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DEVELOPMENT OF STRUCTURAL-PARAMETRIC OPTIMIZATION METHOD IN SYSTEMS WITH CONTINUOUS FEEDING OF TECHNOLOGICAL PRODUCTS

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Підвищення ефективності безперервних технологічних процесів на практиці супроводжується певними труднощами. Наявність цих труднощів обумовлена тим, що якість вихідного технологічного продукту функціонально пов'язана з величиною енергоспоживання. В свою чергу, відсутність необхідних ступенів свободи, в рамках досліджуваної системи, обмежує оптимізаційні можливості процесів управління.

Для підвищення ступенів свободи управління технологічний механізм був розділений на технологічні секції. Секції дозволяють збирати незалежні модулі, кожен з яких має свою підсистему стабілізації якісного параметру технологічного продукту.

Такий підхід дозволив встановлювати різні траєкторії зміни якісних параметрів технологічного продукту в рамках однієї виробничої стадії.

В результаті дослідження було встановлено, що зміна структури технологічного механізму (кількості модулів) і траєкторії зміни якісного параметру технологічного продукту дозволяє змінювати загальну величину енергоспоживання і зносу робочих механізмів устаткування.

Запропонований підхід дозволив отримати дві ступені свободи управління: можливість зміни секційної структури в модульні системи, що само стабілізуються, і зміни траєкторії якісного параметра технологічного продукту в рамках виробничої стадії.

Отримання ступенів свободи управління, в свою чергу, дозволило змінювати ефективність використання ресурсів безперервного технологічного процесу і розробити метод структурно-параметричної оптимізації. В якості критерію оптимізації використовувався оціночний показник, який пройшов перевірку на можливість його використання в якості критерію ефективності.

В результаті, оптимізаційні можливості управління істотно зростають.

Принципи підходу розглядаються в роботі на прикладі одно-, двох- і трьох стадійного процесу безперервного нагріву рідини

Ключові слова: структурно-параметрична оптимізація, ефективність безперервного процесу, безперервний технологічний процес

1. Introduction

At the stage of automation development [1], it was obvious that the main problem of any production structure is maximizing resource efficiency in the required quality with the necessary performance production course [2].

Technologically more difficult these issues are resolved in systems with continuous input products supplying. For achievement of required quality here it is necessary to resolve the tasks of output products qualitative parameters stabilization [3].

It is known that additional launch losses reduce the overall technological process efficiency, for the maximization of which the continuous systems initially have fewer possibilities. This is due to the fact that in systems of this class, the quality and productivity are functionally interrelated [4].

For example, if a consumer needs a hot liquid of the set temperature, then changing the intensity of cold liquid supply and selecting the intensity of energy product supply, one can choose the most efficient mode of the heating system functioning.

But the consumer needs a product that has not only the required qualitative, but also the quantitative parameters. Therefore, the problem of increasing efficiency in continuous systems is associated exclusively with the use of structural changes in the technological part.

The degree of freedom of control can be obtained if inventory control systems (the buffering system) are arranged between the systems the technology products qualitative parameters of which change.

In that case, within the continuous system, the issue of ensuring the required qualitative parameter of an output product, taking into account the efficiency maximum is resolved. Within the buffering system, it is possible to receive an output product with the necessary qualitative and quantitative indices, taking into account the maximum efficiency as well [5] (Fig. 1).

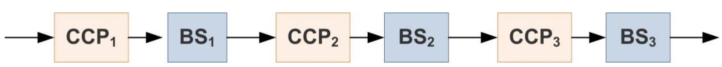

Fig. 1. The structure of a continuous production process, the conversion stages of which are separated by buffering systems: CCP – continuous conversion process, BS – buffering system

The practical implementation of this principle can be restrained by two factors.

The possibility of intermediate buffering can be excluded for technological reasons.

The second factor has an economic basis. Buffer systems link large volumes of intermediate products. The performance of converting system should be higher when it is the closer to the beginning of the technological chain. Otherwise, the principle of the production process continuity and the possibility of its optimization at subsequent stages will not be ensured. Accordingly, the more productive transforming system interacts with a buffering system with a large volume of buffering mechanism.

Due to this, the dimensions of the technological systems increase significantly.

For these reasons, the majority of power-consuming and resource-intensive industries use the technology of continuous converting process [8] (Fig. 2).

