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МЕТОДИКА РОЗРАХУНКУ ОПТИМАЛЬНИХ ПАРАМЕТРІВ ПРОКАТКИ

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На підприємствах різних галузей промисловості ще в недостатній кількості використовуються машини з різними за конструкціями роликовими робочими органами, які в залежності від технологічного процесу виконують різноманітні операції. Такі машини потрібно удосконалювати особливо малогабаритні з керованими процесами, в яких основний процес проходить в робочій зоні. Попередньо проведений аналіз роботи певного класу машин показав недостатню їх продуктивність та якість готової продукції. Зазначена проблема показала сучасні тенденції в удосконаленні роликових робочих органів в машинах різних класів де за допомогою них проходять різні робочі процеси. Метою дослідження є розробка методу визначення та розподілу величини стиснення тістової заготовки в проміжку між вальцьовими робочими органами, з підвищенням якості продукції та опису даних процесів за допомогою математичної моделі. Проведено аналіз складності процесу нагнітання, недостатньої стабільності та надійності роботи; при нерівномірній подачі компонентів в робочу камеру. Крім того, на якість подачі валків впливає ряд інших факторів: фізико-механічні властивості сировини, режим роботи, недостатній імпульс зовнішніх сил при осьовому переміщенні, надмірна кількість робочих органів. Визначення руху середовища в проміжку між валками є однією з досить складних задач. Вирішення цих завдань можливе на основі ретельного вивчення суті процесу, що відбувається під час прокатки. Такий підхід дозволить визначити характер стадійного розподілу злипання тіста в проміжку між валками з урахуванням кута контакту. Таким чином, конструкція поверхні нового валка дозволила зменшити вплив на тісто і, таким чином, підвищити якість формування при тих же технологічних параметрах. При цьому зменшуються втрати сухих речовин і технологічний брак. Розроблена модель дозволяє визначити стисливість тіста при початкових і кінцевих значеннях в'язкості при заданих технологічних і конструктивних параметрах а проведений аналіз може бути основою для розробки інженерних методів проектування робочих органів для регулювання стабільності процесу.

Ключові слова: *трифазне середовище, валки, реологія, деформація зсуву, тісто, газова фаза.*

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METODS OF CALCULATION OF OPTIMAL PARAMETERS OF ROLLING

Enterprises in various industries are still using machines with different designs of roller working bodies, which, depending on the technological process, perform various operations. Such machines need to be improved, especially small-sized machines with controlled processes in which the main process takes place in the working area. A preliminary analysis of the operation of a certain class of machines showed insufficient productivity and quality of finished products. This problem has shown modern trends in the improvement of roller working bodies in machines of different classes where different work processes are carried out with their help. The aim of the study is to develop a method for determining and distributing the amount of compression of the dough piece in the gap between the roller working bodies, improving product quality and describing these processes using a mathematical model. The paper analyzes the complexity of the injection process, insufficient stability and reliability of operation; with uneven feeding of components into the working chamber. In addition, a number of other factors affect the quality of rolls feeding: physical and mechanical properties of raw materials, operating mode, insufficient impulse of external forces during axial movement, and an excessive number of working bodies. Determining the movement of the medium between the rolls is one of the most difficult tasks. The solution to these problems is possible on the basis of a thorough study of the essence of the process occurring during rolling. This approach will make it possible to determine the nature of the stage distribution of dough sticking together in the gap between the rolls, taking into account the contact angle. Thus, the surface design of the new roll made it possible to reduce the impact on the dough and thus improve the quality of forming with the same technological parameters. At the same time, dry matter losses and process rejects are reduced. The developed model makes it possible to determine the compressibility of the dough at the initial and final viscosity values at given technological and design parameters, and the analysis can be the basis for the development of engineering methods for designing working bodies to regulate the stability of the process.

