Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2023, № 1 (109) https://doi.org/10.33108/visnyk_tntu2023.01
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 664.643

PECULIARITIES OF HEAT EXCHANGE IN DOUGH UNDER ROTARY ROLLERS ACTION

Volodymyr Piddubnyy[1]; Lyudmila Kahanets-Havrylko[2]; Viktor Fedoriv[3]; Viktor Senchishin[4]; Ihor Stadnyk[4]

[1]National University of Trade and Economy, Kyiv, Ukraine
[2]Uzhhorod trade and economic professional college of the State trade and economic university, Uzhgorod, Ukraine
[3]Podilsky State University, Kamianets-Podilskyi, Ukraine
[4]Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary. *Any impact of mechanical action on a viscous medium contributes to the transformation of a volumetric spongy-reticular solid structure into a gluten skeleton, as it defines the elastic and viscous characteristics of the medium and it is important in gas dispersion in a liquid. Thus, the aim of the study under consideration was to determine the relationship between the working surface of the working body and the amount of heat Q transferring per unit of time from the roller wall to the medium. The problem of the development of a generalized model of a working process of rollers' action on the medium has been solved due to the study under discussion. The problem is aimed at obtaining the structural, expenditure, and energy characteristics, as well as at determining the ways of increasing the efficiency of such class of machines operation under deformation modes conditions.*

Some peculiar features of the compression area have been taken into consideration in cases when the temperature pressure value by the angle of rotation varies constantly. It was proved, that the heat-transfer coefficient value α *can be calculated quite approximately as it is necessary to take into account an available area influencing the heat exchange and the movement speed on the working dough roller surface in the injection area. Some temperature state variations of the dough in bagels production during its compressing, injection, and transportation have been determined. It was admitted, that the impact of the liquid phase temperature of the working medium* T_X *is determined by the value of its kinematic viscosity* ν_X*. The temperature variations were determined by means of thermal imaging of a pilot plant.*

Key words: *dough, injection, heat conductivity, heat spread, heat flow, roller, phase, medium.*

https://doi.org/10.33108/visnyk_tntu2023.01.043 *Received 10.01.2023*

Statement of the problem. The ways to increase the quality of mixture formation in the food industry and pharmacy are very important. So, nowadays, this problem has been paid great attention to both in our country and abroad. Obviously, under market economy conditions the most efficient is the process and equipment where energy- and material-saving technological processes are optimized.

Flour is one of the most popular products of processing. An impressive amount of flour has been produced and consumed all over the world in various sizes, forms, textures, and tastes, a great variety of semi-finished products. It should be admitted, that semi-finished products manufacture depends not only on the input ingredients but on the parameters of the equipment on which they are produced.

In most cases, the equipment for this operation is selected taking into account the peculiarities of production, the specified productivity, characteristics of the raw materials, indicators of the quality of the finished mixture, and the economic capabilities of the enterprise. Mechanical mixing and forming have acquired the widest use in the food industry due to their

Corresponding author: Ihor Stadnyk; e-mail: igorstadnykk@gmail.com

relative simplicity, as well as the variety of sizes and designs of working bodies. As the authors [1] claim, working bodies not only serve for mixing but they are also a versatile means for homogenizing low-viscosity and viscous media and their transportation. They provide uniform and intensive mass exchange between the solid phase and the liquid one.

Technological machines of different designs differ in the degree of influence on the components [2]. This influence leads to obtaining a final product with different structural and mechanical properties and finished products of different quality. Studying the influence of individual machines on the properties of semi-finished products allows searching for the most efficient designs to determine the optimal process modes.

The authors admit [3, 4] that currently, the necessary microstructure of the semi-finished product, which determines its behavior and quality, is not taken into account when choosing such technological equipment or carrying out modernization with appropriate parameters. Therefore, a promising direction for mixing the mixture of components is the use of a new generation of equipment that would increase turbulence and circulation of flows while reducing energy consumption and metal capacity.

In fact, the design of equipment of domestic production for preparing viscous liquids and their formation hasn't been developed nowadays, and existing machines are quite conservative and inefficient. Moreover, these machines practically do not meet the requirements posed by the present economic market. The action of the working body and working chamber of the machine is partially absent or unbalanced, and adjustment of the operating modes is not provided, which leads to an increase in the heating of the environment with its insufficient aeration.

