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SYNTHESIS OF THE STRUCTURE FOR THE OPTIMAL SYSTEM OF FLOW TREATMENT OF RAW MATERIALS

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Показано, що сучасні роботи, присвячені оптимізації технологічних процесів, не враховують у власних моделях систем і в критеріях вимоги до загальної ефективності процесу і відповідності цілям власника комерційного виробничого підприємства. Для цього необхідно знижувати витрати і час технологічної операції, а також максимізувати додану вартість основного продукту.

Оцінка ефективності системи потокової обробки сировинної продукції виконується з використанням спеціальної моделі, яка була синтезована в ході даної роботи. Запропонована модель відрізняється тим, що включає блоки обчислення вартості одиниці продукції в залежності від якісного показника і ступеня відповідності висунутим кількісним і якісним обмеженням. Є блоки обчислення динаміки зміни якісного показника готового продукту в залежності від потоку сировини і енергії, що підводиться на обробку. Також необхідні блоки обчислення витрат ресурсу і енергії для транспортної та обробляючої частин системи на інтервалі, що визначається як час проходження умовної порції через установку.

Використання розробленої моделі дозволяє визначити значення показника ефективності для будь-якого допустимого технологічного режиму і провести глобальну оптимізацію процесу. Таким чином, здійснюється перехід від вимог ефективності в загальному вигляді до налаштувань параметрів технологічного процесу.

Запропоновано в аналітичній формі показник ефективності, що підходить в якості критерію оптимізації режимів технологічної установки з безперервним подаванням сировинного та енергетичного продуктів.

Експериментально досліджена модель проточного електричного водонагрівача з блоками розрахунку тимчасових і вартісних параметрів, яка показала свою адекватність. Проведена верифікація розробленого критерію оптимальності і доведена можливість його використання для визначення оптимальних допустимих режимів роботи технологічного обладнання з безперервною подачею сировини і енергії

Ключові слова: показник ефективності, технологічна установка, потокова обробка, модель оптимальної системи

1. Introduction

Systems processes at any enterprise should proceed in such a way that operating results are maximally consistent with the purpose of the owner [1].

To ensure such an alignment, it is required to reduce costs and duration of a technological operation, as well as maximize the added value of the primary product [2]. In a general case, the extrema of these functions do not match [3]. A solution could be found while resolving the problem on global optimization for a single unified criterion [4]. It should be noted that a large number of technological equipment in ore-mining and chemical industries, and these include almost all the tools that perform basic technological operations, operate at continuous supply of raw materials [5]. Enterprises solve the low-level automation tasks, implement workshop SCADA systems and primary elements of MES-systems [6]. However, they still have not applied mathematically substantiated models and methods of control over technological equipment, in order to ensure their optimal functioning in global terms [7].

Optimization is difficult due to a changing demand, volatile prices for raw materials and energy resources, instability of raw material quality indicators [8].

Solving a scientific-applied problem on the synthesis of optimal systems for the flow processing of raw materials makes it possible to improve efficiency of enterprises through better management of resource-intensive processes [9] at each stage of production based on a single criterion for effective use of resources.

2. Literature review and problem statement

Most often, the concept of “system” is defined as “a set of interrelated elements that act as a whole with all its internal and external relationships and properties” [10, 11]. The scientifically grounded approach to the synthesis of production systems is based on the idea that the result of development is the derived generalized class of minimal structures [12, 13] that describe the technological and managing aspects for specific processes. Correspondingly, the system, in addition to the modules for calculating dynamic indicators of energy and product conversion [14], should include the subsystems that calculate a set of parameters to assess the optimality of the process. It is obvious that the management part of these structures, as well as computational models, based on them, is determined by the applied criteria of optimality.

Papers [15, 16] tackle the optimization of technological processes of drying while increasing energy efficiency. Study [17] addresses control over a group of pumping units and reduction of specific energy consumption. The considered works are typical in that they employ traditional approaches to forming the optimality criteria. They imply description of quality requirements to the process, as well as the proposed constraints, in the form of weighted sums that form the additive criterion. The disadvantage of a given approach is that there is no strict mathematical justification for the weighting coefficients chosen by a method of expert estimations, which could lead to the inappropriate underestimation of the system's performance and might increase costs.

It is worth noting that the models described in papers [17, 18, 19] are aimed at increasing the observability over a technological system and improving the quality of control, while not comprehensively resolving the task on maximizing the profits from an operation when reducing physical and material costs. The issue on the synthesis of a fully-fledged system could be resolved if the optimization criterion to be used is the resource utilization efficiency formula.

The estimation indicator reported in [20] has passed all stages of verification to be applied as an indicator of efficiency [21].

For the process of a batch product treatment, which takes into consideration the total costs (including the cost of raw materials, cost of energy, the cost of the resource used), the value of the output product, time cost, the criterion takes the form:

$$E=\frac{(PE-RE)^2T_1^2}{PE\cdot RE\cdot T_{op}^2}, \tag{1}$$

where PE is the cost of the resulting product, RE are the total expenditures, T_1 is the dimensionality ratio, T_{op} is the operation duration.

The well-known criterion (1) is subject to limitations associated with its insensitivity in the region of negative assessments of added value and low sensitivity to a change in registration signals at small degrees of freedom in control. In addition, this criterion does not take into consideration the technological limitations set for a qualitative or quantitative characteristic of the finished product, which is required to optimize the entire technological chain at an enterprise.

