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PECULIARITIES OF HEAT EXCHANGE IN DOUGH UNDER THE ROTATING ROLLERS ACTION

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Summary*.The analytical analysis of roller impact on the medium and its behavior at deformation influences are carried out, ways of choosing the optimal method of the process for providing the maximum or minimum value of parameters (criterion) are proposed. The physical essence of the equation of energy flows of the medium mass deformation intensity, which depends on the method of applying mechanical forces, the degree of its previous dispersion (recipe) and its physical and mechanical properties, is considered. For more visual view and understanding of the overall research performance, the scheme of causal relationships between the medium and the roller, determining the temperature change of the dough injection process, is proposed. It is noted that the determination of the influence of deformation processes temperature during the process of medium injection by roller operating bodies plays an important role for calculations and designing of molding, sheeting equipment. The influence of thermal circulatory chaotic streamsthe character resulting in general heat circulation disfunction in the medium during the injection is considered. At the same time, the level of such disfunctions can be deep enough with changes in the contours directions influencing the process, according to each particular period of the deformation stage in the injection unit of the molding machine.*

Key words*: dough, injection, heat conduction, heat propagation, heat flow, roller, phase, medium.*

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Statement of the problem. One of the ways to reduce production cost is optimization of production hardware implementation in terms of energy, i. e., reduction of thermal and (or) electrical energy consumption per final product unit. In order to achieve this effect it is necessary to determine material flows energy potential at each stage of production technological process, the need of energy for implementation of the given material flow transformations and possible ways of thermal energy chemical bonds energy loss minimization.

It is well-known that roller machines are used in various branches of Ukraine industry. Among different directions the food processing industry should be distinguished. Machines designed for viscous medium formation should influence it in such a way that raw materials and finished product losses are minimal and product quality is high. Such approach causes the need to provide complete conformity of processing modes, design shapes and parameters of operating roller elements, structural-mechanical properties of viscous medium.

Among the thermal processes used in production the process of heat transfer from its sources to the processed material hold pride of place. The energy exchange between the moving parts is due to direct collisions. In this case the molecules of more heated body part having larger energy transfer the part of energy to neighboring particles with less energy. In gases the energy transfer is due to the molecules and atoms diffusion, in liquid and solid dielectric materials – by elastic waves. In metals the energy transfer is caused mainly by free electrons diffusion.

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Generated thermal circulating flows more often have chaotic character resulting in general thermal circulation loss in the medium. At the same time the levels of such losses can be deep enough with direction changes in its contours. Thus, hydrodynamic modes in injection unit of the forming machine are determined by heat flow produced in the dough while interacting with roller operating elements surfaces.

The speed of any process and, for this reason, the speed of substance transfer after the beginning of roller operating elements due to system response changes gradually: at first it increases to a certain maximum value, remains for some time at this value and then with the approaching to the equilibrium state it gradually slows down up to zero (process shutdown). The additional higher temperature constantly emerges between the medium and operating member. There is the difference in temperature potential $\Delta t = t_1 – t_2$ which causes heat transfer from the more heated point to the less heated one. The difference of temperature potentials Δt at relevant points is the deviation measure of their state from equilibrium between them. This temperature causes heat transfer from the heated point to the less (cooler) one in the medium located in space between the rollers. Thus, this characterizes the potential difference in the roller surface and medium (dough) itself. That is why we proposed methods of determining the temperature differential in the forming machine roller unit in comparison with the new construction.

Analysis of available investigation results. Determination of temperature flows during the process of dough injection by roller operating elements is of great importance in the calculation structural and technological parameters of forming, rolling and mixing equipment. The obtained data solve a number of problems concerning the application of different methods for thermal control of the process of operating elements action on medium. However investigation [1] of the process of dough compression between the rollers only the kinetics of its injection separately from its structure change does not allow to determine the optimal process parameters. The change of the dough physical-chemical properties under the operating element action is considered in paper [2], but the temperature determination method is not presented. The sequence and mechanism of the temperature change effect on the structure during yeast dough injection is not considered completely by Bloksma A. B., Niemann W. In their rheological investigations E. I. Muratova, P. M. Smolihina reveal the temperature value for the medium structure change, but the method of the process temperature field determination is not evident. The temperature effect is more clearly shown in paper [3], where the modeling of the viscous medium in the gap between rollers is described and the temperature distribution is presented.

