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MODELLING THE FORMATION OF PHASE CONTACT BETWEEN COMPONENTS DURING THE MIXING PROCESS ON A NEW DOUGH MIXER

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Abstract. *The article is deals with solving the problems of energy and resource saving in the bakery, pharmaceutical and processing industries by introducing a weighted mixing state taking into account the stage-by-stage process of forming a viscoelastic-plastic medium. The main objective of the study was to determine the optimal dough mixing parameters to achieve the desired rheological properties. Using the experimental data, effective design solutions were developed that ensure stable dough quality and increase production output. It is noted that the study of mixing components in the bakery industry of Ukraine using batch and continuous machines is one of the most important technological operations and the pace of its development towards improving the design and technological parameters of the machine and process to improve the quality of the mixture structure remains relevant. Scientifically sound and adequate mathematical models have been developed to improve the design of the mixer. The modelling of the interface in the presence of free surfaces of components during mixing in a suspended state is carried out. A step-by-step method for determining the intensity of formation of phase contact surfaces and their renewal is proposed. An analysis of the interaction of components under the established influence of the mixer design has been carried out, which made it possible to further reveal ways to calculate the design parameters of means for their dosing and mixing, depending on the nature of the phases in each case. It is noted that the influence of the surface layer of the phase on its total flow rate is determined by the specific energy. It is shown that the process is governed by the equations of turbulence quantity (k) and turbulence dissipation (ε). The presented models consider the interaction between flour particles and the liquid phase in a turbulent medium and their influence on the flow characteristics. The step-by-step interaction of the components in contact with each other to improve the intensification of the mixing process is theoretically and experimentally substantiated. The value of the surface energy and the value of the surface tension and particle energy, which depend in each case on the nature of the process phases, are generalised.*

Key words: *mixing, turbulence, turbulence dissipation, liquid components, stream, phase, specific surface area.*

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1. INTRODUCTION

Mixing of components is widely used in food, processing, agricultural production, pharmacy and other industries. Global experience shows that the mechanical action of various designs of working bodies is now considered one of the most progressive measures to save costs for preparing a homogeneous mixture of components. Implementation of the principles of rational mixing is a key area of technology development, especially in the context of creating a new generation of machines with a simple design and appropriate parameters.

In modern bakery production, considerable attention is paid to improving technological processes to increase productivity and quality of the final product. One of the key stages of production is the preparation of dough for in-line production lines. Traditional methods of batch dough preparation are not able to ensure consistent dough quality at high production volumes, which necessitates the introduction of continuous dough preparation technologies, whose main objective is to ensure consistent product quality through continuous kneading.

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Therefore, it is important to consider this process as a complex, multifactorial one, given its stochastic nature and the need for physical research and mathematical modelling. Developing machines with a simple design is an important aspect, as it contributes to efficiency and reduces production costs. After all, simplified design makes it easier to control the mixing process, which ensures a more accurate and efficient result.

One of the important advantages of a mixer should be the ability not only to ensure volumetric mixing of the components, but also to smooth out changes in the concentration of the resulting mixture due to uneven loading. In particular, in the first minutes of the process for mixing liquid components with flour.

In practice, various mixer designs are widely used in various technological processes. However, the intensity of the mixing process and their ability to equalise the concentration of components over time are insignificant. For example, when using spiral working bodies, the temperature partially increases, which affects the technological process when forming the structure of the mixture. In addition, such mixers increase energy consumption due to the high specific process operation.

Improvement of these quality characteristics is achieved by improving the design of mixers, choosing the optimal modes of their operation, which is ensured, in particular, by developing their adequate mathematical models. Thus, the difference between the new machines, as noted by the authors of [1, 2], is based on the construction of its simple design with appropriate parameters that would reflect the essence of the process of mixing, mixing and kneading a viscoplastic material without changing its rheology. The use of fluidisation allows to obtain a medium with a uniform distribution of components throughout the volume of the working chamber when the forming layers interact. Taking these parameters into account helps to optimise and control the processes, ensuring the high quality of the resulting structure of the mixed components.

