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DEVELOPMENT OF A METHOD FOR THE ACCELERATED TWO-STAGE SEARCH FOR AN OPTIMAL CONTROL TRAJECTORY IN PERIODICAL PROCESSES

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Робота відноситься до області оптимізації технологічних процесів, зокрема до питань пошуку оптимальної траєкторії управління з використанням експериментального підходу. Показано, що існує клас операційних процесів, в рамках якого оптимізаційний підхід не може бути реалізований з використанням технології динамічного програмування. Запропоновано метод прискореного двоетапного визначення оптимальної траєкторії для періодичних операційних процесів

Ключові слова: оптимальна траєкторія, практичний метод оптимізації, двоетапна оптимізація, пошукова оптимізація

Работа относится к области оптимизации технологических процессов, в частности к вопросам поиска оптимальной траектории управления с использованием экспериментального подхода. Показано, что существует класс операционных процессов, в рамках которого оптимизационный подход не может быть реализован с использованием технологии динамического программирования. Предложен метод ускоренного двухэтапного определения оптимальной траектории для периодических операционных процессов

Ключевые слова: оптимальная траектория, практический метод оптимизации, двухэтапная оптимизация, поисковая оптимизация

1. Introduction

To maintain results of procedural activities of business enterprises maximally in line with their owners’ goals, enterprises integrate special indicators into their control systems, the so called optimization criteria.

In theory, use of the optimization criterion capacities should ensure selection of such a mode of operation of production structures, which will ensure maximum financial capabilities for their owners.

In the course of evolution of the notion about the role played by control in solving this problem, an "optimal control" concept was formed. Optimal, that is, the best control should provide the owners with implementation of maximum opportunities of the operational process results.

However, practical achievements of the theory of optimal control remain rather modest so far. This is indicated by the fact that despite the successes in automation of manufacturing processes, the processes of searching for optimal control are, in fact, not automated.

A great impact on the methods of searching for optimal control was provided by R. Bellman's Dynamic Programming in which he described the technique of searching for optimal control for a number of elementary operational processes.

In work [1], as the author himself admitted, he gave an intuitive definition of the principle of optimality. This definition, due to the popularity of the Bellman's work, has left a serious imprint on the notion of optimizing for an entire generation of control specialists.

Thus, according to [1], a sequence of the operation subproblems in which each subsequent choice with respect to the preceding one should be the best is considered to be optimal. At the same time, the best variant of evolution of events is movement along local extrema.

In [1], instead of the mathematical category of "search for extremum", a cybernetic concept of "search for the optimum" was used. This has resulted in the fact that the concepts of "optimality criterion", "optimal control", "optimal trajectory", etc. are fairly freely interpreted nowadays.

Moreover, practice has shown that application of the dynamic programming method in searching for an optimum is only possible in a narrow class of problems, i. e. in those cases when solution of a part of the subsequent task from the current operation can be performed relatively independently of the results obtained in the previous task.

This situation is possible in cases when quality of the product of the directional effect does not change during operation.

For example, this can be a process of horizontal load displacement or longitudinal wood sawing.

At the same time, there is a large class of operational processes in which a stage-by-stage comparison of a part of the completed task with the result of the next stage is impossible.

For example, the process of sequential temperature rise in a steel-smelting furnace requires different consumptions of the energy product at each heating stage and different time for each operation stage.

In the process of crushing solids, each stage of crushing also requires its own expenses.

Besides, each stage of change in quality parameters of the product of directional effect is accompanied by its level of the process equipment wear.

In this connection, it is of interest to develop a practical method for determining optimal control based on an adequate economic-cybernetic model of the system process.

2. Literature review and problem statement

At present, importance of optimal control is perceived as an axiom. Despite this, the theory of optimal control is going through not the best time.

This is largely due to the fact that the search for optimal solutions has intensively begun to develop thru the efforts of specialists in the mathematics and the optimization theory [2] is still widely accepted as a branch of mathematics [3].

The methodological apparatus formed within the framework of the historically developed approach was reflected in a science branch called "operations research" [4]. However, within the framework of this approach, only some particular problems related to optimization and search for an optimal control trajectory have been solved [5, 6].

Practitioners try to use traditional economic indexes to solve optimization problems [7].

Attempts to develop a system-based approach to solving the optimization problem within the framework of the traditional economic approach have led to creation of the so-called "balanced indicators": KPI and BSC. At the same time, authors of the analytical review [8] have identified 787 various packages of balanced KPI indicators offered as a solution of the problem of determining effectiveness of operational processes.

In their turn, technical experts try to use technical indicators as a criterion of optimization. In this capacity, the following is used: minimum power consumption [9], maximum speed [10], minimum trajectory [11], minimum error [12], fuel consumption [13], etc.