Analysis of available investigations. So, in the compression unit of the molding machine, three disturbing factors act simultaneously at all stages of the working process: energy input or output with the mass of the dough (migration effect), heat input or output, and mechanical work input.

When schematizing, the working process is divided into separate processes, where the most important influencing factors are identified, and secondary ones are neglected. To determine the change in the parameters of the working environment in the working chamber located in the inter-roller compression zone, we consider the amount of heat that had entered the system.

Thanks to the discrete action with a large free surface of the roller and a small contact area with the mass of the environment in the working chamber, heat exchange occurs by convection through heat conductivity inside the environment, which is shown in the Reynolds and Prandtl numbers [7,8].

The generalized criterion equation of the collective heat exchange is expressed by the following function: $Nu = f(\mathrm{Re}, Pr, \frac{L_1}{L_0})$

where Pr - Prandtl number – physical properties of the medium and characterizes the similarity of physical properties of the heat carriers during convective heat exchange. For the heat exchange at the medium injection (mechanical displacement) the Fourier number, and the Froude number can be neglected.

Thus, the above-mentioned kind of heat exchange during the medium displacement under the rollers' action can be written as follows:

$$Nu = \frac{\alpha D}{\lambda} = C\,\mathrm{Re}^m\,\mathrm{Pr}^n\left(\frac{L}{D}\right)^p,$$

where D – a roller diameter, m; L – a roller length, m; C, m, n, p – the values found experimentally; Re=wL/v – Reynolds number; Pr=v/a – Prandtl number.

The amount of heat Q transferred per unit of time from the roller wall (constantly has its own variable temperature and is an additional heat source) to the medium can be determined as:

$$Q = \alpha_2 F_c \Delta t ,$$

where F_c – is the heat exchange surface assumed in this case as it is equal to the surface of the medium that is in contact with the roller; α_2 - the heat-transfer coefficient from the roller wall to the medium receiving some extra temperature due the viscous friction; Δt – the difference in temperature of the roller wall and the medium near its surface.

Taking into account, that $\alpha_2 = \lambda Nu / D$, then the general expression of heat amount is as follows:

$$Q = \lambda \frac{Nu}{D} F_c \Delta t . \qquad (1)$$

Thus, if we know the values of the variables, we can obtain a new generalized criterion equation to find the value of heat transfer.

The authors of the papers [5, 6] have described the transition process of active influence on the medium mass increase, as well as the volume increase due to the driving factors of potential energy during the intensive formation of some variable impulses of the acting forces.

When determining the coefficients that are included in equation (1), it is necessary to take into account the fact that the value of the temperature pressure is constantly changing by the angle of rotation in the compression section, and the value of the heat transfer coefficient α can be determined quite approximately, as it is necessary to take into account the presence of a section that affects the heat exchange. It is also necessary to know the speed of the movement both on the surface of the roller and of the working dough in the injection zone. These values can be determined experimentally. To determine the change in temperature and pressure by the angle of rotation of the working roller in the injection zone, it is necessary to know the mass consumption of the medium.

The results of the change in the temperature state of the dough for the production of bagels at the roller injection on a forming machine have proved its constant change. The influence of the temperature of the liquid phase of the working medium T_X is determined by the value of its kinematic viscosity ν_X .

Paper purpose. To study the heat spread during the process of injection based on the specific features of heat exchange in a phase environment.

Main material presentation. Let's consider the process of movement of the medium between the rotating rollers. After compression of the medium in zone-2 by the rollers, it enters the main injection zone-3, which, according to Figure 1, can be conditionally divided into three components - the zone of intense heat release-3, the transition zone-2, and the heat dissipation zone-1. For this part, in most designs of the injection unit, a convective heat mode is realized, which involves the simultaneous transfer of heat by radiation and convection.

The formed thermal circulation flows often have a chaotic nature, which also leads to disruptions in the overall thermal circulation in the environment. In this case, the levels of such disruptions can be quite profound with changes in the directions of the dough circuits.

