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Innovative thermodynamic modeling for enhanced yeast dough mixing: energy perspectives and applications

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ABSTRACT

A thermodynamic model for the calculation of energy exchange in the chamber of a new mixer with effective use of structural and technological parameters of the mixing process without the necessary introduction of experimental data correlations in the distribution of fluid velocities is proposed, which determines the relevance of this direction of calculation with the perspective of its development. The purpose of the presented work is to determine the specific power by substantiating the effective mode parameters of the preparation of the mixture (dough) as a result of evaluating the thermodynamic energy parameters of the kneading process. The assessment was carried out by developing a methodology for determining specific costs for creating a viscous medium when mixing components, which allows you to establish the required power depending on the design and technological parameters of the new mixer. The considered principle of the proposed open-type thermodynamic system of the description of the working process of mixing made it possible to reveal and determine the ways of converting energy into useful work of interphase heat and mass transfer of a heterogeneous medium. In the conditions of circulation mixing with multiple mechanical effects on the mixture of components in the closed circuit of the cylindrical working chamber, which is an effective way to achieve homogeneity of the environment, it was possible to obtain an analytical determination of the specific work and power of the drive in the absence of a clear description of the model of the interconnection of components. The proposed thermodynamic description of the system's energy balance allows to perform only a few experiments. In general, the practical value of the given calculations is of practical importance for improving productivity and efficiency and minimizing energy consumption for the process while reducing the dynamic loads of the designed mixer.

Keywords: components, financing, specific costs, specific identity, thermodynamic model, energy balance, investment

INTRODUCTION

High-quality forming mixtures during mixing in the sectors of the national economy is an extremely important task, as it can affect the safety and efficiency of products and the overall success of enterprises in these sectors. After all, in the conditions of a market economy, using modern equipment with accurate regulation and control systems can significantly reduce losses and improve mixing quality. This may include measuring temperature, humidity, pH, and concentration of ingredients to establish the correct mixing parameters. It is important to choose the right parameters, such as speed, time, temperature, and pressure. These directions can be used in the food and pharmaceutical industries to improve energy consumption in mixing processes and ensure high product quality.

According to conventional fuel, the energy intensity of Ukraine is 2.6 times higher than a relatively similar indicator of the industrial development of the world's countries. The data are reflected in the National Development of Industry program **[1]**, **[2]**. Priority areas include the introduction of resource- and energy-saving technologies. In addition, there remains an important direction of mastering the production of the latest technological equipment. Thus, there is practicality in continuing the search and innovation in implementing the mentioned State Program.

One of the ways to reduce production costs is the economical use of thermal and electrical energy per unit of finished products. To achieve a reduction in energy consumption, it is necessary at each stage of the production process to study how much energy the material flows can provide, how much energy is needed to make the necessary changes in these material flows, and how to minimize the loss of thermal energy and energy associated with chemical processes.

An analytical review of scientific works confirms the existence of ways to increase the efficiency of producing quality products and the main laws of improving technological processes **[3]**. This may result from Ukrainian and foreign researchers' work in production and product quality. Mechanical mixing is an important and reliable process that plays a vital role in food production due to its simplicity and versatility.

In addition, it is important to conduct a market analysis and compare different equipment models, considering their technical characteristics, cost, reliability, and warranty conditions. After that, you can make an informed choice that will meet the needs of the enterprise and help achieve the desired results. A wide selection of different types and designs of mixing devices allows you to choose the best option for a specific task and product. According to the authors **[4]**, these characteristics of working bodies make them universal tools for many processes in industry and research. They are used in various industries, including the food, pharmaceutical, chemical, and cosmetic industries, and in laboratory research to solve various tasks related to mixing and homogenization.

An analysis of publications on parameters and characteristics of mechanical mixing using vibratory mixers indicates the importance of further research in this direction. Today, there is no clear theoretical explanation for the required amount of energy to make the necessary changes in material flows in the connection between the main parameters and mixing characteristics **[5]**.

Therefore, creating discrete-impulse influence, pressure pulsations, and liquid flow rate for the development of turbulence in local volumes of flow in the working chamber of the machine is an interesting approach for the modernization and improvement of mixing processes. However, it is also important to consider this approach's potential challenges and limitations, including process stability, equipment costs, and quality control. Detailed studies and modeling may be useful to evaluate and optimize such a method before its implementation in practice, which was considered **[6]**. The approach points to the importance of scientific research and innovation in improving technologies and production processes to achieve quality products and optimize production.

Scientific Hypothesis

The specific power when kneading the components of the yeast dough depends on various factors, such as the kneading time, the temperature of the environment, and the properties of the ingredients used. The basis of the work is the determination of the specific power for the preparation of steam by substantiating the effective thermodynamic energy regime parameters for the analysis of a complex work process. Proposing the hypothesis, we assume that optimal kneading parameters will contribute to increasing the process's efficiency and improving the final product's quality.

MATERIAL AND METHODOLOGY

Samples

Experimental and theoretical research was conducted in the laboratories of Technological Equipment of the Ternopil National Technical University. According to the specified recipe **[7]**, wheat flour of the first grade with a moisture content of 13.6 ±0.2% and a raw gluten content of 26% was used. The materials came from the manufacturer "ZACHID-HLIB-ZBUT-2002" in Ternopil, Ukraine. Pressed yeast was produced according to the technical conditions of TU U 10.8-00383320-001 **[8]** by PrJSC "Company Enzym" in Lviv, st. Ukraine. Granulated sugar met the DSTU 4623:2023 **[9]**standard and was purchased in Rivne, Ukraine.

Chemicals

Water(chemical formula H_2O) was used to mix the components to prepare the paste. Water meets the national standard DSTU 7525:2014 **[10]**.

Animals, Plants, and Biological Materials

Flour of the first grade, made from winter wheat varieties ("*Myras*", "*Shestopalovskaya 28*", "*Flagman*"), grown in the west of Ukraine in the Ternopil region in the forest-steppe zone.

Pressed yeast TU U 10.8-00383320 **[8]**.

Instruments

DMK 30 digital electronic meter (implemented by TechnoSvit LLC, Ternopil, Ukraine).

Altinar-71 analog-digital frequency converter (implementer of TechnoSvit LLC, Ternopil, Ukraine).

