DOI: 10.15587/978-617-7319-59-6.CH9

9 INNOVATIVE SECURITY TECHNOLOGICAL SOLUTIONS IN THE SYSTEM OF MANUFACTURING PRODUCTS FOR THE POPULATION OF TERRITORIES WITH TECHNOGENIC LOAD

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ABSTRACT

The section is devoted to the development and substantiation of scientific provisions for the construction of intelligent control systems for the industrial production of bread with built-in intensifiers of technological processes of ultrasonic nature in the context of ensuring food security. The main scientific results of the work are mathematical models of the processes of preparation and improvement of water quality indicators, preparation and dosage of flour, preparation of bread starter, dough, dispersion for dough of functional applications, proofing and baking processes using ultrasonic monitoring and intensification systems; designing local adaptive control systems for relevant processes; theoretical substantiation of an intelligent control system for the production of bakery products with the development of a conceptual project «Intellectual enterprise for the production of bread for areas with technogenic pressure». It is proved that the development of a reference problem under the conditions of uncertainty of external and internal disturbances not controlled by sensors can be evaluated by an expert system for the formation of algorithms for controlling the technological process of bread production. Thus, the paper systematizes for the first time the theoretical and practical results of intelligent control of complex technological processes for the production of bakery products with digital control algorithms for food industry enterprises in the areas of technogenic load.

KEYWORDS

Food security, technogenic load, smart food product, intelligent enterprise, fuzzy control, expert system, robotic complex.

9.1 GENERAL PRINCIPLES FOR ENSURING FOOD SECURITY IN AREAS WITH TECHNOGENIC LOAD

The world concept of food security was first defined in the mid-1970s during the discussion at the international level of food problems during the global food crisis. The initial attention of world leaders was focused primarily on the problems of food security, namely the availability and, to a certain extent, price stability of basic foodstuffs at the international and national levels.

Subsequently, at the 1996 World Food Summit, a more complex definition was formulated, according to which food security at all levels, from individual to global, is achieved when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet nutritional preferences and dietary needs throughout the active life of a healthy lifestyle.

Sociological studies of the present show that in our time there is not a single state that would not be concerned about food security issues. This applies to the production of food products, their distribution, import and export of food, food consumption, etc. Food security is now considered an important component of national policy, it characterizes the political independence of the country, its economic strength and stability, social security of the population and the ability to meet the food needs of its citizens without prejudice to national interests. At the same time, each country determines its own tasks for improving the food supply of its own population, depending on the level achieved in solving this problem.

An important component of the national security strategy of Ukraine, scientists have identified its economic component, including food security as an independent object of domestic and foreign policy of the state [1]. Also, strategic actions to ensure the economic and physical accessibility of food products of high nutritional and biological value to prevent a sharp decline in the health index of the population of Ukraine have now become the priorities of the social policy of Ukraine.

At the same time, food security necessarily includes not only the consumer aspect – taking into account physiological needs – but also the production aspect, which consists in the priority development of domestic production, and only then – the necessary import of agricultural products and food products.

Thus, it can be stated that food security is determined by the level of efficiency of the entire economy. However, food resources are formed in the process of agro-industrial production. Therefore, such subsystems of the agro-industrial complex as the sale and distribution of food, food reserves and consumption are functional subsystems.

In market conditions, state policy should be aimed at achieving food security, creating the necessary reserves of food and agricultural raw materials, increasing the level of food security, the purchasing power of the population, improving the quality of food and agricultural raw materials, ensuring their competitiveness in the domestic and foreign markets. Solving the problem of food security as an essential component of the sustainable development of the country includes not only the production of a sufficient amount of food, but also the preservation of agricultural resources, their ability to reproduce and productivity, which is necessary to ensure the food security of future generations.

As it is possible to see, an important component of food security is food security. In accordance with the Law of Ukraine «On the Basic Principles and Requirements for the Security and Quality of Food Products», a safe food product is a food product that does not adversely affect human health and is suitable for consumption.

In order to protect the life, health and interests of consumers, the state regulates the security and individual indicators of the quality of food products by: establishing sanitary measures; establishing requirements for individual indicators of food quality; state registration of objects of sanitary measures; issuance, termination, cancellation and renewal of operating permits; informing and raising awareness of market operators and consumers about security and certain indicators of food quality; establishment of requirements for the health status of the personnel of the facilities;

participation in the work of relevant international organizations; implementation of state control; bringing market operators and their officials to justice in case of violation of legislation on security and certain indicators of food quality.

Modern scientific and practical experience shows that the issue of food security must be considered from two positions:

– firstly, from the standpoint of the adequacy of the content of essential nutrients in food products and diets in accordance with the physiological needs of a person in these substances;

– secondly, from the standpoint of protecting the internal environment of the human body from the intake of various toxicants of a chemical and biological nature with food.

This sequence and relationship is due to the fact that it is the deficiency of essential nutritional and biologically valuable substances in food products and their imbalance in the diet that leads to irreversible changes in the internal environment of the body, disruption of cellular metabolism, as well as a significant decrease in the protective potential of the body in relation to harmful environmental factors, which dramatically increases the risk of developing both communicable and non-communicable diseases.

Thus, dangerous food products can be considered not only containing toxic substances of chemical and/or biological origin, but also products with low biological value due to the low content of essential quotas of biologically active substances. This proves that today, in the context of the socio-economic crisis in Ukraine, when assessing food security, it is necessary to take into account not only the content of foreign substances in them, but also their qualitative composition.

This range of questions can be expanded for areas with increased technogenic load, for example, the Donetsk and Prydniprovsky economic regions of Ukraine. The peculiarities of such regions are the increased overall need for food products, both for general and medical purposes, to ensure the health and working capacity of the population, strengthen the protective functions of the human body and prevent pathological conditions that can develop under the influence of environmental factors.

At the same time, it should be taken into account that the artificial enrichment of food products with biological additives is a serious interference in the traditional human nutrition system. Therefore, the modeling of fortified foods should be performed only taking into account scientifically sound, clearly articulated and proven principles [2].

Principle one: in the process of fortifying food products and giving them functional properties, only those nutrients, the deficiency of which actually takes place, should be used. However, they should be fairly common and safe for health. For miners (miners) working underground at a depth of 1000–1400 m, metallurgists and representatives of other heavy professions, chemists whose work is associated with harmful influences, soldiers of the Armed Forces of Ukraine, including in field and extreme conditions, such food components have a complete protein, ascorbic acid, B vitamins, folic acid, keratin, iodine, iron and calcium [3]. At the same time, it is possible to use a more complete set of enrichment additives, including by combining vitamins and minerals with the simultaneous addition of other valuable food components: dietary fiber, phospholipids, supplements of natural origin, which will have a protective, stimulating and, if necessary, therapeutic effect on certain biological systems and functions of the human body.