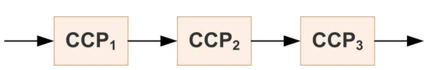

Fig. 2. The structure of a continuous production process in which the converting stages are functionally connected among themselves

With this approach, the careful coordination of the parameters of the functionally related equipment is necessary at the design stage. But in the course of functioning, qualitative parameters of input products, especially on the initial stage of production, can strongly change [9]. Inevitably, cost estimates of input and output production products [10] and also consumer demand for an end product change.

For these reasons, optimization capabilities of continuous engineering procedures of the interconnected converting class systems are extremely limited.

Changing the technological parameter of any process, as a rule, leads to a change in the performance of the entire line equipment, which requires new settings of all architecturally related parts. Such a reconfiguration in resource-intensive and energy-intensive production can take up to half an hour or more [11]. At the same time, such a process is more aimed at stabilizing quality indicators, since increasing the efficiency of one stage of production does not automatically increase the efficiency of all related processes.

Nevertheless, the optimization capabilities of continuous conversion systems can be significantly increased if the technological mechanism is implemented as a sectional structure. In the event that each module of the technological part has its own structure for stabilizing the quality of the output product, efficiency can be improved by changing the control parameters within a single production stage.

Therefore, the development of methods for efficiency increasing of continuous technological processes is an important scientific task.

2. Literature review and problem statement

The issues of the possibility of efficiency increasing for continuous technological processes are being intensively investigated and directed to the optimization problems comprehensive solution. Among the developed directions, it is possible to single out works aimed at improving the design features of conversion systems [12], reducing the process cost by varying the parameters of input technological products [13] and settings decentralization [14]. At the same time, the directions that can solve the use of structural optimization are not investigated in the works.

Most of the works dealing with the theme of continuous technological processes optimization are traditionally associated with the creation of new or development of existing optimization algorithms [15]. Thus, an algorithm for optimizing continuous processes based on the natural hydrological cycle in [16], a combination of the method of hybrid spectral collocation and the method of homotopy analysis in [17] and multimodal optimization in [18] have been proposed. A distinctive feature of these works is the application of various indicators as an optimization criterion. At the same time, none of the indicators investigated in [12–18] has been verified as a criterion that really indicates the regime of the most efficient resource use.

It has been noted in [19] that continuous processes should be optimized taking into account the "competing" system properties. Among these properties are: the deviation of the regulated value from the set value, transition process duration, attenuation of the transition process, stability reserve of the ACS modulo and phase, and so on.

The used indicators allow changing the parameters of the investigated technological processes. But these indicators are used for stabilizing the stable technological process, but not for its optimizing.

For the optimization task solving, effective process time has been proposed to determine in [20].

It is obvious that the optimum mode of functioning of the system corresponds to quite a certain time of the operational process. However, the process performance change leads to a nonlinear change of input and output parameters of the operational process. Therefore, determination of the most effective process time, with such approach, requires the presence of control degrees of freedom. Otherwise, the optimization process requires the output product qualitative parameters change.

Therefore, the process of efficiency increasing is carried out in a fairly narrow range of control changes. Within this range, the qualitative parameters of the independent continuous technological process [21] or the whole continuous production parameters [22] vary within acceptable limits.

Since the range of permissible controls in such conditions is very small, the efforts of technologists are more aimed at solving the problem of stability, rather than process optimization.

Thus, there is the problem of increasing the degrees of freedom of a continuous technological process, in order to increase the optimization capabilities for maximizing the resource efficiency.

3. The aim and objectives of the research

The aim of the work is to increase the number of degrees of freedom in systems of continuous transformation of technological products using the method of structural-parametric stabilization, which will increase their efficiency.

To achieve the aim of the research, the following tasks have been accomplished:

– to construct a sectional model of a dynamic fluid heating system with the ability to determine the energy consumption and wear of heating mechanisms;

– to determine the optimization capabilities of the sectional dynamic heating system under the conditions of the set temperature parameter at the output and the required capacity;

– to develop a method of structural-parametric optimization of the sectional dynamic fluid heating system.

4. Increasing the degrees of freedom of the continuous system using a modular approach

Compared with the periodic systems, the continuous systems do not have degrees of freedom, if the intensity of technological product supply is set.

Fig. 3 shows the structure, within which a cold liquid is heated to the predetermined temperature with the predetermined capacity.