Without clarifying the formation and determination of heat flows in yeast dough it is impossible to substantiate the optimal modes and methods for this process control. Thus, except rational mechanical rollers action on medium, it is necessary to maintain the optimal temperature providing nutrients inflow to the bacteria cells and required moisture and gas exchange.

Nowadays there is the hypothesis [4] of dough temperature change due to the design parameters of operating elements and operating chamber. The fact is that under intensive deforming effect on dough caused by certain operating elements the consumed energy is distributed in two directions. The energy consumed for dough macromolecular structure produces positive technological effect, and its consumption related to internal friction should be considered as useful ones. Consumptions related to external friction of operating elements and mixing container walls followed by heat release have negative impact on technological process. For this reason the rate of mechanical action on the dough should be hold within strictly defined limits.

The method of the optimal energy load control at frictional interaction of friction couples friction of dough with the rollers at different injection modes makes it possible to define the inlet heat to its working surfaces.

According to Meacham and Swanson [5] it is assumed to characterize the optimal control value by specific energy consumption. It is confirmed that there is critical value of speed and consumed energy which has its limits. However, in our opinion, wrong technical decisions are often made. A number of researches (R. V. Kuzminsyi, H. F. Kozlov, V. Ye. Nemyrovskyi) believe that the values of specific works with different force do not give sufficient understanding of the process technological aspects. In their opinion mechanical action of the operating elements during deformation according to specific energy consumption is imperfect.

Thermal processes control is necessary from the following reasons: to limit the heat amount, accumulated by rollers in order to reduce thermal stresses; to decrease surface temperatures in dough below its permissible ones in order to prevent changes in its structural-mechanical properties; to ensure the injection unit operation with acceptable energy load in order to increase wear-friction properties of the roller surface layer; to establish relationship between the rate of surface layer temperature change and temperature gradient along both its surface and thickness.

The process of dough injection where forced convective heat transfer occurs makes it possible to equalize the temperature field in the medium (non-Newtonian liquid), create similar conditions in any area of the operating chamber. This enables to confirm that the temperature at any point at certain period of time approaches reaching the average medium temperature at the beginning and at the end of injection process. However, while injecting yeast bagel dough there is significant difference – the temperature inside the medium does not approach that one formed on the surface roller operating member but gradually decreases. Thus, the injection process after a certain period of time takes the form that practically can be regarded as the regular thermal conductivity mode.

The boundary temperature to which the temperature in the dough approaches is the one at the given injection pressure and internal friction generated by the action of rotating roller operating elements. The produced temperature influences the character of process change: duration, efficiency at each state of injection discrete mode. For values of the temperature field in the dough, the temperature of the surrounding medium is influential.

In fact these phenomena occur simultaneously and certainly affect one another. Convection, for example, is often followed by thermal radiation, and thermal radiation – by thermal conductivity and convection [6].

During discrete deformation on the medium by rollers, the heat radiation on the interfaces is approximately uniform. The propagation cycle is rather short and heat losses on radiation and convection are insignificant. Therefore it can be assumed that the roller lateral surfaces are in adiabatic boundary state and temperature distribution along the plane parallel to the friction surface is uniform. Thus, the temperature in this plane is approximated by the value at the intersection point at one-dimensional analysis by finite difference method.

The rollers together with the dough are the multilayered cylindrical wall with only ¼ of mutual contact (Fig. 1). In this case the thermal resistance of the multilayered cylindrical wall is equal to the sum of resistances of separate layers. The medium itself can be conditionally divided into several layers.

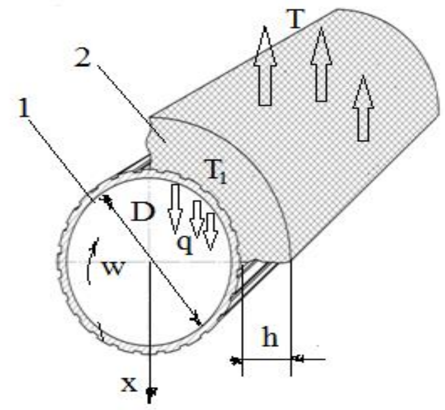


Figure 1. Scheme of pulsed friction contact: 1 – roller operating element, mm; 2 – medium (dough); T – constant temperature; T1 – temperature on the frictional contact surface

The objective of the paper is to investigate the heat propagation during the injection process based on heat transfer peculiarities in phase medium.