Keywords: *three-phase medium, rollers, rheology, shift deformation, dough, gas phase.*

1. INTRODUCTION

Using machine tools with rollers is one of the main areas of rational technical support for product formation in various industries. A key aspect of optimizing technical support for product formation processes across various industries involves the use of machines equipped with roller working tools. Presently, there is not enough large variety of designs of roller working tools, which carry out a technological operation on injection, rolling, transportation of a viscous medium. Many of these machines require refinement and research in order to introduce new developments in their production. Special attention is placed on compact, efficient machines that feature controlled processes within the operating chamber. When creating or upgrading small machines with clearly defined roller working tools, it is crucial to focus on justifying the technological scheme and the corresponding constructive solving of taken decisions. Since the design parameters are interrelated with the process, it substantially affects the feasibility of producing such a machine in enterprises such, technological capabilities of which are focused on repair and restoration of equipment [1,2].

Machines designed to form viscous medium should influence it in such a way that the loss of raw materials and final products were minimum, but the quality of the products were high. This brings the necessity of ensuring that processing regimes, geometric shapes and structural parameters of working roller bodies complete correspond to structural and mechanical properties of a viscous medium[3,7]. The stated problem identified current trends in the design of roller working bodies in machines of different classes, where they carry out working processes: rolling, injection, kneading, transportation. The inventors constantly direct their calculations and designs on optimizing geometric profile and structural elements, use of pre-cast constructions, use of materials and coatings.

Drop of scientific developments behind the practical needs is explained by the various properties of technological environments' properties, variety of materials used for their transportation and the difference in their exploitation conditions of [2,3].

2. EXPERIMENTAL METHODS

Constructive parameters of the rollers have to ensure supply of dough for its alignment and redistribution of its volume mass by injection and transportation in the gap between them. The process of injecting dough with rollers may seem straightforward, but the mathematical model and basic dependencies calculations are quite complex. Now there are some solutions for this problem, based on simplification of the actual process and which do not take into account the influence of the elastic-viscous and plastic structure of dough and the way it acts on pressure fluctuations.

In general, the productivity of the injection unit (kg/s), that has roller working bodies of different diameters, which rotate at different speeds, can be determined by formula [3,4]:

$$П= \pi l\delta\rho(R_1n_1K_1 + R_2n_2K_2), \quad (1)$$

For the case of identical diameters of roller working bodies rotating at the same speed, the productivity is calculated as follows:

$$П= 2\pi l\delta n\rho K, \quad (2)$$

where 1 - the length of the feeder chain, m; b - gap width, m; R_1 and R_2 are the radii of rolls, m; n_1 and n_2 - frequency of their rotation, c^{-1}; $К_1$, $К_2$, - coefficients of feeding the dough, depending on the roll diameter and dough consistency. For the wheat flour dough of the 1-st and premium quality K is 0.7 at R = 0.15 m, with decreasing R - decreases; p - average density of dough, kg / m^3.

Due to the fact that pressure of dough on the roller working bodies is transmitted on the normal, considering working pressure prescribed and the diagrams of its change over the length of the working chamber, it is possible to determine the forces acting on them in the areas of feeding and rolling

$$P_n = 0{,}5P_pRl\alpha \quad (3)$$

$$P_n = 0{,}5P_pRl\beta \quad (4)$$

The moment on the roller working body is created by the action of the tangential forces Pп and Pн , which occur because of friction of dough on the roller and direct opposite to the rotation of rollers

$$M_n = 0{,}5P_pR^2l\tan\varphi \quad (5)$$

$$M_n = P_pR^2kl\tan\varphi \quad (6)$$

where φ is the angle of friction of the dough on the roll working body; for wheat flour dough, depending on the recipe and moisture content, it is 25-30 °; tgφ (varies from 0.47 to 0.57).

Since the roller working bodies are interconnected by gear transmission and rotate in different directions, their torques are folded. In our case, the resulting moment on the drive shaft (in N • m) is

$$M= P_pR^2l(\alpha + 2\beta)\tan\varphi \quad (7)$$

To perform these calculations, it is necessary to find rational constructional size of rolls, which correspond to the designed capacity for given kinds of dough. In present calculations, the effect of the tightening angle (contact) on the distribution of the density of the dough mass at the injection, that is, in the node zones, is not determined.

