes significant changes during baking because this value depends on many factors: the resistance of the dough piece, humidity, temperature, physicochemical and thermophysical properties of the dough, which, in turn, depend on temperature and a number of other factors and also change during the ER heating process. As a result, the electric power supplied to the dough piece (W_{el}) changes significantly throughout the entire process.

Taking these factors into account a heat balance equation was drawn up to determine the resulting power supplied to the dough piece:

$$W_{el}(t) = W_C\,(t) + W_{hl}\,(t) + W_{phc}(t) + W_{ev}(t) + W_{elh} + W_{el/ch}; \quad (3)$$

where $W_{el}(t)$ – electric power; $W_{phc}(t)$ – power spent on physical and chemical processes during baking; $W_C(t)$ – power consumed for heating the dough mass with heat capacity C; W_{elh} – power consumed for heating of the electrodes; $W_{el/ch}$ – power spent on electrochemical reactions; $W_{ev}(t)$ – power consumed for moisture evaporation; $W_{hl}(t)$ – power lost to the environment during heating.

The solution to Eq. (2) is the expression:

$$t(\tau) = t_0 e^{-m\tau} + m e^{-m\tau}\int_0^{\tau} e^{m\tau}\left(t_c + \frac{W(t)\cdot V}{mC}\right)d\tau; \quad (4)$$

In view of the complexity and multifactorial nature of the processes taking place when baking a dough piece, it is a difficult task to determine the type of a functional dependence (3) analytically. Possibility to obtain the necessary relationships experimentally was considered in this work.

Bread making technology. A straight-dough preparation method was used. The processes were carried out in the following sequence:

– weighing components, heating water to 36 °C;
– mixing yeast with flour, dissolving salt in a portion of water;
– dosing components into the bowl of the dough mixing machine;

– kneading dough in a dough mixing machine (Bear Varimixer Teddy), kneading mode - 4 minutes at a speed of ~ 78 rpm, 1.5 minutes at a speed of ~ 208 rpm, a hook was used for kneading;

– fermentation of the dough for 2 hours, at 35 °C, with manual punching after 1 hour and 20 minutes (proofing cabinet Miwe Aero, model AE 6.06.04, Germany);

– cutting dough and forming dough pieces;

– proofing dough in a proofing cabinet at temperature of 40 °C and at relative humidity of 80% for 1 hour (Miwe Klima, type MGT, Germany)

– baking dough by the electric resistance method in the laboratory ER oven;

– cooling the bread.

The dough formula is shown in Table 1.

For successful baking a round piece of dough with a mass of 230 ± 1 g was formed, its edges were cut off so that to obtain area of 50 mm that will ensure close contact of the dough piece with electrodes. The forming scheme is identical to the one described in article (Kulishov et al., 2020). The dough sample had a mass of 150 ± 5 g.

Table 1. The dough formula

Ingredients	The mass of ingredients, g
Wheat flour 1st grade	500.0 ± 1.0
Salt	5.0 ± 0.1
Instant yeast	2.5 ± 0.1
Water	315.0 ± 2.0

Baking of bread dough and sponge cake samples after proofing was carried out at a voltage of 220 V, a frequency of 50 Hz. During baking current flowing through the dough sample was measured using an IEK 266 C ammeter and the dough temperature was measured using a chromel-alumel DTPK011-07/1.5 thermocouple. The thermocouple was connected to an analog input module, which was connected to a personal computer via the RS-485 - USB interface. Data from the input module was processed in MasterScada in real time. The thermocouple was installed in the dough sample at a certain point, in the center, at a height of 45 ± 5 mm from the chamber bottom.

Determination of the heat capacity of the dough. The value of the specific heat capacity of the dough piece c = 1,600 J $(kg\ K)^{-1}$ was determined experimentally on the installation IT-S-400. To measure the heat capacity of materials unable to hold their shape, for example, bulk materials or liquids, the installation was equipped with a cuvette where the dough piece was placed. The description of the installation and measurement procedure is given in the reference source (Platunov et al., 1986).