Proofs are adduced that high accuracy is a confirmation of optimality [14].

Uncertainty in selection of the optimization criterion and imperfection of methods for finding an optimal control trajectory have necessitated application of a mathematical modeling method [15]. However, the result obtained with the use of this method will only be of practical value if the search optimization is based on application of an adequate mathematical model of the object of research. In this case, implementation of this method has one very significant drawback: it is significant time required for the optimization process.

Successful verification [16] of the efficiency index, which can be used as a systemically valid optimization criterion [17] makes it possible to direct studies into a practical plane. However, the problem of speed of determining optimal trajectory remains in this case.

Thus, it is feasible to identify several interrelated problems to be solved in connection with the problem of finding optimal control trajectory. This is definition of an adequate model of the object of research, substantiation of selection of the optimization criterion as well as cost estimation of the main output product in conditions when its qualitative and quantitative parameters change during the operational process.

The final key task is to increase speed of search for of an optimal control path. It is highly desirable to improve efficiency of the task of finding the optimal trajectory by narrowing the region within which it is necessary to use known methods of search optimization.

3. The aim and objectives of the study

This work objective was to develop a method of a two-stage search for an optimal control trajectory for periodic manufacturing processes. First of all, this refers to such operational processes in which application of the dynamic programming method is impossible due to the incompatibility of results of each stage of operation.

To achieve this objective, the following tasks were solved:

– determination of significant factors affecting reliability of optimization;

– determination of possibility of a fast transfer to a control mode close to the optimal one;

– determination of the principle of estimation of the operational process results at the intermediate stages of the operation under study.

4. Development of the method of accelerated two-stage search for an optimal control trajectory for periodic processes

Getting a maximum financial return from the results of the procedural activity of a particular production system requires definition of an optimal control. Here 'optimal' means the control ensuring a phase trajectory at which an extreme value (infimum or supremum) of the optimization criterion is reached taking into account the constraints imposed on the control process.

In a number of cases, when the operation time is not a significant factor, for example, when demand is less than the production capacity, minimum costs or a maximum value of added value cost can be used as an optimization criterion.

4. 1. Assessment of significant factors affecting validity of optimization results

Since a minimum cost is an absolute indicator, consider approach to assessing adequacy of the study object model using an example of its definition. Use the process of batch liquid heating with an electrical heater [18] as the object of research,

Assume that the initial level of the liquid temperature is 20 °C. The heating process stops when the liquid temperature reaches 70 °C.

Like any other operational process, the process of batch liquid heating converts certain input products into output products.

In the case of heating a portion of liquid with an electric heater, consumable input products are cold liquid, electric power and a technical product. In this case, the technical product is wear of the electrical heater during the heating operation.

When intensity of supply of the energy product varies from operation to operation, quantitative parameters (the amount of energy consumption and wear of the electric heater) will vary. The time of the heating operation will also change.

Denote quantitative estimate of the amount of energy consumption during heating operation with RQP. RQW means wear of the electric heater during operation. RQL is the volume of the liquid taken for heating. PQL is the volume of the heated liquid, and TO is the time of operation.

Assume that the decrease in the volume of the heated liquid due to its evaporation during the operation can be neglected.

Fig. 1 depicts dependence of the change in energy consumption and the wear of the heating mechanism on control (UC). Within the framework of each operation, intensity of energy product supply was kept constant.

Define the control, which does not change during the operation as a tight control. Denote such control with U_C.

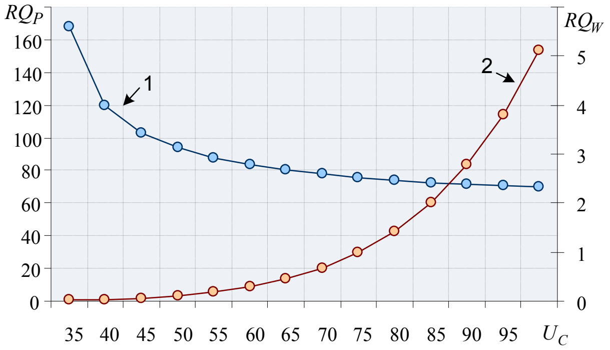


Fig. 1. Variation of significant factors depending on intensity of the energy product supply in the process of heating one cubic meter of liquid to 70 °C: variation of the amount of energy consumption from control (1); variation of the amount of wear of the heater from control (2)

As can be seen (Fig. 1), the power consumption function resulted from the tight control is monotonically decreasing and the wear function resulted from the control is monotonically increasing.

Since the change in equipment wear depending on the performance is a general principle, the possibility of optimizing control without taking into account the wear factor should be substantiated.

For example, the output volume of liquid also changes with respect to the inlet volume during the heating process. The volume loss in the operation also depends on the control.