3. The aim and objectives of the study

The aim of this work is to synthesize a cybernetic model of the optimal system with a continuous supply of a raw material product that would enable determining the effectiveness of the current process, applying the verified optimality criterion.

To accomplish the aim, the following tasks have been set:

– to develop a generalized model of continuous operation;

– to modify and verify the estimation indicator of process effectiveness in order to use it as the optimization criterion;

– to synthesize a functional structure of the system with a continuous supply of raw materials and to generalize its model at the cybernetic level;

– to conduct experimental research into processes in the synthesized system and to search for the optimal controls based on the modified criterion.

4. Modification and verification of the estimation indicator for the effectiveness of continuous operations

One can distinguish separate stages in the technological processes of chemical and mining production, characterized by a continuous and space-extended material treatment with a power supply at separate regions. These could include the following technological processes: grinding of the ore, roasting and heating of iron-ore pellets, the synthesis of technological carbon in chemical reactors, drying of loose products in drum dryers, heating of liquids and gases in heat exchangers and pipelines.

In general, based on papers [3, 5], such processes can be described by the following scheme (Fig. 1).

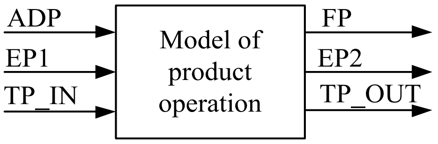

Fig. 1. Conceptual model of the one-stage flow processing of a product: ADP – a flow of product with directed impact; FP – a flow of the finished product; EP1 – a flow of the input energy product; EP2 — a flow of the secondary energy product; TP_IN – a flow of the input technological product; TP_OUT – an output technological product

The term "product with a directed effect" refers to the raw material, which is treated or converted into a finished product during this technological operation.

The primary energy product includes all the energy consumed by a technological installation (mostly electricity and hydrocarbon fuels). The secondary energy product is typically the thermal energy of flue gases utilized at additional technological operations of a given enterprise.

The input technical product constitutes the initial resource of equipment prior to the onset of a technological plant operation. During its operation, the resource is consumed at a certain rate, which is why one can argue about a flow of the technical product that is spent on treatment. At any time point, it is possible to determine the residual resource of the installation, which would act as the output technical product of the subsequent technological operation.

The continuous mode of flow treatment of a raw material is typically characterized by the performance efficiency of a functional system. However, evaluation of effectiveness can only be performed based on the results of the completed operation. The time of an operation within a continuous technological process is the time it takes for a conditional batch of a raw material to pass through a technological installation.

The price of the output finished product may vary depending on a certain qualitative indicator (for example, the degree of grinding the ore, output temperature, humidity, etc.). In the process of forming technological modes the valuation of the output products of an operation could turn out to be lower than the valuation of the input products of the operation. Since expression (1) is not sensitive to the negative outcome of the operation, it is required to modify the optimization criterion. The resulting expression takes the form:

$$Eff=sign(PE-RE)\frac{(PE-RE)^2T_1^2}{PE\cdot RE\cdot T_{op}^2}. \tag{2}$$

In some cases, a situation occurs where a subsequent technological process requires improvement in productivity of processes in the examined system, however, in this case, effectiveness of the studies process decreases.

In such cases, productivity growth could be improved by reducing the quality of the output product, provided its quality parameters are within acceptable limits. In this case, the valuation of the output product naturally decreases. In order to take into consideration a change in the value depending on performance, expression (2) is supplemented with function $Yr()$:

$$Eff2 = sign(PE \cdot Yr - RE)\frac{(PE \cdot Yr - RE)^2 T_1^2}{PE \cdot Yr \cdot RE \cdot T_{op}^2}, \tag{3}$$

where $Yr=f(F_{set}, F_{act})$ is the function of product's value adjustment depending on the qualitative or quantitative indicators; F_{set}, F_{act} are, respectively, the assigned and actual magnitudes of the indicator.

Function of product's value adjustment $Yr(F_{set}, F_{act})$ for criterion (3) can be built based on the Gaussian function whose values might populate the range $[a; 1]$:

$$Yr(F_{set}, F_{act}) = a + be^{-\frac{(F_{set}-F_{act})^2}{2\sigma^2}}, \tag{4}$$

where σ is the factor that assigns the width of a bell-shaped function, b is the factor that assigns the height of a bell-shaped function.

To comply with the conditions for finding the set of values of function Yr in the range $[a; 1]$, it is possible to introduce condition:

$$a + b = 1, 0 < a < 1.$$

At a zero deviation of the limitation indicator, the value of a correction function equals unity; when ascending, it exponentially decreases depending on the σ factor. It should be noted that the exponential function in criteria (3) equally describes the positive and negative deviations of the parameter from assigned values. In the case where the deviations are not equivalent, one should use the product of two sigmoid functions or a two-way Gauss function, known from the theory of fuzzy systems to describe membership functions.

For expression (3), verification should be undertaken to determine whether the expression might be employed as a criterion for effectiveness.

The principles of verification of performance criteria are set out in [21, 22]. This procedure is based on the argument, proven in [20], on that out of possible operations, all other things being equal, the more effective is the following:

– an operation that takes less time;

– an operation that requires fewer summary costs;

– an operation that requires a smaller value of resources and raw materials;

– an operation that produces the output product that is greater in value;

– a closer regulatory indicator value to the desired value (for criterion (3)).

