Automatic control and maintaining of cooling process of bakery products

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Abstract. During the development of automation control of the bakery products cooling process using a 'cooler' it is necessary to build an integrated control system, which allows to optimize the process parameters in case of a variety of work situations that may occur in the bakery enterprise. The main task for control of such multifactorial object is to reach a certain temperature in the center of the product by maintaining the temperature of the cooling air near the surface of the loaf set in the limits $t \pm \Delta t$, its velocity $v \pm \Delta v$ and humidity $\varphi \pm \Delta \varphi$, and maintain the speed of the conveyor within $Vc \pm \Delta Vc$ using the frequency converters. Simultaneous exposure to multiple channels of control allows selecting the optimal combination of the cooling process control commands, yielding the product with necessary temperature and mass. Automatic control and regulation of the cooling process is based on the fact that the current value of the adjustable parameters in mismatch block is compared with predetermined values of the corresponding parameters, and the mismatch signals are formed, which are amplified to a value sufficient to trigger actuators that provide executive regulators. Novelty of the paper consists in the development of the process control system based on the mathematical model which allows calculating the temperature at the center of freshly baked products by the surface temperature of the product at any time of location in the cooling zone. Experiments were carried out on the bread made in the laboratory and cooled after baking, by natural and forced convection. Baking was conducted in a special parallelepiped tins with lids. Thus, the output product had a parallelepiped shape. Process of cooling by natural convection was implemented in a cooling chamber, which allowed to measure temperature and relative humidity. Temperatures changing in the center of the loaf and weight loss were recorded during the experiments. Cooling time was determined by the time required to achieve the temperature in the center of the loaf 30°C. On the basis of the experimental data a mathematical model and the computer system, allowing calculating the parameters of cooling and in time to make a regulatory influence on one of the control channels and thus optimize the process parameters were built.

Key words: heat transfer, mass transfer, automation, spiral conveyor.

INTRODUCTION

The question of cooling bakery products has been widely discussed in scientific and industrial circles during last 10 years. The main purpose for cooling freshly baked products is to prepare the product for processing in the subsequent steps of cutting and packing, and the reduction of weight loss which occurs due to shrinkage and can reach up to 4%. Conditionally two periods of shrinkage are distinguished. The first period is characterized by rapid change in velocity of shrinkage from the maximum value at the

beginning of the process to a value slightly larger than values of shrinkage rate of the second period, which in turn is characterized by a low rate of shrinkage (Fig. 1).
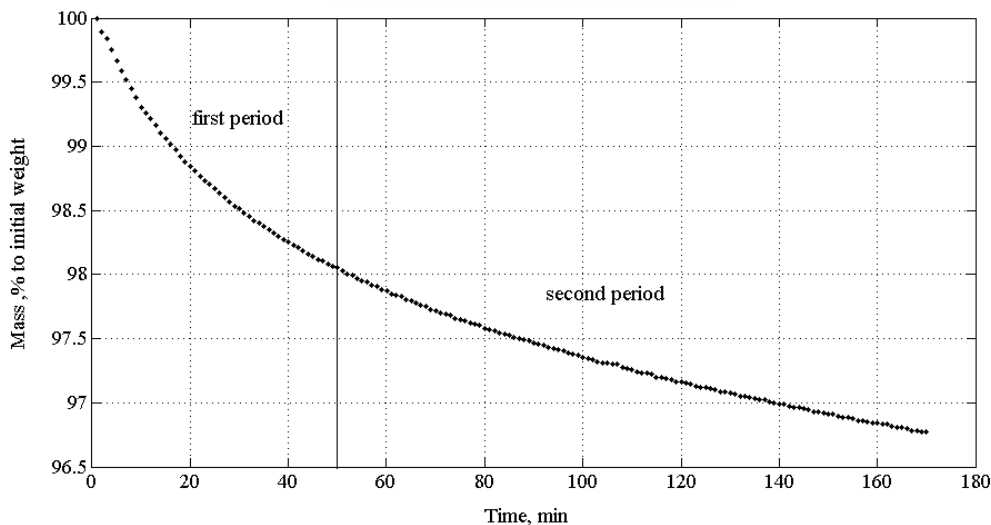

Figure 1. Two periods of mass loss during natural cooling at ambient temperature 20.6°C.

The most effective way to reduce weight loss of bakery products is to reduce the duration of the first period of shrinkage. In industrial practice, such reduction is achieved by accelerated cooling of the bread which is just taken out of the oven to the temperature of the warehouse.

There are different methods and technical solutions implemented for cooling bakery products, but the spiral-conveyor system which is called 'cooler' is considered to be the most effective in terms of productivity and the occupied area.

The advantages of applying spiral conveyor systems have been widely discussed for over 5 years (Pastukhov & Danin, 2011). However, today the problem of the use of spiral conveyor devices for reducing the duration of the cooling process and shrinkage of bakery products remains actual in the scientific community.