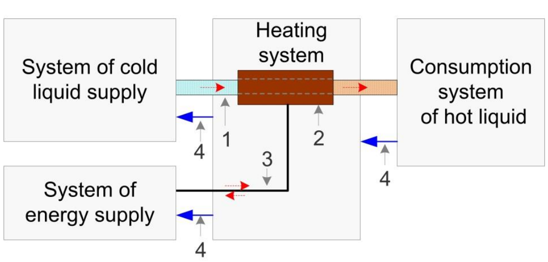

Fig. 3. The structural diagram of interaction of one heater heating system with the counterpart systems: 1 — end-to-end channel of liquid movement; 2 — technological heating mechanism; 3 — energy supply channel; 4 — control channels

In this case, there is a single control of energy product supply, in which the specified technological parameters will be set.

For example, in the liquid batch heating system, the heating to a set temperature at a certain time moment can be obtained using many controls. To do this, you can change the intensity of heating in time during one technological operation process.

Thus, in continuous systems, with a rigidly defined structure of the technology part, there are no opportunities for the implementation of optimum control with the use of parametric optimization principles.

Increases in degrees of freedom can be achieved if a multisectional technological mechanism is applied.

To conduct the research, the liquid heating system multi-section model has been created, which has the possibility to stabilize the temperature parameters at the sectional modules output. Fig. 4 shows a model consisting of 20 fluid flow sections that are combined into two self-stabilizing modules.

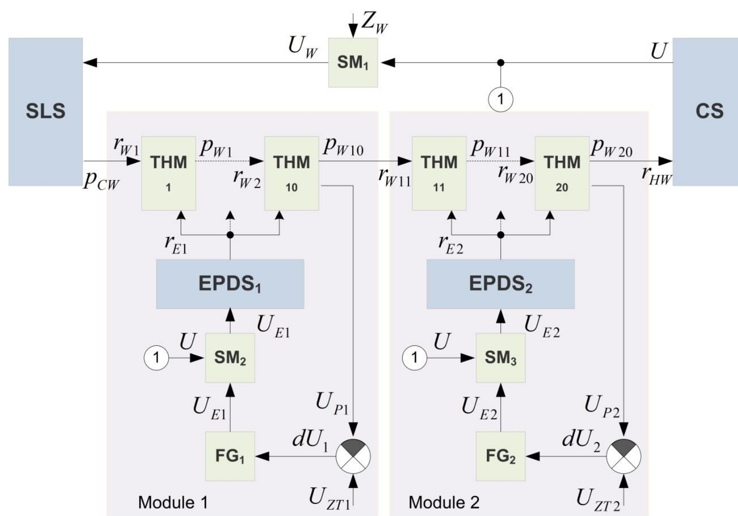

Fig. 4. Structural diagram of the dynamic fluid heating system with two sectional stabilization modules: SLS — cold liquid supply system; CS — system of heated liquid consumption; EPDS — energy product delivery system; THM — technological heating mechanism; SM — synchronization mechanism for data transmission; FG — functional generator

The heating system operation starts when the signal U is supplied by the system of heated liquid consumption to the synchronization input of the SM_1 mechanism. This signal is also fed to the synchronization inputs of the mechanisms SM_2 and SM_3.

The second input of the SM_1 mechanism is fed with a cold- liquid rate setting signal (Z_W), which, at the time of the U signal, starts to enter the input of the cold-liquid supply system of the SLS. With the release of the SLS, a cold liquid (p_{CW}) begins to flow to the input of the heating mechanism, made of series-connected technological mechanisms.

The input of the first section receives the input flow of liquid rW1, and its output generates a more heated fluid flow pW1. The output fluid flow pW1 of the first heating section is the input flow rW2 of the second heating section, and so on.

We consider the temperature parameter stabilization using the example of the first heating module operation. In this case, the first heating module includes ten heating sections.

From the output of the last heating section, the temperature parameter U_{P1} is applied to the inverting input of the two-input adder. The second input of the adder receives the reference value of the heating temperature U_{ZT1}. At the output of the adder, a signal d_{U1} is generated, which is fed to the input of the functional converter F_{P1}. The functional converter includes a proportional-integrating link.

At the output of the functional converter, a control signal U_{E1} is generated, which is fed through the synchronization mechanism to the SM_1 input. From the output of $SEPD_1$, the flow of electricity is supplied to the power inputs of technological heating mechanisms THM_1–THM_{10}.