It is during mixing that the structural and structural-mechanical properties of the product are formed. This process can take place under the influence of mechanical stress and as a result of other phenomena that create conditions for the interaction of components with subsequent phase transformation and structure formation. The degree of their dispersion and the nature of their subsequent properties depend on the processing modes of the components. The authors of [3] note that special devices with various designs of stirrers are most widely used, which are designed specifically to create conditions for qualitative effects on components.

Other mixing processes [3, 4] include equipment that transports and pumps components, namely: a pump, pipelines through which the liquid passes, transporting screw mechanisms; spontaneous passage of the process, i.e. static mixing without the participation of mechanical devices. The process of spontaneous passage occurs as a result of diffusion of components, or forced as a result of energy supply from the outside, for example, by means of heat carriers, or by creating a flow heterogeneity. This creates the basis for the formation of the product structure in a static and dynamic state.

Therefore, when developing technological equipment for mixing and stirring, the basic principle is based on the types of working chambers and working bodies. There is a fairly wide range of different machine models that have been developed and are well known in the national economy.

The authors point out [3] that the use of the fluidisation process proves to be an effective method of obtaining a medium with a uniform distribution of components. In their research, they revealed the interaction of the forming layers when creating optimal conditions for mixing the material. The authors of [5] also consider the process as multifactorial and taking into account its stochastic nature, which requires the integration of various parameters and factors. After all, modern technologies allow the use of artificial intelligence and machine learning algorithms to optimise processes and predict results. Detailed research allows for a better understanding of the process and its optimisation, and mathematical models become the basis for forecasting and improving efficiency.

The creation of physical and mathematical models for the development of modern process control systems in dispersed systems is a critical task in scientific and industrial terms. Over the past decades, a significant number of models of transport processes in dispersed systems have been developed. The use of two-phase flow models stands out because of its advantages, especially the lack of the need for empirical parameters.

The process of modelling the mixing of components, as noted by the authors of [6, 7], can be carried out using different approaches and methods. These are empirical, statistical, analysis of the structure of component flows, mechanics of continuous media, and entropy-information. Mathematical models of mixing are common: cellular, ideal displacement and ideal mixing, diffusion and combined [8], as well as the method of discrete elements [9, 10].

Review of recent research and findings. The majority of Ukrainian continuous wheat dough production schemes use the A2-KHTT continuous kneading machine. When preparing and organising production in one or two shifts, it is very important to choose a technological process for dough preparation. To reduce the duration of the dough preparation process, one way is to use intensive mechanical processing of the dough and create new high-speed dough mixers that help reduce the process time. The authors of [11, 12, 13] proposed ways to modernise the A2-KHTT dough mixer, where four brake blades are hinged on the side of the cylindrical kneading chamber, which makes it possible to adjust their working surface. The new kneading body is made in the form of a helical strip with a profile similar to the cross-section of a dolphin fin with an angle of attack of 32...35° (Fig. 1).