Experimental installations. To carry out an experiment to determine the values included in the Eq. (4) the installation described in (Kulishov et al., 2020) was used.

Further, in order to check the mm by comparing the dynamics of temperature changes obtained using mm and the experiment, a number of experiments were carried out on baking dough pieces of different sizes, and in one case, a different weight. To perform these experiments another installation was used.

The main elements are the casing, the hinged bottom, and the removable electrodes. The casing elements are made of non-conductive material with a low thermal conductivity coefficient. Grooves for electrodes are cut in the side walls of the casing with a pitch of 13 mm, which makes it possible to carry out experiments with a wide range of distances between the electrodes. The electrodes are made of 3 mm thick AISI

304 stainless steel. To check the mathematical model, the experiments on baking dough pieces of the following weights and sizes were carried out:

1. Dough piece L:W:H 150×49×80 mm, weight 227 g;
2. Dough piece L:W:H 80×62×80 mm, weight 150 g
3. Dough piece L:W:H 65×75×80 mm, weight 150 g.

To limit the lengths of the dough pieces, special partitions made of monolithic sheet polycarbonate 4 mm thick were installed in the chamber.

The installation drawing is shown in Fig. 1.

During the experiments on checking the mm, the same formula and technology of dough preparation and ER baking were used as in the main experiment.