Thus, the hydrodynamic modes in the injection node of the forming machine are determined by two reasons. The first one concerns the thermal flow formed on the roller surfaces. The second reason relates to the formation of flows involving the gas phase.

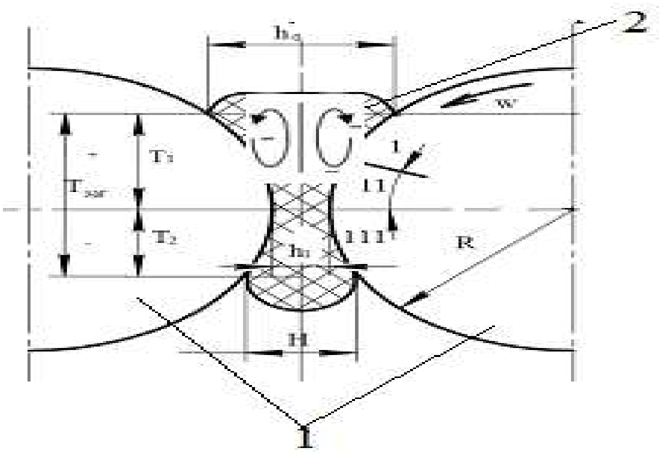


Figure 1. Scheme of temperature distribution at injection:1 – rotary rollers; 2 – working medium dough

It is evident, that each of the above-mentioned reasons is characterized by its driving factors. For the first reason, the temperature difference between the environment and the roller heat agent-coolant is a driving factor. In the second case, the presence of dispersed gas phase is the driving factor. The value of thermal flows depends on the speed of the environment movement and the discreteness of the roller action, the mass of the dough in the working chamber and in the loading hopper, which leads to partial fermentation of sugar. A certain level of generalization can be represented by the fixing capacity of the environment for the gas phase.

In the system under consideration, the primary energy source is present in the form of the chemical energy of carbohydrates, which should be transformed into carbon dioxide. In this case, the formation of carbon dioxide has a double thermodynamic manifestation, that is accompanied by the release of thermal energy and the formation of dispersed gas phase CO_2. The gas permeability of the dough is a criterion for assessing the amount of the holding gas phase.

The released thermal energy in combination with the thermal energy of viscous friction is realized in a form that can hypothetically be considered as a system for transforming thermal energy into mechanical work of mixing (reverse movement) of the environment. In accordance with the ideal Carnot cycle, the efficiency of such a system is determined by a well-known dependence [8]:

$$\eta = \frac{T_{\text{з}} - T_2}{T_{\text{з}}}, \qquad (2)$$

where $T_{\text{з}}$ – the dough absolute temperature and viscous friction respectively, $T_{\text{з}}=T_{\text{т}}+T_{f}$.; T_2 – the dough temperature at the exit from the roller gap.

When we assume $T_1 = 300.3$ K and $T_2 = 297.4$ K, then we obtain

$$\eta = \frac{300.3 - 294.4}{300.4} \cdot 100 = 1{,}864\,\%.$$

The efficiency calculation in the form of an expression can be considered noticeably approximate. The circulation mode is affected by structural parameters, dough structure (available gas), and the gravitational field. However, at significant volumes of the medium, the mode is disturbed and leads to limited efficiency values.

The value Δt instability is caused by the fact, the more increased value h_0 (the dough layer in the chamber), the lower temperature in the circulation section of the liquid phase is. The temperature has the biggest values when the dough leaves the roller clearance. The heat-transfer coefficient α_1 from the medium to the roller wall depends on physical-chemical parameters of the medium, the rollers motion velocity, their structural parameters; the rate of updating of the liquid phase in transverse planes and the contact area of the liquid phase in the roller clearance (compression). The last one should be a full-value reaction of the system to a change of holding capacity in the gas phase.

The elastoplastic deformation of the dough shearing has caused some decrease in the walls thickness, their breaking, merging (coalescence) of separate bubbles to create a smaller volume [9]. To compare the level of change of the main characteristics of spring-elastic properties the density rarefaction coefficient has been used [8].

$$\mathrm{K}=1-\frac{a_k}{a_n},$$

where a_k and a_n – final and initial values of modulus of viscosity.