The adder, functional converter, synchronization mechanism and the energy product supply system, together with the signaling channels combining them, form a feedback loop. Therefore, sometime after the work start, the predetermined temperature is set at the heating modules output.

At the second output, in general, the last module, the heating temperature required by the consumer is set. For this, the U_{ZT} signal is used.

At the output of the first heating module, an arbitrary value of the temperature parameter U_{ZT1} can be set, in the range from the initial liquid temperature at the module input to the heating temperature of the subsequent module. This provides the degree of freedom necessary for control. At the same time, the corresponding energy capacity is automatically set by the $SEPS_1$ and $SEPS_2$ outputs.

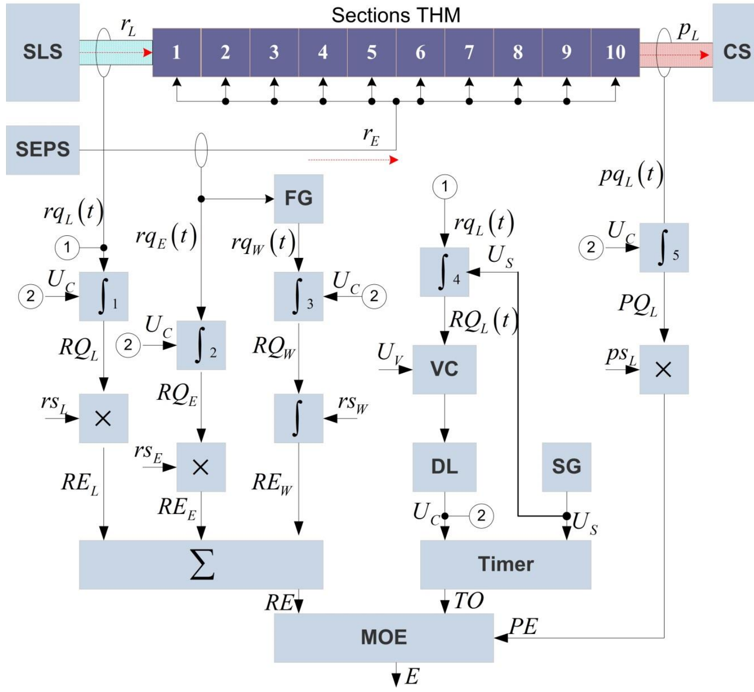

Fig. 5. The system for generating and processing the heating operation data: $rq_L(t)$ – registration signal of input fluid flow; $rq_E(t)$ – power flow registration signal; $rq_W(t)$ – registration signal of heating mechanisms wear flow; $pq_L(t)$ – recording signal of heated liquid flow; RQ_L – input fluid volume; RQ_E – amount of energy consumption; RQ_W – wear value of heaters; PQ_L – heated liquid volume; rs_L – cost assessment of input fluid unit volume; rs_E – cost assessment of energy product unit; rs_W – unit wear cost assessment; ps_L – valuation of heated liquid unit volume; RE_L – cost assessment of input volume of liquid; RE_E – valuation of consumed electricity; RE_W – cost evaluation of wear of heaters; RE – valuation of input operation products; PE – valuation of operation output products; TO – operation time; U_S – signal of operation beginning; U_C – signal to complete the operation; U_V – total volume of heating mechanisms

5. Formation and processing of data for the liquid heating operation

In order to process the heating operation data, the input and output technological products are registered and can be displayed in the form of corresponding registration signals: $rq_L(t)$ – the signal of input fluid flow; $rq_E(t)$ – registration signal of energy product flow; the signal of heated liquid flow $pq_L(t)$ (Fig. 5).

The registration signal of heating mechanisms wear can be defined analytically, in the form of the signal which is functionally connected with the registration signal of a flow of the electric power.

For determination of the electric heater wear during the technology operation, the expression $T = T_n k_u^{-\alpha}$ was used [23]. Here are: T – electric heater service life; T_n – number of working hours with a rated voltage; k_u – relation of the actual tension to nominal; α=14 – change indicator of average electric heater-service life.

The heating operation is defined by the moment of its beginning and the moment of the end. As heating of flowing liquid goes continuously, the moment of the operation beginning (t_S) is established randomly, with the use of the generator of a single pulse signal (GS). At this moment, resetting of accumulative integrators is performed and the process of integration of registration signals of technology products begins.

