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DEVELOPMENT OF A CONCEPTUAL MODEL OF A ROBOTIC COMPLEX FOR THE PRODUCTION OF RAVIOLI OF SPECIAL FORMS

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Abstract

The article provides a substantiation of the conceptual model of the production process of special forms of dumplings. It is the first stage in the development of a model of this process as a control object. The purpose of which is to form an objective basis for the development of an effective system for automatic process control. The development of the conceptual model presupposes the specification and description of the properties of control channels and acting disturbances to the level of their mathematical model, which can be implemented in a simulation environment. Problems of identification of the mathematical model of the process of the production of dumplings, i. e. obtaining a mathematical description of processes based on the results of its purposeful experimental research, due to its complexity as a control object.

The experimental approach, in this case, gives much more reliable results on the properties of the process. An attempt to obtain such general properties on the basis of experimental data would inevitably lead to the need for very complex and lengthy multifactorial experiments and nontrivial procedures for their processing. But this will leave open the question of the adequacy of the model for those conditions of the process and types of raw materials that were not covered by the experiments. Fundamentally important is the fact that the mathematical model of the process is developed as a model of the control object.

Model can be used in two ways. This is due to the fact that in the closed circuits of the SAC, the discrepancy between the models can be considered as a manifestation of uncontrolled coordinate and parametric disturbances. It is in conditions of this kind of disturbances that the SAC must fulfill its functional purpose. The developed mathematical model of the production process of special forms of dumplings will be used by us only in the direction, when it is of great importance not so much quantitative as its qualitative correspondence to the original object.

Keywords: ravioli, guarantee function, conceptual scheme, SAC, energy efficiency, optimization, special cubic shape.

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1. Introduction

Every nation has its own particular regional food culture. Ravioli as food products play an important role in the food culture of Ukraine, Russia, China. Ravioli are even used as ceremonial products [1]. A large number of studies are devoted to increasing the competitiveness of the food market and expanding the range of products [2].

The quality of ravioli is influenced by the characteristics of the flour [3], the rheological properties of the dough [4], protein polymerization [5], temperature [6, 7] etc.

The problem of maintaining quality, reducing energy costs in the production of ravioli is relevant. The aim of the work is development of a conceptual model of a robotocomplex for producing ravioli of special forms.

2. Literature review and problem statement

The ravioli production has fundamental features that must be taken into account when developing automatic control systems, claiming energy efficiency.

Let's list the factors, savings in financial expenses, can be achieved by changing them:

1) currently, for the production of manufacture goods and ravioli the main task that is controlling finished products, with a high percentage of the human factor;

2) the technological process of production consists of defrosting minced meat before modeling, and re-freezing it after receiving the product, that entails additional financial costs;

3) current form of ravioli manufactures is traditional.

The following factors are characteristic of minced meat and dough:

1) the recipe of products and their composition change due to the presentation of increasingly high requirements to products: increased nutritional value, cost reduction, expansion of the resource base, enrichment with vitamins and additives [7, 8];

2) the characteristics of the original product, even within the same recipe, always differ from each other (the composition of the dough and the composition of minced meat) and, therefore, during the process they can change significantly.

Let's point out two factors, those can be changed to perform the effectiveness of the system. The first factor is a changing form of the product in the direction of complication, excluding counterfeiting. The second factor is improving warehousing, performing density and transportation. Combining the above factors, we can create a new ravioli of a special form. And the technological process for the products production, in which the secondary defrosting of ingredients is not required. The optimal and difficult to implement form of ravioli is cubic form. This form:

1) will be a protection against a fake product manufacturer;

2) allows incoming raw materials (meat) to process (produce minced meat), and to store frozen ingredients (minced cubes);

3) will give the opportunity to work with raw materials, without subjecting them to full defrosting and further re-freezing;

4) receiving products with a given shape, also carries a reduction in energy costs during storage and transportation of products;

5) minimize human factors in production.

Research on unconventional ravioli is rare. It is mainly 3D printing food [9].