The second principle: it is necessary to take into account the possibility of chemical interaction of enrichment additives with each other and with the components of the product and choose only those forms, combination methods and stages of application that will ensure their greatest preservation during production and subsequent storage. So, for example, bread and pasta, fish products, side dishes are recommend to be enriched with B and K vitamins, as well as calcium and iron for consumption by groups of people living in areas with a high level of radiation pollution, tuberculosis, etc.

Principle three: fortification of food with vitamins and minerals should be carried out according to WHO standards.

Fourth principle: enrichment of food products with vitamins, minerals and other dietary supplements should not impair the consumer properties of these products: reduce the composition, content and digestibility of other food components, significantly change the taste and aroma properties of products, as well as their shelf life.

Food products that will comply with the listed principles of usefulness for consumers, in terms of nutritional value and therapeutic and prophylactic properties, and the principles of environmental friendliness – the absence of harmful effects on the ecosystem at all stages of the life cycle – are commonly called reasonable food.

An important direction in the implementation of the sustainable development strategy of Ukraine is the development of a system for the production of reasonable food in sufficient quantities to ensure a regular balanced diet of the population, especially in areas with a pronounced technogenic load.

This task was included in the National Economic Strategy of Ukraine for the period up to 2030, approved by the government. And, in our opinion, it can be successfully implemented only taking into account the ideas and technologies of the neo-industrialization of Industry 4.0, which involves the widespread use of smart technologies, the Industrial Internet of Things (IIoT), robotic complexes, including for the development of industrial engineering and the food industry. The use of this approach will significantly increase labor productivity and the level of product quality at food industry enterprises through the use of unmanned technologies based on the automation of production processes, the use of robotics and IIoT.

Within the framework of this strategy, the key issues in the development of the food industry at the present stage are the development and implementation of new standards of food and environmental security, the search for optimal ways of processing products with the preservation and development of their beneficial properties, and the economical use of resources of all kinds.

The object of the study was the intelligent control systems for the industrial production of bread, bakery, flour products under conditions of uncertainty and technogenic pressure. The prerequisite for such a choice was the social nature of this product group, due to accessibility for all segments of the local population. Bread and bakery products are regular consumption products in Ukraine, which makes them the most convenient components of the diet, through which you can adjust its nutritional and preventive value in the right direction.

The need for bread is 300–500 g/day, depending on the age of the person, the nature of work, national characteristics and economic factors. In Ukraine, about 7 million tons of bread and bakery products are produced annually, or 130 kg per capita [4].

The value of bread lies in the fact that it contains almost all the nutrients a person needs. With the right production technology, the entire mass of bread (100 %) is edible. Almost half of its solids are carbohydrates (45–55 %), of which starch is the main one. Depending on the type of flour, bread contains 5–8 % proteins.

Due to rye and wheat bread, a person satisfies his need for proteins by 25–30 %, in carbohydrates – by 30–40 %.

The biological value of bread depends on the usefulness of proteins, the content of vitamins, ash elements, etc. in it. 100 g of bread contains 5–8 g of protein. The physiological value of bread proteins from flour of the highest grades is 20–25 % of the norm. According to the FAO, rye bread proteins are better balanced than wheat bread.

An important indicator of the biological value of bread is the content of vitamins in it. Bread is the main source of B, PP, E vitamins. Of the minerals, it contains phosphorus, calcium, iron, magnesium, etc. According to the content of vitamins and ash elements, bread made from low-grade flour and especially upholstery flour is dominated by bread baked from high-grade flour.

Bread differs from many other foods in that it is well absorbed by the body. This is due to the fact that it has a porous, soft, elastic and non-sticky crumb, which contains denatured proteins, partially gelatinized and dissolved starch, and highly softened grain segments. Therefore, all components of the bread are available for the action of the enzymes of the alimentary canal.

The energy value of bread is quite high. So, 100 g of it, depending on the yield and type of flour and dough recipe, give the body 798–1390 kJ, which is about 35 % of its energy needs.

Currently, scientists and technologists of the food industry are looking for ways to improve the quality, nutritional and biological value of bakery products, giving them functional properties, which is embodied in the creation of innovative products, the production of which requires special approaches.

The practical experience of bakery manufacturers shows that the characteristics of the main input raw materials (flour and water) can differ significantly depending on the batch of products, storage conditions and terms, season, region of origin and the degree of its environmental pollution [5].

These factors are the reason that manufacturers have to periodically work in conditions of uncertainty, when the adjustment of the technological process must be carried out depending on the set and parameters of the input raw materials. Often this happens without sufficient justification, on the basis of practical experience or even at the level of the technologist's intuition, which leads to destabilization of product quality and, as a result, a decrease in consumer demand for it.

Today, data on the relationship between the properties of the main components (flour, water or other liquid, yeast, fortifying and improving additives) and recommendations for optimizing technological processes for the production of bakery products under conditions of uncertainty are insufficiently substantiated.

Therefore, the priority areas for stabilizing the quality of bakery products are objective control of the parameters of the input raw materials; water treatment; purification and improvement of the input characteristics of other main ingredients; accounting for input parameters of raw materials in the construction of the technological process for the production of bakery products; application of technologies for economical use of material and energy resources.

The main goal of this study is to develop an intelligent system for the production of innovative varieties of bakery and flour products for areas with a high level of anthropogenic impact.

The subjects of the research are the ingredients for the production of bread, bakery and flour products (flour, water, yeast, etc.), dough, dough, methods of supplying the energy of ultrasonic vibrations, ultrasonic analyzers and intensifiers of technological processes for the production of bakery products, control and measuring equipment. production of bread and flour products.

9.2 DIRECTIONS FOR THE USE OF ULTRASONIC TECHNOLOGIES IN THE IMPLEMENTATION OF INNOVATIVE TECHNOLOGICAL SOLUTIONS FOR FOOD PRODUCTION

For food industries operating in areas with technogenic pressure, it is necessary to regularly monitor the environmental component, namely the input characteristics of water, flour, and other ingredients, and predict their impact on the initial indicators of finished products. Such long-term excitations should be taken into account when designing the phase of automated control systems, which should adapt in pace with the process of input ingredients in the process of making bread starters and various types of dough.