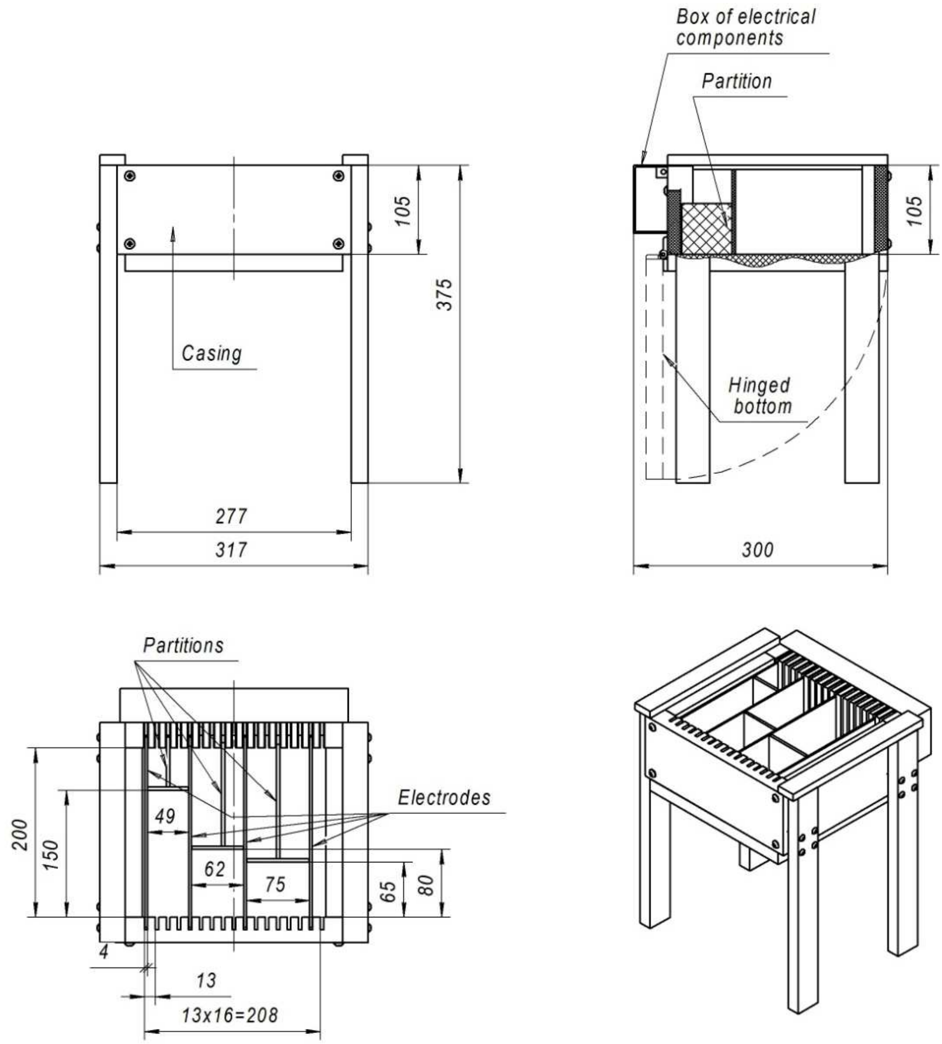

Figure 1. Installation drawing.

RESULTS AND DISCUSSION

Experimental determination of the components of a mathematical model

Curves of current, temperature and weight of evaporated moisture were obtained in the experiment and are shown in the Fig. 2.

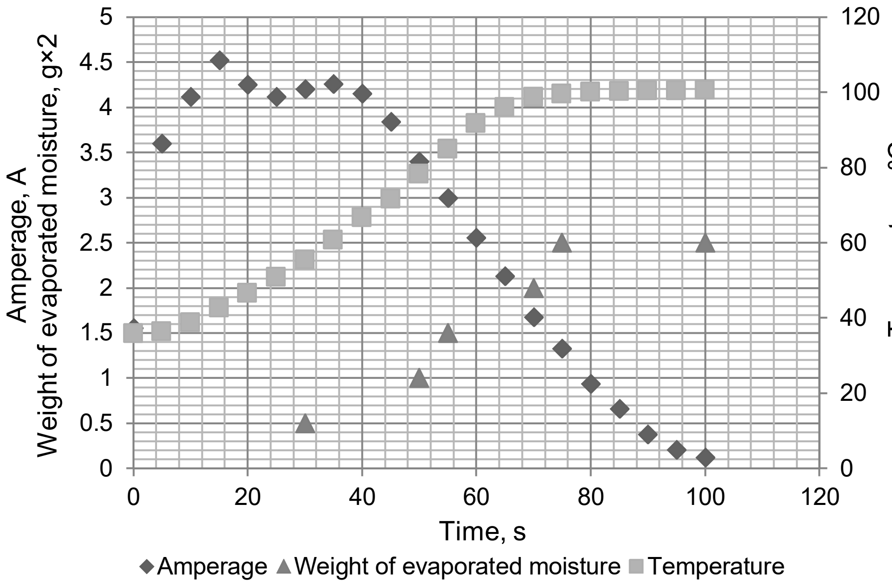

Figure 2. Curves of current, temperature and weight of evaporated moisture versus time of baking.

The amount of energy spent on baking was determined by processing the data obtained during the experiment. After recalculation the specific power consumption for baking 1 kg of dough was 397.4 kJ kg^{-1}.

The temperature dynamics is represented by data from one of the temperature sensors. This is explained by the fact that the difference between the readings from other sensors does not exceed 4 °C, thus confirming the assumption 1 and allowing to consider the temperature field of the dough piece uniform. The amount of evaporated moisture was 5 g, which confirms the accepted assumption 4.

The authors compared the experimental results with works on a similar subject. It is worth noting that the comparison should be made taking into account the differences in the bread formula and technology and the weights of dough pieces.

Nevertheless, there is a certain similarity of the experimental data of work (Kulishov et al., 2021) in the behavior of temperature and current during ER baking with the graphs obtained during experiments in this work.

The study (Masure et al., 2019) is rather difficult to compare with the data presented in the given work, since the object of the study in this work is gluten-free bread, its formula and technology differ significantly from those used in the article. The ER heating mode used by the authors is controlled by changing the voltage of the PID controller so as to obtain a temperature profile identical to the profile obtained when baking bread in a convection oven, while the ER baking voltage remains constant in the article.