In general, to obtain finished products of manufactures, it can be provided by fairly simple ACSs that implement only the regulation functions, i. e. stabilization of process variables of the process at their given values. These control functions are implemented on the basis of the simplest typical algorithms, as a rule, PID control algorithms. This is only possible due to the fact that the recipe of finished semi-finished products and the characteristics of raw materials and ingredients are not changed. This causes the two most important circumstances for managing the process:

1) unchanging of found at the stage of special studies of the optimal modes of production. As a result, there is no need to implement control functions during the process, such as optimization and adaptation;

2) the lack of disturbances in raw materials, i. e. the lack of operational process variables, the consequences of which are necessary to be compensated by ACS, when implementing the regu-

lation function. Disturbances those persist are associated with fluctuations in ambient temperature and the speed of pneumatic operation, according to specified algorithms. The intensities of these disturbances are rather low, and the task of stabilizing them is fairly simple.

Thus, an effective SAC must solve the problem of optimizing the current mode of conducting a technological process for a particular raw material directly during its processing [10]. In this case, the recommended values of mode variables, taken from recipes or obtained in laboratory conditions, should be considered as quasi-optimal and used in search engine optimization as initial approximations.

This is due to the fact that a change in the characteristics of raw materials and ingredients changes the values of mode variables and the properties of the controlled object (CO) for control channels. It is necessary to take into account the fact that ensuring the robustness of the system, when implementing adaptive algorithms, will not be as effective. After all, with sufficiently intense disturbances, these algorithms do not converge well and create a significant component of the system's motion, and this, in turn, creates additional control errors. In this case, it is more expedient for us to use control algorithms [11], those are special for technological type objects, which provide extending if stability margins of systems compared with standard algorithms.

3. Development of a conceptual model of a robotic complex for the production of special shapes ravioli

3. 1. Process line analysis

The most important control channels (**Fig. 1**) are the feed of the ingredients channels (frozen minced meat –15 ... –30 °C and warm dough 20 ... 25 °C). On certain conditions of disturbances in raw materials and in combination with them other conditions for the maintenance of TP, the process of obtaining finished products changes its properties from static to astatic. This greatly complicates the management of the process, and can also affect the operation of the equipment and lead to negative consequences up to an emergency stop. The situation is complicated by the fact that the most effective modes of equipment operation can be achieved, when the raw materials are supplied in a mode close to sticking dough and equipment jamming mode. This contradiction can be resolved by ensuring that a predetermined compromise is maintained in real time between the probability of an emergency and the maximum allowable temperatures by guaranteeing control [12].

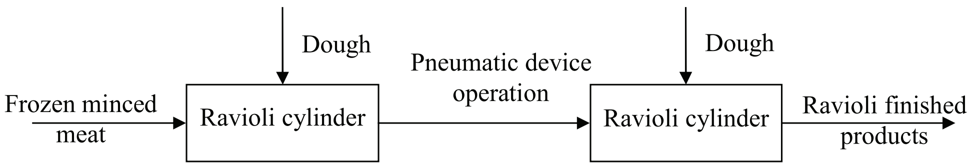

Fig. 1 Technological scheme of ravioli products production process

Next, we will consider equipment for the production of ravioli products (RP) of strict cubic form. The technological process is implemented on the ravioli equipment.

Equipment for the production of ravioli of special cubic shape (**Fig. 2**), is a cylinder-type equipment with a production speed of RP 600-1200 pieces per hour, the weight of one ravioli of special form is 12 gram, in size 22×22×22 mm. Equipment, developed by Pavel Golubkov.

A new approach to the development of new products is based on the creation of targeted equipment, which is responsible for carrying out most of the work on the production of a new product and its storage before marketing. Parallel development of products of complex forms, with already existed and used at the enterprise technologies, leads to saving not only time, but also financial resources. This may allow, on the basis of this information, to use the resources of the management of the device so purposefully that the product maximally meets the required quality.

The guarantee function [13] should provide:

a) real-time evaluation and on its sliding intervals of the current values violations probability of the restrictions, established by the regulation (tolerance fields), including the above parameters, characterizing the quality;

b) correction of the current temperature modes of the incoming raw materials, in which the values of these probabilities would not exceed their specified maximum allowable, pre-set values.