Since it is planned to use ultrasonic analyzers and process intensifiers in the project of an intelligent enterprise for the production of bakery and flour products, first of all, mathematical modeling of the process of diffusion of a passive impurity in a liquid medium under the influence of ultrasound was carried out using a sequential construction method [6].

A preliminary analysis of this process showed its exceptional complexity, due, in particular, to the presence of acoustic cavitation and the associated difficulties in its mathematical modeling. The Boussinesq hypothesis on the theory of turbulence made it possible to describe the local mixing that occurs during acoustic cavitation using the cavitation diffusion coefficient, which indicated the possibility of using the methods of mathematical physics to model the process of diffusion of a passive impurity in a liquid medium. At the first stage of modeling, the expediency of constructing a mathematical model in the form of a second-order partial differential equation of a parabolic type was determined:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) = D_0\frac{\partial}{\partial x}\left(\exp(-kx)\frac{\partial c}{\partial x}\right), \tag{9.1}$$

where c – impurity concentration in the medium, kg/m^3; t – time, s; x – the coordinate directed towards the propagation of the ultrasonic wave, m (the origin of coordinates is located at the entrance to the medium); D – diffusion cavitation coefficient, m^2/s; D_0 – diffusion cavitation coefficient at the medium inlet, m^2/s; k – absorption coefficient of ultrasound in a liquid medium, 1/m.

For the convenience of solving equation (9.1), it was reduced to a dimensionless form based on the theories of similarity and dimensions. For this purpose, dimensionless variables were introduced:

$$\xi = k \cdot x, \tag{9.2}$$

$$\tau = t \cdot D_0 \cdot k^2. \tag{9.3}$$

The variable ξ determines the dimensionless distance associated with the value of the ultrasonic absorption coefficient of the liquid medium k.

The variable τ determines the dimensionless time for the absorption of ultrasound by a liquid medium, which is related both to the initial value of the cavitation diffusion coefficient D_0 and to the coefficient of ultrasound absorption by the liquid medium k.

Through further transformations, the value of the stationary impurity concentration in a liquid medium was invented:

$$\widehat{c}_s = \frac{1}{\xi_0} \int_0^{\xi_0} \varphi_1(\xi) \mathrm{d}\xi, \tag{9.4}$$

where $\xi_0 = k \cdot l$ (when setting the boundary value problem, it was assumed that the ultrasonic wave passes through a layer of a liquid medium of thickness l).

To obtain specific results, let's use the initial concentration distribution and obtained the value of the stationary impurity concentration in the liquid medium, which was sought:

$$\widehat{c}_s = \frac{\xi_0^4}{30}. \tag{9.5}$$

Fig. 9.1 shows graphs of the initial and stationary impurity concentrations in a liquid medium.

The analytical solution of the problem formulated above presents difficulties associated with the dependence of the cavitation diffusion coefficient on the spatial coordinate. Therefore, to estimate the time interval for the establishment of a stationary regime, it is proposed to consider a simpler problem in which the diffusion cavitation coefficient does not depend on the spatial coordinate. By setting the limiting values of the cavitation diffusion coefficient, it is possible to estimate the minimum and maximum values of the time for establishing a stationary regime.

When solving the problem of modeling the process of diffusion of a passive impurity in a liquid medium under the influence of ultrasound, it is necessary to implement a dual approach. Given that the mathematical model is described by a differential equation with varying coefficients, the solution of which analytically causes significant difficulties, it was decided to simplify the equation to obtain an analytical solution. At the same time, the use of the numerical method as the second approach made it possible to choose a parameter in the analytical solution in such a way as to minimize the differences between the solutions obtained by the two methods.

In this case, the impurity concentration in a liquid medium can be calculated by the formula:

$$c(x,t)=\widehat{c}\left(kx,tD_0k^2\right)\cdot m\cdot\int_0^l\varphi(x)\mathrm{d}x. \tag{9.6}$$

Thus, to pass to real values, it is necessary to know the values D_0, k, l, m, $\varphi(x)$. Analyzing the features of the parameters, we can conclude that to determine the parameters D_0 and k, it is necessary to implement experiments that will allow us to study the attenuation of ultrasound in a liquid medium, which is being considered. The parameter m is determined by weighing the mass of the impurity loaded into the liquid medium. The function $\varphi(x)$ determines the initial impurity distribution in the medium during the experiment.

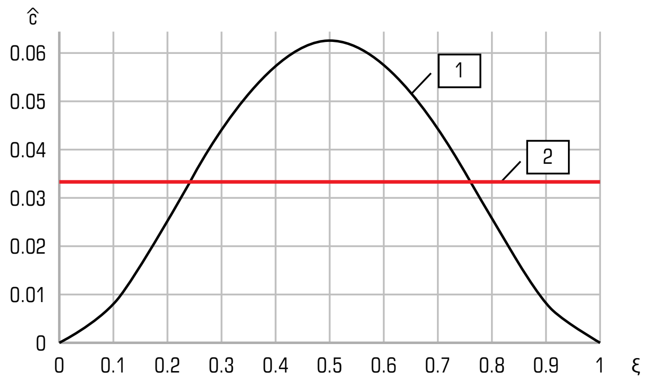


Fig. 9.1 Distribution of impurity concentration in liquid medium ($\xi_0=1$):
1 – initial distribution of impurity concentration in liquid medium;
2 – stationary distribution of impurity concentration in a liquid medium

Fig. 9.2 shows a graphical representation of the results of the numerical solution of the problem according to the data in **Table 9.1**.

An analysis of the numerical solution of the problem shows that the maximum impurity concentration in the medium shifts to the right along the horizontal axis with time.

The application of the theory of similarity and dimensions made it possible to significantly simplify both the solution of the problem posed and the further study of the obtained solution, which is explained by a decrease in the number of variables combined into dimensionless complexes.

Next, let's consider a mathematical model of the interaction of ultrasonic vibrations with food raw materials, which is a heterogeneous medium. Assuming that the state of a heterogeneous medium is described by a mathematical model using a second-order differential equation with constant coefficients, a spectral analysis of this medium was carried out using ultrasound.