In a general case, it can be asserted that the operational process model, which is used for optimization requires substantiation for its simplification. In a general case, it is necessary to take into account the change of the product of directional effect (in this case, the heated liquid) and the equipment wear in operation resulted from the control of energy consumption.

4. 2. The need for comparison quantitative estimates of the processed products in the optimization process

Since the quantitative parameters of the input and output products of the heating operation are incompatible with each other, it is impossible to judge which mode of operation of the heating system is most advantageous.

This suggests that the search for optimal (tight) control or an optimal control trajectory cannot be realized relying on technical indicators, even if the manufacturing model of the object under consideration is adequate.

To enable optimization, it is necessary to transform the manufacturing model of the object under consideration into an economic-cybernetic model.

Denote cost estimate of a unit of energy consumption with RSP, cost estimate of a unit of wear with RSW, cost estimate of a unit of the heated liquid with RSL. Then the operation cost (RE) can be determined from expression

$$RE = RQ_L \cdot RS_L + RQ_P \cdot RS_P + RQ_W \cdot RS_W.$$

Assuming that RS_P=0.3 monetary units, RS_W=3 monetary units, and RS_L=0.8 monetary units, obtain a change in costs resulted from the change in control (U_C) (Fig. 2 and Table 1).

Table 1

Change in costs by their types resulted from the change in the level of tight control

U_C	RQ_P	RQ_W	RQ_L	RE_P	RE_W	RE_L	RE
35	167.8	0.023	0.98	50.34	0.068	0.784	51.19
40	119.9	0.036	0.98	35.97	0.108	0.784	36.86
45	103.3	0.063	0.98	30.98	0.189	0.784	31.95
50	93.9	0.108	0.98	28.17	0.323	0.784	29.27
55	87.8	0.179	0.98	26.35	0.536	0.784	27.67
60	83.5	0.286	0.98	25.05	0.858	0.784	26.69
65	80.3	0.445	0.98	24.10	1.335	0.784	26.22
70	77.8	0.672	0.98	23.33	2.016	0.784	26.13
75	75.8	0.991	0.98	22.75	2.973	0.784	26.51
80	74.2	1.429	0.98	22.27	4.287	0.784	27.34
85	72.7	2.014	0.98	21.82	6.042	0.784	28.64
90	71.5	2.790	0.98	21.45	8.371	0.784	30.61
95	70.5	3.803	0.98	21.14	11.410	0.784	33.33
100	69.7	5.120	0.98	20.92	15.360	0.784	37.06

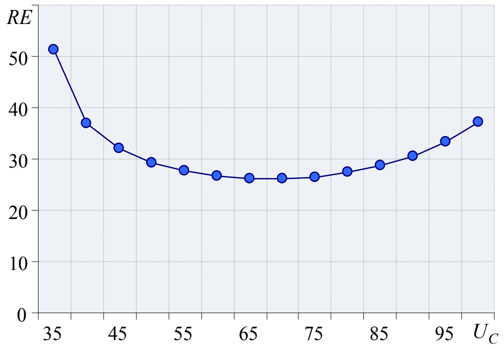


Fig. 2. Change in general costs resulted from the change in the magnitude of tight control

Any operation is carried out in order to increase the value of the output products of the operation relative to the value of the input products. Therefore, quantitative parameters of the output products must also be reduced to comparable cost quantities.

Assuming that the liquid volume loss during heating is insignificant, the cost minimum will correspond to the maximum value added cost.

4. 3. Defining trajectory of the control within which minimization of costs is ensured

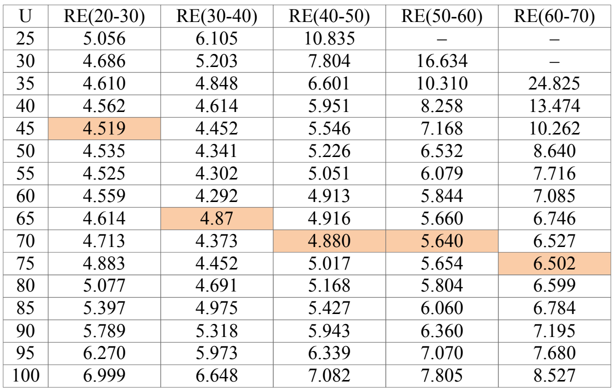
The problem is that the study of the function of costs change resulted from control (Fig. 2) does not ensure determination of the cost infimum.

Suppose that there is a trajectory corresponding to the optimum control at which minimum possible costs are achieved.

Hypothesize that the function RE[U] infimum is attained in the process of changing the control in a nonlinear trajectory. For this to be done, it is necessary to define such control change trajectory at which the costs are less than the value $RE[U_{70}]=26.13$.