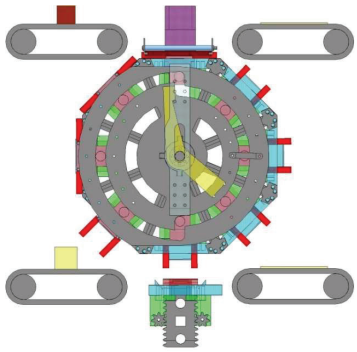

Fig. 2. 3D model of equipment for the production of ravioli products of special forms "CUB-2015"

This can ensure compliance with product quality requirements and trouble-free fault-tolerant operation of equipment, including, and this is important – in the vicinity of the maximum permissible loads of pneumatic equipment. Exactly this can create the necessary conditions to minimize the specific energy consumption for the TP. The function of optimizing the current mode should allow purposefully redistributing process management resources to achieve maximum economic effect with unconditional fulfillment of all technological and operational requirements. It should be emphasized, that the action of all the listed functions, those the SAC by the process must implement, is interconnected in the most essential way. At the same time, the effectiveness of the functioning of each of them largely affects the efficiency of the others and vice versa. Therefore, the development of an effective SAC by the process of ravioli production is a holistic and fairly knowledge-intensive task.

3. 2. Development of a conceptual model of the production process

The initial stage of such development should be the construction of the most common (conceptual) model of production process of RP as CO (**Fig. 3**). Such a model is the first stage of concretization and formalization of the new control tasks those were formulated above. It will form the basis for the development of SAC with a targeted set of functions that will allow to solve the formulated control tasks and to achieve the main goal of developing such SAC – improving product quality and energy efficiency of TP RP production.

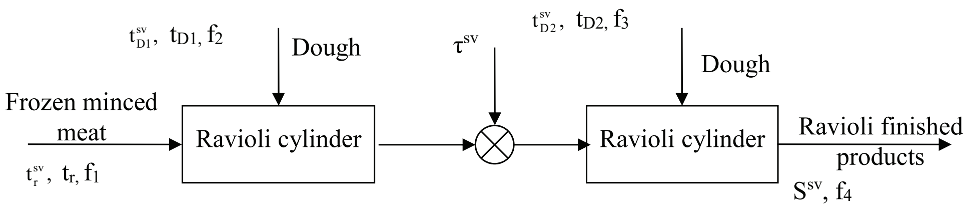

Fig. 3. Parameterized technological scheme of RP production process: tr^{sv} – set value of ravioli temperature; t_r – ravioli temperature; S^{sv} – set value of ravioli form; τ^{sv} – idle time specified by technical regulations; t_{D1}^{sv} – set value of top dough temperature (1 serve); t_{D1} – top dough temperature (1 serve); t_{D2}^{sv} – set value of bottom dough temperature (2 serve); t_{D2} – bottom dough temperature (2 serve); f_1–f_4 – uncontrollable disturbances

The above analysis briefly shows us the features of the RP production process and determines the composition of the backbone functions of the SAC of this process. The analysis of changes in the properties of products with changes in the properties of plant materials, significantly affecting the quality indicators of the finished product, energy efficiency and stability of TP, was carried out in the tables of the technological process.

The composition of potential control actions is determined; changing which you can influence the course of the production process RP. Realizing the necessary management functions, one can present a conceptual model of the RP production process as a block diagram, look at **Fig. 4**.

The arrows those indicate the variables on the diagram indicate the direction of their interaction – "from cause to effect", and the rectangles indicate the presence of non-unit operators for the transformation of these variables.

The following groups of variables are highlighted on the structural diagram:

1) variables those are indirect indicators of quality of the RP process and available for measurement in real time [14];

2) variables, characterizing the temperature mode of operation – T^{sv} – internal temperatures T^{sv}_{D1C}, T^{sv}_{D2C}, T^{sv}_{D3C} vegetable raw materials: incoming minced meat, incoming dough in two zones and incoming the second zone of minced meat with dough;

3) equipment performance variables: pneumatic equipment operation and time, needed for auxiliary operations, τ^{id} – downtime, (variables f_1–f_4 and T_{mm} indirection changing).