Results of test calculations are summarized in Table 1. Function $Yr(F_{set}, F_{act})$ acquires the following parameters: σ=2, a=0.3, b=0.7.

The modified performance indicators are sensitive to the sign of the difference between the value of the output product and cost. Indicator (3) is sensitive to the deviation of regulatory indicator F from the desired value F_{set}, thereby lowering the value for process efficiency at an increase in absolute deviation.

If, all other conditions being equal, the value of the output product increases, cost or operation duration decrease, the performance indicator then increases its value. Verification results affirm the possibility of applying indicators (2) and (3) as optimization criteria for a continuous operation of transforming the product with a directed effect.

Table 1

Results of verification calculations of the modified performance indicators

PE	RE	Top	F_{set}	F_{act}	$Yr()$	$Eff1$	$Eff2$
1	2	3	4	5	6	7	8
4	2	2	6	5	0.957589	0.12500	0.10933
5	2	2	6	5	0.957589	0.22500	0.20292
4	3	2	6	5	0.957589	0.02083	0.01500
4	2	3	6	5	0.957589	0.05556	0.04859
4	1	2	6	5	0.957589	0.56250	0.52286
4	2	1	6	5	0.957589	0.50000	0.43732
3	2	2	6	5	0.957589	0.04167	0.03314
5	2	1	6	5	0.957589	0.90000	0.81169
3	2	3	6	5	0.957589	0.01852	0.01473
4	2	2	6	4	0.845161	0.12500	0.07048
5	2	2	6	4	0.845161	0.22500	0.14655
4	3	2	6	4	0.845161	0.02083	0.00357
4	2	3	6	4	0.845161	0.05556	0.03132
4	1	2	6	4	0.845161	0.56250	0.41911
4	2	1	6	4	0.845161	0.50000	0.28192
3	2	2	6	4	0.845161	0.04167	0.01414
5	2	1	6	4	0.845161	0.90000	0.58618
3	2	3	6	4	0.845161	0.01852	0.00628
4	2	2	6	7.5	0.908171	0.12500	0.09172
5	2	2	6	7.5	0.908171	0.22500	0.17772
4	3	2	6	7.5	0.908171	0.02083	0.00918
4	2	3	6	7.5	0.908171	0.05556	0.04077
4	1	2	6	7.5	0.908171	0.56250	0.47699
4	2	1	6	7.5	0.908171	0.50000	0.36690
3	2	2	6	7.5	0.908171	0.04167	0.02408
5	2	1	6	7.5	0.908171	0.90000	0.71087
3	2	3	6	7.5	0.908171	0.01852	0.01070
4	4.3	2	6	7.5	0.908171	–0.00131	–0.00713
5	5.3	2	6	7.5	0.908171	–0.00085	–0.00599
4	4.3	2	6	7.5	0.908171	–0.00131	–0.00713
4	4.3	3	6	7.5	0.908171	–0.00058	–0.00317
4	4.3	2	6	7.5	0.908171	–0.00131	–0.00713
4	4.3	1	6	7.5	0.908171	–0.00523	–0.02851
3	4.3	2	6	7.5	0.908171	–0.03275	–0.05297
5	5.3	1	6	7.5	0.908171	–0.00340	–0.02395
3	4.3	3	6	7.5	0.908171	–0.01456	–0.02354

5. Synthesis of the cybernetic model structure for a continuing transformation of the channeled product

Based on papers [23, 24], with respect to indicators (2) and (3), one can select those elements in the examined systems without which the estimation accuracy of the formed mode's effectiveness decreases while the search for optimal controls becomes impractical.

This provides the basis for the synthesis of a cybernetic model of the system for a continuous transformation of technological products.

When calculating the valuation of input products, it is required to take into consideration the following parameters [5, 6]:

– cost of the input product – PE_{in};

– cost of energy for product treatment – RE_{proc};

– cost of energy for product transportation – RE_{traff};

– cost of the used resource of the treating part – RE_{res1};

– cost of the used resource of the transporting part – RE_{res2};

– fixed costs that do not depend on the mode of operation of equipment, which include the cost of staff time, tax and lease payments attributable per time unit – RE_{add}.

Thus, the calculation of costs should be performed according to formula:

$$\begin{aligned} &RE = PE_{in} + RE_{proc} + RE_{traff} + \\ &+RE_{res1} + RE_{res2} + RE_{add} = C_{in}\int_{t1}^{t2} F\cdot \mathrm{d}t + C_{E1}\int_{t1}^{t2} P_{proc}\cdot \mathrm{d}t + \\ &C_{E2}\int_{t1}^{t2} P_{traff}\cdot \mathrm{d}t + C_{res1}\int_{t1}^{t2} fV_1(P_{proc})\cdot \mathrm{d}t + \\ &+C_{res2}\int_{t1}^{t2} fV_2(P_{traff})\cdot \mathrm{d}t + C_{add}\int_{t1}^{t2} 1\cdot \mathrm{d}t \end{aligned} \tag{5}$$

where $t1$, $t2$ is the starting and end operation time of the installation; C_{in} is the cost per unit of the input product (a raw material); C_{E1} is the energy cost per unit for product treatment; C_{E2} is the cost per unit of energy for transporting the product; C_{res1} is the cost per unit of resource of the treating part of the technological installation; C_{res2} is the cost of a resource unit for a transporting part of the technological installation; C_{add} is the cost per unit of time of operation of the technological installation regardless of mode; F is a product flow (for example, kg/s); P_{proc} is the power of the treating part of the technological installation; P_{traff} is the power of the transporting part of the technological installation; $fV_1(P_{proc})$, $fV_2(P_{traff})$ are the functions that determine the rate of resource utilization of, respectively, the treating and transporting parts of the technological installation depending on the used power.