Thus, taking into account the complexity of theoretical determination of the convective heat flow value $\dot{Q}_k$, the conception of a heat flow from the dough compression Q_{cm} has been used in calculations which includes the value of the specific heat of absorption of the convective heat flow. The determination of the specific heat of absorption q_A is based on general principles of the specified mass exchange process in a roller working chamber.

A heat flow transferred to or from the liquid phase of the working environment can be calculated by the equation [8]:

$$Q_A = g_d \cdot m_A = \frac{g_d \cdot m_{x1} \cdot (x_k - x_n)}{\mu_x}, \tag{3}$$

where g_d – differential heat of gas dissolution (gas component); x_k, x_n – final and initial relative molar fractions of the absorbed gas in the liquid phase of the working environment; μ_X – molar mass of the liquid; m_A – mass rate of the absorbed gas (gas component).

Since there are some technological requirements to spongy structure of bagels, so the equilibrium concentration in the dough should take place regarding the gas phase. Accordingly, it is described by Henry's law [7, 10]

$$x_i = \frac{1}{E} \cdot p_i\,, \tag{4}$$

where x_i – molar concentration of the absorbed gas in the dough that is in thermodynamic equilibrium with the gas phase where the partial pressure of the absorbed component is equal to p_i; E – Henry's constant that is found from the dependence:

$$lnE = -\frac{g_d}{R \cdot T} + const \tag{5}$$

For the boundary conditions, for example, at atmospheric pressure we have:

$$\ln(\frac{E}{E_{atmos}} = \frac{g_d}{R} \cdot (\frac{1}{T_s} - \frac{1}{T}). \tag{6}$$

The final concentration of the absorbed gas in the dough $\bar{x}_{к}$ when calculating can be the one that equals to the concentration under equilibrium conditions. In this case, on the basis of the above-mentioned, the heat flow transferred to or from the dough during the process of injection will be as follows:

$$Q_a = \frac{m_x pR\mu}{\frac{1}{T_2} - \frac{1}{T_1}}.$$

That is why in the general theory of calculation of the injection unit it is necessary to take into account the processes of absorption in the working chamber, which haven't been described yet at all theoretically. Obviously, the considerable complication of the processes is the main reason of this situation.

The average temperature of the gas-liquid phase $t = 0,5 \cdot (t_X + t_Y)$ and the pressure $p = 0,5 \cdot (p_{Y1} + p_{Y2})$ can be assumed as the working temperature in the above-mentioned technique of calculation of absorbed gas consumption.

The total heat exchange of the roller surface with the environment, taking into account an insignificant difference in temperatures $T_x - T_{nc}$, the specific heat flow $\tilde{q}_{п.с}$ can be taken into consideration in the following form:

$$g_{nc} = \frac{c\,(T_{cm} - T_{nc})^n \cdot F_{cm}}{m_{Y1}}, \qquad (7)$$

where T_{cm} – temperature of the roller external wall that does not interact with the environment; F_{cm} – the calculated surface of the roller; c, n – empirical coefficients that are chosen according to the *table* 1 for different types of surfaces.

Table 1

Empirical coefficients to determine heat loss into the external environment

Surface type	$\bar{c}$	$\bar{n}$
Vertical	1,4	1,33
Horizontal upper	1,7	1,33
Horizontal lower	0,64	1,25

When calculating the roller temperature in the period of all stages (tightening, compression, injection), the equation of heat transfer as a flat plate with two-sided heat transfer can be used [7, 8]:

$$Vc\rho\delta\left(\frac{-\partial T}{\partial x}\right)dx = n\alpha(T - T_c)dx$$

where – the roller speed of motion; c – specific heat capacity of the roller; ρ – specific weight of the roller material; δ – thickness of the roller cylindrical wall; x – the distance traveled by the roller with the medium from the previous stage; п – the coefficient taking into account the cooling scheme of the roller (at two-sided heat transfer n=2, and at one-sided – 1); α – heat-transfer coefficient; T_c – temperature of the external environment (cooler).