Statement of the problem. 33% moisture content dough for bagels made of high quality wheat flour on pressed yeast was prepared by dough method with fermentation period 60 minutes at temperature 32–33°C. The pressed yeast quality comply with DSTU. The investigation of heating and dough sheeting processes was carried out on the forming machine B-54 at confectionary plant (Ternopil) and on physical models developed at FPT department (TNTU).

During the process of dough movement between the rotating rollers (Fig. 2), after medium compression by rollers zone – 2, it is brought to the main injection zone – 3, which can be relatively divided into three components – intense heat radiation zone – 111, transition zone – 11, and heat rejection one – 1. For this part in most injection unit structures the convective thermal mode is implemented. This mode involves simultaneous heat transfer by radiation and convection.

The generated circulation flows occurring during the injection have mainly chaotic character. They result in failures of general heat circulation in medium. The levels of such failures are rather deep with changing directions in generated dough contours.

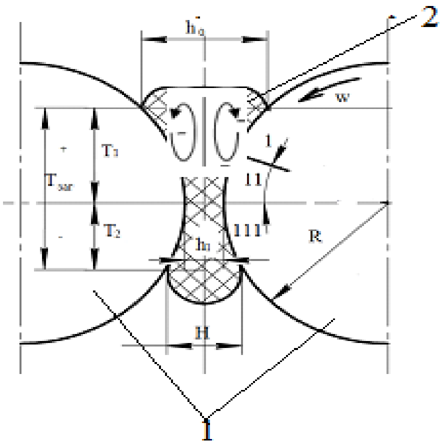


Figure 2. Scheme of injection temperature distribution: 1 – rotating rollers; 2 – dough is the operating medium

Thus, the emerged hydrodynamic modes in the forming machine injection unit can be determined on the basis of two main reasons. The first one refers to the heat flow produced on the roller surfaces. The second concerns the flow generation involving the gas phase of dough fermentation process.

Each of the above mentioned reasons is characterized by its driving factors: for the first reason it is the medium temperature differences and roller operating element of heat transfer-coolant: for the second one is availability of dispersed gas phase. Therefore the total value of temperature flows depends on movement speed, discrete action of roller operating speed. The weight of yeast wheat dough and in the operating chamber and charging hopper resulting in partial fermentation of sugar in it is important.

Experimental data for determination the temperature of the roller operating element heating in the injection process were obtained by means of thermocouples located in the interaction zone (Fig. 3). The temperature change was recorded by three thermocouples fixed on the roller surface relatively at the distances 5; 15 and 25 mm from the roller end.

In order to determine the heat radiation on the friction surface (the boundary roller-dough) the converse thermal conductivity model was constructed. The dough heating temperature in the contact area with rollers was determined by calculations and on the basis of the obtained data the flow axial force defined. As the temperatures gradient in the solid body is determined on the basis by experimental measurements, the heat flow can be calculated as the product of thermal conductivity coefficient of the solid body on the surface temperature gradient. In the inverse temperature setting the finite difference method is used to estimate the heat flow *q(t)* on the boundary under friction provided that transition temperature values on the roller surface are known.

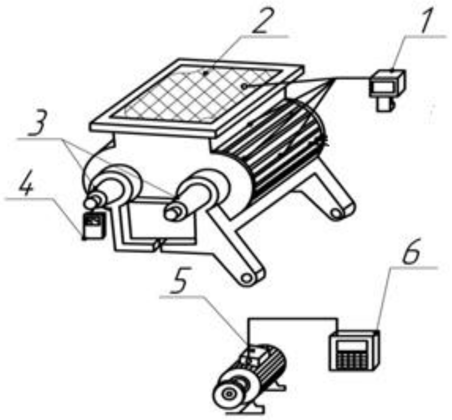


Figure 3. Scheme of the injection unit for determining the temperature and flow capacity: 1 – potentiometer; 2 – medium (dough); 3 – roller operating elements; 4 – tachometer; 5 – electric motor; 6 – watt meter

Method of complex determination of effective thermophysical characteristics of bagel dough is used and thermal conductivity dependence λ, volumetric heat capacity c_ρ, temperature conductivity a on temperature at the stages of its discrete injection of the whole mixed mass is determined in this paper. The calculations are carried out under injection conditions: the medium temperature T_c – 18ºC; the dough temperature T_t – 25…28ºC; the thickness of dough layer on the roller is assumed to be 20–22 mm; the average dough speed 2.0 m/s, density ρ=1165 kg/m^3.