A dough with a moisture content of 33% was prepared for high-quality wheat flakes using pressed yeast. The dough was made through an opaque method with a fermentation period of 60 minutes at a temperature of 32-33°C. The quality of the pressed yeast met the standards specified by DSTU. The characteristics of the wheat flour used in the preparation are as follows:

- Moisture content (%): 14.5.
- Raw gluten content (%): 28.
- Gluten resistance to compression (IDK-1 device): 54 units.
- Gluten stretch (cm): 14.

Various structural schemes involving roller working bodies can be mathematically characterized using time-dependent continuous functions. These functions encompass geometric dimensions of the equipment, characteristics of the working rolls, and the physical and mechanical properties of the viscous medium, all of which are influenced by rolling conditions. Utilizing developed methodologies for describing the dough injection process in the gap between rolls, the hydrodynamic theory of pseudoplastic fluid calibration was applied. This theory facilitates establishing quantitative relationships between the material properties and the geometric features of the working space in different processing conditions [4].

Employing this theoretical framework, numerous formulas were derived to calculate the pressure within the roll gap, considering parameters such as medium viscosity. The experimentally determined dependencies are expressed using partial algebraic functions. To generalize these partial dependencies, the multifactor Protoediakonov function is utilized, which, when applied to chemical research results, provides accurate outcomes.

The characteristics of the dough with an indestructible structure were examined using the RV-8 device. Experiments were conducted under low shear forces, below the threshold shear stress. Deformation values, indicated by arrow deviations, were recorded every 10-20 seconds. By knowing the geometric characteristics of the device and the measurement data, the shear stress (τ') is calculated using the formula:

$$\tau^{'} = \tau - \tau_{\kappa} = \frac{(m - m_0) g R_{pul}}{2\pi R_{int}^2 \quad _{rol}}$$

where m is the load mass rotating the rotor, consisting of the masses of two weights and cups (excluding the value compensating for bearing friction); m_0 is the load mass at which the rotor begins to rotate, g is free fall acceleration, R_{pul} roll pulley radius, R_{int} internal swath radius, h_{rol} distance between rolls. Consequently, the plastic viscosity was determined according to Machihin U., 1991 [5]:

$$\mu_{пл} = (\tau - \tau^1) / \gamma$$

Formulation of the problem. Analysis of studying the dough injection and the performance of existing machines indicates the complexity of the process, insufficient stability and reliability of the work; the components are fed into the working chamber unevenly. In addition, a number of other factors influence the quality of injection of rolls: physical and mechanical properties of raw material, operation mode, excessive number of working bodies, the insufficient pulse of external forces in axial displacement, etc., because, the design, parameters of working bodies and kinematics of motion are not still sufficiently studied [6,7]. Therefore, despite a significant number of scientific achievements, development of new more promising constructive technical solutions of working bodies, working chambers with improvement of quality indicators of products based on the construction of a mathematical model remains an urgent problem.

In experiments, when compressing dough in a closed chamber, it shows the properties of elasticity largely because the gas phase and partly because of elastic protein skeleton. Determination of the effect of dough compression in the process of pouring justifies further technological processes and study of its properties. The compressibility of the yeast dough [6] is due to two reasons: the compressibility of gas bubbles and deformation of structural grid. In terms of rolling, it is unreasonable to talk about the decrease of distance between molecules of biopolymers in the dough, because it requires too high pressure. Accordingly, we note that the volume of semi-finished product is reduced only due to compression and subsequent dissolution of gas bubbles in the liquid phase of dough[8,9].

As we can see, determining the motion of the environment in the gap between rolls is one of rather complex. At the same time, it is a very important practical problem which is connected with the necessity of making various calculations of forming working rolls and determining their impact on the environment [10]. To solve such a kind of problems, it is necessary to involve algebra of logic and set theory, properties of medium, allowing to consider the layout as an ordered set of working units, and their various combinations as logical relations of elements of this set [11,12]. Solving these tasks is possible on the basis of thorough study the essence of the process that occurs during rolling. Such approach will allow us to determine the nature of stage distribution of dough join ability in the gap between the rotating rolls, taking into account the angle of contact [13,14].