After integration and taking into account the roller temperature at the exit from the section T_{ent}, we have obtained the equation:

$$T = T_0 + (T_{ent} - T_c)exp\left(\frac{-nx\alpha}{\rho c K_1 V}\right), \tag{8}$$

where K_1 – the coefficient of correction characterizing a fraction of the roller length with some dough on its surface.

To determine the dough temperature after discrete action of the roller on it, as well as the temperature of cooling at the exit from roller's clearance, the problem of heat conductivity for an unlimited flat wall has been used

$$\frac{\partial T(x,\tau)}{\partial \tau} = \frac{\lambda}{\rho}\frac{\partial^2 T(x,\tau)}{\partial x^2},$$

Under conditions $\tau > 0$; $\delta/2 < x < \delta/2$;

$$T(x,0) = f(x)$$
$$\lambda \frac{dT(\frac{\delta}{2\tau})}{dx} = \alpha_b \left[T_0 - T(\frac{\delta}{2\tau})\right]$$
$$\lambda \frac{dT(\frac{\delta}{2\tau})}{dx} = \alpha_n \left[T_0 - T(-\frac{\delta}{2\tau})\right],$$

where – δ – thickness of dough strips; α_b and α_n – heat-transfer coefficient on the upper (external) and the lower (internal) strips of dough; T_0 – temperature of the external environment (room).

Having taken into account, that cooling lasts seconds in the open space before the feed for formation, we have used the formula:

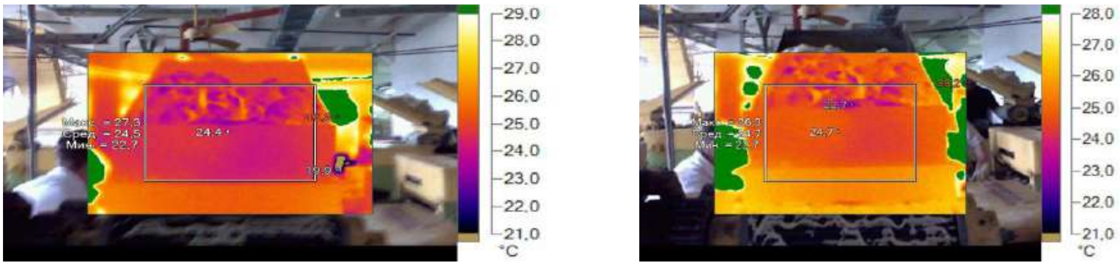
$$\alpha = \alpha_a\left(\frac{T^{0.04}}{29} + 1.2\upsilon^{0.1}\right),$$

where α_a – coefficient of correction; v – speed of the dough strip motion m/c.

The first adjunct of the formula shows the heat removal from the roller due to radiation, the second one – due to the convection.

When calculating the heat model of the roller state, 150 Kcal/m^2.g.°C was assumed as a base value of the heat-transfer coefficient under air cooling conditions. The coefficient of correction K_1 for each specific state can be determined by means of comparison of the experimental and calculated data. It can be obtained by experiments by means of the roller temperature measuring at the beginning and at the end of the discrete process. Nevertheless, these measurements can't be made with the necessary degree of accurateness. So, the single way to determine K_1 is the comparison of the estimated and the actual temperature of the roller at the known temperature of the environment.

In order to qualitatively assess the heat losses to the environment, which are known to depend on the temperature of the object, a thermal imaging survey of the experimental setup was performed, the results of which are presented in Figure 2. The thermal imaging survey was carried out for a range of old and new rollers under the specified technological modes of the forming machine. The results presented in Figure 2 were obtained for the first time using thermal imaging with the Fluke Ti25 thermal imager.



a) b)

Figure 2. Thermal imaging of the roller working chamber: a) a new design of the roller; б) the conventional design of the roller

The results of temperature calculation of the rollers made of steel 08kp at injection are shown as the curves of cooling in fig. 3.