Lenovo G 500 personal computer (implemented by TechnoSvit LLC, Ternopil, Ukraine).

Communication with a PC (implemented by TechnoSvit LLC, Ternopil, Ukraine).

Power Suite software version 2.3.0 (implemented by TechnoSvit LLC, Ternopil, Ukraine).

Laboratory Methods

Depending on the specific requirements and characteristics of the mixing process, there may be different combinations of these methods and approaches to achieve a successful result. In our study, to achieve the distribution of the components before the period when the absorption of the liquid components of the flour particles has passed, the main strategy is to speed up the mixing process and ensure the uniformity of the distribution of the components as much as possible. After all, the first mixing stage involves obtaining a mixture by combining flour and liquid ingredients in a thin layer. This is known as the "binding" or "wet mixing" stage.

This process is important in the good distribution of the liquid components in the flour to obtain a uniform mixture before the following operations. It is important to consider that the effectiveness of the "binding" stage can be achieved due to the correct combination of flour and liquid ingredients in a thin layer to create a quality mixture. The basis of the second stage of the process, where the components must be mixed in a weighted state in a continuous flow with the assistance of working bodies, creates conditions for intensive mixing to achieve the desired distribution of components in the mixture. In this case, the integration of working bodies and the continuous flow of components affect the achievement of high-quality structuring.

To perform experimental research, a physical model was developed, which is schematically presented in Figure 1. With the help of the developed mixer, the processes that take place during the circulation of the flow of the formed liquid mixture under the action of the plate-shaped working body and the suspended state on the other side are considered.

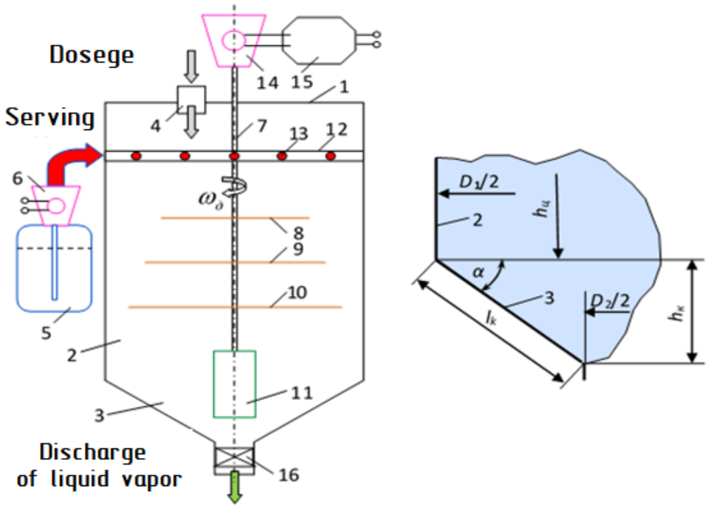


Figure 1 Scheme of the new mixer components: 1 – working chamber; 2, 3 – cylindrical and conical particles of the working chamber; 4 – loading neck; 5 – water container; 6 – water supply pump; 7 – drive shaft; 8, 9, 10 – disc-shaped working bodies; 11 – stirrer blade; 12 – water supply; 13 – water spraying devices; 14 – electric motor; 15 – control unit; 16 – drain tap.

Figure 1 does not show the flour vibrodispenser, which creates conditions for spraying flour over the entire volume of the cylindrical chamber. Thanks to this mixer design, uniform layer-by-layer mixing of the components is ensured, and the quality of the created environment is improved. The design parameters of the mixer are given in Table 1.

An important assumption for the thermodynamic model about region Y is that subsystem X receives energy from an external source. This assumption indicates the possibility of inputting or outputting energy to subsystem X from an independent source that is separated from other parts of the system and is important for regulating the work process, creating conditions for certain effects, or ensuring energy balance in the system.

Usually, to calculate the efficiency of a system or equipment, it is important to consider all factors, including the power consumption of the working body and the losses that may occur during power transmission through the shaft and bearing assembly. Minimizing such losses can lead to improved efficiency and equipment life. Therefore, the working body's consumed energy is spent without considering the mechanical loss of power in the shaft seals and the bearing assembly. The mechanical energy of subsystem X can perform technical work in subsystem Y. At the same time, there is a change in parameters: pressure and temperature, both of the gas subsystem and the entire system. Such a change in system parameters aims to increase the efficiency of the system's functioning and achieve the target destination of the system flow.

Table 1 Design parameters of the mixer.

Mixer indicators	Value
Cylindrical chamber diameter, m	0.25
Total height of the chamber, m	0.55
Number of disc working bodies, pcs.	3
Diameters of the disc working body, m	0.23, 0.21, 0.19
The distance limit between plate-shaped r.o.m.,	0.1-0.15
Speed, rpm	160-200
second sender flour, kg/s	0-0,08
water-yeast mixture feeds, kg/s	0-0.05

The process of determining the components of the working mixture was considered according to the "black box" method in the form of an energy balance calculation scheme (Figure 2).

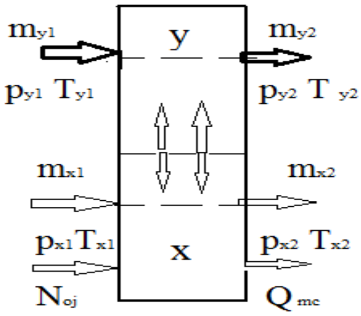


Figure 2 Scheme for calculating the energy balance of yeast dough during pulsed mixing of components: X is – a liquid subsystem; Y is a gas subsystem.

Studies were considered according to the developed methodology **[11]**. The nature of the mixing process in the developed laboratory unit allows us to reveal ways of determining the specific power when mixing components. The degree of chamber filling was determined using the Altinar-71 analog-to-digital converter. With the help of the converter, the impact on the scattering energy, mixing in the environment, and the actual volume that can be effectively used in the researched process were determined. The rate of oxygen absorption can be determined by equating the rate of oxygen dissolution to the rate of its consumption by yeast cells **[12]**. All the oxygen consumed by the cell is spent on the process during the mixing period.