The results of the experimental data of the study (Derde et al., 2014) are also difficult to compare with this work, since the authors investigate changes in moisture distribution and physical changes in starch of breads conventionally baked or using an ERO. At the same time, the temperature kinetics of both baking methods are the same, which is achieved by voltage regulation during ER baking (similar to the research method mentioned above).

By analyzing the curves of current strength and temperature versus time, it can be established that a significant part of the power consumed is spent on physicochemical processes. Indirectly, this can be judged by a sharp change in the electrical resistance of the dough piece. The power consumption for heating the dough piece is a small part of the power consumption:

$$Q = c \cdot (t_k - t_0) = 1600(98 - 36) = 100\,\frac{kJ}{kg};$$

Let us trace how the temperature of the dough piece would change if all the supplied power was spent on heating it, that is $W_C = W_{el}$. Let us define the change in electrical power through the dependence of the specific electrical resistance ρ(t) of the dough piece on temperature:

$$W_{el}(t) = \frac{U^2}{R(t)V} = \frac{U^2}{\rho(t)l} \quad (5)$$

The dependence ρ(t) will be determined by measuring values of the current strength and voltage, the dimensions of the dough piece and the temperature during the experiment. The calculation results are given in Table 2.

Table 2. Temperature dependence of the parameters of the dough piece

t, °C	Experiment ρ(t), Ohm·m	Experiment $W_{el}(t)$, $W\cdot(m^3)^{-1}$	Correction W(t), $W\cdot(m^3)^{-1}$	K(t)
35.8	17.1	1.14	0.0557	20.4
36.4	11.4	1.7	0.223	7.63
38.7	10.2	1.9	0.372	5.12
42.6	10.0	1.93	0.379	5.09
46.5	10.5	1.84	0.418	4.41
50.9	10.6	1.83	0.435	4.21
55.4	10.4	1.86	0.514	3.62
60.8	10.5	1.85	0.561	3.30
66.6	11.	1.76	0.472	3.72
71.5	12.2	1.69	0.647	2.46
78.3	13.7	1.41	0.630	2.24
84.8	15.8	1.22	0.651	1.88
91.6	18.8	1.03	0.423	2.44
96.0	23.1	0.838	0.249	3.37
98.6	29.2	0.662	0.196	3.38

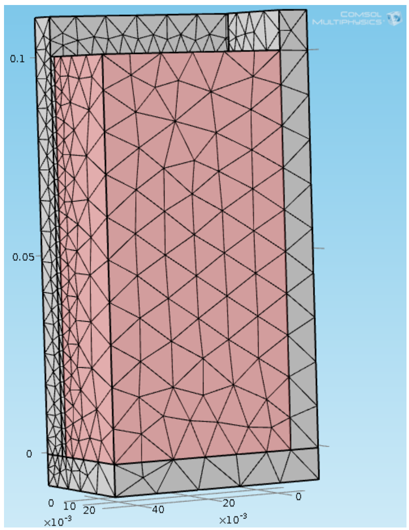

Figure 3. Numerical model of the experimental installation.

Thus, based on the data in the Table 1 and expression (5), let us solve Eq. (3) numerically with the object model compiled in Comsol Multiphysics. The Fig. 3 shows an image of a model compiled for ¼ part of the installation due to its symmetry. The results of numerical calculation (curve 1) and experiment (curve 2) are shown in the Fig. 4.