The hot copper constantan joint of thermocouple with relatively graduated table is used. During the complex temperature measurements simultaneously in several object coordinates the battery of differential microthermocouples with six single joints is used. The cold joint of the battery is common. The hot joints in batteries are equal to the amount of the measuring device points.

The occurring thermocouples thermo-EMF is proportional to the hot and cold joints temperature difference measured by compensating type devices – potentiometers or milivoltmeters. The results reliability during the temperature measurements by thermocouples was provided by previous calibration of produced thermocouples directly in the laboratory. Thermocouples calubration includes determination of potentials of the produced thermocouples battery and relative indicators of the reference thermometer (Fig. 4).

After thermocouples calibration according to measuring data, the table and calibration curve of thermocouple E in milivolt, $E = f(t)$ – thermo-EMF dependence developed by thermocouple (according to milivoltmeter indicators) on the temperature of its hot joint are constructed.

The rule of the 3rd metrological indicator A for used measuring devices is taken as the basis for metrological indicator determination:

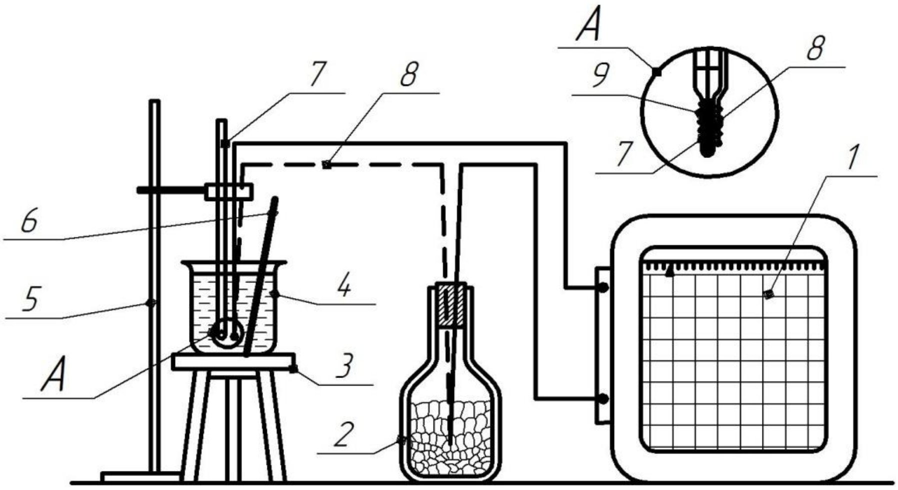


Figure 4. Installation for thermocouples calibration: 1 – measuring self-recording device; 2 – Dewar vessel with ice; 3 – electric heater; 4 – container with working fluid; 5 – fixing tripod for thermometer and thermocouples; 6 – glass rod for mixing; 7 – mercury thermometer; 8 – single copper-constantan thermocouple; 9 – fixing thread for hot joint of thermocouple

The rule of the 3rd metrological indicator A for used measuring devices is taken as the basis for metrological indicator determination:

$$A = \frac{3\sigma}{\bar{y}_j},$$

where σ is the root mean square deviation in repeated measurements,

$$\sigma = \sqrt{\frac{\sum_{j=1}^{n}(y_j - \bar{y}_j)^2}{n-1}},$$

where $\bar{y}_j$ – is the average value of the measuring parameter,

$$\bar{y}_j = \frac{\sum_{j=1}^{n} y_j}{n},$$

where n is the number of repeated measurements.

The condition for sufficient accuracy for experimental investigations is the value A=0,1:

$$A = \frac{3\sqrt{\dfrac{\sum_{j=1}^{kn}(y_j - \bar{y}_j)^2}{n-1}}}{\dfrac{\sum_{j=1}^{n} y_j}{n}},$$

For the investigated parameter / $t_{вк}$ / y_j / 1 series the value A is calculated:

$$A = \frac{3\sqrt{\dfrac{38{,}68}{11}}}{16{,}1} = 0{,}035.$$

Since, for the measuring temperature values the metrological indicator A do not exceed 0,1, it is sufficiently accurate in measuring devices.

On the basis of metrological analysis the measurement mean square errors are determined.

Statistical analysis of the investigation. For unbounded plate (roller surface) with corresponding thickness δ heated by thermal flow with constant density g_d the differential equation of non-stationary thermal conductivity: $\frac{\partial t}{\partial \tau} = \alpha \frac{\partial^2 t}{\partial x^2}$ with initial conditions $t(x,0)=t_0=const$ is used.