The operation comes to the end at the moment when the integral value of intensity of liquid flow becomes equal to the internal volume of the channel of section heating mechanisms

$$\int_{t_S}^{t} rq_L(t)\,\mathrm{d}t \to U_V = 20\pi R^2 L.$$

At this time, the voltage comparator VC is switched. The differentiating link DL allocates the leading front of KN, and forms the signal of operation completion U_C. As a result, the TO signal is generated at the timer output, numerically equal to the time of the heating operation.

The system for the formation and processing of the operation data under investigation makes it possible to determine all the parameters and indices of the operational process necessary for research.

6. Determination of optimization opportunities for the section model of the dynamic liquid heating system

For carrying out a control research, the system with one liquid heating module which consisted of 20 sections of heaters had been created.

The ambient temperature was 20 °C.

In case of the set heating temperature (U_{ZT}=100 °C), the power of electricity supply was automatically established at the level of 60.7 kW. The heaters wear within the heating operation was 0.0097 %.

At the second investigation phase, the optimization possibility of the heating process by using a two-modular architecture of the heating system was defined. For this purpose, the U_{ZT1} value was changed from 40 to 85 °C. The energy power given by the SPEP1 and SPEP2 systems was changed automatically (Fig. 6).

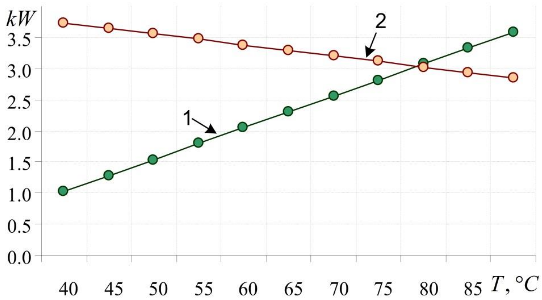

Fig. 6. Changes of the given electric power on heating modules sections depending on the established first module temperature reference value: 1 — change of energy supply on the first module; 2 — change of energy supply on the second module

Fig. 7 shows how the total value of energy consumption of the heating system and the heating mechanisms wear changed during the change of capacities given on the heating mechanisms of 1 and 2 modules.

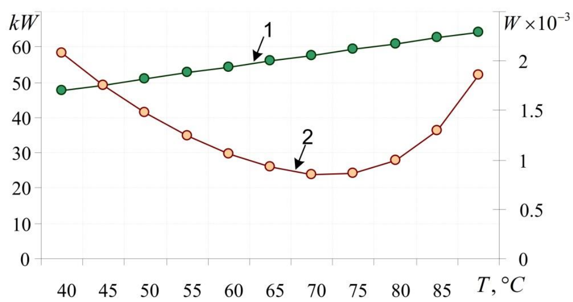

Fig. 7. Change of energy consumption (1) and wear of heaters (2) depending on the change of the temperature parameter reference value of the first module in the two-modular heating system

At the same time, the energy consumption values increase linearly, and the wear change function has a minimum. This means that the total minimum of costs will correspond to the minimum value of heaters wear.

The energy consumption of the two-modular system does not exceed the energy consumption of the one-modular heating system, and wear, due to optimization, is significantly reduced. At the same time, it is necessary to increase the temperature range of the first modular system to minimize wear.

This means that the heating section model provides the optimization possibility due to redistribution of capacities between system modules.

At the following stage, the possibility of structural optimization of the heating process was investigated by the use of different numbers of heating sections in system modules. At the same time, temperature parameters at the level of U_{ZT1}=70 °C, U_{ZT2}=100 °C were stabilized.

The number of the sections which are a part of the modules changed.

The number of heating sections in the module 1 changed from 6 (Fig. 8) to 14. At the same time, the total number of sections of the heating system did not change.

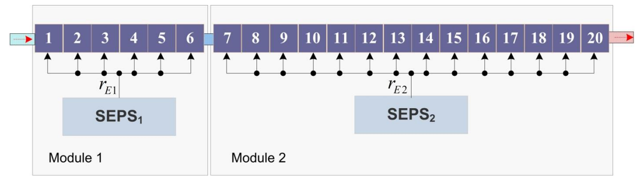

Fig. 8. The principle of redistribution of heating sections between modules

Researches showed that redistribution of heating sections between modules does not lead to the shift of a minimum of heaters wear (Fig. 9).