Controls of U_C type in which intensity of the energy product supply does not change within the framework of the operation will be defined with "tight control" term.

To search for the control to which infimum of costs corresponds, plot a family of RE[U] graphs for various temperatures in 10 °C steps (Fig. 3).



U	RE(20-30)	RE(30-40)	RE(40-50)	RE(50-60)	RE(60-70)
25	5.056	6.105	10.835	–	–
30	4.686	5.203	7.804	16.634	–
35	4.610	4.848	6.601	10.310	24.825
40	4.562	4.614	5.951	8.258	13.474
45	4.519	4.452	5.546	7.168	10.262
50	4.535	4.341	5.226	6.532	8.640
55	4.525	4.302	5.051	6.079	7.716
60	4.559	4.292	4.913	5.844	7.085
65	4.614	4.87	4.916	5.660	6.746
70	4.713	4.373	4.880	5.640	6.527
75	4.883	4.452	5.017	5.654	6.502
80	5.077	4.691	5.168	5.804	6.599
85	5.397	4.975	5.427	6.060	6.784
90	5.789	5.318	5.943	6.360	7.195
95	6.270	5.973	6.339	7.070	7.680
100	6.999	6.648	7.082	7.805	8.527

Fig. 3. Change in costs as a result of control at various liquid heating stages

The values marked in Fig. 3 are minimum costs within a separate heating stage.

At once it becomes possible to check how the liquid heating costs will change with a tight control U_{70} and compare the results with the data of Table 1.

$$RE_{70}[20-70]=RE_{70}[20-30]+RE_{70}[30-40]+$$
$$+RE_{70}[40-50]+RE_{70}[50-60]+RE_{70}[60-70]=$$
$$=4.713+4.373+4.88+5.64+6.527=26.13.$$

Investigating how costs vary from operation to operation, a conclusion can be drawn that the method of searching for optimum within the framework of one operational process cannot by defined in this case.

In the case of liquid heating, this is due to the fact that in the process of increasing the heating temperature, the costs of each subsequent step increase in relation to the previous step (Fig. 4).

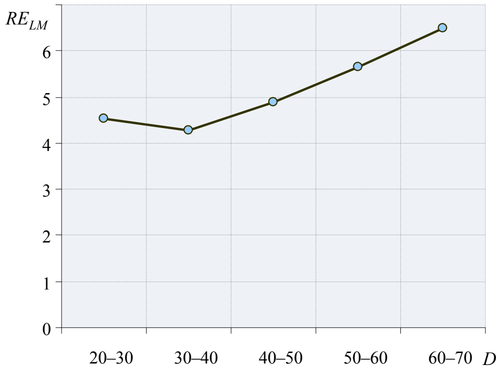


Fig. 4. Variation of the value of local minimum cost (RE_{LM}) with variation of the heating range (D)

The exception is the first stage of heating the costs of which with the control unchanged can be either lower or higher than those of the second stage of heating.

Consider why it is impossible to reach the optimum in succession, in the search mode.

Suppose, for example, that the initial control was U_{35}. After heating to 30 °C, the heating costs will be $RE_{35}(20-30)=$

=4.61. According to the optimum search algorithm, using the half-division method, it is necessary to change the control, carry out the next stage of the heating operation and decide whether the direction of the control change was chosen correctly. However, this cannot be done since the cost increases at each heating stage.

So, both variants, $U_{30}(30–40)=5.203$ and $U_{40}(30–40)=$ $=4.614$, are more than the costs that were at the stage of heating from 20 to 30 °C under control $U_{35}=4.61$.

Of course, the trend is clear. Increased control leads to lower costs but this can only be determined by comparing the controls at the heating stage (30–40). However, making a test step from the level (20–30), it cannot be evaluated because there is only one attempt in dynamics.

Thus, for the class of manufacturing processes in which the optimization criterion naturally worsens its indices at each subsequent step, it is impossible to use the dynamic programming method in the process of search optimization.

If minimum costs within each temperature range are selected, an optimal control trajectory will be obtained which will be as follows in this case:

$$U_{OPT}[20–70]=(U_{45}[20–30];$$

$$U_{65}[30–40];\ U_{70}[40–50];$$

$$U_{70}[50–60];\ U_{75}[60–70])\ \text{(Fig. 5)}.$$

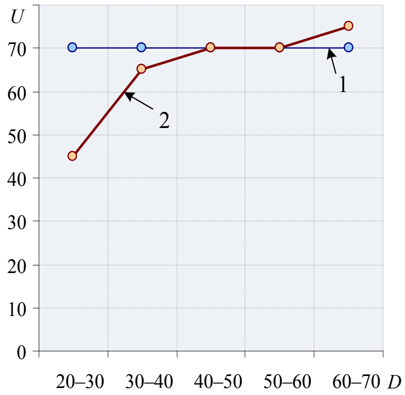


Fig. 5. Change of control by minimum costs depending on the heating stage: tight control (1); control which provides an optimal trajectory of cost change (2)