Heat transfer by thermal conductivity is due to the mass transfer energy:

$$\mathrm{g} = -\lambda \mathrm{grad} t + \sum_{1}^{n} i_k \gamma_k,$$

where g is the surface heat flow density of the heat flow, W/m^2; $i_к$ is water or steam enthalpy, *J/kg*, transferred in the presence of temperature gradient grad t with intensity $\gamma_к$, kg/(m^2 s).

The boundary conditions of the second order:

$$\frac{\partial t(\delta,\tau)}{\partial x} = -\frac{\mathrm{g}(t)}{\lambda} \cdot \frac{\partial t(0,\tau)}{\partial x} = 0.$$

The solution of the given equation under the given boundary conditions makes it possible to determine the temperature field $t(x,\tau)$ and the field of heat flow in the roller (surface) plate.

The determination λ was carried out on the basis of generalized equation obtained by means of the second order mode and solution of other equations for temperature field determination:

$$\lambda = h\left[\frac{F\left(u^{-1}(\Delta t_1^{11} + \Delta t_2^{11}) - u^{-11}(\Delta t_1^{1} + \Delta t_2^{1})\right)}{\overline{u^1 - u^{11}}} - R\right]^{-1},$$

where F is Fourier number, nondimensional process time $F = {}^{\alpha\tau}/_{\delta^2}$; u is dough surface heating rate, К/с, $u = {}^{at}/_{dt}$; Δt is temperature differential on the dough surface, K in (^{1}) and

(^{11}) different thermal modes; h is the dough layer thickness, m; R is ballast heat resistance, m^{2}K/W, equal to h/λ.

Direct measurements were carried out in the experiments, i. e. The required values were obtained directly as the result of the experiment. A number of repeated direct measurements of the same value were processed mathematically using the probability theory and statistics methods. The law of Student random error distribution was used to analyze the result error for large and small number of measurements.

For physical experiment planning we used Seidel-Gauss method which ending is the multifactor correlation dependence on the basis of the obtained Protodiakonov function. Its application for processing the results of chemical investigations made it possible to get reasonable results

$$Y_{\Pi} = \frac{\prod_{i=1}^{k} y_i}{y_{\text{сер}}^{k-1}},$$

where y_i are partial functions determined by means of the smallest squares method; k is factors number; y_{av} is the average of all taken into account experimental results.

The investigations were carried out according to the plan with relative experiment planning matrices with indicated number of experiments and factors change limit. The temperature occurring in dough during motion was used as optimization parameter. This temperature depends on the input parameters and can be represented in the following way:

$$T = (P, d, h),$$

where T is temperature, P is pressure, d is roller diameter, h is the thickness of dough mass between the rollers.

While planning the experiments for determination of the functional dough temperature change the standard symmetric plan-matrix of three-factor experiment on three stages of factors variation for total number of experiments of one replication $N = p^k = 3^3 = 27.$ The experiments were carried out in three replications of each numbered plan-matrix line. The sequence conducting the first and the following experiments were determined according to numbered order of randomized plan-matrix of three-factor experiment.

The experimental data array was processed by means of application software program «Statistica-12» for computer.

The approximate response function, or optimization parameter, that is the dough temperature T, determined experimentally, was defined in the form of mathematical model of complete second order polynomial.

$$\begin{gathered} \text{y} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + \\ +b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + +b_{33}x_3^2, \end{gathered} \tag{1}$$

where x_1, x_2, x_3 – is relatively coded dough pressure notation P, rollers diameter d, gap between the rollers h; h; $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{11}, b_{22}, b_{33}$ – is constant term and coefficients of values of the corresponding factor x_i and their interaction.