Two different methods of influencing the environment in the working chamber of the mixer were used to achieve the desired result - the formation of a homogeneous mixture of components. The main key elements of the installation description are the chaotic behavior of the dosed components, where the interaction and mixing occur in the first stages. This behavior reveals the impulse effect, which is carried out with the help of a flour vibrator and a liquid mixture dispenser. Impulses in the dosing process can change their nature in intensity or time interval. In addition, the continuous impact of the large surface of the working body ensures constant impact, creating a stable and gradual change in temperature. The temperature in the environment has limits and a possible gradual increase in temperature is carried out within its limits. Such an approach using different exposure and temperature control methods creates a new approach to achieving the desired results in research on the proposed physical model of the mixer.

Description of the Experiment

Sample preparation: Opar samples were prepared by mixing first-grade wheat flour with water according to a specified recipe. The settling process was studied under certain temperature and humidity conditions for the development of enzymatic processes. Afterwards, samples were taken for further studies, including measurements of crude gluten content and other physico-mechanical and rheological parameters.

Number of samples analyzed: We analyzed 12 samples.

Number of repeated analyses: All measurements of instrument readings were performed two times.

Number of experiment replications: The number of repetitions of each experiment to determine one value was two times.

Design of the experiment: Passing the mixing process: Components are introduced into the working chamber of the machine in a pulse or discrete mode, that is, at certain moments of time or certain steps. At the same time, components are loaded and selected through different camera ends, which is important for our process. After all, the finished mixture is submitted to the further technological process **[13]**. In this way, it is possible to change and improve the process of loading and mixing components in the working chamber if the process is carefully analyzed, and its advantages and disadvantages can be identified. Therefore, during the first minutes of their introduction into the working chamber, the dosing components behave chaotically with interaction and mixing. This approach allows you to use two ways to influence the working chamber's environment. Impulse exposure, on the one hand, indicates that a flour vibrator and a liquid mixture dispenser with variable intensity or time intervals carry out the exposure. continuous exposure to the large surface of the working body creates a stable and gradual change in temperature. At the same time, the temperature in the environment has its limits and can gradually increase to its limit.

A theoretical approach to the energy balance equation: Analytical determination of the specific work and power of the drive is quite challenging due to the lack of explicit dependencies of units that describe the models of the interconnection of components in the working chamber of the mixer under discrete-impulse influence. The limited study of these factors' influence on the system's energy balance during experiments affects the performance of many experiments.

A thermodynamic description of the mixing workflow in the proposed mixer reveals and provides important context for understanding the energetic and thermal aspects of the forming system. It emphasizes the main points of the description, focusing on aspects of thermodynamics, which studies the relationships between energy, heat, and mechanical work in a system.

Conducting a thermodynamic description of the work process is focused on aspects of thermodynamics, which studies the relationships between energy, heat, and mechanical work in a system. Our component interaction system is open and can exchange energy with the environment. It can involve heating or cooling and converting energy into work. It converts energy into work or vice versa, indicating that it is in a "quasi-steady equilibrium" state. This state of the system changes very slowly compared to other processes. This mode allows you to perform some simplified thermodynamic analyses.

Using a thermodynamic model to analyze a complex work process that includes two subsystems and energy exchange through an open boundary between them describes the presence of two subsystems in a working chamber where the working environment is in a two-phase state. This indicates the presence of different phases in the dough (liquid and gas) in the formed system and is important for the analysis and control of thermodynamic processes. This model requires complex mathematical and physical analysis to determine and optimize the work process according to the tasks. It can be useful for developing new technologies, increasing the efficiency of work processes, and solving complex engineering tasks.

Using "quasi-steady equilibrium" for simplified thermodynamic analyses is important because it allows one to focus on basic thermodynamic relationships while avoiding significant changes in the system.

Statistical Analysis

To establish the technological efficiency or to determine the energy costs of the discrete-pulse mixing of components during the preparation of liquid steam, experimental comparative studies of consumption power consumption were conducted depending on the established cycle of operation of the electric motor 14 (Figure 1).

Preparation of liquid foam took place in three ways, which differed from each other in the nature and sequence of the adopted cycle:

- "Cycle 1": the electric motor 14 (Figure 1) was turned on simultaneously with the start of loading the metered components of the mixture (metered flour and metered water-yeast mixture) into the working chamber of the mixer, while the time of operation of the disk disks 8, 9, 10 and the stirrer 11 was t_z = 2.8-3.05 min;
- "Cycle 2": the electric motor was turned on 1.2 min after the start of loading the dosed components of the mixture (dosed flour and dosed water-yeast mixture) into the working chamber of the mixer, while the time of operation of disc disks 8, 9, 10 and stirrer 11 was t_z = 2.8-3.3 min;
- "Cycle 3": the electric motor was turned on 2.2 min after the start of loading the dosed components of the mixture (dosed flour and dosed water-yeast mixture) into the working chamber of the mixer, while the total working time t_z = 2.9-3.4 min.

As a result of the statistical processing of the experimental data set, a regression equation was obtained in the form of a linear model, which is written as a function $P_i = a_0 + b_1 t + b_2 T$ and functions $k_{io} = a_0 + b_1 t + b_2 T$ that characterize the functional change of the optimization parameter for the three cycles of operation of the mixer electric motor:

- energy consumption P_1 ("cycle 1"), P_2 ("cycle 2"), P_3 ("cycle 3"):

$$\left.\begin{aligned} P_1 &= -2{,}86 + 1{,}31t - 0{,}014T; \\ P_2 &= 0{,}45 - 0{,}24t + 0{,}022T; \\ P_3 &= -0{,}91 + 0{,}4t + 0{,}006T \end{aligned}\right\};$$

Figure 3 shows the dependencies of the functional change in the consumption of power consumption P_i as a function of $P_i = f_P(t;T)$, Figure 4 – dependencies of functional change in power consumption P_i as a function of $P_i = f_P(t)$ for three cycles of operation of the discrete-pulse mixer motor.