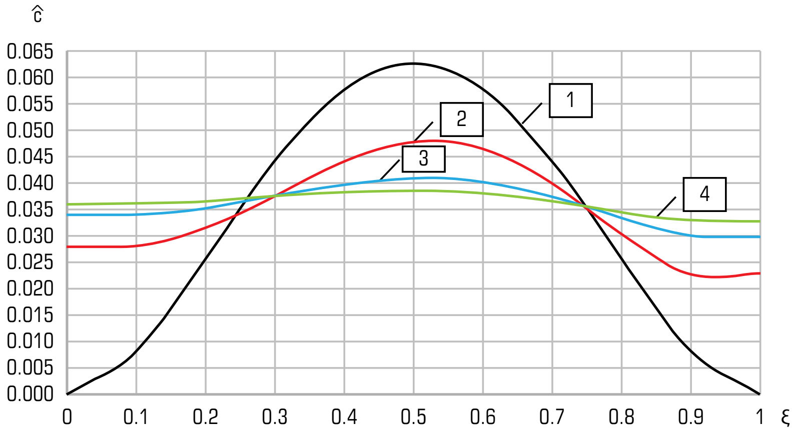


Fig. 9.2 The results of calculations of the dependence of the impurity concentration in a liquid medium on distance for different moments of time in the numerical solution of the problem: 1 – τ=0; 2 – τ=0.03; 3 – τ=0.06; 4 – τ=0.09

Table 9.1 Results of solving the problem by the quantitative method

ξ \ τ	**0**	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**
0	0	0.018	0.024	0.028	0.031	0.033	0.034	0.035	0.036	0.036
0.1	0.008	0.018	0.024	0.028	0.031	0.033	0.034	0.035	0.036	0.036
0.2	0.026	0.026	0.029	0.031	0.033	0.034	0.035	0.036	0.036	0.036
0.3	0.044	0.040	0.038	0.038	0.037	0.037	0.037	0.037	0.037	0.037
0.4	0.058	0.052	0.047	0.044	0.042	0.041	0.040	0.039	0.038	0.038
0.5	0.063	0.057	0.052	0.048	0.045	0.043	0.041	0.040	0.039	0.038
0.6	0.058	0.053	0.050	0.046	0.044	0.042	0.040	0.039	0.038	0.038
0.7	0.044	0.042	0.041	0.040	0.039	0.038	0.037	0.037	0.037	0.036
0.8	0.026	0.027	0.029	0.030	0.031	0.032	0.033	0.034	0.034	0.034
0.9	0.008	0.014	0.019	0.023	0.026	0.028	0.030	0.031	0.032	0.033
1.0	0	0.014	0.019	0.023	0.026	0.028	0.030	0.031	0.032	0.033

The aim of the research was to search for a «transferring function» of food raw materials, with the help of which it would be possible to identify the structural elements of food raw materials –

to determine its physical and mechanical properties. Formulas have been obtained that make it possible to determine the parameters of the state of food raw materials using such characteristics of the spectral density as the resonant frequency, the magnitude of the resonance and the quality factor of the oscillatory system:

$$k = \omega_0, \tag{9.7}$$

$$h = \omega_0 \frac{4Q+1}{2\sqrt{4Q^2-4Q-1}}, \tag{9.8}$$

where k, h – numerical parameters associated with the properties of food raw materials, 1/s; Q – the quality factor of the oscillatory system; ω_0 – the resonant frequency, rad/s.

The quality factor of the oscillatory system is determined by the formula:

$$Q = \frac{\omega_0}{\Delta\omega}, \tag{9.9}$$

where ω_0 – the resonant frequency, rad/s; $\Delta\omega$ – bandwidth of the oscillatory system, rad/s.

The values of these parameters, obtained using ultrasonic vibrations, allow continuous monitoring of the state of food raw materials to assess its quality. Maintaining the quality of the state of food raw materials at a given level will allow, thanks to its operational control, to improve the final product. For the practical implementation of the results of mathematical modeling in practice, it is necessary to conduct a series of preliminary practical experiments to assess the spectral characteristics of the state of the food product, corresponding to the standard of the required quality, for each specific case and adjust the monitoring system.

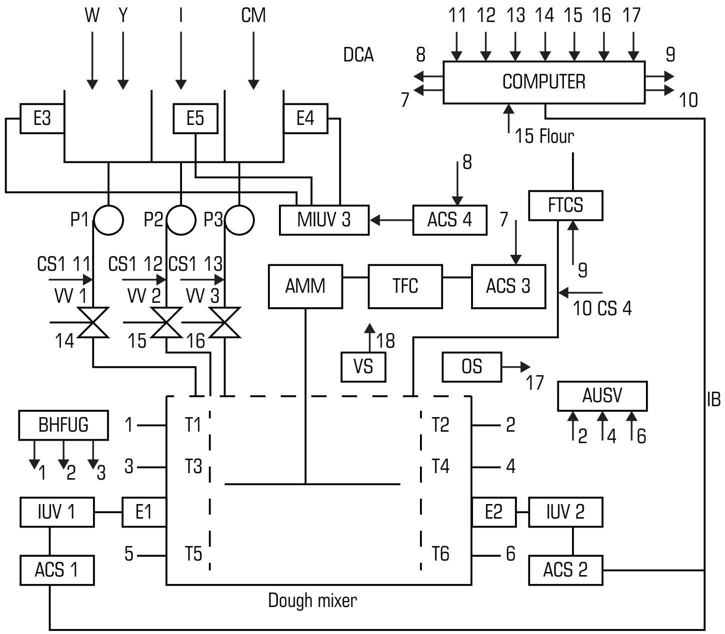
9.3 PRACTICAL ASPECTS OF THE USE OF ULTRASOUND FOR MONITORING AND INTENSIFICATION OF TECHNOLOGICAL PROCESSES IN BAKERY PRODUCTION

When setting up robotic intensifiers of the technological process for the production of bakery products, it was found that water treatment with ultrasonic vibrations at a frequency of 30 kHz with a power of 200 W (interaction time 186–192 s) makes it possible to achieve the most rational effect on its quality indicators: water hardness decreases by 1 % from the previous values, pH decreases by an average of 0.28–0.35 units, the iron content decreases by an average of 25–28 % [7].

The efficiency of using ultrasonic cavitation for water disinfection was also determined: the impact of ultrasonic vibrations at a frequency of 22 kHz with a power of 200 W (interaction time 210 s) leads to a decrease in the total microbial number (TMN) by 5 times.

A method has been developed for dispersing particles of functional additives [8–10] into dough due to controlled cavitation processes created by low-frequency ultrasonic vibrations. To do this, rational modes of sonication of the dough with functional applications at the stage of its preparation are determined: sound pressure of 135–140 dB at a frequency of 22±1.50 kHz increases the productivity of the dough mixer by 12–15 % and ensures the production of innovative food products (bakery products of functional additives animal and/or plant nature in an amount of 5 to 10 % of the total mass).