It can be assumed that the difference between $t1$ and $t2$ matches the time it takes for a conditional batch of the product to pass through the technological installation, and then $Top=t2-t1$.

A change in the instantaneous resource consumption depending on the intensity of equipment operation is described by a power function, while the cost of staff time and related costs are constant.

The cost of the output product (excluding a secondary energy product) depends on its quantity and the quality indicator (for example, in the case of flow heating – on temperature):

$$PE = Cf(Q)\int_{t1}^{t2} F\cdot \mathrm{d}t, \tag{6}$$

where $Cf(Q)$ is a function that determines the cost of products depending on the value of a qualitative characteristic; Q is the qualitative characteristic (in the case of a flow heater, temperature; for a drying plant, humidity).

Since a change in control influences, both along the transportation channel and the processing channel, leads to a change in the quality of the resulting product, we must agree to that it has a variable cost, determined by a continuous differentiable function from the quality indicator (shown in Fig. 3).

The price of the obtained corresponding energy product may depend on the amount of a heat carrier, temperature, as well as actual need.

The structure of the model shown in Fig. 2 is composed of the following units:

– calculation of the dynamics of change in the qualitative indicator of the finished product, depending on the amount of supplied raw materials and energy for treatment per unit of time, as well as on other external significant parameters;

– calculation of the amount of the finished product and a change in the load to the treating part of the technological installation depending on the amount of supplied raw materials and energy for treatment and transportation per unit of time;

– determining the price of input raw materials and the finished product depending on qualitative indicators;

– determining the price of the output accompanying energy product depending on qualitative and quantitative indicators;

– determining the amount of supplied raw materials and the resulting finished product;

– calculation of the consumption rate of the treating part's resource depending on the amount of energy supplied for treatment per unit of time;

– calculation of the consumption flow of resource of the transporting part depending on the amount of supplied raw materials and energy supplied for transportation per unit time;

– calculation of the energy consumed by the treating and transporting parts of the installation;

– calculation of cost of all raw material and energy expenditures;

– calculation of the time that a conditional product batch would take to pass through the treating part;

– calculation of performance indicator.

In the context of a given scheme (Fig. 2), controlling variables are P_{proc} – the power of the treating part, and P_{traff} – the power of the transporting part of the technological installation. Based on the assigned parameters, we determine F – a product flow (kg/s), time points for generating the reset pulses (RP) for integrators that calculate valuations of the output products and costs.

The structure given here is universal and minimally required; the results of its operation do not depend on the specific technological process that undergoes the process of optimization. With its help, it becomes possible to construct models for well-defined operations and to compare efficiency of the formed modes. In addition, the search optimization methods make it possible to identify the most efficient mode of operation and to achieve an optimum within the limits assigned. Even if the global optimum is beyond the natural limitations of technological equipment, in the presence of two or more control channels, it is required to determine a working point with the greatest possible indicator of effectiveness. That cannot be done in the absence of such models and criteria.