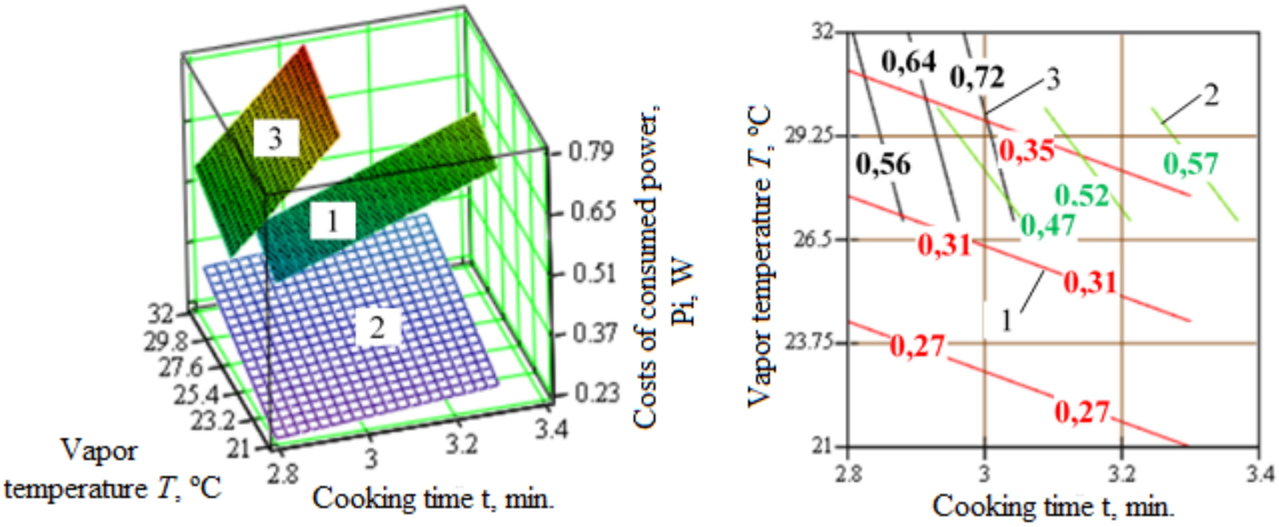
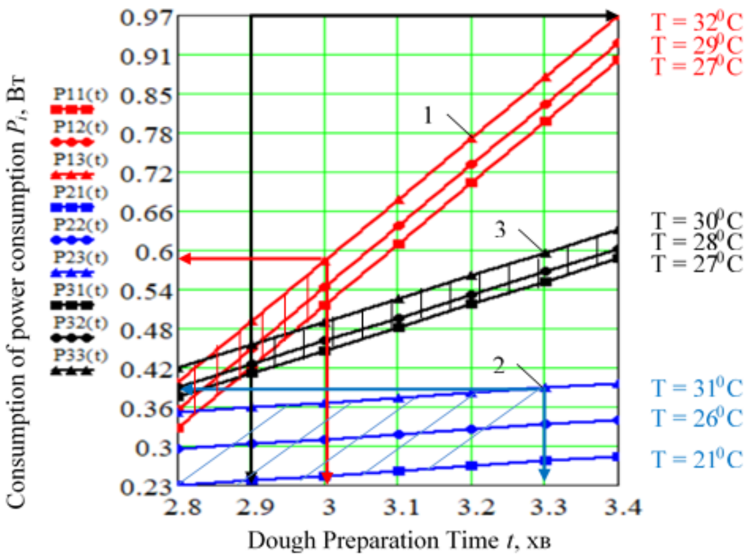


Figure 3 Dependence of the change in consumer power costs as a function $P_i = f_P(t;T)$: 1 – the electric motor. was turned on at the beginning of loading the dosed components of the mixture into the working chamber of the mixer, the working time t = 2.8-3.05 min; 2 – the electric motor was turned on 1.2 minutes after dosing the components into the working chamber, working time t = 2.8-3.05 minutes; 3 – the electric motor was turned on 2.2 minutes after dosing the components into the working chamber, working time t = 2.9-3.4 minutes.

Based on the analysis of figures 3 and 4, it was found that the lowest values of the power consumption P_i obtained with the variant of the electric motor operation for "cycle 2", and the indicators of the approximated values of the power consumption P_2 are in the range from 0.23 to 0.39 W.



$$P_2 = f_P(t_2;T_2);\ P_3 = f_P(t_3;T_3)$$

Figure 4 Dependence of power consumption P_i as a function: 1 – "cyc 1":2 – "cycle $P_i = f_P(t)$2"; 3 – "cycle 3".

This indicates that mixing the components in a suspended state has a positive effect on the duration of the process, or the preparation time of the liquid dough and the temperature of the dough, which are quite favorable and of good quality for satisfactory performance of the prepared liquid dough.

Switching on the electric motor of the discrete-pulse mixer during the discharge of the dough and partial mixing of dosed components ("cycle 1" and "cycle 2") leads to a reduction in the process time, but increases the consumption of consumer power. Therefore, the proposed dough preparation method allows you to optimize the process and is promising for its introduction into production to prepare bakery confectionery products.

RESULTS AND DISCUSSION

The difference in the approaches of different authors in the analysis and calculations of mixing machines reflects the complexity and multifaceted nature of this problem. Different parameters and influences are important in real mixing systems, and authors may use different methods and models to analyze them. Different approaches can be important to understand which aspects are being investigated and how they affect the analysis results. In such cases, it is important to clearly describe the conditions and assumptions on which the calculation is based and consider them in the context of the specific application of the mixing system.

Thus, the change in the total internal energy of the chemical bonds of the material flow is an important factor in the analysis of the process of transformation of the environment during the interaction of new working bodies. This is because, during any chemical or physical process in the system, there are changes in the energy of chemical bonds between atoms and molecules. These changes can be accompanied by the absorption or release of energy during the destruction of chemical bonds during mechanical impact **[14]**, **[15]**. This reaction can be endothermic or exothermic, and it is important to consider how energy interacts with the environment. In researching a new mixer, this means taking into account heat losses, convection heat transfer, and other effects that affect the energy distribution in the system. The energy balance equation allows you to consider all important sources and consumers of energy in the system, which helps to understand how energy is distributed during the process. Consider the work process in a working chamber with a homogeneous state of the working environment, in which gas bubbles are considered ideal and specific heat capacities remain constant during minor temperature changes during the action of working bodies (compression, crushing, stretching). Considering the ideal nature of the gas and the constancy of the specific heat capacities, we can obtain important data for designing and optimizing work processes in your system. This approach makes it possible to simplify calculations and modeling of work processes.