Total costs in controlling the heating process by the following trajectory:

$$RE_{OPT}[20–70]=RE_{45}[20–30]+$$
$$+RE_{65}[30–40]+RE_{70}[40–50]+$$
$$+RE_{70}[50–60]+RE_{75}[60–70]=$$
$$=4.519+4.287+4.88+5.64+6.502=25.828.$$

Thus, definition of an optimal control trajectory for reaching minimum costs requires extensive studies of related and significant time costs.

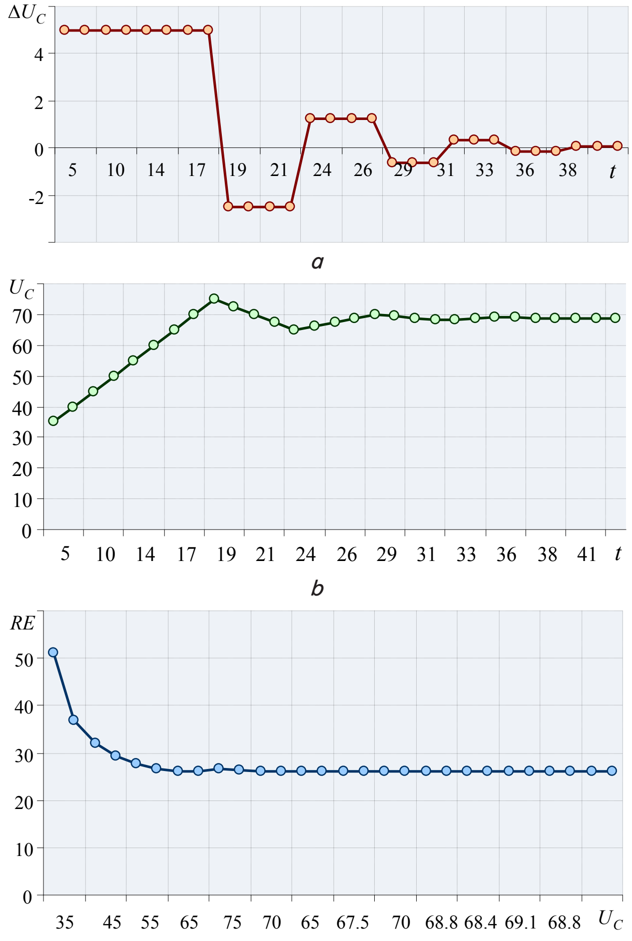
4. 4. Determination of the rigid optimum extremum as the first stage of the optimization process

Time to search the optimal trajectory by the criterion of minimum costs can be significantly reduced if the process of finding the infimum is divided into two stages.

As can be seen from Fig. 5, the optimal trajectory of minimum costs is in the vicinity of the extremum of the tight control. Therefore, it is expedient to divide the search optimization into two stages.

At the first stage, it is possible to perform a multi-operation search for the minimum of the RE [U_C] function using known algorithms of search for extremum with a transition to the region of minimum tight control of the U_C and only then search for the optimal control trajectory in the vicinity of the U_C control.

In this case, search for a tight control value can be performed relatively quickly and what is most important, in a fully automatic mode, e.g. using the half-division method (Fig. 6).



a

b

c

Fig. 6. The process of automatic search for minimum costs using the half-division algorithm: *a* – change of the tight control step; *b* – change of the tight control; *c* – change of the tight control costs

The search algorithm is implemented as follows:

Suppose that the first operation is performed with an energy product feed rate of 35 kW.

Upon completion of the operation, the total costs are determined.

Further, the control changes in steps of 5 units in the direction of increasing intensity of the energy product supply. That is, the change in control leads to the energy product supply with an intensity of 40 kW.

Upon completion of the heating operation, the resulted total costs of the operation are determined again.

If the costs are reduced with increase in intensity of the energy product supply from operation to operation, the process of changing control continues in steps of 5 units.

This proceeds as long as costs decrease with control increase.

If increase in control and, correspondingly, increase in intensity of the energy product supply results in an increase in the heating operation costs, the direction of the change in the control step is reversed. In doing this, the control change step is halved.

Thus, the heating system in the search mode moves to such an intensity of the energy product supply at which the costs have a value sufficiently close to the minimum.

At the second stage, the search for the infimum of costs is carried out in the vicinity of the tight control.

4. 5. The feature of optimization by the criterion of resource effectiveness

To determine the optimal control by the criterion of resource effectiveness, it is necessary to additionally determine the operation time (TO) and make cost estimate of the output product.