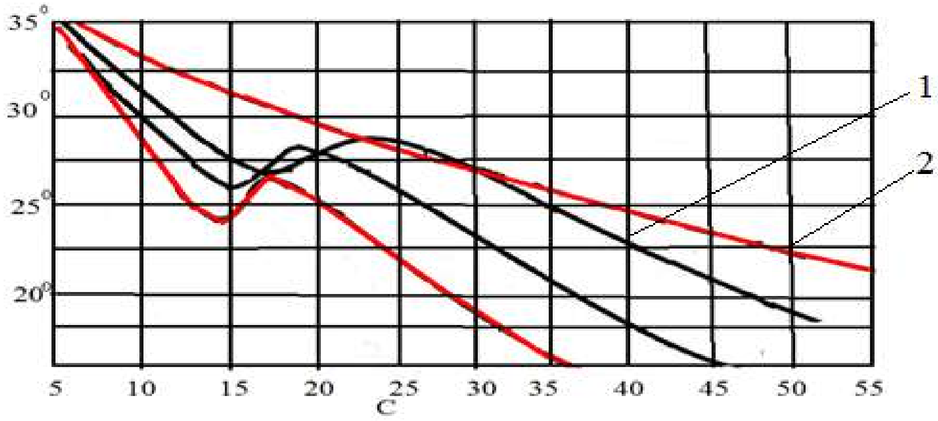


Figure 3. Change of temperature of the rollers' surface during the injection process

According to the process, the rollers were cooled naturally with calm air in the workshop. Starting from 18...27 c of the compression and injection process (curve -1), the cooling of the old design roller at calm air environment has a characteristic temperature increase on both the external and internal surfaces by 25...28°C. At the same time, the curves of the new roll have a smoother temperature transition with a better heat transfer to the environment. This process takes 5 seconds less to cool the roll to a temperature of 260°C for the new design, compared to 280°C for the old design. This phenomenon is caused by the heat release during the viscous flow of the environment and the friction of the roll surface. There is no additional heat release for new designs.

At the necessary resistance of deformation, the calculation of temperature is closely connected with the phase transformations in the environment. Such thermal-physical parameters as heat capacity c and heat transfer coefficient α define the accuracy of temperature prediction.

The change of temperature of the roller in the deformation and cooling area during an idling period has been calculated by the formula (8). The calculations have been made under the following injection conditions: temperature of the environment Te was 18^0C; the temperature of the dough was 28^0C; the thickness of the dough layer on the roller was assumed as 25…35 mm; the average velocity of the dough was 2.0 m/c, the density $\rho=1165kg/m^2$. The thermal-physical dependences of the bagel dough properties on the temperature are determined by the formulae λ(W/mK), c(J/kgK):

$$\lambda = 1.153(0.278 + 0.0045T)$$
$$C = 4167.4(0.58 + 0.0011T)$$

The temperature calculations have been made for two designs of the rollers at the specified technological parameters of injection (fig. 4).

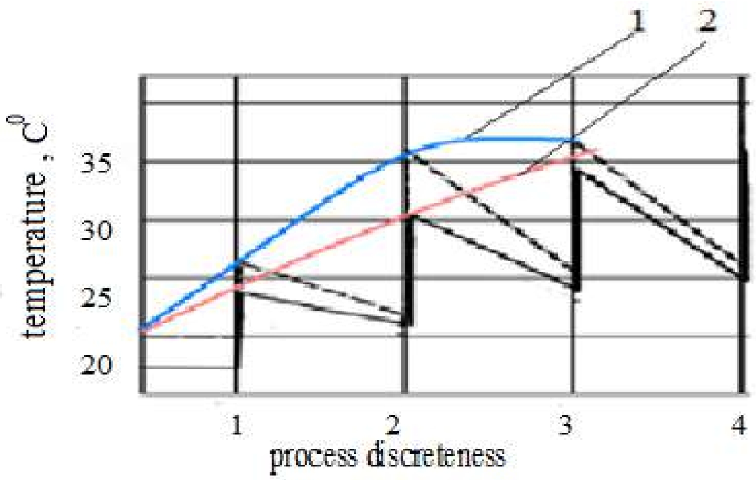


Figure 4. Impact of the injection stage on the temperature of the roller:
1 – for the old design; 2 – for the new one

In fig. 4 there are dependences showing thermal efficiency of rollers of old and new designs after each discrete injection. In the coordinate system these dependences look like straight lines with almost the same angle of inclination but with different values. We should admit some quite significant difference in efficient accumulation and transfer of the obtained temperature by the roller when interacting with the environment. Simultaneously, as we can see on the figure, after the third cycle of injection, the temperatures have the same values. It proves the temperature stability in further injection of the medium.