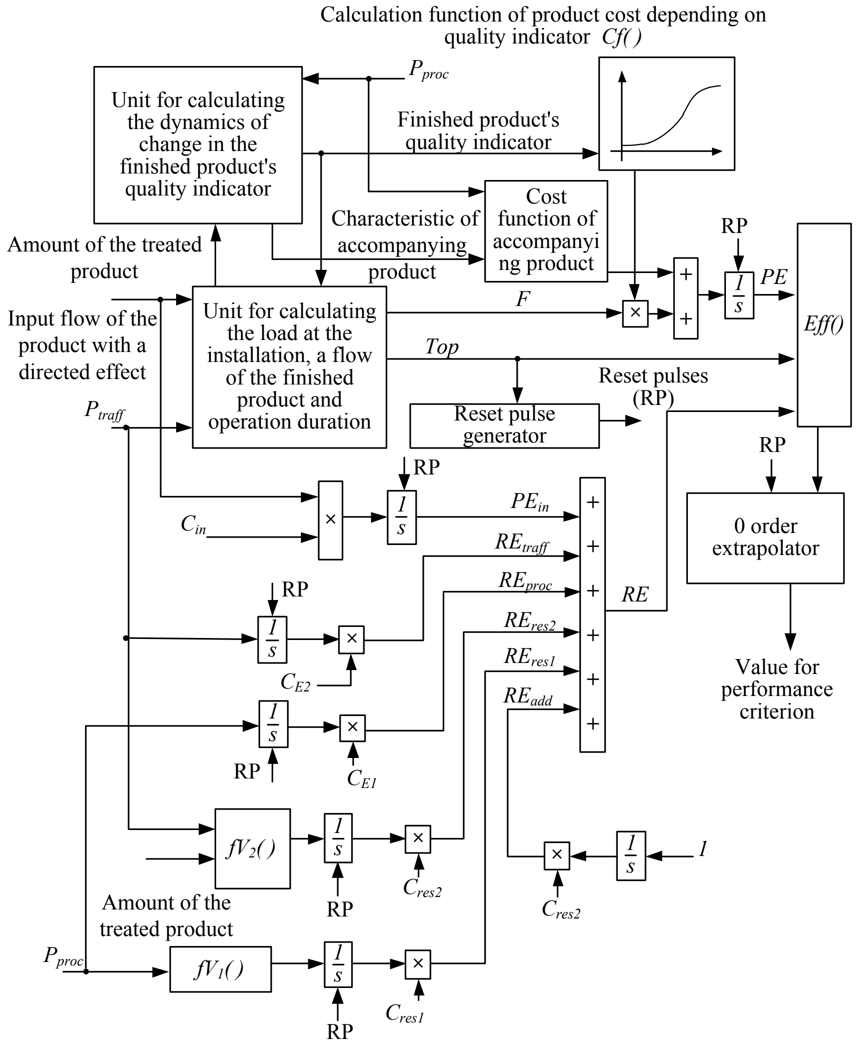

Fig. 2. Structure of a cybernetic model for the continuous transformation of the channeled product

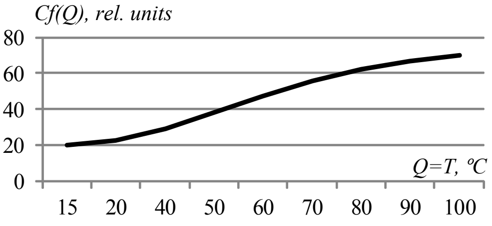

Fig. 3. Dependence of the product unit cost on temperature

6. Experimental study of processes in the synthesized system; search for optimal controls

To confirm the adequacy of the above consideration, we shall construct a model for the flow-through water electric heater, which could be applied to verify the validity of the proposed approach, to optimize control and to perform the verification of criteria.

The unit cost of a product depending on a qualitative indicator, temperature, is assigned by the dependence shown in Fig. 3.

Accept the following parameters for the study model:

- weight of a conditional product batch, kg: 2.6;
- a range of change in water feed, kg/s: 0.02–0.09;
- a corresponding range of change in a pump power, W: 200–400;
- a range of change in a heating element power, W: 500–14,000;
- the time taken for a conditional portion to pass through the heater, s: 30–96.

The developed computational simulation model of the flow heating process is a system of dynamic links and functional transforming elements [26] (Fig. 4).

To model the operation of a flow heating, it is required to set initial parameters: temperature of the liquid at the inlet to the installation, ambient temperature, the amount of fixed costs, the cost of electricity, the cost of resource for a transporting and treating part of the installation, a function of dependence of resource utilization rate on power used by the transporting and treating parts of the installation, a function of dependence of energy losses on the qualitative indicator of a product. Dependence of energy losses on a product flow is disregarded.

It is worth noting that the magnitude of instantaneous heat losses depends on the temperature difference of the product and the environment and affects the magnitude of the product's resulting temperature. The time taken for the conditional batch of liquid to pass determines the integration time of costs, the amount of input and output products.

For criterion (3), we accept as the limiting technological parameter a temperature, which has the desired value of 73 °C, and which should not leave the range of [67; 79] °C. Function of product's value adjustment $Yr(F_{set}, F_{act})$ for criterion (3) can be built based on the exponential bell-shaped function whose values could be in the range of [0.3; 1]:

$$Yr(F_{set},F_{act})=0{,}3+0{,}7e^{-\frac{(F_{set}-F_{act})^2}{2\sigma^2}}=e^{-\frac{(73-F_{act})^2}{2\cdot 4^2}},$$

where σ is the factor that assigns the width of the bell-shaped function.

At a zero deviation, the multiplier's value is unity; when ascending, it is exponentially decreasing depending on the σ factor. It should be noted that the exponential function in criteria (5) equally describes the positive and negative deviations of the parameter from the assigned values. The chart of function $Yr(F_{set}, F_{act})$ is shown in Fig. 5.

Exploring the course of a technological process using a computational model allows us to build a dependence of the efficiency indicator based on formulae (2), (5) on controlling influences at the remaining parameters fixed. Experimental results for indicator (2) are summarized in Table 1. Maximum efficiency is achieved at a flow of 0.0619 kg/s and a power of the heater of 16,400 W.