'Cooler' (Fig. 2) is a multitier spiral conveyor system positioned in the chamber made of insulating material. Due to the action of the cooling air flow of the required humidity in the working area of 'cooler' the cooling of freshly baked bread takes place. The product goes through all tiers from lower to upper. Thereafter, the cooled loaves are dropped from the upper tier into a hopper or fed by an additional transporter to the weight table, slicing machine or packaging machine.
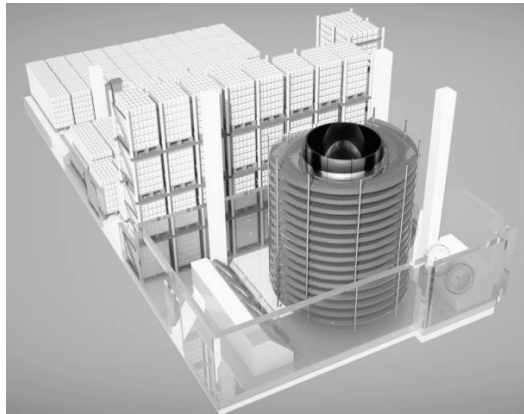
Figure 2. Spiral 'cooler'.

In order to maintain the bakery products cooling automation scheme, it is necessary to develop an integrated management system, which allows optimization of the process parameters in the case of performance of different technological situations that may arise in the bakery enterprise, and ensuring efficient operation equipment without excessive energy consumption (Pastukhov, 2013).

A standard block diagram of a system for automatic monitoring and control of the cooling process is shown on a Figure 3. Transducer (sensor SE) –thermometer provides the conversion process of variable parameter Y (product temperature) in the signal, convenient for further processing in the secondary converter (SC). Setter (Set.) evaluates and gives the required value of the controlled parameter Y, and it forms the set point signal $Xset$ that in the mismatch block (MB) is compared with the current value of the controlled parameter Xm, then the mismatch signal enters to the input of the forming unit (FU): $\Delta X = |Xset - Xm|$. Depending on the requirements for quality of regulation the signal outputs from the forming unit (FU) to the power amplifier (PA) in order to strengthen the signal to the value which is required to trigger the actuator (Act.), which, through the regulatory body (RB) provides a change of flow of energy or material flow in the object of regulation (OR) in the form of a regulatory impact X_R.
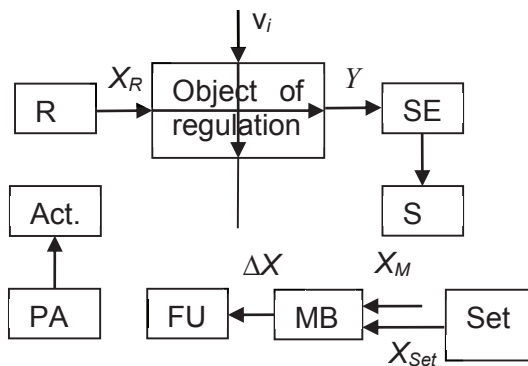

Figure 3. Block diagram of automatic regulation and control system.

In other words, the system of automatic control and regulation of the cooling process is based on the fact that the current value of the adjustable parameters in mismatch block is compared with predetermined values of the corresponding parameters, and the mismatch signals are formed, which are amplified to a value sufficient to trigger actuators that provide the job of the regulatory bodies. The aim of this study is to compute the set of parameter values used in the cooling set point adjuster – setter (Set.). The computer system for calculating the temperature at the center of the loaf, depending on the temperature of its surface is developed. The system takes into account the thermal properties (Jarny & Maillet, 1999), shape and mass of the freshly baked product, and therefore can be used for calculating of the cooling parameters of various assortments of bakery products and other food products. The calculations are based on experimental studies (choice of initial and boundary conditions for modelling), literature data (Zueco et al, 2004) and mathematical modelling.

The development of autonomous regulation systems begins with parametric and structural analysis of the control object.