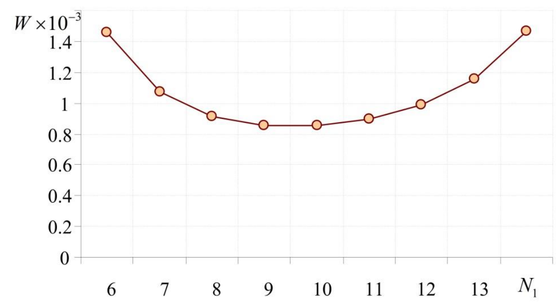

Fig. 9. Dependence of the heater wear value on the number of heating sections which are parts of the first module

Further researches were conducted for the heating system that consists of three modules. Each module was equipped with 7 sections of heaters.

On the basis of research of the two-modular heating system, the hypothesis was adopted that for minimization of wear, temperature conditions of each previous heating module have to be displaced to the right from the settings of uniform distribution.

So, if the heating temperature should vary from 20 °C to 100 °C, uniform distribution of heating between the modules will lead to the settings U_{ZT1}=46.7 °C, U_{ZT2}=73.4 °C, U_{ZT3}=100 °C.

The change of the reference value *Uzt*1 towards increase showed that the minimum of wear is in the area of 53 °C (Fig. 10).

After that, the reference value *Uzt*2 changed towards an increase. The minimum wear of thermal sections was defined with the temperature setting about 81 °C (Fig. 11).

The conducted researches show that the modular creation of the heating system technology part allows increasing the number of degrees of freedom. At the same time, such technology parameter as wear has an extremum that allows using optimization methods to increase the efficiency of the continuous engineering procedure.

It should be noted that a decrease in wear during the operation can be accompanied by an increase in energy consumption, and an increase in the number of heating sections to the change of the operation time.

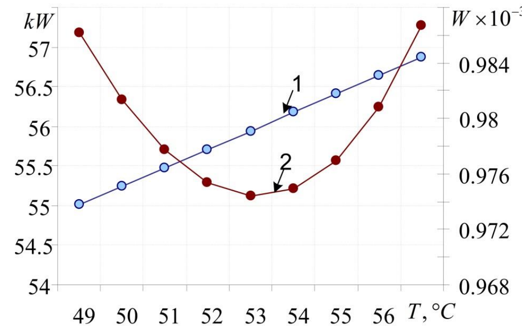

Fig. 10. Change of energy consumption and wear of heaters depending on the change of the temperature parameter reference value of the first module in the three-modular heating system: 1 – energy consumption value; 2 – wear value of electric heaters

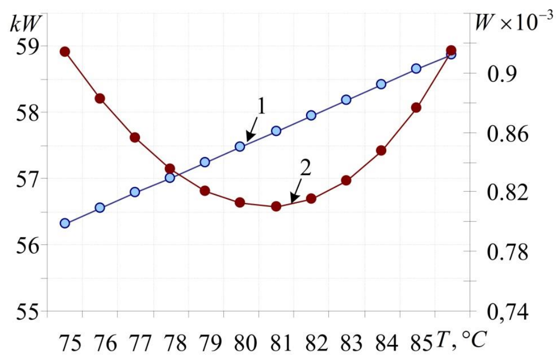

Fig. 11. Change of energy consumption and wear of heaters depending on the change of the reference value of the temperature parameter of the second module in the three-modular heating system: 1 – energy consumption value; 2 – wear value of electric heaters

Since the improvement of one parameter may lead to the deterioration of another parameter, a generalized estimate should be used to state the effect of the heating operation [24]. This indicator has been verified for its adequacy to an indicator of effectiveness [25–27].

For the sake of definiteness, let us assume that the cost estimate of the unit of electric power consumption is 0.02, the valuation of the unit of wear is 100, the value of a unit of cold liquid is 1, and the valuation of the heated liquid is 3.2. If we determine the operation efficiency with one heating module, we will get:

$$E=\frac{(3.2-2.38)1^2}{2.38\cdot 3.2\cdot 0.333^2}=0.786.$$

The splitting of the heater sections into two modules made it possible to select the heating mode of the first module, in which the efficiency of the process increased by 61.6 %, and the maximum was E=1.27 (Fig. 12).