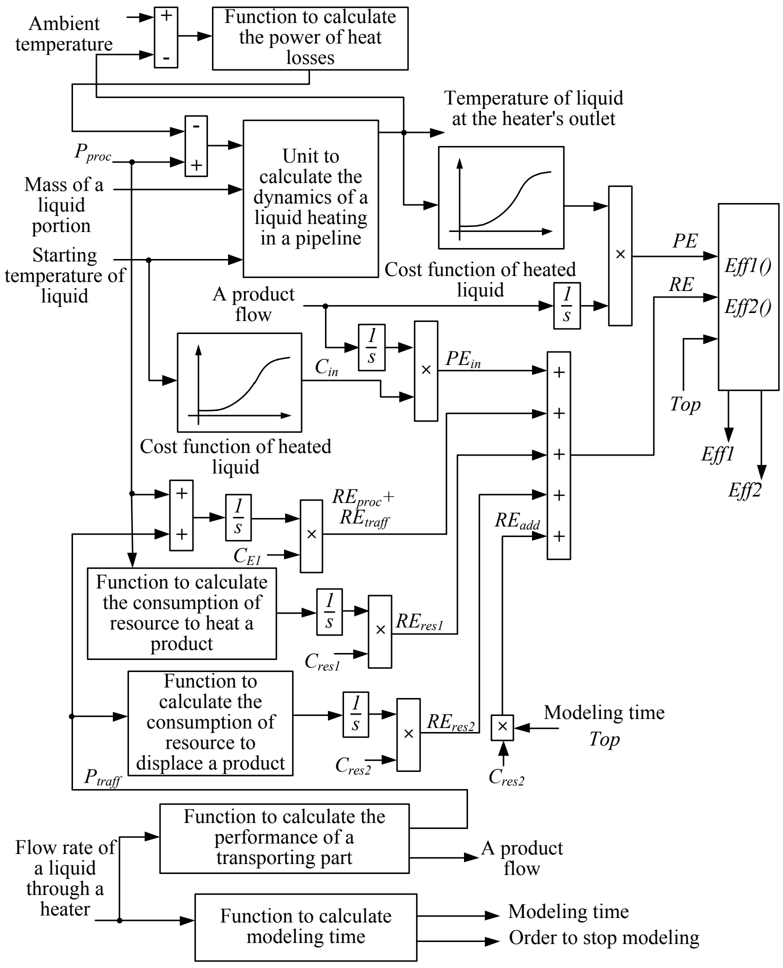

Fig. 4. Principal diagram that describes the model of the one-stage flow-through heating of a fluid portion with computing the efficiency indicator

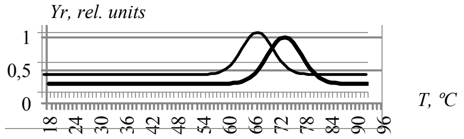

Fig. 5. The chart of function for the product value adjustment

Table 2 gives numerical results of simulation; Fig. 6, 7 show the shape of the surface of indicator's functions (2). We observe a considerable deterioration of the process in the region of high performance efficiency of the transporting part and in the region of low performance of the treating part, when the cost of a product is too low at a large flow of raw materials. By increasing the scale in the region of an extremum (Fig. 7), one can see both the presence of a global extremum for the efficiency indicator and the local extrema. Such a shape of the response surface raises higher requirements to the methods and algorithms for the automated search for a global extremum in effectiveness.

We shall investigate the dependence of criteria on process parameters for the neighborhood of an extremum derived from Table 1 using the dynamic model that corresponds to Fig. 4. The results of our study are summarized in Table 3.

Experiments with an alternate change in parameters of the technological process were carried out in order to unambiguously establish a definite sensitivity of the indicator to them, and the possibility of using it as a criterion.

Table 2

Results of model study into dependence of indicator (2) on controlling influences

A product flow, kg/s Power, W	0.07222	0.0619	0.05417	0.04815	0.04333	0.03939
8,000	–2.1E-04	–1.4E-05	–3.6E-06	–5.5E-07	2.2E-10	2.4E-07
9,200	–1.2E-04	–3.2E-06	–8.9E-08	3.5E-07	1.3E-06	1.6E-06
10,400	–1.0E-04	–8.6E-08	7.8E-07	2.3E-06	2.3E-06	1.7E-06
11,600	–8.7E-05	1.1E-06	3.7E-06	3.8E-06	2.7E-06	1.4E-06
12,800	–9.0E-05	3.5E-06	4.5E-06	3.0E-06	1.3E-06	2.1E-07
14,000	–1.0E-04	5.5E-06	3.6E-06	1.5E-06	1.5E-07	–3.0E-07
15,200	–9.7E-05	6.7E-06	3.6E-06	9.9E-07	–2.1E-08	–2.3E-06
16,400	–1.0E-04	7.6E-06	3.1E-06	2.2E-07	–1.1E-06	–6.3E-06
17,600	–1.2E-04	6.9E-06	1.7E-06	–9.8E-08	–4.5E-06	–1.3E-05
18,800	–1.3E-04	6.3E-06	6.2E-07	–1.8E-06	–9.9E-06	–2.1E-05
A product flow, kg/s Power, W	0.03611	0.03333	0.03095	0.02889	0.02708	0.02549
8,000	6.1E-07	5.9E-07	3.9E-07	2.0E-07	4.0E-08	–1.0E-09
9,200	1.2E-06	7.6E-07	3.3E-07	7.4E-08	–2.1E-08	–2.8E-07
10,400	8.5E-07	3.0E-07	1.8E-09	–2.0E-07	–1.1E-06	–2.7E-06
11,600	4.1E-07	–1.2E-11	–5.0E-07	–2.1E-06	–4.5E-06	–7.4E-06
12,800	–9.8E-08	–1.6E-06	–4.6E-06	–8.4E-06	–1.3E-05	–1.7E-05
14,000	–3.0E-06	–7.5E-06	–1.3E-05	–1.9E-05	–2.5E-05	–3.1E-05
15,200	–7.4E-06	–1.4E-05	–2.1E-05	–2.9E-05	–3.6E-05	–4.3E-05
16,400	–1.4E-05	–2.3E-05	–3.2E-05	–4.0E-05	–4.9E-05	–5.7E-05
17,600	–2.3E-05	–3.4E-05	–4.5E-05	–5.5E-05	–6.4E-05	–7.3E-05
18,800	–3.4E-05	–4.7E-05	–5.9E-05	–7.0E-05	–8.1E-05	–9.1E-05