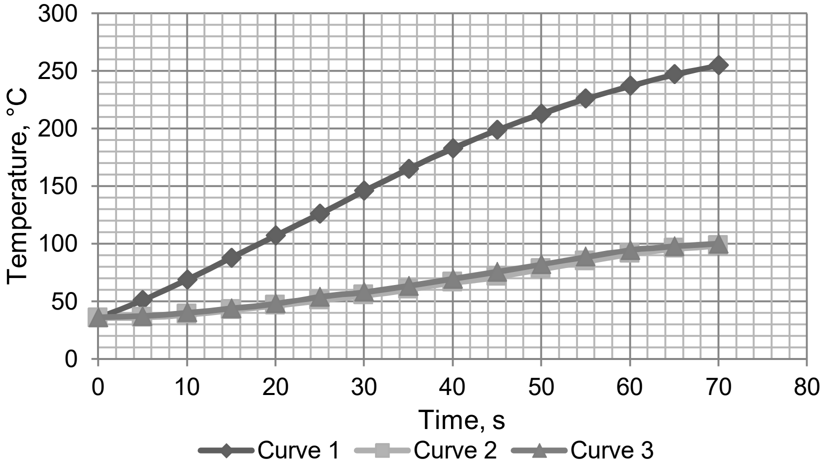

Figure 4. The results of the numerical calculation of the temperature during heating the dough piece and the experimental curve during baking.

Analyzing the discrepancy between the temperature curves 1 and 2, a correction to the initial data of the numerical model characterizing the dependence of the heat source power can be made. The calculation of the correction is carried out on the basis of the possibility to estimate the power consumed for heating the dough pieces W_C and the heat exchange with the environment W_{hl} at each of the baking stages from the experimental curve 2:

$$W_c = \frac{cM\big(t(\tau_{i+1}) - t(\tau_i)\big) \cdot (\tau_2 - \tau_1)}{V}; \tag{6}$$

$$W_{hl} = \frac{\alpha S(t(\tau) - t_f)}{V}; \tag{7}$$

where τ_i, τ_{i+1} are two adjacent points in time on the diagram, the Fig. 3; $\tau_j = (\tau_i + \tau_{i+1})/2$ is a point in time characterizing one of the baking stages, s; M – wheight of the dough piece, kg; c – specific heat capacity of the dough piece, $J\cdot(kg\cdot K)^{-1}$;S is the area of the heat transfer surface, m^2, α is the heat transfer coefficient, determined on the basis of criterion relations for heat transfer under free convection conditions, $W\cdot(m^2\cdot K)^{-1}$.

The calculation of the heat flux W_{hl} within the scope of the experiment showed that $W_{hl} / W_{el} < 0.005$, which makes it possible to neglect this value for this experimental installation.

Based on the results of calculations by formulas (6), (7) and the value of the total consumed electrical power W_{el} (t) calculated by formula (5), we can find the overall power consumption for components which are hardly definable by calculation, namely heat loss due to heating of the electrodes W_{elh}, heat loss due to electrochemical reactions $W_{el/ch}$, evaporation of liquid $W_{ev}(t)$ and physicochemical processes $W_{phc}(t)$, taking place during baking. Thus, the dependence W(t) was obtained on the basis of expression (5) and presented in the column 'Correction' of the Table 2. It should be noted that the values of W(t) presented in the Table 2 can be used only for dough pieces with thickness l and heat exchange surface area S corresponding to the design of this cell.

In order for the developed thermal model to be applied for different sizes of dough pieces, the following transformation was carried out:

1) connection between the consumed electric power $W_{el}(t)$ and the initial data for the thermal model W(t) using the proportionality coefficient K(t) is established:

$$K(t) = \frac{W(t)}{W_{el}(t)}; \tag{8}$$

The result of calculating K (t) is shown in the Table 2.

2) Expression (8) is transformed to find the power density of heat release W(t) based on the temperature dependence of the specific electrical resistivity:

$$W_{el}(t) = \frac{U^2}{\rho(t)l^2K(t)}; \tag{9}$$

Expression (9) allows to calculate the power of heat release in a dough piece in the form of a parallelepiped with random geometric dimensions. If the contribution of the heat transfer due to the convective-radiant heat transfer has a significant effect, the value of W(t) should be increased by the value of W_{hl}, calculated by expression (7).