Fig. 9.3 shows a diagram of an experimental setup for studying the effect of low-frequency ultrasonic vibrations from 20 to 40 kHz and high-frequency ultrasonic vibrations with frequencies from 100 kHz to 1800 kHz.



ACS 1, ACS 2, ACS 3 – adaptive control systems;
AMM – asynchronous mixer motor;
AUSV – analyzer of ultrasonic vibrations with sensors-receivers T2, T4, T6;
BHFUG – a block of high-frequency ultrasonic generators with transducers T1, T3, T5;
CM – chopped meat products;
COMPUTER – electronic computer;
CS 1, CS 2, CS 3 – consumption sensors;
DCA – dispersive-cavitational apparatus;
E1, E2, E3, E4, E5 – ultrasonic emitters;
FTCS – flour transportation control system;
I – ingredients;
IB – information bus;
IUV 1, IUV 2 – intensifiers of ultrasonic vibrations;
MIUV 3 – multichannel intensifier of ultrasonic vibrations;
OS – odor sensor;
P1, P2, P3 – pumps;
TFC – three-way frequency converter of the mixer motor;
VS – visualization system;
VV 1, VV 2, VV 3 – vent valves;
W – water;
Y – yeast

Fig. 9.3 Scheme of the experimental unit for preparing dough with ultrasonic intensifiers

The unit consists of two parts: dispersion-cavitation and dough mixing apparatus.

In experimental studies, let's use emitters E1, E2 with AUSV1, AUSV2 with a frequency of ultrasonic vibrations F=20–22 kHz. The choice of such a frequency range is explained, firstly, by the property of ultrasonic vibrations to uniformly penetrate into small pores and capillaries of the dough throughout its volume, and secondly, by the ability to study the dispersion process due to cavitation flows of liquid with particles of crushed functional ingredients and their ability to uniformly test volume, thirdly, to perform controlled squeezing of flour particles and functional applications using ultrasonic vibrations.

The constructed system is distinguished by a large number of connections for controlling the robotic complex and consists of local systems: ACS1, ACS2 – adaptive control systems for intensifiers; AUSV 1, AUSV 2, AUSV 3 – adaptive control systems for the productivity of the dough mixer; ACS4 – adaptive control systems for a multichannel ultrasonic intensifier with emitters E3, E4, E5.

In the robotic complex, purified and prepared water [6, 10] with dispersed yeast particles is supplied to the dough mixing apparatus by a pump P1. The system for monitoring the performance of the pump P1 provides for the determination of the parameters of the flow rate of the CS1 and the position of the actuator A1, the signals 11 and 14 of control and management of which are sent to the computer. The supply of ingredients (I) to the dough mixer is performed by a pump (P2) with a flow sensor CSA2 and an adjustable valve CS2, the signals of which 12, 15 are sent to the computer. The supply of dispersed particles of functional applications is performed by a pump (P2), cost control is performed by the control system CS3 with an actuator A3, the signals of which 13, 16 are sent to the computer. The flour transportation control system provides for cost control using the CS4 system, the signal 10 from which enters the computer.

The following functions are performed in the dispersion-cavitation apparatus (DCA): controlled water purification; preparation of functional applications and other ingredients.

With the help of AUSV developed software products and developed methods of control, the computer controls the process of ultrasonic cavitation. At the same time, robotic intensifiers MIUV1 and MIUV 2 with systems ACS1, ACS2 and sensors for monitoring the parameters of the technological environment T2, T4, T6, interacting with the dough, form the rarefaction phase of the ultrasonic wave. As a result of this controlled phenomenon, breaks in weak points (cavitational nuclei) occur in the core of the technological medium of the dough mixer. In this case, these are particles of flour, yeast, air bubbles, particles of functional ingredients dispersed in the dough.

By means of AUSV and transducers T5, T6, the computer determines the limiting value of the intensity of ultrasound. Therefore, MIUV 1 and MIUV, due to the cavitation-dispersion process, disperse the particles of functional applications into the dough.

As the ultrasonic intensity increases from 100 dB to 140 dB at a frequency of 22 kHz, the rate of ultrasonic dispersion increases. Moreover, it depends on the characteristics of the flour and the magnitude of the forces of interaction between the individual particles of flour and particles of functional ingredients.

The productivity of the dough mixing apparatus is regulated using the ACS3, TFC3 and AP3 systems. Data from the OS visualization system, which involves the use of infrared optical sensors and remote sensing odor sensors, enters the computer and, after calculation using neural networks, informs the operator about the readiness of the product. In the dough readiness system with applications, sensors for controlling dough density T2 and its homogeneity T4 play an important role.

Thus, in the section, methods have been developed to control the parameters of the density of bread dough, arising under the influence of ultrasound of cavitation bubbles of the «dough-functional additives» medium, and to intelligently control the processes of dispersion of functional applications in dough and the productivity of the dough mixer by adaptive control of the power of the ultra-number of bonds.

It has been proven that ultrasonic vibrations, forming a cavitation-dispersing effect, provide a uniform distribution of moisture between flour particles, faster wetting of the particles of the dispersed phase, which causes an adhesive and cohesive effect of flour with particles of additives. As a result, mixing of dispersed flour particles with particles of crushed functional additives under the action of ultrasonic vibrations leads to the formation of a homogeneous heterogeneous medium.

In the process of cavitation dispersion of flour particles and particles of functional ingredients in a powerful field of ultrasonic waves with a frequency of 22 kHz, moisture with dissolved proteins, sugar, and other ingredients will form a thin film on the surface, which will improve not only the appearance of products, but also positively bakery products.

9.4 INTELLECTUALIZATION OF INDUSTRIAL PRODUCTION OF BAKERY PRODUCTS USING ULTRASONIC TECHNOLOGIES

The next step was to develop an intelligent control system for the production of bakery products, in which the analysis of disturbances in raw materials, water and equipment was performed using a system for monitoring the performance of technological equipment.