If the cost estimate of the output product obtained in the completed operation (PE) is made at a level at 35 monetary units, a change in three parameters (RE, PE, TO) as a result of tight control will be obtained (Table 2 and Fig. 7).

Table 2

Change of global parameters of the operation of heating one cubic meter of fluid to 70 ºC depending on the tight control

U_C	RE	TO	PE	ELS
35	51.19	4.83	35	0
40	36.86	3.03	35	0.00029
45	31.95	2.33	35	0.00154
50	29.27	1.91	35	0.00876
55	27.67	1.63	35	0.02084
60	26.69	1.42	35	0.03638
65	26.22	1.27	35	0.05208
70	26.13	1.14	35	0.06563
75	26.51	1.04	35	0.07126
80	27.34	0.96	35	0.06644
85	28.64	0.89	35	0.05102
90	30.61	0.83	35	0.02631
95	33.33	0.77	35	0.00397
100	37.06	0.73	35	0

Using expression (1) [17]

$$\mathrm{ELS}=\frac{(\mathrm{PE}-\mathrm{RE})^2\,\mathrm{T}_1^2}{\mathrm{RE}\cdot\mathrm{PE}\cdot\mathrm{TO}^2}, \tag{1}$$

which has been verified for compliance with the efficiency formula [16, 19, 20], find that control UC=75 corresponds to the maximum efficiency (Fig. 8). Here T1 is the time for determining potential effect of operation (T1 is always 1).

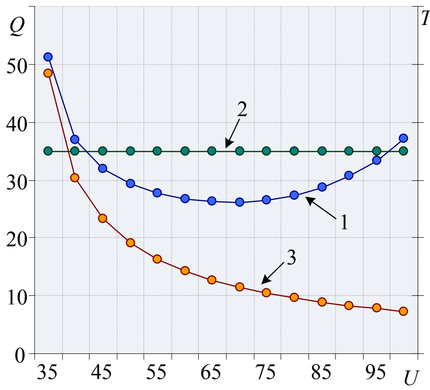


Fig. 7. Diagrams of change of parameters of operation of heating one cubic meter of fluid to 70 °C depending on the tight control: cost estimate of the heated liquid (1); costs estimate (2); time of the heating operation (3)

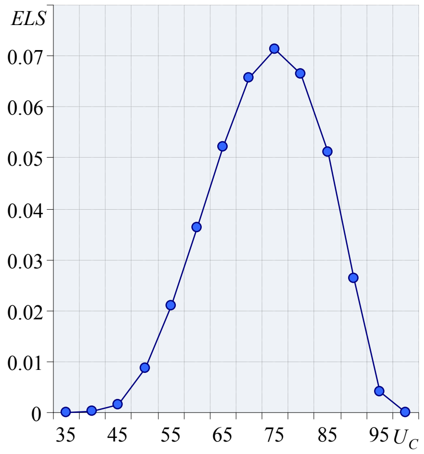


Fig. 8. Change of efficiency of the heating operation in the tight control function

Next, it is necessary to determine the operation time at each control stage (Table 3).

Table 3

Change in the heating time within individual operation stages

TO(20–30)	TO(30–40)	TO(40–50)	TO(50–60)	TO(60–70)
0.603	0.814	1.444	–	–
0.467	0.578	0.867	1.847	–
0.397	0.461	0.628	0.981	2.361
0.347	0.383	0.494	0.686	1.119
0.308	0.328	0.408	0.528	0.756
0.281	0.286	0.344	0.431	0.569
0.256	0.256	0.300	0.361	0.458
0.236	0.231	0.264	0.314	0.381
0.219	0.208	0.239	0.275	0.328
0.206	0.192	0.214	0.247	0.286
0.194	0.175	0.197	0.222	0.256
0.183	0.164	0.181	0.203	0.231
0.175	0.153	0.167	0.186	0.208
0.167	0.142	0.158	0.169	0.192
0.158	0.136	0.144	0.161	0.175
0.153	0.128	0.136	0.150	0.164

It can be seen that the time of each stage of the control operation increases with increase in the degree of availability of the output product (Fig. 9).