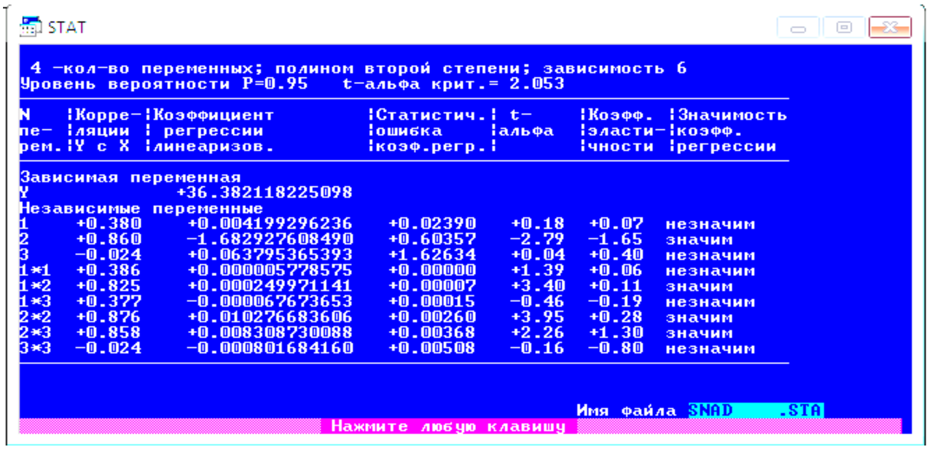
At probability level p=0,95 and value t – alpha criterion equal 2,053, we got the following statistic data (Fig. 5): coefficient of multiple determination D=0,962; coefficient of multiple correlation R=0,981; standard estimate deviation is S=0,637; F – Fisher criterion F=47,671. Coefficient D is significant with the probability level P=0,9999.

Estimation of experiments reproducibility was carried out according to Cochran criterion at 5% significance level.

Coefficients of regression equation or approximation function represented in the form $T = f_T(x_1, x_2, x_3)$ under the conditions of orthogonality and symmetry of plan-matrix of the planned factor experiment were determined in accordance with the standard method by known dependences.

After the estimation of statistic significance of regression equation coefficients by t_T – Student test and verifying approximation model validity according to F – Fisher test and transition from coded factors notations to natural ones we derived the regression equation characterizing the dough temperature change T depending on change $200 \leq P \leq 700$ N, $15 \leq h \leq 35$ mm, $155 \leq d \leq 165$ mm

$$T = 36{,}4 + 4{,}2 \cdot 10^{-3}P - 1{,}7L + 0{,}06h + 2{,}5 \cdot 10^{-4}PL - 6{,}8 \cdot 10^{-5}Ph + 8{,}3 \cdot \\ \cdot 10^{-3}Lh + 5{,}8 \cdot 10^{-6}P^2 + 0{,}01L^2 - 8{,}0 \cdot 10^{-4}h^2. \quad (2)$$



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 4 -кол-во переменных; полином второй степени; зависимость 6
Уровень вероятности P=0.95   t-альфа крит.= 2.053
---------------------------------------------------------------------------
N    ¦Корре-¦Коэффициент            ¦Статистич.¦ t-      ¦Коэфф. ¦Значимость
пе-  ¦ляции ¦ регрессии             ¦ошибка    ¦альфа    ¦эласти-¦коэфф.
рем. ¦Y с X ¦линеаризов.            ¦коэф.регр.¦         ¦чности ¦регрессии
---------------------------------------------------------------------------
Зависимая переменная
Y               +36.382118225098
Независимые переменные
1     +0.380     +0.004199296236     +0.02390     +0.18   +0.07   незначим
2     +0.860     -1.682927608490     +0.60357     -2.79   -1.65   значим
3     -0.024     +0.063795365393     +1.62634     +0.04   +0.40   незначим
1*1   +0.386     +0.000005778575     +0.00000     +1.39   +0.06   незначим
1*2   +0.825     +0.000249971141     +0.00007     +3.40   +0.11   значим
1*3   +0.377     -0.000067673653     +0.00015     -0.46   -0.19   незначим
2*2   +0.876     +0.010276683606     +0.00260     +3.95   +0.28   значим
2*3   +0.858     +0.008308730088     +0.00368     +2.26   +1.30   значим
3*3   -0.024     -0.000801684160     +0.00508     -0.16   -0.80   незначим
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Figure 5. Program file «Statistica-12»

Based on the obtained regression equation (2), characterizing the functional dough temperature change T depending on the pressure change in the injection unit within $200 \leq P \leq 700$ N, gap between the rollers $15 \leq h \leq 35$ mm, and rollers diameter $155 \leq d \leq 160$ mm, the response surface and two-dimensional cross section of the functional dough temperature change is constructed (Fig. 6).