For effective design and management of energy exchange systems, it is important to consider hydraulic losses (energy dissipation), evaluate their impact on process efficiency, and, if necessary, take measures to reduce these losses. In energy performance calculations, the hydraulic loss coefficient is an important variable in hydraulic systems and fluid or gas transportation systems, and it helps ensure the efficient operation of these systems **[16]**, **[17]**. In our case, the processes of movement of the general system are complex and cannot be adequately described using standard correlation coefficients for determining energy consumption in the mixer. In general, the accurate determination of energy characteristics in complex systems requires research, numerical calculations, and experiments, as well as careful analysis and consideration of all factors affecting the processes in the system. Therefore, a thermodynamic energy exchange model was used, which does not require correlations based on experimental data to determine energy characteristics in mixing systems, especially when determining the distribution of fluid movement speeds. Sometimes, the accuracy of such correlations can be lower than temperature field measurements (Figure 5).

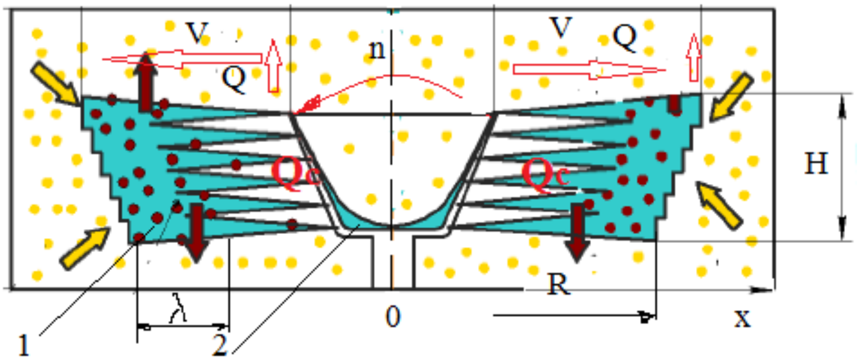


Figure 5 Scheme for calculating the interaction of components - distribution of the mixture at the outlet and from the surface of the disc working body; 2- disc working body within the radius R_{dgp} and time τ for the element of the dispersed gas phase during the existence time τ_0.

Taking into account specific aspects of the process of interacting components, key questions that may arise regarding their realism in the context of reality have been identified. Therefore, such as the heat balance equations of the gas-dispersed phase and the calculation of the specific power are important and correspond to the assumptions of real conditions. Considering that in the working chamber, the mixture is saturated with the gas phase and gradual fermentation, which constantly changes the value of the gas-dispersed phase, representative assumptions were made in the conditions of the real process. In the assumption, we did not take into account the change in the properties of the forming medium at different points; non-stationarity of mixing conditions and heat balance, especially in the case of changes in mixing volume or temperature; rheological properties, such as mixture viscosity, to more accurately reflect their behavior during mixing. The need for assumptions made regarding the properties of the resulting mixture and mixing conditions allows us to understand how the considered factors can affect the results of the study, how this can affect the accuracy of the model, and the relevance of the results obtained.

The heat balance of the gas-dispersed phase element is given by equation (1):

$$q_{\lim} = -\lambda \left(\frac{\partial t}{\partial} \right)_{\lim} = r\rho_{\lim} \frac{dR}{d\tau} \tag{1}$$

Where:
r is the specific heat of vaporization, R is the radius of the gas-dispersed phase; τ is time.

Integrating certain values of the radius of the element of the gas dispersed phase from 0 to R_{dgp}, and the time τ from o to τ_0 (τ_0 is the time of the gas dispersed phase) made it possible to obtain:

$$\int_0^{\tau_0} q_{\lim} d\tau = \int_0^{\tau_0} r\rho_{gas} \frac{dR}{d\tau}, \tag{2}$$

$$q_{\lim}\tau_0 = r\rho_{gas}R_{dgp}, \tag{3}$$

$$q_{\lim} = \frac{r\rho_{gas}R_{dgp}}{\tau_0}. \tag{4}$$

In general, the heat flow from the formed medium to the element of the gaseous dispersed phase is determined by the expression (1):

$$Q_{\lim} = N_{gen}q_{\lim} = \left(N + N_{mov}\right)\frac{r\rho_{gas}R_{dgp}}{\tau_0}. \tag{5}$$

Heat flux density, however, has the value of heat potential. It crossed the boundary of phase separation (liquid/gas phase) with the molecules of the evaporating liquid phase during the time τ0.

Assuming the absence of energy-mass exchange in the mixer with the external environment (leakage through the wall), the equation of the energy balance of the system has the form:

$$N_{oi} \pm \dot{Q}_{н.c} \pm \dot{Q}_m = \sum \Delta H \tag{6}$$

Where:
$\sum \Delta H$ – the total change in the enthalpy working environment (between the intersection of a given system); N_{oi} – power supplied to the disc working body; $\pm\dot{Q}_{н.c}$ – heat flow between the formed medium and the external environment; $\pm\dot{Q}_m$ – heat flux in the generating medium (viscous friction).

Mostly, these flows are directed into the environment. Therefore, in the future, we consider it as a negative value in the energy balance equation.

As for the value $\sum \Delta H$, it is given according to the scheme (Figure 1) by the equation:

$$\sum \Delta H = \Delta H_Y + \Delta H_X. \tag{7}$$

$$\sum \Delta H = \left(m_{Y2} \cdot h_{Y2} - m_{Y1} \cdot h_{Y1}\right) + \left(m_{X2} \cdot h_{X2} - m_{X1} \cdot h_{X1}\right). \tag{8}$$

Where:

m_Y i m_X – Mass consumption of the working environment; h_Y, h_X – Specific enthalpy of media; Indices "1" and "2" of these values are the input and output states of the components of the working environment.

In some cases, the indexes of component parameters may differ from those specified in equation (8).

The proposed changes in the mass flow rate of gas and liquid at the moment of flow between the working bodies allow equation (6) with consideration of (8) to be given as specific values. Therefore, we denote the partial ratio of the mass flow rate of the input values of the environment B, since it is constantly changing:

$$g = \frac{m}{m_{Y1}} \tag{9}$$

So, we obtain from equation (6) the expression of the specific work of mixing

$$l_{oi} = (g_{Y2} \cdot h_{Y2} - h_{Y1}) + c_f \cdot (g_{X2} \cdot T_{X2} - g_{X1} \cdot T_{X1}) + \tilde{q}_{н.c.} \tag{10}$$

or

$$l_{oi} = l_Y + l_X + \tilde{q}_{н.c.} \tag{11}$$

Thus, the amount of specific mixing work and specific power can be determined based on the specific work of each subsystem with heat losses to the environment **[18]**, **[19]**.