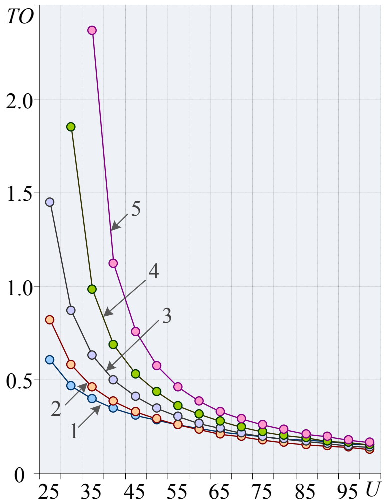


Fig. 9. Graphs of change in the heating time within individual operation stages: in the heating temperature range from 20 to 30 °C (1); in the heating temperature range from 30 to 40 °C (2); in the heating temperature range from 40 to 50 °C (3); in the heating temperature range from 50 to 60 °C (4); in the heating temperature range from 60 to 70 °C (5)

To assess effectiveness at each intermediate stage of control, it is necessary to make cost estimate of the intermediate output product. To this end, expression (2) can be used:

$$\mathrm{PE}_{\mathrm{CL}}=\frac{\mathrm{RE}_{\mathrm{CLM}}\cdot \mathrm{PE}_{\mathrm{F}}}{\mathrm{RE}_{\mathrm{FM}}}, \qquad (2)$$

where $\mathrm{PE}_{\mathrm{CL}}$ is the value of the cost estimate of the output product at the current operation stage; $\mathrm{RE}_{\mathrm{CLM}}$ is the value of the cost estimate of the input product at the current operation stage at the minimum point; PE_{F} is the cost estimate of the output product at the final stage of the operation under study; $\mathrm{RE}_{\mathrm{FM}}$ is the cost estimate of the output product at the final stage of the operation under study at the minimum point (Table 4).

Table 4

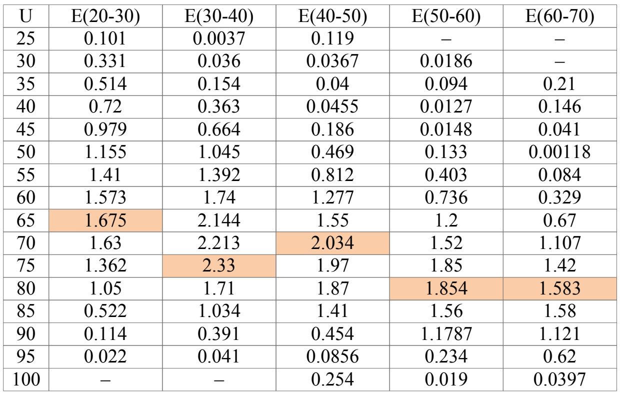
Dependence of the change in minimum costs and cost estimates of output products on the heating stage

Stage	(20–30)	(30–40)	(40–50)	(50–60)	(60–70)
$\mathrm{RE}_{\mathrm{CLM}}$	4.519	4.287	4.880	5.640	6.502
$\mathrm{PE}_{\mathrm{CL}}$	6.124	5.810	6.613	7.643	8.810

Fig. 10 shows the results of change in resource efficiency within each stage of change in the output product temperature. The markers indicate maximum efficiencies within a separate heating stage.

Maximum values of efficiency are compared with the line of tight control in Fig. 11.

As can be seen from Fig. 11, the optimal control trajectory is close enough to the tight control line.



U	E(20-30)	E(30-40)	E(40-50)	E(50-60)	E(60-70)
25	0.101	0.0037	0.119	–	–
30	0.331	0.036	0.0367	0.0186	–
35	0.514	0.154	0.04	0.094	0.21
40	0.72	0.363	0.0455	0.0127	0.146
45	0.979	0.664	0.186	0.0148	0.041
50	1.155	1.045	0.469	0.133	0.00118
55	1.41	1.392	0.812	0.403	0.084
60	1.573	1.74	1.277	0.736	0.329
65	1.675	2.144	1.55	1.2	0.67
70	1.63	2.213	2.034	1.52	1.107
75	1.362	2.33	1.97	1.85	1.42
80	1.05	1.71	1.87	1.854	1.583
85	0.522	1.034	1.41	1.56	1.58
90	0.114	0.391	0.454	1.1787	1.121
95	0.022	0.041	0.0856	0.234	0.62
100	–	–	0.254	0.019	0.0397

Fig. 10. Results of changes in the resource efficiency within each stage of change in the output product temperature

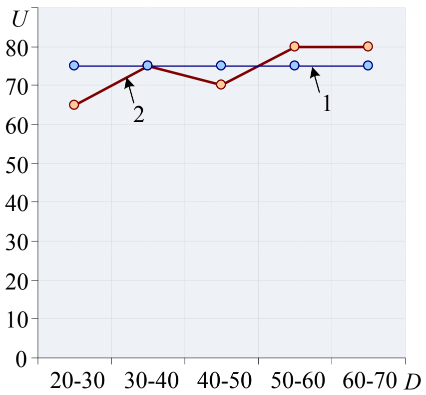


Fig. 11. Change of the control for the maximum efficiency depending on the heating stage: tight control (1); optimal control trajectory (2)

5. Discussion of the study results related to determining the optimal control trajectory

The conducted studies have shown that two classes of operational processes can be distinguished in relation to the task of determining the optimal trajectory.