Changing the τ^{sv} – time of the paste, leads to an increase in the temperature of the minced meat and a decrease in the temperature of the dough, applied to the minced meat.

The amount of downtime during the execution of the technological process can be defined as the volumetric capacity of the line. The productivity of the line directly depends on time, required to perform glinting of ravioli in the forth zone of ravioli equipment, and also on time of waiting mode of the equipment, which can be changed, according to the technological regulations 4 times, from 1 to 4 seconds.

It should also be noted, that the time, required for feeding the raw material to the machine, depending on the ingredients of the dough and minced meat, can vary by 2 times, from 3 to 6 seconds. The time, spent on the operation by the actuator, is 2 seconds in both directions. It is also necessary to take into account the fact that from the top to the lower chamber the ravioli comes in 5 cycles of the cylinder. As a result, the time, taken to move, may vary significantly for different types of products and amounts from 6 to 12 seconds to produce one unit, and the time, spent in the cylinder of minced meat with 50 % of applied dough, is from 30 to 60 seconds.

For a minute, when the dough with a temperature of 25 °C is in contact with minced meat, which has a temperature of (–13) °C, it will cool down. This will negatively affect the formation of seams, when sculpting in the lower part of the chamber. Such conditions can lead to an increase in the time, required for simulation, an increase in the production time of the RP.

The values of volumetric productivity at the equipment output are denoted as τ^{sv}, $\Delta\tau^1$, $\Delta\tau^2$, τ^{TS} and $u\tau$ (**Fig. 5**). Formally, the dependence of the change of these variables on $u\tau$ can be written as follows:

$$u\tau=(\Delta\tau^1+\tau^{sv}+\Delta\tau^2+\tau^{TS})*5. \quad (1)$$

The work of the forces (moments), necessary for the rotation of the cylinder and the extension of the grip by pressure, is converted, ultimately, into heat. The energy for doing this work is taken from the electrical network and converted into mechanical, through the means of operation of the compressor and the actuator.

The power and efficiency coefficients for each specific recipe during production are non-linear functions of the arguments of technological equipment downtime:

$$u\tau=\int_{t_{\min}}^{t_{\max}}\left(\Delta\tau^1+\tau^{id}+\Delta\tau^2+\tau^{TS}\right)*5, \quad (2)$$

where: $\Delta\tau^1$ and $\Delta\tau^2$ the coefficient of the minimum and maximum idle time intervals in $[t_1, t_2]$. The control task, realized due to changes in $\Delta\tau^1$ and $\Delta\tau^2$, should be the task of regulating (stabilizing) $u\tau$ n a neighborhood that tends to $t_{\min}$ subject to restrictions on other process variables. The analysis of the conceptual model of the RP production process, obtained above, makes it possible to concretize the principal features of the RP production process as CO.

They can be formulated the next way:

1. Incompleteness of information on the state of the characteristics of the raw materials (minced meat and dough) during the process is not actually controlled. Laboratory measurements of these characteristics, even in the case of the use of express methods, introduce delays those are many times longer than the product's stay in the chambers of the heating and modeling zones, which does not allow this information to be used to control the current RP production process modes. In addition, the results of such measurements are represented by the lattice low-frequency function of time. Its values, due to the transposition of relatively high-frequency unfiltered factors, "measurement noise", to the low-frequency region, have errors those cannot be estimated.

2. Restriction of resources on process management. Potentially, the following variables can be used as control actions in SAC of the RP production process:

a) changing in the supply of raw materials to the equipment;

b) changing in power supply to the heaters (heating elements) of heating zones.

The essence of the restrictions:

1) the number of targeted effects on regulated variables, the change of which is available during the process, is significantly less than the number of these variables;

2) heaters power change range;

3) the cooling of the minced meat inside the equipment is not provided;

4) changes in the supply of raw materials during the RP production process, to a large extent, have similar consequences, and, most importantly, they affect all other regulated variables;

5) technical means for automatic resizing of ravioli products (actuator and corresponding mechanical transmission) are not provided in the basic design of the equipment, although their installation is possible.