The results of the calculation with a numerical model with the power W(t) calculated by expression (9) are presented by the curve 3 in the Fig. 4. Comparing curves 2 and 3 in the Fig. 4, it can be noted that making a correction allows you to obtain a satisfactory convergence of the simulation and experiment results.

The Fig. 5 shows the temperature distribution in the dough piece obtained using a numerical model.

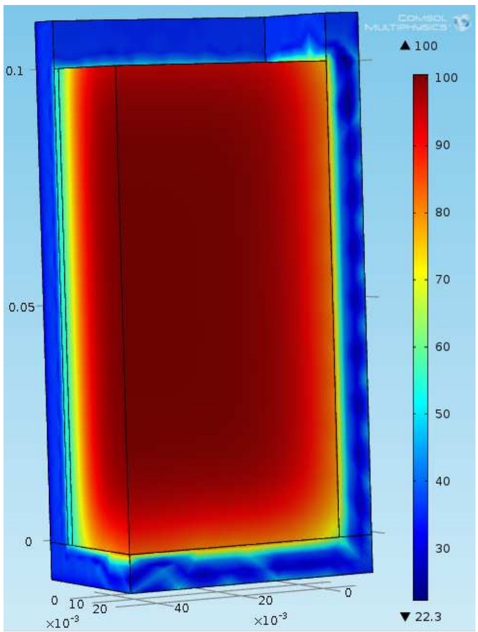

Figure 5. The result of numerical simulation based on the corrected power of the heat source.

Analyzing the data obtained, it can be noted that the dough piece has a temperature field corresponding to the accepted assumption 1. However, when ensuring uniform temperature distribution in practice, it should be borne in mind that the shape of the dough piece does not fully correspond to the parallelepiped. Less electric current flows through the top of the dough piece that rises during proofing, which can lead to insufficient heating of this part of the dough piece. To reduce the influence of this factor, a cell should be manufactured with such a ratio of geometric dimensions that the area of the upper part of the cell isseveral times less than the area of the surfaces of the electrodes in contact with the dough piece. This solution also makes it possible to reduce the outflow of heat into the environment by reducing the heat exchange surface area.

In addition, to reduce the thermal interaction with the cell walls (fulfillment of assumption 2), a heat-insulating material with a thermal conductivity of less than 0.1 $W \cdot (m \cdot K)^{-1}$ should be used.

The developed thermal model also makes it possible to determine the baking time of the dough piece τ. When performing a numerical calculation it should be stopped when the required temperature level in the dough piece is reached. Analyzing the results of experiments on dough pieces of various sizes it was found that the optimal baking parameters are obtained in the dough piece when the temperature reaches 98 °C.

The developed thermal model is suitable for predicting the temperature regime of baking, provided that the formula and baking technology described in the Materials and Methods section of this work are observed. In case of using other formulations and technologies, the parameters of the model should be adjusted.

To check the reliability of the calculations made by numerical model experiments were carried out with dough pieces with the dimensions 62×80×80, 75×65×80 and 49×150×80 mm prepared according to the same recipe. The power W (t) was determined for a voltage of 220 V by the expression (9) as the initial data for the numerical model. Comparison of the temperature curves obtained by the model and experiment are shown in the Fig. 6.