MATERIAL AND METHODS

Fig. 4 shows a parametric diagram of a spiral conveyor as an object of control. The process is represented in the form of a 'black box', which receives unmanaged, disturbing and control actions and outputs formed indicators of the quality of the cooled bakery products. Different types of bakery products have different thermal properties, shape and weight. Therefore, to achieve a temperature of 30°C in the center of the crumb, different cooling parameters are required.
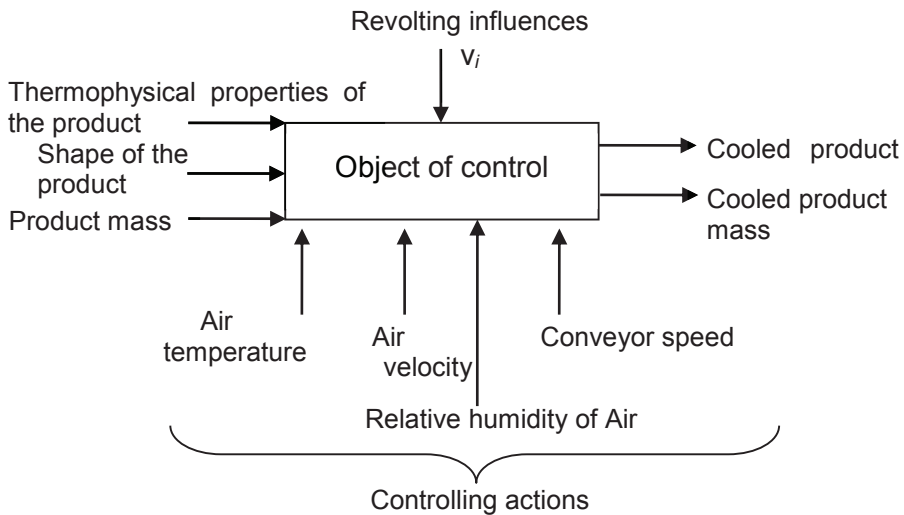

Figure 4. Parametric diagram of the control object.

The input parameters are the thermal properties, the shape and weight of freshly baked products. Cooling process controlled parameters include temperature, humidity and velocity of the cooling air, the velocity of the conveyor belt moving.

Revolting influences *vj* lead to changes in the control parameters. These influences can be external, internal and parametric. External perturbations are heat income through the outer and inner fences of spiral conveyor. Sources of internal disturbances are heat income from the hot fresh bread, illumination, workers and electric motors of air fan coolers.

Parametric perturbations occur as changes in the heat transfer coefficients due to lubrication of inner surface evaporators, appearance of a water stone in a condenser unit, the outer surface rust, etc. Output parameters are the temperature of the cooled product and its weight.

Table 1. Ranges of technological parameters

Technological parameters	Measurement units	Mean value	Technological interval deviation from the mean value	
			from	to
Air temperature	°C	22.0	-2.0	+4.0
Air speed	m s^{-1}	0.5	-0.5	+2.5
Relative humidity	%	50.0	-10.0	+10.0
Conveyor belt speed	m min^{-1}	3.0	-1.0	+1.0

The main task for control of such multifactorial object is to reach a certain temperature in the center of the product by maintaining the temperature of the cooling air near the surface of the loaf set in the limits $t \pm \Delta t$, its velocity $v \pm \Delta v$ and humidity $\varphi \pm \Delta\varphi$, and maintaining the speed of the conveyor within $Vc \pm \Delta Vc$, with shrinkage for each type of product should not exceed the specified in normative documents.

Simultaneous exposure to multiple channels of control allows selecting the optimal combination of the cooling process control commands, yielding the product with necessary temperature and mass.

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

Dough was prepared based on the straight-dough bread making recipe (Finney, 1984) which is given in Table 2.

Table 2. Bread formula

Ingredients	Ingredients, %	Weight, g
Bread Flour	100	1160
Water	62	742
Yeast(fresh)	2.0	24
NFDM	3.0	35
A.P. Shortening	3.0	35
Gran. Sugar	6.0	70
Salt	2.0	23
Total Weight		2085 (approx.)

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 greased unlidded rectangular tins (100 x 100 x 300 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.

Process of cooling by natural convection was implemented in a cooling chamber, which allowed to measure temperature and relative humidity. During the experiments the temperature change in the center of the loaf and weight loss were recorded (weight loss was determined by calculating the difference between weight of the loaf before and after cooling. Mettler PE 3600 precision scale weights were used for measuring the mass of loaves.

Cooling by forced convection was conducted in a climate chamber Votsch VC 7018 (Votsch-Lindenstrath, Germany) equipped with temperature and relative humidity controllers. Air velocity was measured using an anemometer VelociCalc 8355 (TSI, MN, USA), and ranged from 1.5–2.5 m s^{-1}.

Cooling time was determined by the time required to achieve the temperature in the center of the loaf 30°C. Temperature measurement in the middle of the crumb and crust surface temperature was conducted during 12,000 seconds every second using thermocouples connected to a data acquisition system Grant data-acquisition system (UK).

Values of temperature and relative humidity were recorded during cooling and processed by data acquisition system DataLog 20 (AOIP, Orangis, France), Type-K thermocouples and data logger Hygrolog (Rotronic, Bassersdorf, Switzerland).