3. The high level of uncertainty of the properties of the control channels of the RP production process as CO. The recipe of products, and, consequently, the composition of their raw materials, is changing quite dynamically due to the presentation of increasingly high demands on products, in particular – increasing their nutritional value, reducing production costs, expanding the raw material base, enrichment with minerals and vitamins.

At the same time, the characteristics of the original product, even within the same recipe, always differ from each other. This is due to peculiarities of previous technological operations with raw materials, soils in the places of its growth, applied fertilizers, precipitation, storage conditions, amount of proteins, fats and carbohydrates and etc.

This leads to the fact that the regulations, found in the laboratory conditions for maintaining the technological process of RP production, i. e. set of values of mode variables (regulations), for production conditions should not be considered as optimal, but only, and in best case, as quasi-optimal. Such uncertainty is caused by the inevitable differences in the characteristics of the raw materials, design and condition of the working parts of the equipment, which were used in laboratory conditions, and which will be used in production conditions.

In addition, the listed changes to the specific conditions of the RP production affect the dynamic properties of the control channels and, therefore, the quality of the implementation of control functions, in particular, the stability margins of closed control loops. In addition, the listed changes to the specific conditions of the RP production affect the dynamic properties of the control channels and, therefore, the quality of the implementation of control functions, in particular, the stability margins of closed control loops. Since it is impossible to trace and describe the causal relationships between RP production and dynamic properties, the changes of the latter should be considered as their uncertainty, and very significant. The regulation functions are implemented on the basis of the closed principle of control of the corresponding regulators. In this case, control actions are formed on the basis of regulation errors, in accordance with the control algorithms, chosen for regulators:

$$u_d(t) = W^p_{I_{heater}}(\Delta I, t)\left(I^{svv+}_{heater}(t) - I(t)\right), \tag{3}$$

$$u_{nom_i}(t) = W^p_{\theta_i}(\Delta\theta_i, t)\left(\theta^{sv}_i(t) - \theta_i(t)\right), \tag{4}$$

$$u_{\tilde{d}}(t) = W^p_{\theta_d}(\Delta\theta_d, t)\left(\theta^{svv+}_d(t) - \theta\ (t)\right), \tag{5}$$

where $W^{p}_{I_{heater}}(\Delta I,t)$, $W^{p}_{\theta_i}(\Delta\theta_i,t)$, $W^{p}_{\theta_d}(\Delta\theta_d,t)$ – control algorithms of current, temperature of heating zones, temperature in the modeling chamber; $I^{svv+}_{heater}(t)$ – set value of I_{heater}; θ^{sv}_i – set values of $Q_i(t)$, formed from the conditions of ensuring the required product quality; θ^{svv+}_d – set value of $\theta_d(t)$, formed to ensure compliance with the form limits S_F.