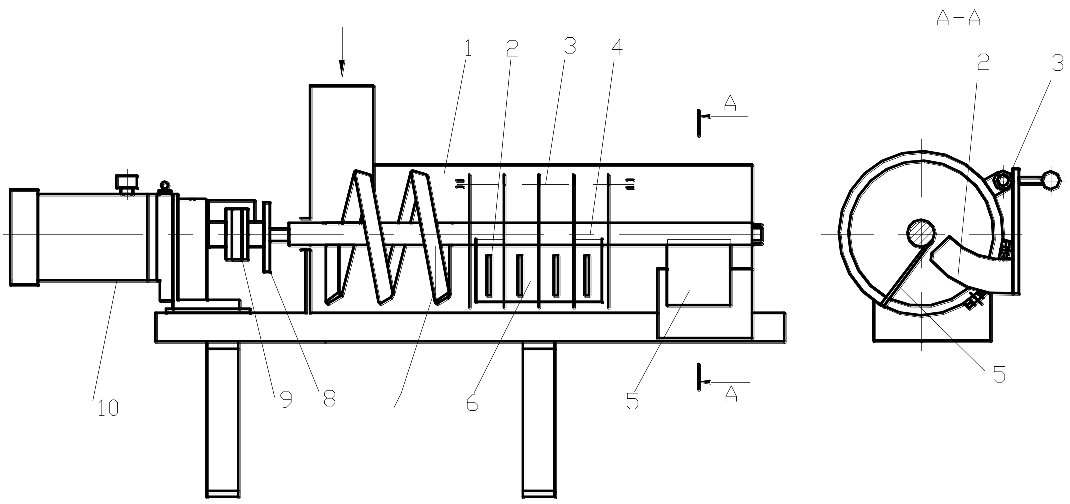

Figure 1. General view of the experimental kneading machine A2-KTT: 1 – kneading chamber; 2 – brake blades; 3 – hinge; 4 – shaft; 5 – scraper; 6 – plasticising discs; 7 – kneading blade; 8 – eccentric; 9 – connector; 10 – gear motor

The obtained data showed the quality indicators of bread due to a reduction in dough preparation time by 60 s and a reduction in fermentation time by 15–18%. I. YA. Stadnyk believes that this was achieved by intensifying the process of kneading dough from wheat flour using a new screw kneading body and regulating brake blades in the kneading machine, which leads to a reduction in the consumption of flour solids during fermentation, a reduction in the production cycle of dough preparation, and a reduction in energy and material consumption [14].

The latest works and research by foreign scientists focus on the introduction of innovative technologies for continuous mixing and kneading of dough, which can significantly increase production efficiency and improve the characteristics of bakery products. Diosna company is actively introducing new technologies for continuous dough mixing, in particular through its Continomixx system. This system provides a capacity of up to 1200 kg/h and includes a CPM 1200 mixer, a CFM 1.350 kneader, Brabender dosing systems and a Seepex pump for dough recirculation. A special feature of the system is the precise dosing of ingredients via PLC, which allows for easy adjustment of recipes during operation, ensuring high efficiency and consistent dough quality.

The Australian researcher Cheio De Oliveira [15] describes a machine for continuous kneading of dough for bakery products such as sandwich bread. It has a tubular chamber with two sub-chambers, in which the dough is moved and kneaded by two rotating shafts. The outlet pre-chamber is equipped with negative pressure facilities, which allows for kneading under vacuum. This improves the quality of the dough and allows for high production rates.

Based on a number of other works and research by foreign scientists, design engineer I. Kovalenko focused his search on the rational and effective impact of the working body and working chamber on the components. The main goal was the efficiency of energy transfer to the processed mixture and the possibility of automatic control of its operation.

2. EXPERIMENTAL METHODS

The objective of this paper is to analyse the design parameters of the developed machine design and to model the process of interaction between components.

A schematic diagram of the physical model of a continuous kneading machine is shown in Fig. 2. It includes: 1. pre-kneading chamber; 2. final kneading chamber; 3. kneading body; 4. control panel. To control the quality of the structure formation process, the following units are used: a temperature sensor for continuous measurement of the dough; an R/S rheometer for analysing the rheological properties of the dough; and an ADS60G moisture meter (AXIS) for determining moisture content.