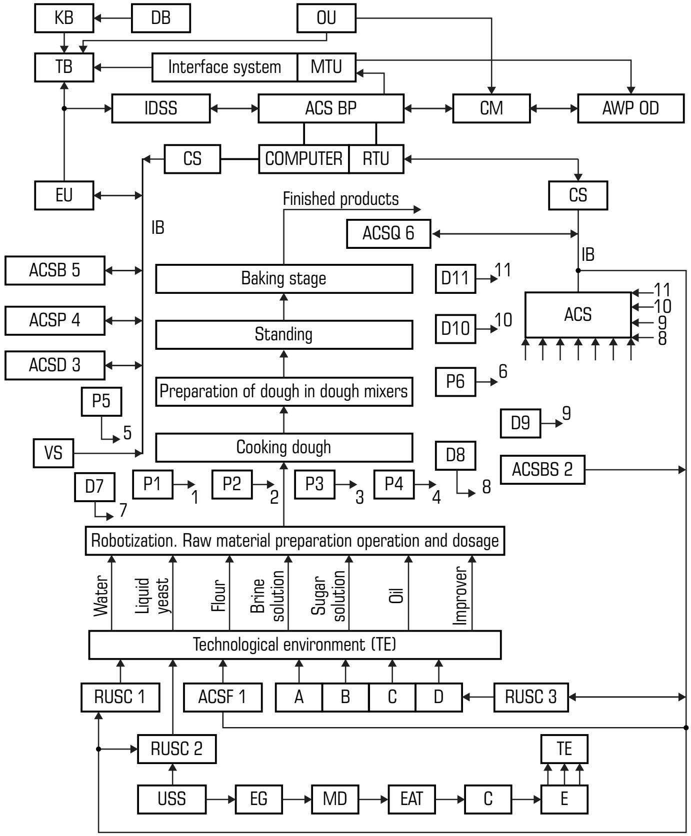
Fig. 9.4 shows a block diagram of a robotic complex for the production of bread. The technological line has built-in ultrasonic devices for water purification, disintegration, mixing and intensification of microbiological, biochemical, colloidal, chemical, hydrodynamic processes of bread production.

In the process control system for the preparation of raw materials, the following blocks with robotic ultrasonic complexes are used:

– RUSC1, RUSC 2 for water purification and yeast disintegration, respectively;

– RUSC 3 – in chambers A, B, C, dispersion methods were used to prepare saline solution, sugar solution and the dosage of fatty products with reinforcing components.

The robotic complex consists of an ultrasonic system (USS) interacting with the technological environment. The ultrasonic vibrating system includes an electronic generator (EG), a matching device (MD), an electroacoustic transducer (EAT), a concentrator (C) and an emitter (E).



ACS – automated control system;
ACS BP – automated control system for the technological process of bread production;
ACSB 5 – adaptive control system for the stage of baking bread;
ACSBS 2 – system of adaptive control of the process of bread srtarter preparation;
ACSD 3 – adaptive control system for dough preparation;
ACSF 1 – system of adaptive control of the stage of flour preparation;
ACSP 4 – system of adaptive control of the proofing stage;
ACSQ 6 – adaptive product quality control system;
AWP OD – automated workplaces of operators and a dispatcher of a bakery;
C – concentrator;
CM – corporate monitor;
COMPUTER – electronic computer;
CS – Communication System;
D7, D8, D9, D10, D11 – sensors;
DB – database;
E – emitter;
EAT – electroacoustic transducer;
EG – electronic generator;
EU – expert system;
IB – information bus;
IDSS – intelligent decision support system;
KB – knowledge base;
MD – matching device;
MTU – Mater Terminal Unit;
OU – output block;
P1, P2, P3, P4, P5, P6 – piezo sensors;
RTU – Romote Terminal;
RUSC 1, RUSC 2, RUSC 3 – robotic ultrasonic intensifiers;
TB – training base;
USS – ultrasonic system;
VS – visualization system

Fig. 9.4 Block diagram of a robotic complex for the production of bread

With the help of an automated control system (ACS), the control of the parameters characterizing the technological operation of preparing the bread starter-dough was carried out. For this, a system of piezoelectric sensors P1–P2, P3–P4, P5–P6, built into the technological environment of the devices, was used. The analyzer consists of three similar channels:

– 1st channel (piezo sensors P1–P2) – indirectly controls the density and other parameters of the dough (the stage of dough kneading);

– 2nd channel (piezo sensors P3–P4) – indirectly controls the fermentation stage of dough, evaluating their uniformity, hydrodynamic parameters and other properties;

– 3rd channel (piezo sensors P5–P6) – determines the concentration of gas bubbles in the dough-dough medium.

When ultrasonic vibrations pass through a dough or dough, due to absorption due to the viscosity and thermal conductivity of the medium, the signal amplitude is attenuated in accordance with the expression:

$$A_y = A_0 \cdot e^{-\alpha y}, \tag{9.10}$$

where A_0 – the amplitude of oscillations emitted by devices of the source of ultrasonic vibrations T1, T3, T5; A_y – the amplitude of oscillations received by the piezoelectric sensors (T2, T4, T6); α – the attenuation coefficient; y – the distance between the piezoelectric elements.

The third channel of the control system is tuned to the resonant frequency of cavitation bubbles liquid-dough-dough. The channel evaluates the optimal parameters of the cavitation effects of the ultrasonic field on the bread starter dough. The main parameter characterizing the effectiveness of the cavitation effect is the cavitation index (CI):

$$IK = \frac{V}{\Delta V}, \tag{9.11}$$

where V – the volume of liquid (dough); ΔV – the volume of cavitation bubbles.

Let's use the cavitation index for an indirect assessment of the efficiency of the robotic ultrasonic complex, preparation of dough and dough.

In the process of developing an intelligent control system for a robotic complex, the following were built: databases (DB), knowledge bases (KB), an expert system, an intelligent decision support system. Identification of the technological process for the production of bread starter dough was carried out using a system of sensors T2, T4, T6, D7–D9, and the knowledge of technologists for expert evaluation of technological processes for bread production was also used. At the same time, the experts turned to a priori acquired knowledge, rules, models, characteristics of the dough and dough, and models of the interaction of ultrasound with biological objects.

In the process of expert research, the following was established:

– the initial temperature of the dough fermentation (28 °C) is lower than the fermentation temperature of the dough (30 °C). The fermentation of the dough lasts 3.5–4.5 hours, depending on the content of flour in it, its variety, quality and quantity of yeast. Humidity and temperature of the dough, the gas-forming ability of flour and their acidity, the density of the dough and the lifting force, the active acidity of the dough determine the rheological properties of the dough and dough;

– the process of preparation of dough and dough can be indirectly controlled by aromatic properties, perceiving the diffusion of water vapor from the surface with the TGS2620 odor sensor (Tagushi Gas Sensor, USA) and visually, using the CB system.