The purpose of the article is to develop the method of determining and distributing the level of compression of dough in the gap between the roller working bodies.

3. RESULTS AND DISCUSSION

Study of works [1,2] showed that uneven velocity of the medium (yeast wheat cracknel dough) is caused by the nature of the flow. Therefore, a significant factor of increasing the effectiveness of the intensive action of rolls on the environment is even rolling out of its elementary amounts that come from the working chamber of machine. Proceeding from the assumptions that specific supply of the medium is the same for all elementary volumes of the mass in the gap between the rolls, the viscosity remains constant and it has been taken into account in the calculations.

Consider the process of dough rolling between rollers. The regularity of changing the thickness of dough layer during the rolling between the rolls is shown in Fig.1. When cylindrical rollers are used, the thickness of the dough sheet continuously changes in the central region, known as the clogging zone. However, at the exit from the rollers, the thickness remains uniform. Throughout all rolling cycles on the curved surface, the gap in the central part of the rollers remains unchanged from one capture to the next. This ensures the compression and displacement of the dough during the rolling process, resulting in a uniform thickness across the entire sheet. The rollers, which have identical diameters, rotate at the same angular velocity (ω) with radius (R) and length (L).

When forming the material, its deformation passes through the surfaces of the rolls. The deformation process consists in obtaining the effect of compression and stretching. In general, the deformation data is shown in Fig. 1. According to Fig. 1, modeling of acting forces on the material was carried out. In this case, the force of the pressure action, which depends on the angle φ. Angle φ constrains the passage of material between the rotating rolls.

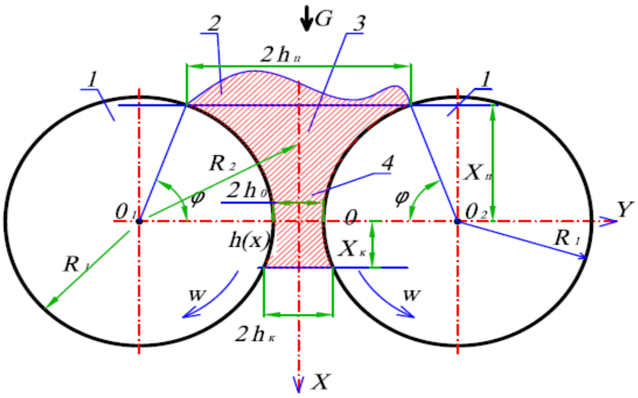

Fig. 1. **Scheme of dough movement in the vertical gap between the rolls: 1 – rolls;2 – dough; 3, 4 - the opposite zone and the direct zone of the joint flow.**

The most critical factor is the pressure component. Considering the design specifics of the injection site, the mathematical model of the process can be represented as follows [6]:

$$P=\frac{2\mu}{R}\int\frac{\left(Q-\dfrac{\omega Rh}{2}\right)d\varphi}{(R+h)\left[\ln\left(1+\dfrac{h}{R}\right)-\dfrac{h}{2}\left(\dfrac{1}{R}+\dfrac{1}{R+h}\right)\right]}+C_3$$

where R-radius of the roller working body, mm; h-gap size, mm; Q- rate of flow of dough, kg / s; µ - viscosity.

If $P(\varphi=0)=P_0$, then: $P_0=\frac{2\mu}{R}\int\Big|_{\varphi=0}+C_3\Rightarrow C_3=P_0-\frac{2\mu}{R}\int\Big|_{\varphi=0}$

$$P(\varphi)=P_0\frac{2\mu}{R}\int_0^{\varphi}\frac{\left(Q-\dfrac{\omega Rh}{2}\right)d\varphi}{(R+h)\left[\ln\left(1+\dfrac{h}{R}\right)-\dfrac{h}{2}\left(\dfrac{1}{R}+\dfrac{1}{R+h}\right)\right]}$$