The splitting of the heating sections into three modules led to the possibility of obtaining the maximum efficiency E=0.73 at the first optimization step, to the efficiency E=0.1 at the second optimization step. And only at the third step of optimization, the efficiency of the three-module system exceeded the efficiency of the two-module system by 2.3 %.

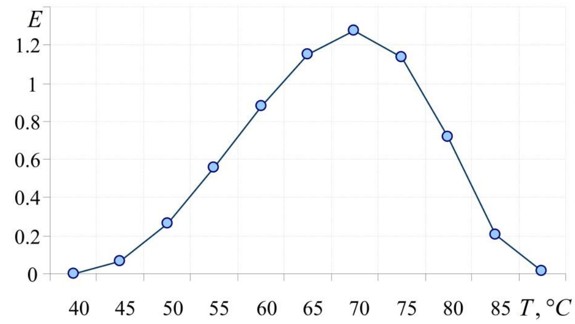

Fig. 12. Changing the resource efficiency in the two-module heating system with the temperature parameter change of the first module

7. Structural-parametric optimization method definition

The conducted researches showed that separation of the technological mechanism into sections allows creating a modular architecture of stabilization of the qualitative parameter of the technological product. In turn, a change in the architecture of the system with a continuous supply of the technological product makes it possible to obtain additional degrees of freedom of control. This approach allows us to implement the method of structural-parametric optimization, which consists of the following:

1. The technological mechanism is assembled from two or more identical modules, in each of which the quality parameter stabilization of the technological product at the individual level is provided. For this, each technological module has its own stabilization structure.
2. After completion of the stabilization operation, for each modular operation, in the search mode, such integral parameters as cost assessment of input operation products, cost assessment of output operation products and operation time are defined. The maximum efficiency of the technology operation is defined. The control of maximum efficiency is fixed.
3. If the number of modules is more than two, the optimization process is repeated cyclically for each modular technology operation from the left to the right.
4. After the search optimization, it is repeated until the efficiency increase is significant.
5. The optimization procedure is repeated for each new structure, therefore, the structure, within which the parametric optimization provides a significant increase in resource efficiency is chosen.

8. Discussion of research results connected with the development of the structural and parametric optimization method

The optimization of continuous engineering procedures under production conditions is a practically difficult task. This complexity is caused by several factors.

The first factor is the complexity of qualitative parameter stabilization of a technology product at the transformation stage. This factor is in many respects caused by delays which are the more significant the longer the converting process.

The second factor is caused by the fact that transformation stages of the technology product are functionally interconnected. At the same time, the performance improvement of one stage of transformation results in the need to synchronize the performance of the entire chain of the connected processes.

Division of one stage of the continuous process into technology modules, with the possibility of independent stabilization, on the one hand, allows increasing the stability of the dynamic system, on the other – expanding its optimization opportunities essentially.

Of course, the division of the technology mechanism into parts can increase by its total cost. In that case, the issues of the research have to consider this factor.

However, the functional independence of the modules of the technology part has some more advantages. It is an increase in maneuverability in the course of delivery of less dimensional equipment and also the possibility of completion of the engineering procedure in case of failure of a separate module.

Of course, the change of the technology product qualitative parameter at intermediate stages, generally, has to be limited so that the quality of the output product does not worsen.

It is possible to refer the need to control the process of wear of technology mechanisms to shortcomings of such approach, as with such approach they will work in the different operational modes. At the same time, the frequency of maintenance and repair works increases.

9. Conclusions

1. A sectional-modular model of the dynamic system has been developed, which provides the possibility of changing the technological mechanism structure. The model can determine the value of energy consumption and wear of its working sections. This approach ensures independent stabilization of the quality parameter of the technological product in the framework of ensuring the required productivity.

2. It is found that the proposed approach provides an increase in optimization opportunities of control processes. The emergence of such opportunities is caused by the increase in the number of degrees of freedom by changing the stabilization parameters at the previous stages of the engineering procedure. Increase in degrees of freedom of control allows expanding the possibilities of search optimization, and, respectively, engineering procedure resource efficiency. In the reviewed example, the efficiency of resource use was increased by 61.6 %.

3. The feature of the proposed method of structural and parametric optimization is the increase in the number of degrees of freedom of control of the continuous technological process. This gave an opportunity to perform cyclic and consecutive optimization by the resource efficiency criterion. The division of the technology part into modules is stopped if search optimization results do not lead to a significant change of resource efficiency.

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