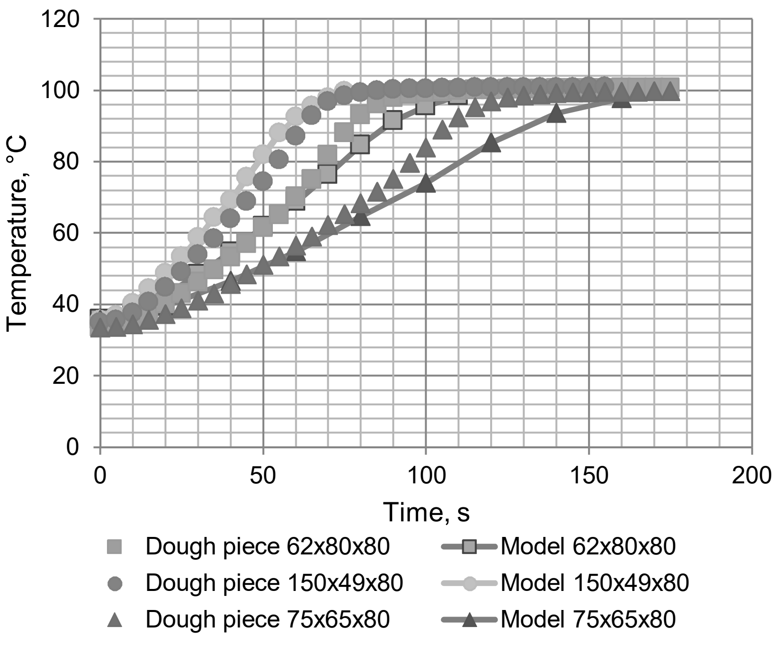

Figure 6. Comparison of simulation and experiment results.

Based on the results of experiments and simulation a statistical analysis of the results was carried out using the Fisher test in Microsoft Excel software. The data on the temperature change obtained by experiment and the mathematical model are shown in Table 3. The results of one-way ANOVA test performed in Microsoft Excel are shown in Table 4.

Table 3. Data obtained experimentally and using the model

150×49×80			80×62×80			65×75×80		
t, c	model	experiment	t, c	model	experiment	t, c	model	experiment
	T, °C			T, °C			T, °C	
0	35.7	34.99	0	35.76	33.97	0	35.73	33.6
5	36.9	35.61	10	37.8	36.33	20	39.55	37.33
10	40.4	37.57	20	42.8	41.59	40	46.68	45.77
15	44.5	40.74	30	48.4	47.76	60	54.9	56.4
20	48.7	44.85	40	54.6	55.25	80	64.8	68.24
25	53.4	49.04	50	61.8	63.8	100	74.1	83.93
30	58.9	53.97	60	68.8	73.43	120	85.4	96.88
35	64.3	58.37	70	76.4	87.55	140	93.6	99.21
40	69.2	63.94	80	84.6	95.8	160	97.8	99.58
45	75.6	68.8	90	91.47	98.82			
50	82	74.49	100	95.6	99.81			
55	88.1	80.61	110	98.44	100.26			
60	92.5	87.17						
65	95.6	92.96						
70	98	96.86						
75	99.7	98.42						

Table 4. The results of one-way ANOVA test

	62×80×80					
Source of variation	*SS*	*df*	*MS*	*F*	*P*-Value	*F* critical
Between groups	59.85042	1	59.85041667	0.098629404	0.756439297	4.300949462
Inside groups	13,350.07	22	606.8212326			
Total	13,409.92	23				
	75×65×80					
Source of variation	*SS*	*df*	*MS*	*F*	*P*-Value	*F* critical
Between groups	44.7458	1	44.7458	0.070663168	0.793768532	4.493998418
Inside groups	10,131.63	16	633.2266375			
Total	10,176.37	17				
	150×49×80					
Source of variation	*SS*	*df*	*MS*	*F*	*P*-Value	*F* critical
Between groups	132.4785	1	132.4785031	0.25495387	0.617297564	4.170876757
Inside groups	15,588.53	30	519.6175423			
Total	15,721	31				

The following statement was taken as the null hypothesis: the differences between the temperature values calculated by the mm and those obtained during the experiment are caused by random factors, the averages in all classes are equal, and the method for determining the temperature - mm or experiment - does not affect the result. Based on the results of the calculation it was determined that the calculated value of the Fisher criterion is less than the value from the Table, which justifies acception of the null hypothesis. This fact allows to consider the model as adequate.

CONCLUSION

The developed mathematical model based on the equation of the non-stationary thermal regime of a body with an internal heat source allows to determine the dynamics of temperature changes during baking dough pieces by the electric resistance method using numerical solution in Comsol Multiphysics with an accuracy sufficient for practical use.

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