Let's introduce the designation:

$$I_k(\varphi)=\int_0^{\varphi}\frac{h^k d\varphi}{(R+h)\left[\ln\left(1+\frac{h}{R}\right)-\frac{h}{2}\left(\frac{1}{R}+\frac{1}{R+h}\right)\right]} \qquad k=0{,}1$$

$$I_1(\varphi)=\int_0^{\varphi}\frac{h^k d\varphi}{(R+h)\left[\ln\left(1+\frac{h}{R}\right)-\frac{h}{2}\left(\frac{1}{R}+\frac{1}{R+h}\right)\right]}$$

Then: $P(\varphi)=P_0+\frac{2\mu}{R}\left(QI_0(\varphi)-\frac{\omega R}{2}I_1(\varphi)\right)$

We eliminate the variable Q from the conditions that the pressure distribution is a periodic function of the angle φ, , φ, that is: $P(\varphi+2\pi)=P(\varphi)$

in a partial case $\varphi\left(\frac{\pi}{2}\right)=P(0)=P_0$, therefore:

$$P=P_0+\frac{2\mu}{R}\left[QI_0\left(\frac{\pi}{2}\right)-\frac{\omega R}{2}I_1\left(\frac{\pi}{2}\right)\right] \qquad (8)$$

From the equation it is seen that the size of the daugh placement (angle of the surface of feeding the mass on the roll) vastly determines the value of pressure. Function P (φ) depends on angle, and not on time, that is why, the derivatives are not the characteristics of speed and acceleration of the sealing process. We introduce additional functions that reveal the discreteness of the injection process:

$$F(\varphi)=\ln\left(1+\frac{h}{R_2\cdot\sin(\varphi)}\right)-\frac{h}{2}\cdot\left(\frac{1}{R_2\cdot\sin(\varphi)}+\frac{1}{R_2}\right)$$

$$L(\varphi)=Q-\omega\cdot R_2\cdot\sin(\varphi)\cdot\frac{h}{2}$$

Taking into account our data and using (8) the graph of Fig. 2 was drawn.

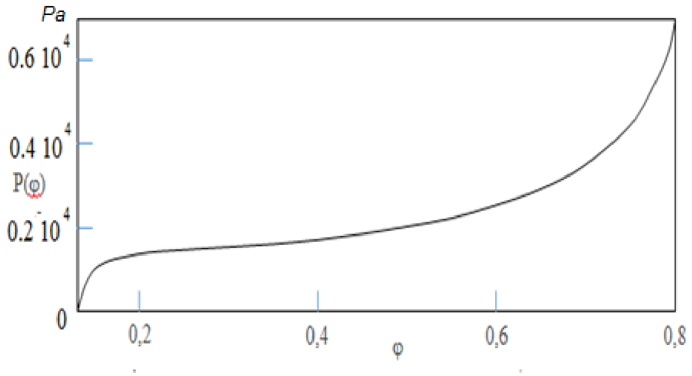

Fig. 2. **Diagrams of the pressure value versus the angle of the dough piece φ. P- pressure value, φ- the value of the gripping angle**

As you can see, the function P (φ) is defined for the angle φ from 0,1277 to 0,8034 rad. It is characterized by three sections, depending on the angle φ (Fig. 2). The first section (the beginning of the process) φ from 0.8034 to 0.65 radians (process of feeding and sealing). It is characterized by a decrease in P (φ) from 0.705.104 to 0.229.104. In this case, there is a nonlinear decrease in the derivative $\frac{dP(\varphi)}{d\varphi}$ and nonlinear decrease of the second derivative $\frac{d^2P(\varphi)}{d\varphi^2}$ to 0. The second section indicates stabilization of the process where φ is from 0.65 to 0.24 radians. It also characterizes a partial decrease of P from $0.229\cdot10^4$ to $0.145\cdot10^4$. Accordingly, there is a linear decrease in the derivative $\frac{dP(\varphi)}{d\varphi}$ nd the second derivative $\frac{d^2P(\varphi)}{d\varphi^2}$ = =0 (or indefinite). The third section at φ from 0.24 to 0.1277 radians: the function P (φ) decreases from

0.145.104 to 0; nonlinear increase of the derivative $\frac{dP(\varphi)}{d\varphi}$; nonlinear decrease of the second derivative $\frac{d^2P(\varphi)}{d\varphi^2}$ from 0.