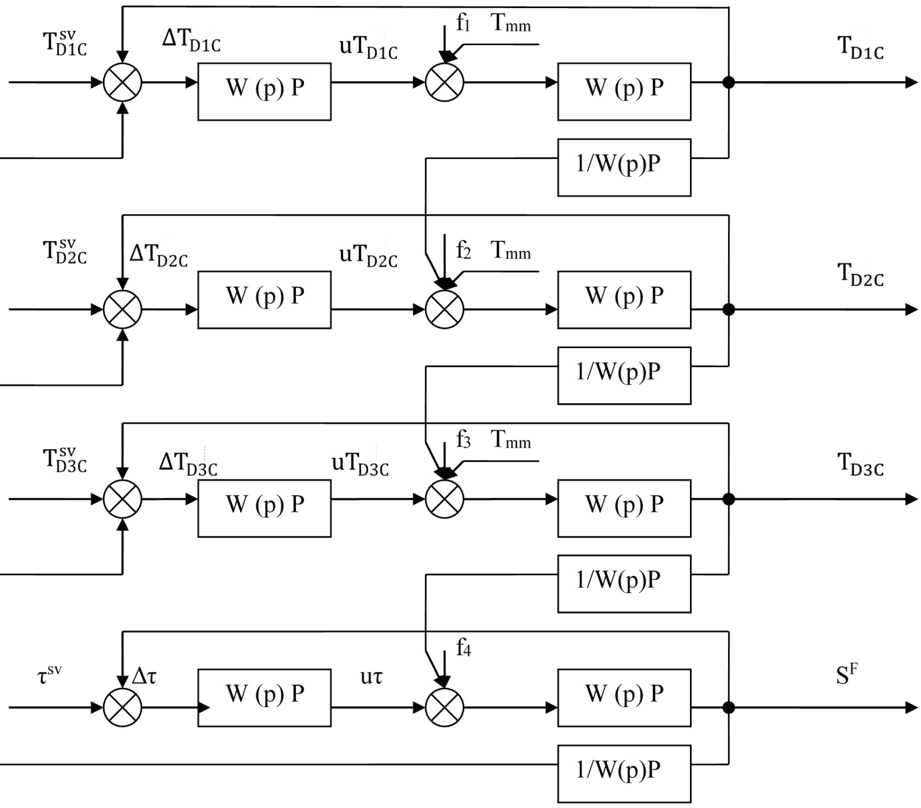

Fig. 4. Block diagram of the conceptual model of SAC: τ^{sv} – set value of time of modeling; S^F – ravioli form; T^{sv}_{T1C} – set value of temperature of dough in the first zone; $T_{T'C}$ – temperature of dough in the first zone; T^{sv}_{T2C} – set value of temperature of dough in the second zone; $T_{T''C}$ – temperature of dough in the second zone; T^{sv}_{T3C} – set value of temperature of dough in the third zone; $T_{T''C}$ – temperature of dough in the third zone; f_1–f_5 – uncontrollable disturbances; T_{mm} – uncontrolled temperature of minced meat

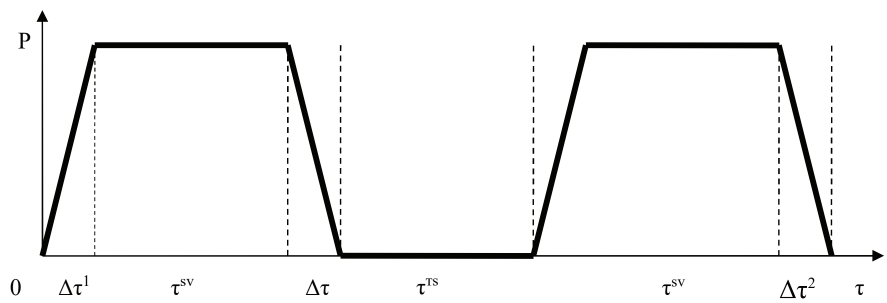

Fig. 5. Time diagram of the pneumatic actuator work: $\Delta\tau^1$ – rod pushing out time; τ^{sv} – idle time according to technological standards; $\Delta\tau^2$ – rod pulling in time; τ^{TS} – technological shutdown time

Optimization functions are designed to ensure the achievement of conditional optima on the energy efficiency of the process (minimum specific energy consumption) and the quality of RP. The value of specific energy consumption is calculated by the averaged over sliding time intervals τ_{cp} of electrical power spent on the process:

$$\eta_{producrion}(t) = \int_{t}^{t+\tau_{av}} P_{RP}(t)\,\mathrm{d}t \Big/ \int_{t}^{t+\tau_{av}} Q_m(t)\,\mathrm{d}t. \quad (6)$$

Note the following:

1. The averaging time τ_{av} should be chosen so that the spectrum of averaged power and performance would suppress high-frequency components, caused by transients in the circuit.

2. *f* the optimal values of $\eta_{production}$ should be compared for different types of raw materials, then this would require sufficiently accurate measurements of $P_{RP}(t)$∈$Q_m(t)$. Such measurements for $Q_m(t)$ are rather complicated. But, since the optimization problem of $\eta_{production}(t)$ must be solved as the problem of current optimization, i. e. within a specific type of raw material, the value of Q_m can be taken fairly approximate, for example, calculated from the value of u_d and the mathematical model.