Crumb and crust moisture was determined gravimetrically after cooling, by sampling them, and heating 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 (deVries et al, 1988; Simpson & Cortes, 2004). The heat diffusion equation (1):

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

where: $\lambda(T)$ - thermal conductivity (W m^{-1}·K^{-1}); ρ_b - density of bread (kg (m^3)$^{-1}$); C_{pb} - 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 (2):

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

where α - heat transfer coefficient (W m^{-2}·K^{-1}); ε - emissivity of bread surface; σ - Stefan–Boltzmann constant; T_{air} - air temperature near the bread surface (K); T_s - temperature of bread surface (K); β - mass transfer coefficient (m s^{-1}); p_s, p_{ext} - partial vapour pressure on bread surface and near the bread surface (3), (Pa)

$$p_s = a_{ws}\ p_s^g ,$$

(3)

where: α_{ws} - water activity at the surface; p^g - saturating vapour pressure at the bread surface and can be found from Antoine's law as (4):

$$p_s^g = 133.3\ e^{\left(18.3036 - \frac{381644}{T_s - 46.13}\right)} ,$$

(4)

Partial vapour pressure in the air near the bread surface p_{ext} depends on relative humidity of the ambient air (5):

$$H_{ext} \cdot p_{ext} = H_{ext}\ p_{ext}^g ,$$

(5)

where: p^g_{ext} - saturating vapor pressure in the ambient air (6)

$$p_{ext}^g = 133.3\ e^{\left(18.3036 - \frac{381644}{T_{ext} - 46.13}\right)}$$

(6)

The mass transfer equations (7; 8):

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

(7)

where: W - local moisture content (W surface = 0.1); $D(W)$ - mass diffusion coefficient (m^2 s^{-1}).

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

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 Wmax 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 and parameters are given in Table 3.

Table 3. Initial Conditions Parameters

Parameter	Value	Units
T_0	372	K
T_{s0}	415	K
W_0	0.7	g water/ g dry matter
W_{max}	0.78	g water/ g dry matter
W_{min}	0.1	g water/ g dry matter

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

On the basis on modelling a computer system (Fig. 5) allowing calculating the parameters of cooling bakery various assortments were developed.

```
fi = 50
R = .05
ro = 470

U = 3
A = 5
A = 7.74 * U ^ .656 + 3.78 * 2.718 ^ (-1.91 * U)
L = .288
LC = .345
C = 2805
TB = 75 + 273
f = .23
DT = 60

S = .0687
TI = 30 + 273
WIDTH 80, 50
PRINT "TIME.          RAD+HEC       Mass"
C = C * ro
fi = fi / 100

XA = fi * EXP(10.56 - 3654 / (TA - 43))
mass = 513
mass1 = 0
time = 0
Bi = A * R / L
k = 1 / f - 1
k1 = SQR(2 * k + 6)
ka = 4 * (k1 + 2 + Bi) * Bi + k1 * (k + 5 + 2 * k1)
ka = Bi * (k + 1) * (k + 5 + 2 * k1) * (Bi + k1) / ka
m = ka * L / (C * R ^ 2)

TS = TA + (TB - IA) * ka * f / Bi
TC = 97 + 273
DO

WS = .6
LS = 7.78 * 10 ^ (-3) * (TS) * WS - 1.69 * 10 ^ (-4) * (TS) - 2.2 * WS + 7.2 *
```

Figure 5. Computing system for calculating the cooling parameters.

The comparison between calculated temperatures and experimental data is shown on Fig. 6. The curves have some distinction, but we can admit that there is a good agreement of model and experiment.
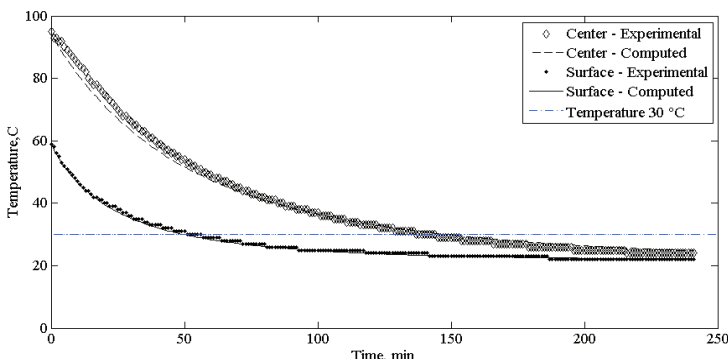

Figure 6. Experimental and computed temperature history during natural cooling at ambient temperature 20.6°C.

CONCLUSIONS

Conducted structural and parametric analysis of a complex multifactorial control object, which is 'cooler', allowed to develop an algorithm for computing the values of temperature, humidity and air velocity which is used for solving the problem of automatic control and process control of cooling the bakery of various assortments. Applying the appropriate set of parameters for the particular kind of product system allows conserving some energy which in the opposite case is just wasted.

To assess the degree of disturbances and control actions influence on the determination of the object control range, selecting the control law and control settings as further work the structural-parametric object diagram will be considered, with the assessment of the functional dependency of units and carried out work on the definition of static and dynamic characteristics of the object.

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