Equation (11) indicates that the specific work is provided that the specific mass flow rate of the environment and the thermal parameters of each subsystem are determined. Typically, specific power is used when comparing energy efficiency

$$N_{num} = \frac{N_e}{\dot{V}_{Y1}}$$

or after transformations

$$N_{spec} = \frac{N_{oi} \cdot \rho_{Y1}}{\dot{m}_{Y1} \cdot \eta_{mech}} = l_{oi} \cdot \frac{p_{Y1}}{R_{Y1} \cdot T_{Y1} \cdot \eta_{mech}}. \tag{12}$$

Where:

N_e – efficient power on the mixer shaft; $\dot{V}_{Y1}$ – volumetric capacity of the mixer; η_{mech} – mechanical efficiency of the mixer; ρ_{Y1} – density of gaseous medium *Y* at the entrance of the working bodies; R_{Y1} – gas became; $\tilde{q}_{н.c} = \dot{Q}_{н.c} / \dot{m}_{Y1}$ – specific heat flow to the environment.

When kneading dough (homogeneous liquid medium), the specific power equation:

$$N_{spec} = \frac{p_{Y1}}{R_{Y1} \cdot T_{Y1} \cdot \eta_{mech}} \left[(g_{Y2} \cdot h_{Y2} - h_{Y1}) + c_f \cdot (g_{X2} \cdot T_{X2} - g_{X1} \cdot T_{X1}) + \tilde{q}_{н.c.} \right]. \tag{13}$$

In this case, we consider:

- ideal, one-component gas;
- homogeneous medium and not compressible;
- gas solubility, condensation, and evaporation of liquid are absent.

Based on what has been said, expression (13) is simplified, since $\dot{m}_{Y2} = \dot{m}_{Y1}, g_{Y2} = 1$ $\dot{m}_{X2} = \dot{m}_{X1}$;

$$h_{Y2} - h_{Y1} = c_p \cdot (T_{Y2} - T_{Y1}) = c_p \cdot T_{Y1} \cdot \left(\pi^{\frac{n-1}{n}} - 1 \right).$$

Given the simplification of expression (13), the specific power would be:

$$N_{spec} = \frac{p_{Y1}}{R_{Y1} \cdot T_{Y1} \cdot \eta_{mech}} \cdot \left[c_p \left(\pi^{\frac{n-1}{n}} - 1 \right) + g_{X1} \cdot c_f \cdot \frac{\Delta T_X}{T_{Y1}} + \frac{q_{н.c}}{T_{Y1}} \right] \tag{14}$$

Where:
c_p – isobaric heat capacity of the specific gas component of the dough; $\pi = p_{Y2} / p_{Y1}$ – compression level of the gas component of the dough; n – showing the compression polytrope; c_f – specific heat capacity of liquid; $\Delta T_X = T_{X2} - T_{X1}$ – changing the heating in the system.

Thus, equation (14) makes it possible to determine the specific power.

The thermal gas flow formed during compression goes not only inward to the formed medium but also to the adjacent working surfaces of the mixer. We assume that surfaces are thermal only to the liquid and do not consider the heat flow from the gas to the environment, that is, heat exchange occurs between the liquid and the surface, but there is no heat loss in the form of radiation to the atmosphere. Component Definitions l_X i l_Y and Thermal Communication $\Delta T_X = f\left(g_{X1}, n\right)$ In this case, it requires considering the energy balance of the subsystem. Since they are interconnected, it is enough to determine the desired parameter l_X and its associated quantities.

Consider the energy balance of the subsystem, the diagram in Figure 6.

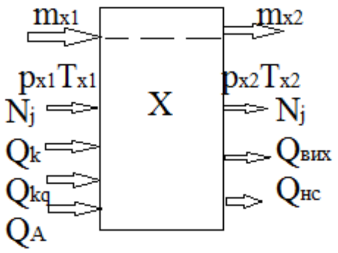


Figure 6 Diagram of the fluid subsystem of energy balance.

The equation for the conservation of energy of the subsystem is as follows:

$$Q_k + Q_{kd} + Q_A - Q_{ev} - Q_{н.c} + N_{oi} - N_i = \Delta H_X \tag{15}$$

Where:
convective heat flow removal from the compressible medium; – heat fluxes of condensation and liquid evaporation processes; Q_A – heat flux is due to the absorption of gas in a liquid; N_i – polytropic compressive power; N_{oi} – shaft power.

This equation shows the dependence of the heating of the liquid in the process of mixing the components since it is proportional. ΔH_X ΔT_X

The given specific values of expression (15) are transformed as:

$$c_f\left(g_{X2} \cdot T_{X2} - g_{X1} \cdot T_{X1}\right) q_k + q_{kd} + q_A + q_{ev} + q_{н.c} + l_{hyd} \tag{15}$$

Where:
$l_{hyd} = \left(N_{oi} - N_i\right) / m_{Y1}$ – specific work is spent on overcoming hydraulic resistances in the medium (dissipation of energy consumption during fluid movement). It is determined from experimental studies.

The solution of equation (16) is carried out concerning the parameter T_{X2}

$$T_{X2} = \frac{g_{X1}}{g_{X2}} \cdot T_{X1} + \frac{q_k + q_{kd} + q_A - q_{ev} - q_{н.c} + l_{hyd}}{c_X \cdot g_{X2}}. \tag{17}$$

Its dependence is established by: the specific heat flux of convective heat transfer between gas and liquid $q_к$, the process of condensation of the vapor phase of the liquid q_{kd}, absorption of gas into the liquid q_A, evaporation of a liquid into a compressible gas q_{ev}, heat exchange with the environment $q_{н.c}$ and the specific operation of hydrodynamic flow rates in the mixer chamber. These values can be determined based on generally accepted laws and regularities of heat and mass transfer.