In the future, the expert system (ES) becomes a trained artificial neural network (ANN) and, in combination with an electronic computer (ECM), processes and evaluates information coming from sensors:

– piezoelectric elements P2, P4, P6;

– from the D7–D11 sensor system;

– sensors that control the parameters of the MIUV system Z_H, R_K, K_S, IK.

As a result of EU identification:

– determines the optimal operating time of robotic complexes RUSC 1, RUSC 2, RUSC 3 and power;

– performs the prediction of parameters: K_2 – hydrodynamic conditions of fermentation of the dough and kneading dough; P_0 – the lifting force of the bread starter; ρ_o, ρ_d – the density of bread starter and dough, respectively; λ_m – the mass conductivity coefficient; a_m – the coefficient of internal mass transfer, which depends on temperature and moisture and indicates the intensive property of flour to external disturbances of water, solutions and other improvers.

The main task of the expert system is to choose the optimal inserts in proportion to the integral differential controllers (ADD-regulators) ACSF 1, ACSBS 2, ACSD3, ACSP4, ACSB5.

In the process of experimental studies, it was found that:

– at the ultrasonic frequency f_1=600 kHz, the signals from the sensor P2 (A_y 2) indirectly identify the factors K_2, P_0, ρ_o;

– at ultrasonic frequencies f_2=400 kHz, the signals from the sensor P4 (A_y 1) indirectly identify the factors ρ_t, λ_m, am.

The architecture of an intelligent enterprise management system for the production of bakery products according to IDSS includes:

– expert system (ES), training unit (TU), knowledge base (KB), database (DB), output unit (OU), corporate monitor (CM), automated workstations (AWS) of operators and a bakery dispatcher and interface systems (interactions with an expert, an object and a user);

– APCS for the production of bread production (APCS BP) with a computer at the upper level and local systems of the lower (operational) level.

Bread production process control system built on the basis of SCADA systems includes three structural components:

1) RTU, MTU and CS. RTU (Romote Terminal Unit) – a terminal that processes information from sensors P1–P6, D1–D11;

2) visualization system (machine vision);

3) robotic ultrasonic intensifiers RUSC 1, RUSC 2, RUSC 3. RTU systems operate in hard real time. In turn, MTU (Mater Terminal Unit) is a dispatch control center with automated workstations for operators and a dispatcher. The main task of the MTU is to provide an interface between the operator and the bakery control system.

The CS (Communication System) system is a communication system (communication channels, information bus (IB).

The main task of the CS system is the transmission of control signals to the RTU. The work-technological complex includes:

– systems for adaptive control of individual technological processes and stages ACSF 1, ACSBS 2, ACSD3, ACSP4, ACSB5, ACSQ 6;

– an automated control system (ACS), to the input of which, through ports 1–11, signals are found from sensors T2, T4, T6 – indirectly evaluating piezoelectric elements: rheological properties of dough and dough, dough lifting force, active acidity of dough, acidity of dough and smell (D7, D8), the forming ability of the dough piece (D9), the duration of the proofing of the dough pieces, the proofing temperature, the humidity in the proofer.

The mass of the dough piece is controlled by the D10 sensor system. The porosity of bread, its acidity, form stability, humidity, temperature in the center of the pulp, the duration of baking dough pieces are controlled by the D11 sensor system and the visualization system (VS).

The system uses the apparatus of artificial neural networks to find solutions for optimal modes of operation of the stages of bread production. This is achieved by recognizing production situations and identifying S_n – problem situations in tempo with the process of bread production. Recognition of situations S_b and S_n from a set of n situations will be called the classification process. With this interpretation, as the initial result at the output of the output unit (OU) of the IDSS system, let's obtain the situation number S_b or S_n. To train a multilayer INN, the method of error back propagation was used. In the process of training the network, the learning expert sets: the learning rate, the number of situations S_b, S_n for each of the technological stages. This approach can significantly improve the accuracy of situation recognition and assessment of the state of the performance of technological processes: dough fermentation, dough homogeneity and control of bread baking processes.

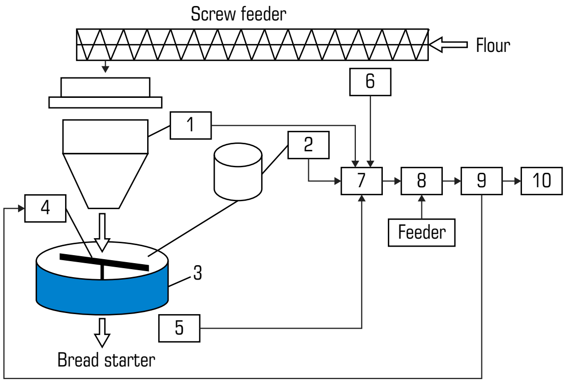
The process control system for bread production uses algorithms for intelligent control of the processes of preparing raw materials, preparing dough, dough, aging and baking with expert assessment of the quality of raw materials, semi-finished products and finished products with decision support subsystems, developed in detail by the authors. An intelligent decision support system based on information from the sensors of the DB, KB, TB, output blocks, the EU expert system and ACSF 1, ACSBS 2, ACSD3, ACSP4, ACSB5, ACSQ 6, changes the operating modes of ultrasonic systems RUSC1, RUSC2, RUSC3. This is carried out through performing mechanisms by working out optimal management actions on a heterogeneous technological environment. Flour parameters are assessed by the expert product quality management system ACSQ6. The recommendations of the latter through RTU, CS enter the automated control system for the stage of preparation and dosage of flour (ACSF 1). IDSS recommends in an interactive mode using KM a way to improve the properties of flour, dough and dough by fortifying the properties of bread.

Later, intelligent control systems for the technological process of production of bakery products were developed at its individual stages. So, **Fig. 9.5** shows a block diagram of the control of the production of bread starter, and **Fig. 9.6** – an adaptive digital control system for the entire dough mixing department with additional capabilities for reproducing the technology of low-temperature slow fermentation of dough, as well as an integrated system for freezing dough semi-finished products.

Algorithms have been developed that are embodied in adaptive systems for optimal control of bakery production processes, implemented using modern microprocessor systems that work with identifiers and provide automatic quasi-optimal adjustment of control systems for technological stages of food production. It has been established that the optimal quality parameters of the technological process of bread production can be determined and adjusted using adaptive digital controllers.