The first class includes operations the optimal control within which can be determined in the course of the same operations. A typical example here is the problem of searching for optimal control in the process of uniform load displacement. Since the intermediate results of this operation are comparable to each other, methods of search optimization can be implemented in the course of the operation.

The second class includes operations with non-linearly varying results of step-by-step execution of the operational task. These tasks include processes that require heating, crushing, pressure rise. Thus, heating cost increases nonlinearly with temperature rise. In the process of pressure rise, costs increase nonlinearly as well, etc. For such operations, the search for an infimum or supremum of an optimal control trajectory by enumeration of existing controls is very time-consuming.

In this situation, a quick automatic transition of control to a region close to the optimal trajectory makes it possible to significantly shorten the search time and improve efficiency of the search process.

Thus, the combination of multioperational search optimization with further correction of the control trajectory in the vicinity of a tight optimum may prove to be an almost acceptable solution.

Optimum control is based on comparing expert or cost estimates of input and output products in a given operation. Therefore, the optimal control trajectory must be rebuilt whenever there is a change in the demand for or cost estimate of any processed product.

Therefore, the search for an infimum or supremum of a control trajectory is a permanent process in a rapidly changing market environment.

6. Conclusions

1. The cybernetics of the manufacturing process shows that the change in control leads to a change in amount of energy consumption and equipment wear during the production step. Thus, in order to obtain reasonable optimization results, feasibility of simplifying search models must be substantiated.

2. The speed of search for an optimal trajectory can be increased if the optimization process is implemented in two stages.

At the first stage, it is expedient to search for a tight optimum in an automatic mode using tried-and-true methods of searching for an extremum.

At the second stage, determination of the optimal trajectory is carried out in the vicinity of the tight control.

3. The process of optimization by the criterion of effectiveness requires cost estimation of the output product at each selected stage of the production step.

Since qualitative parameters of the output product at different operation stages are quantitatively incomparable, cost estimate of the output product relative to the minimum costs of the corresponding operation stage was determined in this work. In this case, the magnitude of the cost estimate for the output product is determined as the result of ratio of the product of the minimum costs at a certain stage multiplied by the total cost estimate of the output product obtained in the tight control mode to the total costs determined at the common point of the minimum.

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DEVELOPMENT OF COMPUTER-INTEGRATED SYSTEMS FOR THE AUTOMATION OF TECHNOLOGICAL PROCESS OF ASSOCIATED GAS PROCESSING

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Проаналізована переробка супутнього нафтового газу. Запропонована процедура побудови комп'ютерно-інтегрованої системи автоматизації технологічного процесу переробки газу. Особливістю процедури є комплексне розв'язання задачі ефективного розрахунку технологічного процесу і керування їм сучасною системою керування. Процедура використана для розробки технологічного процесу переробки газу нафтового родовища середньої потужності. Процес забезпечує якісну переробку газу при значних збуреннях

Ключові слова: ректифікація, метан, пропан-бутан, система автоматичного керування, комп'ютерно-інтегрована автоматизація

Проанализирована переработка попутного нефтяного газа. Предложена процедура построения компьютерно-интегрированной системы автоматизации технологического процесса переработки газа. Особенностью процедуры является комплексное решение задачи эффективного расчета технологического процесса и управления им современной системой управления. Процедура использована для разработки технологического процесса переработки газа нефтяного месторождения средней мощности. Процесс обеспечивает качественную переработку при значительных возмущениях

Ключевые слова: ректификация, метан, пропан-бутан, система автоматического управления, компьютерно-интегрированная автоматизация

1. Introduction

The use of associated petroleum gases (APG) is an important line of increasing efficiency of oil well operation. The problem is given a considerable attention both by governments and businesses of a number of leading oil-producing countries [1, 2].

Ukraine is potentially capable to satisfy all domestic demands for oil and gas [3]. For economic and political reasons, it has been more profitable in the past to import oil and gas, however, due to the recent change in the world political situation, the urgency of developing and improving efficiency of using own oil and gas fields has increased significantly. It is unacceptable that about 75 % of Ukrainian APG is not utilized but burnt in torches [4]. In this work, detailed data on composition of Ukrainian APG deposits are presented. In addition to the negative effects to environment, burning of gas is simply economically unjustified in most cases. There are no legislative regulations for APG utilization and processing methods in Ukraine.

The technical side of the APG processing problem is connected with the computer-integrated automation of the technological process (TP) of APG processing with its productivity tied to the current field productivity.

The main principles underlying the proposed procedure are as follows:

– automation of the technological process development;

– computerized integration of the process equipment and the automatic process control system;