Consider the structural scheme of the ACS that implements the selected functional organization. Obviously, the functional organization of the SAC, discussed above, defines only the most general requirements for the developed system. This commonality causes considerable freedom in the concrete realization of functions. Of course, the number of implementation options that can be attributed to the competitive group is large and can hardly be finally determined. It is important to consider not just competitive, but alternative options that have different advantages and disadvantages and therefore may be relevant for specific models of RP production equipment, with their features. The next, after the functional organization, the level of specification of the SAC is its structural organization. It reflects the specific implementation of functions through the block diagram. Consider the following block diagram of the SAC of the RP production process, which specifies the management concept, adopted here.

The principal feature of the SAC, the block diagram of which is shown in **Fig. 6**, is that it uses the data of temperatures in the first two zones and the results of control actions in them, predicts the temperature for the third zone.

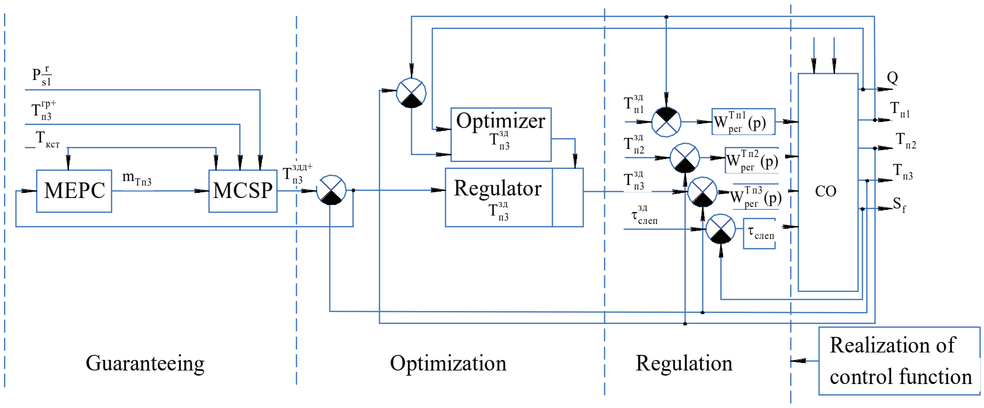

Fig. 6. Structural scheme of SAC of RP production process in case of using of algorithm of predicting the temperature for the third zone

We emphasize that this scheme involves the use of control actions for each channel in the continuous change mode. The regulation functions are implemented on the basis of the closed principle of control of the corresponding regulators. In this case, control actions are formed on the basis of regulation errors, in accordance with the control algorithms, selected for regulators. Optimization functions are designed to ensure the achievement of conditional optima on the energy efficiency of the process (minimum specific energy consumption) and the quality of ravioli products.

The value of specific energy consumption is calculated from the averaged over the sliding time intervals τ_{av} of the electric power, spent on the process, and the time, spent on heating the dough:

$$\eta_{production}(t) = \int_{t}^{t+\tau_{av}} P_{RP}(t)\,\mathrm{d}t \Big/ \int_{t}^{t+\tau_{av}} Q_m(t)\,\mathrm{d}t. \quad (7)$$

The task of optimizing quality in this (**Fig. 6**) structure of SAC is solved by changing the heater power, as well as measuring the difference between the steady-state temperatures in the first TP1 and second TP2 control loops and the transition time between zones, during which the temperature values are lowered. During the process, quality indicators stabilize at the optimal level.

In (**Fig. 7**) presents a fragment of the results of experiments on the study of dynamic channels of temperature regimes.

The obtained results prove the adequacy of mathematical models.