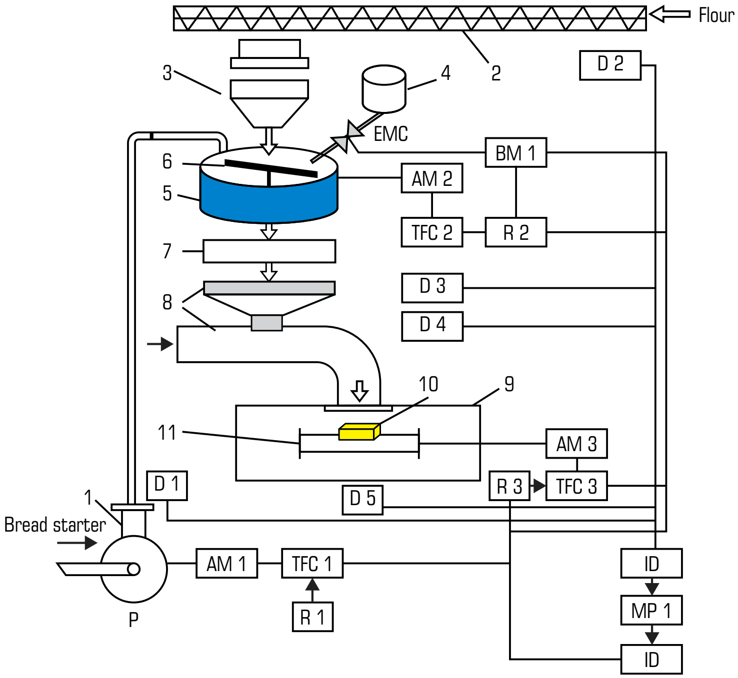
Thus, the complex influence of the frequency, intensity and speed of ultrasonic vibrations, the creation of cavitation effects, dispersion, disintegration, coagulation allows to optimize the operations of preparing bread starter and dough. That is, with the help of robotic complexes built into the technological process of bread production, it is possible to achieve a higher quality of bakery products.

Systems for monitoring the performance of equipment and the quality of water, raw materials, bread starter, dough are based on agency technologies, which makes it possible to build adaptive control systems for the dough preparation and bread baking complex based on fuzzy controllers.



1 – automatic device;
2 – automatic water measuring device;
3 – dough mixing machine;
4 – stirrer motor;
5 – bread starter quality sensor;
6 – flour quality sensor;
7 – MP;
8, 9, 10 – dough mixer loading system 3

Fig. 9.5 Block diagram of the control of the bread starter production process



1 – pump with electric drive AM 1 – TFC 1;
2 – screw flour sensor;
3 – automatic device;
4 – automatic water meter tank;
5 – dough mixing machine;
6 – electric stirrer AM 2 – TFC 2;
7 – five-section bunker;
8 – robotic production complex;
9 – refrigerating chamber;
10 – bread;
11 – conveyor with electric drive AM 3 – TFC 3

Fig. 9.6 Adaptive digital control system for the dough mixing department

An analysis of the results of the functioning of the algorithm and structure of the adaptive automated control system (ACS) with monitoring of equipment performance (monitoring of product quality) allows us to conclude that the method of constructing adaptive ACS allows to synthesize fuzzy controllers for elementary operations of technological processes of bread production, taking into account the nonlinearity of objects of control project.

It is proved that the development of a reference problem under the conditions of uncertainty of external and internal disturbances not controlled by sensors can be evaluated by an expert system for the formation of algorithms for controlling the technological process of bread production. Taking into account the knowledge and skills of operating personnel in an expert control system with agency technologies for monitoring the performance of equipment and the quality of raw materials, including water [11], makes it possible to build intelligent control systems for the industrial production of bread with optimization of its performance parameters and minimization of specific energy consumption.

A multi-level intelligent system for automated control of the technological process of bread production has been developed. The architecture of this system uses a robotic complex with an intelligent decision support system and training units, databases and knowledge, a unit for displaying information on a corporate performance monitor, an automated workplace with an interface system, and an artificial neural network for recognizing emergency, abnormal and normal situations.

It should be noted that the use of robotic complexes with built-in monitoring systems and ultrasonic intensifiers in the industrial production of bakery products allows reaching a new level of quality and security of reproduction of technological processes and the final product, due to unmanned technologies with adaptive production control systems.

Thus, the development of systems for multi-purpose control of technological processes of bakery production based on product quality control and intelligent technologies will help increase labor productivity and reduce the specific losses of food, energy and other types of resources.

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The scientific novelty of the research carried out lies in the development of an intelligent system for monitoring and controlling the performance of equipment and the quality of water, flour, bread starter, dough based on agency technologies, which allows building adaptive control systems for a complex for automated dough preparation, molding products, baking bread, based on fuzzy controllers. its packaging and freezing.

It is proved that the development of a reference problem under the conditions of uncertainty of external and internal disturbances not controlled by sensors can be evaluated by an expert system for the formation of algorithms for controlling the technological process of bread production.

Thus, for the first time, the theoretical and practical results of intelligent control of complex technological processes for the production of bakery products with digital control algorithms for food industry enterprises are systematized in the work. The principle of their operation is based on the functionality of microprocessor control systems for complex technological processes of production, IIoT, digital platforms, distributed control and software products. The intelligent enterprise provides not only automatic provision of the normal flow of production of bread and flour products, but also automatic control of the start and stop of devices for repair work and critical situations.

It is predicted that the developed intelligent energy saving management systems at food industry enterprises will improve the efficiency of high-quality production and reduce energy costs by 10–15 % of the normal system capacity.

The paper proposes several new systems for quality control of bakery products and technological processes, as well as control algorithms using intelligent mechanisms. A number of adaptive process control systems have been developed.

A conceptual approach to the implementation of research on the development of the project «Intellectual enterprise for the production of bread and flour products» is proposed.

The development of systems for multi-purpose control of technological processes of bakery production based on product quality control and intelligent technologies will help increase productivity, reduce specific losses of input raw materials, human resources, electricity, gas, etc.

The paper analyzes the features of the technological processes of bakery production and the production of flour products as complex objects of quality management, the analysis of existing systems for the production of bakery and flour products at the enterprises of the industry and the determination of the main parameters of the operation of automated technological processes for the production of reasonable food products.

Perspective ways of improving product quality management systems and increasing the efficiency of managing the technological complex of a bakery based on modern achievements in science and practice of managing bakery equipment have been identified, which will improve the ecological state of the environment.

The carried out systematic analysis of the technological subsystems of the bakery made it possible to single out their performance characteristics in terms of assessing the complex indicators of the quality of raw materials, semi-finished products and finished products, and also proved the socio-economic essence of the concept of reasonable food products and their synergistic effect for regions with a technogenic load.

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