From the above-stated justified influence of the interaction of a roll and dough it follows that the optimum elasticity of the dough essentially depends on the ratio of the given values of compression between them. Very insignificantly it depends on the ambient temperature in the temperature range from 20° C to 35^0 C. Given the fact that there is a change in compression of dough with deviation, and accordingly, its structural and mechanical properties, using the mathematical model (8), we determined the effect of the optimal level of compression of the dough on the structure of the finished product. In this case, the experimental data on changes in the viscosity values relative to the velocity of tensile angle of dough were used [15]. It is stated that this dimension varies in small values, so for the dough viscosity at the beginning of discrete action of the rolls, the changes are slight. Thus, the design of the surface of a new roll has allowed to reduce the impact on the dough and, in the same way, to improve the quality of the forming with the same technological parameters. At the same time, losses of dry substances and technological shortage decrease. Graphic dependence of the optimum compression degree of the dough on the ratio of the given values of change in viscosity with the course of the angle of tightening is shown on Fig. 3. At the same time, change of structure of the finished crackles according to discretion of the injection process, due to the developed method is reflected.

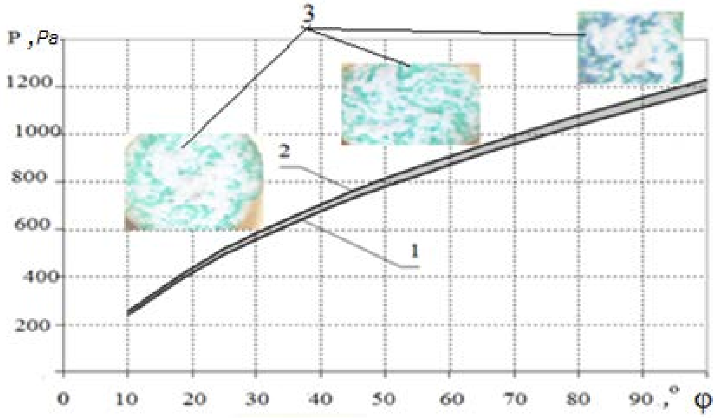

Fig. 3. **Phases of dough structure depending on the pressure P and stretching φ angle of the dough for compression during injection in the second section: 1 - compression after many stretching cycles; 2 - compression at the beginning of stretching; 3 - structure of the finished cracker.**

From the graphic dependence (Fig. 3) it follows that compression of the mass of dough occurs at gradually changing pressure. This value varies in small values and it is insignificant for viscosity of dough at the beginning of discrete action of the rollers. This is evident on the structure of cracknel. Thus, the new roll's surface design has allowed to reduce the impact on dough and, in the same way, to improve the quality of forming with the same technological parameters. At the same time, losses of dry substances and technological shortage decrease.

4. CONCLUSIONS

The main purpose of this study is to develop a method for determining and distributing the amount of compression of the dough piece between the rolling working bodies, improving product quality and describing these processes using a mathematical model. The analysis showed that the injection process is complex, with insufficient stability and reliability of operation due to uneven feeding of components into the working chamber.

The physical and mechanical properties of the raw material, the operating mode, insufficient impulse of external forces during axial movement and an excessive number of working bodies affect the quality of roll feeding. One of the most challenging tasks is to determine the movement of the medium between the rolls. A thorough study of the rolling process made it possible to determine the nature of the stage distribution of dough sticking in the gap between the rolls, taking into account the contact angle. The surface design of the new roll reduces the impact on the dough and improves the quality of moulding under the same process parameters, which reduces dry matter losses and process rejects.

The developed mathematical model allows to determine the compressibility of the dough at the initial and final viscosity values according to the specified technological and design parameters. The analysis can be the basis for the development of engineering methods for designing working bodies to regulate the stability of the process.

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