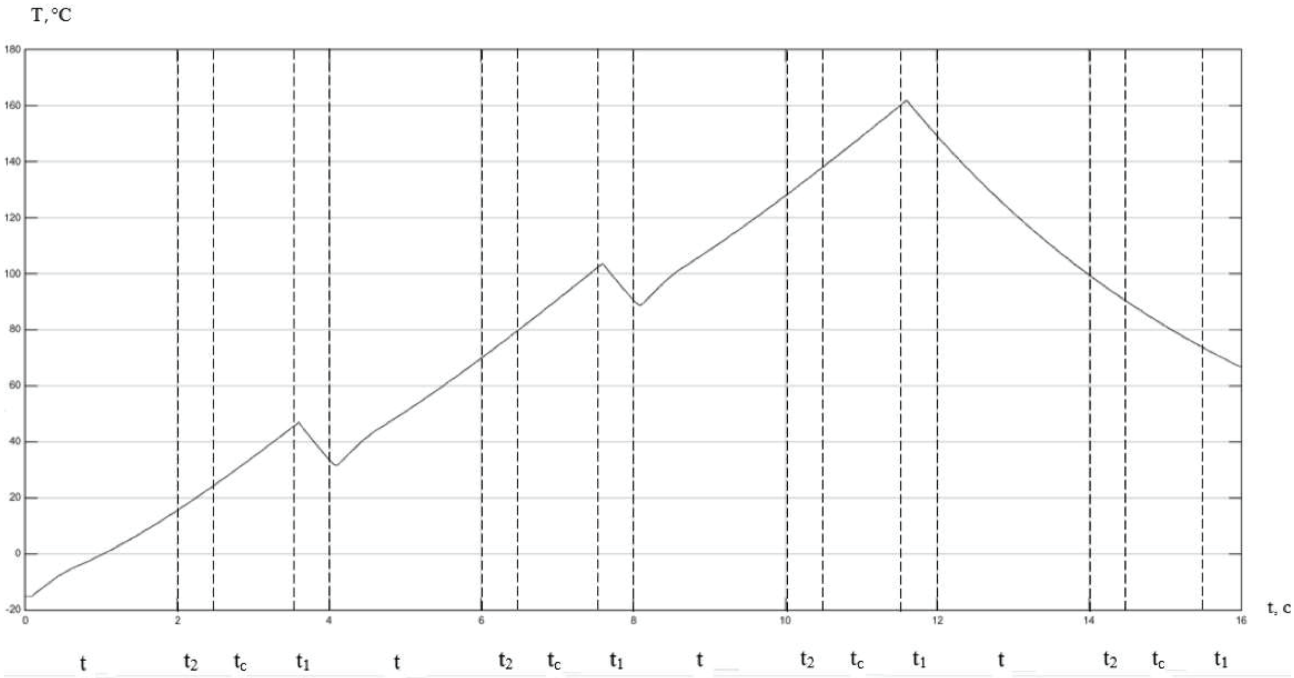

Fig. 7. Fragment of experimental research results: t – technical waiting time; t_2 – time of extension of the rod of the pneumatic cylinder; t_1 – return time of the pneumatic cylinder; t_c – cast time

4. Discussion of results

The structural diagram, as a graphical form of the conceptual model, has reflected in a convenient form the interconnection of input, internal and output variables of the CO. At the stage of development of the SAC of RP production, the features of the EA, listed above, are presented in the form of problems, the degree of overcoming of which, ultimately, will determine the level of effectiveness of the SAC. It is obvious, that a constructive approach to the development of an effective SAC should be adequate to the problems, and, above all, should be systemic, in our case system-functional. Within the framework of such an approach, the methodological basis consists of the concepts of "functional organization of the system" and "development of the system in the direction of increasing functional integrity". It became the basis for the development of the concept of building effective SAC of the RP production process. The implementation of such a concept, due to the specific properties of the CO is a fairly knowledge-intensive task. In particular, because the number of regulated variables of the RP production process is very much higher than the number of control actions available for implementation, it is impossible to stabilize the process for all regulated variables based on classical approaches to the construction of SAC. Its solution leads to the need to expand the composition of functions, implemented by the system due to optimization functions, measurement of indirect ravioli quality indicators in real time and improvement of the implementation of traditional functions, i. e. regulatory functions.

5. Conclusions

The developed conceptual model of the RP production process made it possible to identify the key features of the CO:

a) a high level of incompleteness of information on the state of the process and the consequences of control actions;

b) a significant limitation of resources for managing the process;

c) a high level of uncertainty in the properties of the equipment for RP production as an CO.

The developed block diagram of SAC by the RP production process and key control algorithms specify the adopted control concept, solving the formulated problems, ensuring that all process requirements, established for the process regulation, including – restrictions on the values of variables, as well as the synergistic nature of the interrelationships of the various functions of the process control system. The need to expand the composition of the functions, implemented by the system, and improve the implementation of traditional functions leads to a significant complication of the algorithms, implemented by the SAC.

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