Kneading temperature readings refer to microbiological, physical, and chemical influences. They can approach the optimal and stable temperature due to heat transfer. Therefore, the disadvantage, in our opinion, is the accumulation of heat in the medium. We do not take into account the condensation of the vapor phase of the liquid q_{kd}, absorption of gas components into the working fluid q_A, or Evaporation of a liquid into a compressible gas q_{ev}, because they have a fairly limited period of existence. In addition, they can be compensated for by heat transfer by mass transfer in the forming dough. Based on this:

$$T_{X2} = \frac{g_{X1}}{g_{X2}} \cdot T_{X1} + \frac{q_k - q_{н.c} + l_{hyd}}{c_X \cdot g_{X2}}.$$

Hydrodynamic losses (specific work) in the mixer can be defined by the expression:

$$l_{hid.mov} = \frac{k_{mov} \cdot \rho_X \cdot \omega^3 \cdot r_2^5}{m_{Y1}} \tag{18}$$

Where:

ρ_X – density of the formed medium; ω – Shaft speed; k_{mov} – power factors determined experimentally; r – the radius of action of the working body on the mass of the medium. Its values depend on the geometry and Reynolds numbers Re_{mov} Defined by the expression:

$$\mathrm{Re}_{mov} = \frac{2 \cdot \omega \cdot r_2^2}{\nu_X}. \tag{19}$$

Where:

ν_X – kinematic viscosity of the medium at average temperature.

Effects of working environment temperature are determined by the value of kinematic viscosity ν_X.

Experimental and theoretical studies of the specific power Npyt during mixing and operation of a new mixer are important for determining its efficiency in various conditions of the interaction of components and the influence of the mechanical action of working bodies on them. Considering the context of mixing efficiency in determining energy consumption per process allows different mixing methods or equipment to be compared in terms of efficiency. It remains quite relevant how the change of thermodynamic parameters in expression (14) will affect the value of specific power. After all, from the above, it will be kneading without considering the constructive parameters.

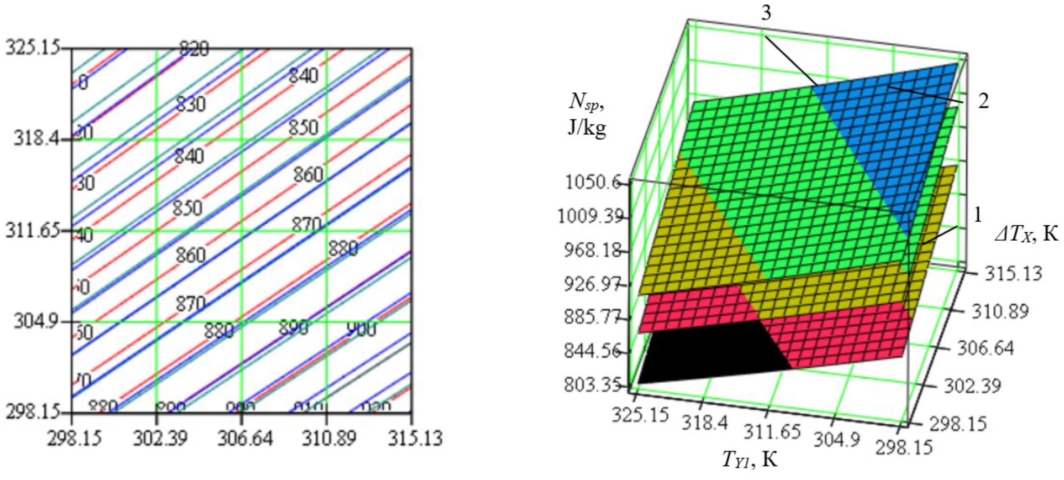


Figure 7 Dependence of specific power on changes in temperature indicators at the stages of the process: 1 – p_{Y1} = 208 Pa; 2 – p_{Y1} = 224 Pa; 3 – p_{Y1} = 236 Pa.

Based on equation (14), the thermodynamic data of the process were established. Dependencies in Figure 7 show that the specific power has an increase in its values relative to the passage of the structure formation of the dough mass.

So, in the first minutes of dosing (suspended state), we have low indicators of the created pressure in the system. These data change accordingly at the other two stages of dough mass formation, as there is a slight increase in the mechanical action of the working organs. Therefore, from the initial compression at 208 Pa of the first stage, it gradually increases in the other two. Increasing the influence of the mechanical action of the working bodies on forming the mass structure (plasticization) leads to a change in pressure from 224 Pa to 236 Pa. The fact that the specific power during its transition at each process stage has its smoothly interconnected values relative to thermodynamic processes is also worth noting.

Comparing model predictions with experimental data is an important step in validating and confirming the relevance and accuracy of the model. Such an analysis helps to determine how well the model reproduces real conditions and whether its predictions can be trusted in various scenarios of the real process. Therefore, equation (14) helps to determine whether the acquired knowledge is transferred from the model to the reality of the process or whether the model needs adjustment. The heat balance equation of the gas-dispersed phase and the calculation of specific power are key elements of modeling mixing processes in various technical applications. These mathematical models and formulas were used in the practical construction of the design parameters and process of the new mixer. They establish the impact on the design of mixing equipment and the optimization of mixing processes. Thus, the heat balance equation of the gas-dispersed phase allows us to determine how heat is transferred between different phases in the system during mixing. This is important for understanding energy losses and process efficiency. Changing parameters in the heat balance equation may affect the need to simplify the process or other aspects of heat exchange. The specific power calculation equation allows you to determine how much energy is consumed or generated during mixing per unit volume or mass of components. Changing the parameters in the equations affects the amount of power needed to achieve a specific degree of homogeneity when mixing components.

In each specific case, the effect of temperature on the specific power may be different, and to accurately determine this effect, you need to consider the specific conditions and properties of the system. Note that the effect of temperature change on specific power in a thermodynamic (isentropic) process also plays an important role in the gas law, which describes the dependence of gas pressure, volume, and temperature during kneading of yeast dough. Summarizing the results of experimental studies (Figure 5), it can be seen that the specific power in the isentropic process depends on the temperature change between the initial and final states of the mixing process. Indicators of statistical processing of experimental data of consumer power consumption for steam preparation and substantiation of effective thermodynamic energy regime parameters of specific power noted their dependence on changes in temperature indicators at the stages of the process.