Table 3

Results of verification experiments

No. of entry	Varied parameter	Base value of parameter	Changed value of parameter	Value for efficiency indicator *Eff1*	Value for efficiency indicator *Eff2*
1	Original variant (*P* – 16,400 W, *F* – 0.0619 kg/s, operation duration is 78 s, temperature is 79.63 °C, a conditional batch weight is 2.6 kg)			7.5665e-06	–2.2767e-04
2	Operation duration	78 s	85.8 s	6.25e-06	–1.88e-04
3	Operation duration	78 s	70.2 s	9.35e-06	–2.81e-04
4	Total cost		+10 %	2.32e-07	–3.058e-04
5	Total cost		–10 %	2.777e-05	–1.555e-04
6	Product value		+10 %	2.53e-05	–1.62e-04
7	Product value		–10 %	5.85e-08	–3.147e-04
8	Heat losses		–10 %	7.775e-06	–2.455e-04
9	Heat losses		+10 %	7.355e-06	–2.105e-04
10	Mass of a conditional batch	2.6 kg	2.8 kg	2.045e-05	–1.756e-04
11	Mass of a conditional batch	2.6 kg	2.4 kg	7.1e-07	–2.92e-04
12	Product temperature	79.63 °C	90 °C	2.197e-05	–6.025e-04
13	Product temperature	79.63 °C	73 °C	1.36e-06	1.36e-06
14	Product temperature	79.63 °C	71 °C	4.435e-07	–1.93e-06
15	Product temperature	79.63 °C	67 °C	–5.84e-07	–2.663e-04
16	Raw material temperature	18 °C	12 °C	1.925e-06	9.45e-07
17	Raw material temperature	18 °C	22 °C	1.218e-05	–5.926e-04

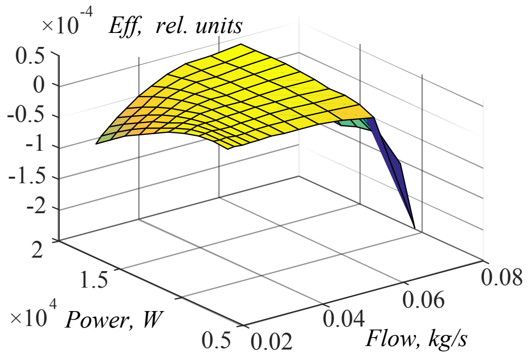

Fig. 6. Response surface of the performance indicator for a flow-through liquid heater depending on the flow of raw materials and power

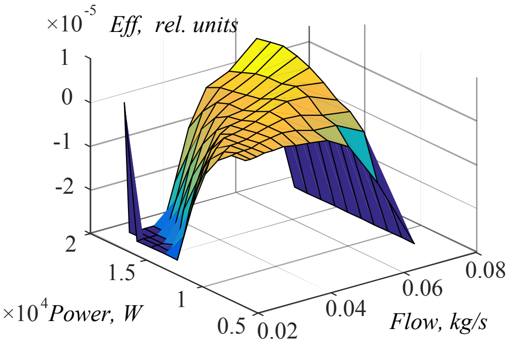

Fig. 7. Response surface (with an enlarged extremum region)

7. Discussion of results of modeling the system of flow treatment

The existence of a detailed model of the process allows us to perform verification of proposed criteria (2), (3). The response surface of performance indicator for the flow-through heater at constraints for a qualitative indicator (temperature) is shown in Fig. 8.

The maximum of indicator (3) is reached, based on the simulation results, under the following mode: heater's power (*P*) – 15,200 W, flow (*F*) – 0.0619 kg/s, and is 6.683e-06 relative units. The qualitative parameter acquires a value for the maximum of indicator (2) – 79.63 °C, for the maximum of indicator (3) – 75.12 °C, which confirms the logic of reasoning.

An analysis of the response surface, which describes a change on the indicator of effectiveness due to controlling influences, reveals that it has, in addition to a global extremum, many local ones. It was observed that a decrease in the step of change of controls leads to a growth in the density of local minima and maxima. Finding technological modes with the maximal effectiveness using classical optimization methods is difficult and thus it is necessary to apply specialized search and stochastic methods.

For the considered class of one-stage operations with a continuous supply of products and constraints for technological parameters, it is necessary to test, using model experiments, the above considerations employed for verification. In addition, in order to successfully verify the criteria put forward, it is necessary to compare and demonstrate that the efficiency of the process for parameter (2) is higher in the following cases:

– there are lower energy losses during treatment or the larger output quality indicator of a product;

– lower energy costs for transportation;

– the larger output of finished products;

– the larger mass of a conditional batch;

– the higher starting temperature of a raw material;

– a closer value of the quality of output products to the standard value (for criterion (3)).

The results of verification study (Table 2) reflect a change in the value of effectiveness criterion in line with formulae (2) and (3). The corresponding change in parameters that exerting a direct impact on effectiveness (the cases described by lines 5, 6, 9, 10, 15, 16 in Table 2) leads to a change in the value for each criterion in the same direction. This confirms the adequacy of the criteria.