Having analyzed the above-mentioned results of measurements and calculations, we have made some general substantiations concerning the rotary rollers action on the environment:

– the temperature in the working environment in radial direction is increasing when approaching the working roller with a drop in $\left(4-7\right)\,°C$ at velocity u=(0.4-1) m/s and the relative radius of the medium on the roller and the roller itself $r_2/r_1 = 1,2$; this difference depends on the value of compression increase degree;

– the temperature in the working environment in the compression and injection section is practically changing by the angle of the roller rotation that proves its intensive transportation and partial mixing;

– the temperature of the roller body surface t_{dis} is distributed uniformly by the angle of its rotation, and when the injection pressure increases it is increasing linearly, and repeats the outlet temperature increase with the difference of approximately $7°C$;

– the temperature of the working environment and the roller surface in the axial direction is distributed uniformly in new designs. When determining the temperature in the axial direction any change hasn’t been observed.

Conclusions. Having considered the above-mentioned general substantiated actions of rotary rollers on the environment, we have come to the following conclusions:

- it is possible to intensify the process of injection by means of constant temperatures assurance;
- by means of contact interaction of the dough surfaces with a rotating roller due to heat exchange;
- the constructive implementation of the roller using the material with the heat-conductivity coefficient for maximum heat emission of the temperature to the environment.

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УДК 664.643

ОСОБЛИВОСТІ ТЕПЛООБМІНУ В ТІСТІ ПРИ ДІЇ ОБЕРТОВИХ ВАЛКІВ

Володимир Піддубний[1]; Людмила Каганець-Гаврилко[2]; Віктор Федорів[3]; Віктор Сенчишин[4]; Ігор Стадник[4]

[1]Київський національний торговельно-економічний університет, Київ, Україна
[2]Ужгородський торговельно-економічний фаховий коледж державного торговельно-економічного університету, Ужгород, Україна
[3]Подільський державний університет, Кам'янець-Подільський, Україна
[4]Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Вплив механічної дії на в’язке середовище сприяє формуванню об'ємної губчасто-сітчастої суцільної структури в глютеновий каркас, оскільки він визначає еластичні та пружні властивості середовища й актуальний при диспергуванні газу в рідині. Тому мета дослідження – було встановлення зв’язку між робочою поверхнею робочого органа та кількістю теплоти Q, що передається за одиницю часу від стінки валка до середовища. Вирішено задачу розроблення узагальненої моделі робочого процесу дії валків на середовище. Вона спрямована на отримання конструктивних, витратних та енергетичних характеристик і визначення шляхів підвищення ефективності роботи такого класу машин у деформаційних режимах.*

Розглянуто особливість ділянки стиснення, де величина температурного напору за кутом повороту весь час змінюється. Відзначено, що величина коефіцієнта тепловіддачі α *може бути визначена досить приблизно, оскільки необхідно враховувати наявність ділянки, що впливає на теплообмін та швидкість руху на поверхні валка робочого тіста у зоні нагнітання. Встановлено зміну температурного стану тіста при виробництві бубликів у процесі його стискання, нагнітання та транспортування. Відзначено, що плив температури рідинної фази робочого середовища* T_X *визначається величиною її кінематичної в’язкості* ν_X*. Визначення зміни температури виконано тепловізійною зйомкою дослідної установки.*

Аналіз наведених результатів вимірювань та обчислень встановив, що із різниці ефективного накопичення та віддачі отриманої температури валком при взаємодії з середовищем після третього циклу нагнітання температура має однакове значення. Це свідчить про стабільність температури в подальшому нагнітанні середовища. Також температура робочого середовища на ділянці стиснення й нагнітання практично змінюється за кутом повороту валка, що свідчить про її інтенсивне транспортування й часткове перемішування. При визначенні температури в осьовому напрямку не виявлено жодної її зміни.

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

https://doi.org/10.33108/visnyk_tntu2023.01.043 *Отримано 10.01.2023*