The problems of the modern trend in the design of mixing working bodies in machines of various classes for performing the work processes of mixing, injection, kneading, and transportation, focused on improving productivity, efficiency, and reducing energy consumption, are presented. This makes it possible to predict the improvement of the geometry of the working bodies to reduce the resistance from the mixture of components and the formed viscous medium and avoid unforeseen consumption of energy resources. These directions in the design of mixing working bodies are also aimed at achieving greater productivity, quality, and stability in machines of various classes that perform various work processes. Inventors **[20]**, **[21]** often directed design calculations toward profile efficiency and optimization in precast applications. Circulation mixing, carried out by repeated mechanical effects on the liquid in a closed circuit of the working chamber, can be a very effective method for achieving a homogeneous environment. This process consists of the liquid circulating the circuit and undergoing mechanical effects such as displacement, turbulence, and pulsations.

In the works of the authors **[22]**, **[23]** it was noted that circulation mixing with multiple mechanical effects on the components in the closed circuit of the working chamber is an effective way to achieve homogeneity of the medium. Thanks to the repeated mechanical impact, large contact surfaces between the bulk components and the liquid are achieved, This creates the possibility of changing the mixing parameters, such as speed, time, and others, which allows you to adjust the process to increase efficiency for specific requirements and production tasks. This is important in many manufacturing processes where product accuracy and uniformity are critical.

In general, as noted by the authors **[24]**, **[25]** circulation mixing is an essential technology for achieving uniformity and efficiency in various production processes where the mixing of liquid materials is required. It can produce products, chemical reactions, biological processes, and many other applications.

Methods for determining specific costs for forming a viscous medium when mixing components are an important tool for developing optimal design parameters of machines and equipment **[26]**, **[27]**. These techniques make it possible to establish the necessary capacity required to ensure the appropriate quality and productivity of the process. Research and tasks in mixing and thermophysical processes are of great practical importance. They can contribute to improving production processes and the efficiency of resource use. Some key aspects and benefits of these tasks are:

1. A detailed analysis of thermophysical processes helps to understand how heat and other physical parameters affect the mixing process and how this affects quality and performance **[28]**, **[29]**.
2. Evaluating and optimizing energy use is key to reducing costs and improving process sustainability **[30]**.
3. Optimizing the hardware implementation of the mixing technology allows for improving the accuracy and efficiency of the process **[31]**, **[32]**.
4. Understanding the factors that affect temperature flows allows you to manage these processes and achieve the desired results **[33]**.
5. Combining theoretical research and experiments allows you to build and test reliable models in practice **[34]**.

At the same time, there is a possibility of dosing components in a state of vibrating boiling with a corresponding decrease in the technological resistance of the medium. In addition, creating a vibration field reduces the influence of some factors. These factors, such as the friction of the components on the walls of the working chamber, the geometrical parameters of the local processing area, and the physical and mechanical properties of the components **[35]**, **[36]**, prevent the uniform distribution of the components in the volume of the mixer. The authors of the work **[37]**, **[38]** reveal the fundamental advantages of vibration action. Yes, this action allows you to effectively solve technological problems in preparing compound feeds, premixes, protein-vitamin supplements, and others.

The analysis of theoretical studies showed **[39]**, **[40]** that using rheological dependencies during the work processes of mixing the medium depends on the specific situation and process requirements. There are situations when considering rheological properties is important, but there are also cases when it is unnecessary or far from always appropriate. Deformation processes that occur when the temperature changes in the working chamber can be very complex and challenging to measure due to many factors that affect these processes. However, this complexity can also open up new research opportunities. Alternative studies can lead to developing new methods and technologies for controlling and optimizing deformation processes at a temperature change. To succeed in such studies, combining theoretical approaches with experimental methods, such as temperature field measurements and strain analysis, is important.

These research areas can significantly contribute to the industry's development and help solve problems related to mixing and heat balance in real production scenarios.

CONCLUSION

In general, the specific power of the mixer depends on the specific mixer and the properties of the liquid being mixed. Considering these parameters and performing the appropriate calculations carefully is important to optimise the mixing process. The considered dependencies are correlated with the expressed design parameters of the mixer in compliance with the technological regime. The directed movement of temperature flows in the improved heat exchange processes of the working chamber of the mixer made it possible to conduct a thermodynamic description based on an open thermomechanical system. The mixing energy balance calculation schemes using the "black box" method allow us to consider the process as two subsystems with a two-phase state of the working medium and energy exchange through an open boundary separating these subsystems. The set of theoretical calculations for determining the influence of the parameters of the hydrodynamic mixing process on the properties of the resulting dough with established specific costs considered the nature of the directed influence of the energy balance on the structural properties of the system. It is possible to judge the effective scheme of the developed technological equipment for carrying out mixing processes according to the established directions for determining specific costs. Based on the analysis, it was established that the lowest values of power consumption Pi were obtained with the option of operation of the electric motor-reducer for "cycle 2", and the indicators of the approximate values of power consumption P2 are in the range from 0.23 to 0.39 W. Any change in the mixing parameters leads to a change in the properties of the medium. Changing the state parameters of gases (vapors) and liquids is a gradual transition of matter from one state to another. The considered parameters are important for kneading from analysing the results of determining the specific power. The results of the presented rationale for determining the specific power in the mixer range from 844.56 J/kg to 1050 J/kg. Therefore, in comparison with conventional calculation methods, the proposed method allows directed control of the process of dispersion and homogenization. The developed specific surface of our system allows us to ensure the sorption activity of the components without increasing costs, maintaining the temperature parameters of the process, and undoubtedly obtaining a high-quality mixing process and kneading components while reducing specific costs. Understanding the heat balance and specific power allows you to optimize the efficiency of mixing processes, considering the energy costs and needs of the system. Modeling these processes can serve as a basis for developing optimization strategies, for example, the selection of optimal equipment turnover or the location of dosing equipment. In summary, heat balance and specific power calculations influence mixing equipment design and can be key to optimizing mixing processes in various industries. Consequently, comparing the models shows a high correspondence to the experimental data, which allowed us to determine how well they are adapted to different scenarios and variable conditions, where the conditions can vary.

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