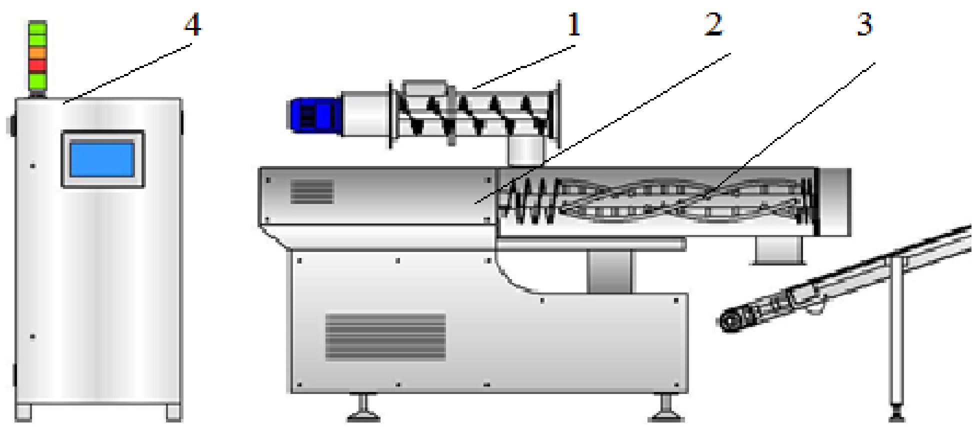

Figure 2. Physical model of a continuous kneading machine

In the pre-mixing stage, the flour and liquid recipe ingredients are fed into the pre-mixing chamber 1 (premixer), where they are evenly mixed with the liquid phase. The premixer ensures efficient initial mixing, which is critical for the formation of the gluten network in gluten. The mixture is then fed into the final kneading chamber. In the final kneading chamber 2, the kneading body 3 performs mechanical work at a given rotational speed (Fig. 3).

Figure 3. Dough kneading in the final kneading chamber

3. RESULTS AND DISCUSSION

In the course of the study, a series of dough mixing experiments and mathematical modelling were carried out to determine the optimal design of the working body of a continuous kneading machine. When creating a model for the implementation of two-phase flow, the physical aspects of phase interaction and heat transfer were taken into account, which is important in practical applications. Therefore, the implementation of a two-phase flow of a medium involves the inclusion of a continuum equation for each phase, taking into account their interaction based on the difference in physical properties. The effects of turbulence in the areas of mixing of the two phases are also taken into account. The use of turbulence equations, such as the turbulence number equation (k-epsilon) or the RANS (Reynolds-Averaged Navier-Stokes) equation, helps to determine the properties of a turbulent two-phase flow. In the research, a simpler variant was chosen, the k-epsilon turbulence model for two-phase flow, which can be modified to account for turbulence in both phases. The simplified approach takes into account the interaction between different phases and the unique properties of each phase.

Given the complexity of the research, we conducted a prediction of the two-phase flow behavior. In the turbulent kinetic energy (k) equation for the two-phase flow modification, an additional term was added that accounts for the interaction between the phases:

$$\frac{\partial(\rho_k)}{\partial t} + Uj\frac{\partial(\rho_k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon + \rho\varepsilon_1 + \emptyset_k \qquad (1)$$

Where ϕ_k is an additional term that accounts for the interaction between the phases in the turbulent kinetic energy model.

Similarly, an additional term is introduced to modify the turbulence dissipation equation to account for the interaction between phases:

$$\frac{\partial(\rho_\varepsilon)}{\partial t} + Uj\frac{\partial(\rho_\varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + \emptyset_\varepsilon \qquad (2)$$

Where ϕ_ε is an additional term that accounts for the interaction between the phases in the turbulent dissipation rate model.

Left-hand side (1): $\frac{\partial(\rho_\varepsilon)}{\partial t}$ is partial derivative of turbulent kinetic energy with respect to time.

$Uj\frac{\partial(\rho_\varepsilon)}{\partial x_j}$ is convective term, reflecting the transport of turbulence relative to the coordinate axes.

Right-hand side (1): $\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right]$is diffusive term, reflecting the diffusion of turbulent kinetic energy through space.

$C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + \emptyset_\varepsilon k$ are other additional terms that include the interaction between turbulent phases.