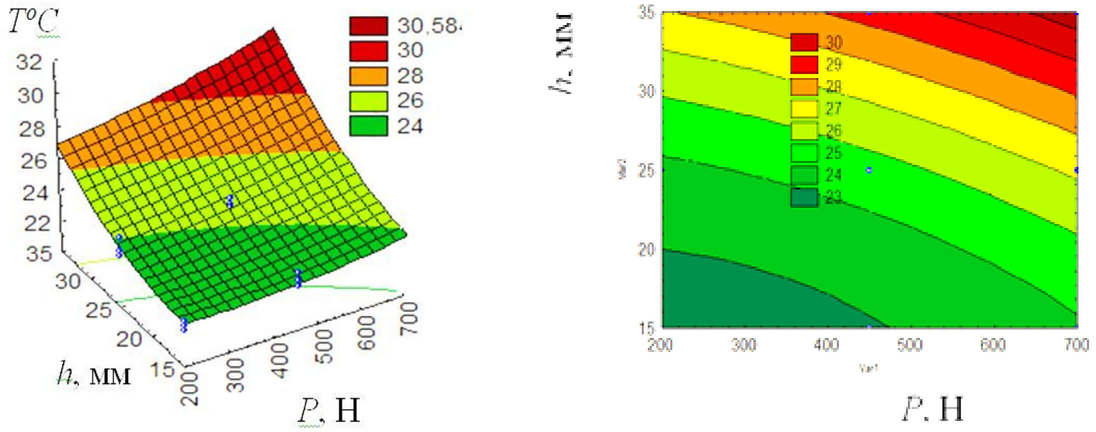

Figure 6. The response surface and two-dimensional cross section of the functional dough change as the functional $T = f_T(P; d)$

Conclusions. Analyzing the above given results of measurements and calculations we can make the following general substantiation of rotating rollers action on the medium:

- the temperature of operating medium in the radial direction increases while approaching to the operating roller with difference in 4–7^{o}C at speeds $u = (0{,}4 - 1)$ *m/s* and relative radius of medium on the roller and the roller itself $r_2/r_1 = 1{,}2$; the value of this difference depends on the value of compression growth degree;
- the temperature of the operating medium on the compression and injection area changes practically by the roller rotation angle indicating its intensive transportation and partial mixing;
- the temperature of the roller body surface t_b is uniformly distributed according to its rotation angle, when the pressure increases the injection rises linearly and repeats the outlet temperature increase with difference about 7^{o}C;
- the temperature of the operating medium on the roller surface in axial direction is uniformly distributed in new structures. While determining the temperature in axial direction no changes were detected.

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ВПЛИВ ОБЕРТОВИХ ВАЛКІВ НА ОСОБЛИВОСТІ ТЕПЛООБМІНУ В ТІСТІ

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Резюме. *Проведено аналітичний аналіз дії валків на середовище та його поведінка при деформаційних впливах. Запропоновано шляхи вибору оптимального варіанта процесу для забезпечення максимального або мінімального значення параметрів (критерію). Розглянуто фізичну сутність рівняння енергетичних потоків інтенсивності деформації маси середовища, що залежить від способу прикладання механічних сил, ступеня його попередньої дисперсності (рецептура) і його фізико-механічних властивостей. Для більш наочного вигляду й розуміння загального виконання досліджень запропоновано схему причинно-наслідкових зав'язків між середовищем і валком, що визначають зміну температури процесу нагнітання тіста. Відзначено, що визначення впливу температури деформаційних процесів при проходженні процесу нагнітання середовища валковими робочими органами відіграє важливу роль для розрахунків та конструювання формувального, розкочувального обладнання. Проведено дослідження поширення теплоти в процесі нагнітання, що ґрунтується на особливостях теплообміну в фазовому середовищі. Розглянуто вплив теплових циркуляційних хаотичних потоків, характер яких також призводить до порушень загальної теплової циркуляції в середовищі при нагнітанні. Встановлено вплив зміни конструктивних і технологічних параметрів на температури робочого середовища, залежність загального значення температурних потоків від швидкості руху тіста й дискретності дії валкового робочого органу. Визначено гідродинамічні режими, які виникають у вузлі нагнітання формувальної машини на основі теплового потоку, що утворюється на поверхнях валка й утворення потоків за участю газової фази процесу бродіння тіста. При цьому рівні таких порушень можуть бути досить глибокими зі змінами напрямків у їх контурах, які впливають на процес, відповідно до кожного певного періоду стадії деформації у вузлі нагнітання формувальної машини.*

Ключові слова: *тісто, нагнітання, теплопровідність, поширення теплоти, тепловий потік, валок, фаза, середовище.*

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