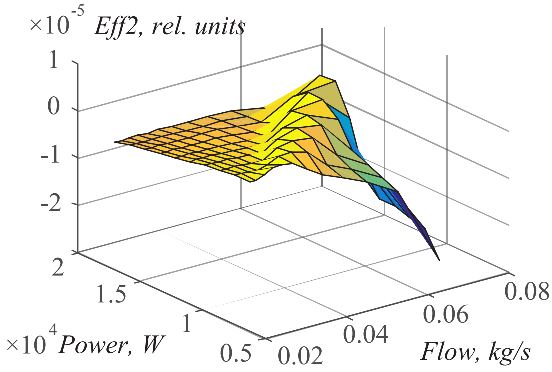

Fig. 8. Response surface of performance indicator for the heater at constraints for a qualitative indicator

Increasing the parameters that have the opposite effect on efficiency (the cases described by lines 1–4, 7, 8 in Table 2) leads to a decrease in the value for the criteria, which also confirms their adequacy.

Variants 11–14 describe those cases when a technological parameter falls within the valid range, or is located at the border of valid values, or leaves the permissible range. Criterion (2) *Eff*1 grows at an increase in the temperature of the output product, while criterion (3) *Eff*2 – only when the controlled parameter approaches the standardized value.

It should be noted that the examined computational model employed conditional functions describing a change in the value of products, the cost of the consumed resource, power of heat losses. For industrial applications, it will be necessary to establish actual dependences.

The model considered is rather abstract and is suitable for a limited class of real installations. However, it might form the base for a possible synthesis of models of extreme efficient control over existing installations for roasting and drying of granulated products, as well as installations of chemical synthesis. It will be required to take into consideration the multistage character of treatment and a large number of controlled process variables. That would make it possible to develop new controlling software and to obtain a real economic effect.

Known models of technological processes of continuous treatment do not compute parameters required to evaluate their effectiveness. These include: the time taken for a conditional batch of a raw material to pass through the installation, a change in the cost of primary and related products depending on qualitative indicators, assessment of resource and energy costs for the transportation and treatment of a channeled product. Known optimization methods make it possible to accelerate and automate the process of finding an extremum of quality; however, the applied computational models do not allow the unambiguous connection between technological settings that define the mode and the degree of its efficiency. In this case, it is not correct to argue about attaining the best regime.

8. Conclusions

1. For the technological process of a one-stage treatment, characterized by a continuous supply of raw materials, energy and resource consumption, optimization can be performed by using a specialized model. It reflects the patterns in a dynamic process that has two channels of control – over a flow of raw materials and energy costs related to treatment. In addition, the model takes into consideration the constantly changing value of the output product depending on the quality indicator and the imposed constraints on the volume of output product or its qualitative properties.

2. Solving the task on optimization is impossible without using a substantiated criterion. It is based on the indicator of effectiveness as a measure of correspondence of the outcomes of work of the functional system to the goals of the owner. The formulated criterion takes into consideration the time taken for a conditional product batch to pass through the installation, total expenses, the cost of a conditional batch of the output product, depending on the quality indicator. The criterion is also sensitive to the sign of cost difference between a finished product and its cost, which makes it possible to unambiguously identify unprofitable modes – the difference is negative, and the profitable ones – the difference is positive. The value of the output product is adjusted via a function that calculates the degree of belonging of the regulating parameter to the permissible range.

It is appropriate to adjust the cost via the Gauss function whose values are in the range (0; 1], provided that deviations from the desired parameter's value are equal. If the deviation directions are not equal, one should use, on order to adjust the value of an output product, a product of two sigmoid functions, or a two-way Gaussian function. The application of a given correction function makes the criterion more convex in the region of an extremum and sensitive to the technological constraints for the parameters of a flow treatment process.

The total cost is calculated as the sum of integral values of the cost of utilized raw materials and the energy used on treatment and transportation, the cost of the utilized resource of the treating and transporting parts, the magnitude of fixed costs to maintain the operation of a technological installation.

3. Based on the criteria developed, we synthesized a structure of the functional system with a continuous supply. It could provide the search for optimal controls, provided one knows the functional dependences of resource consumption, the dependence of the cost of the output product on a quality indicator, the permissible range of the regulatory indicator. The structure is minimally possible and is suitable for all production systems that perform continuous technological operation, which includes the functions of transporting a product and treating it using an external energy source.

4. Model study of the water heating system in a flow-through heater with independent channels of control over the flow of fluid and the heater's power confirmed the possibility to estimate the overall effectiveness of the regime, differentiation of profitable and unprofitable modes. It was established that for the accepted unit cost of a raw material, finished product, energy and resource, the unconditional global optimum is in the following neighborhood: power of a heater is 16,400 W, flow rate is 0.0619 kg/s. Introducing a symmetric constraint for a temperature of 73 °C shifts the optimum in the region of the heater's power of 15,200 W. In this case, the value for a criterion changed from 7.57E-06 to 6.68E-06 (decreased by 12 %), which explicitly confirms that the criterion matches the requirements put forward.

5. Verification of the proposed criteria for the installation of a flow fluid heating was performed by independently alternating change in all parameters that affect performance by 10 %. The results clearly demonstrate a direct change

in the value for parameters' criteria that directly affect the efficiency. In addition, for parameters that are inversely proportionally influence the effectiveness, we confirmed an appropriate change in the values of optimization criteria. The proposed model of a functional system, together with the analytical expression of the criterion, ensures the search for a global optimum in the operation of a continuous technological installation with respect to constraints.

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