Left-hand side (2): $\frac{\partial(\rho_\varepsilon)}{\partial t}$ is partial derivative of turbulent dissipation rate with respect to time.

$Uj\frac{\partial(\rho_k)}{\partial x_j}$ is convective term, reflecting the transport of turbulent dissipation rate relative to the coordinate axes.

Right-hand side (2): $\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right]$ is diffusive term, reflecting the diffusion of turbulent dissipation rate through space.

$C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + \emptyset_\varepsilon$ are other additional terms that include the interaction between turbulent phases.

Thus, in both equations, the left-hand side reflects changes in time and space, while the right-hand side includes diffusion and other additional terms that describe the physical processes occurring in the system, such as the diffusion of turbulence and its interaction with the phases. In this case, it can be imagined that hygroscopic flour "absorbs" the liquid phase, which resembles the process of turbulence diffusion in turbulent flow equations. Therefore, if we consider the turbulence equations through the lens of hygroscopic materials, we can view the right-hand side of the equation, which is responsible for the diffusion of turbulence, as a process of absorption or uptake of turbulent energy by the material.

Therefore, the process of absorption or uptake of turbulent energy by a flour particle can be envisioned as a way in which the energy of the turbulent flow is transferred to the particle itself. This process influences the distribution of turbulent energy in the system, which is important for understanding and modeling turbulent flows in technological processes.

Since the particle absorbs energy from the turbulent flow at the initial stage of mixture formation, we model the process by including an additional term that accounts for the effect of energy absorption in the particle's equation of motion within the final kneading chamber.

A simple model of particle motion has the following form:

$$m\frac{dv}{dt} = Fdrag + Fturb,$$

where *m* is the mass of the particle;
v is the velocity of the particle;
t is time;
Fdrag is the drag force (e.g., friction);
Fturb is the force produced by the turbulent flow.

To model energy absorption, we add an additional term to this equation that accounts for the change in the particle's energy due to the absorption of turbulent energy:

$$m\frac{dv}{dt} = Fdrag + Fturb + \alpha\frac{dEturb}{dt}, \quad (3)$$

where α is the coefficient of turbulent energy absorption;
Eturb is the energy of turbulent flow.
Model (3) allows to take into account the effect of turbulent energy absorption on the movement of a flour particle in a turbulent flow of the new design of the operating tool.

For more accurate modeling, numerical analysis methods can be used, such as finite element methods or computational fluid dynamics methods. The authors [15, 16] used the relationships between the liquid flow velocity and the particle diameter at different layer porosities in their studies. They noted that the drag force of the medium does not affect the flow turbulence but allows achieving the appropriate mixing state. Many studies confirm that within the micro-volumes of the mass being mixed, there can be an infinite variety of mutual arrangements of the component particles. Therefore, the authors [15, 17] note that the ratio of components at the points of the mixture is a random variable, and therefore, methods for assessing its quality should be statistical.

The general equation for the amount of turbulence k, taking into account the absorption of turbulent energy, is as follows:

$$\frac{\partial(\rho_k)}{\partial t} + Uj\frac{\partial(\rho_k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] - \alpha_k k + P_k - \rho\varepsilon + \rho\varepsilon_1 + \emptyset_k, \quad (4)$$

where α_k – turbulent energy absorption coefficient;
ρ_k – amount of turbulence;
Uj – velocity components;
μ – dynamic viscosity;
μ_t – turbulent viscosity;
σ_k – model coefficient;
P_k – urbulent energy generation time;
ρε and $\rho\varepsilon_1$ – factors related to turbulence dissipation;
ϕ_k – other factors that take into account the interaction between phases.

Equation (4) takes into account both diffusion processes and turbulent energy absorption, which affect the amount of turbulence k in the system.

The general equation for the turbulence dissipation ε, taking into account the turbulent energy absorption, is as follows:

$$\frac{\partial(\rho_\varepsilon)}{\partial t} + Uj\frac{\partial(\rho_\varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - \alpha_\varepsilon\varepsilon + \emptyset_\varepsilon, \quad (5)$$

where ρ_ε – turbulence dissipation;
σ_ε – model coefficient;
$C_{1\varepsilon}$ and $C_{2\varepsilon}$ – model constants;
k – turbulence amount;
ρ – density;
α_ε – turbulent energy absorption coefficient;
ϕ_ε – other factors that take into account the interaction between phases.

Equation (5) takes into account various physical processes, such as diffusion, dissipation of turbulent energy, velocity, and absorption of turbulent energy by particles or the medium. In expressions (4,5), there is an additional term ϕ_k and ϕ_ε.

4. CONCLUSIONS

The obtained theoretical and experimental results of mixing components in a new machine allowed us to consider the effect of changing technological parameters on the area of interaction in the uniform distribution of recipe components. The equation of turbulence quantity (k) and the equation of turbulence dissipation (ε) in the modelling of turbulent flow are analysed. The concept of turbulence intensity and the size of turbulent vortices in creating favourable conditions for the formation of the structure of mixed components is revealed. It is established that the design of the working body has a partial effect on the interaction of components and determines the time of mixture formation. Consideration of the process of hydration and heat transfer, taking into account the movement of phases on their surface interaction, noted the formation of an additional dissipative energy flow.

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УДК 621.646.1

МОДЕЛЮВАННЯ УТВОРЕННЯ ФАЗОВОГО КОНТАКТУ КОМПОНЕНТІВ ПРИ ЗМІШУВАННІ НА НОВІЙ ТІСТОМІСИЛЬНІЙ МАШИНІ

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Резюме. *Присвячено розв’язанню проблем енерго- та ресурсозбереження в хлібопекарській, фармацевтичній та переробній промисловості за рахунок упровадження зваженого стану змішування з урахуванням стадійності процесу утворення в’язко-пружно-пластичного середовища. Основна мета дослідження полягала у визначенні оптимальних параметрів замішування тіста для досягнення бажаних реологічних властивостей. Використовуючи експериментальні дані, розроблено ефективні конструктивні рішення, які забезпечують стабільну якість тіста та підвищують продуктивність виробництва. Відзначено, що дослідження змішування компонентів у хлібопекарській промисловості України на машинах періодичної та безперервної дії є однією з найважливіших технологічних операцій і темп її розвитку в бік удосконалення конструктивно-технологічних параметрів машини та процесу для поліпшення якості структуроутворення суміші, залишається актуальним. Розроблено науково обґрунтовані й адекватні математичні моделі для вдосконалення конструкції змішувача. Проведено моделювання границі розділу фаз за наявності вільних поверхонь компонентів при змішуванні у зваженому стані. Запропоновано покроковий шлях визначення інтенсивності утворення поверхонь фазового контакту та їх обновлення. Наведено аналіз взаємодії компонентів при встановленому впливі конструкції змішувача, що дозволив у подальшому розкрити шляхи проведення розрахунку конструктивних параметрів засобів для їх дозування і змішування залежно від природи фаз у кожному випадку. Відзначено, що плив поверхневого шару фази на її загальні витрати визначається питомою енергією. Показано, що процесу служать рівняння кількості турбулентності (k) та дисипації турбулентності (ε). Приведені моделі розглядають взаємодію між частинками борошна та рідкою фазою у турбулентному середовищі та їх вплив на характеристики потоку. Теоретично й експериментально обґрунтовано покрокову взаємодію компонентів при їх контакті на вдосконалення інтенсифікації процесу змішування. Узагальнено величину поверхневої енергії та величину поверхневого натягу й енергії частинки, що залежать у кожному випадку від природи фаз процесу.*

Ключові слова: *змішування, турбулентність, дисипація турбулентності, рідкі компоненти, струмінь, фаза, питома поверхня.*

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