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RESEARCH AND MODELING OF OIL REFINING TECHNOLOGICAL PROCESSES OPERATING IN THE CONDITION OF STOCHASTIC UNCERTAINTY

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Abstract

As it is known, one of the initial and important stages in the creation of optimal control systems of oil refining technological units is the development of a mathematical model that can adequately record the processes at any time.

The operative and accurate measurement of all input and output variables is one of the important conditions in the development of a mathematical model of technological processes.

Studies have shown that the lack of information about the state of complex oil refining processes in many cases reduces their efficiency and effectiveness. On the other hand, the wide range of both quality and quantity of raw materials for processing makes their efficiency even more unsatisfactory. Under these conditions, it is difficult to develop mathematical models that can adequately describes the static modes of technological processes; the development of mathematical models is relevant both in scientific and practical terms.

A priori information required on input and output variables during normal operation of the technological complex in order to implement mathematical models identification for the vacuum block of the oil refining process unit is provided in the article. On the basis of this static information, mathematical dependencies were constructed between the variables characterizing the static mode of technological processes and the adequacy of the obtained mathematical models was confirmed through the statistical apparatus.

In order to solve the problems, the research was determined to be able adequately describe the current technological conditions, which can quickly adapt to current technological situations and ensure the production of oil fractions with relatively stable quality, regardless of the disturbing effects of the system.

Keywords: oil refinery, technological process, random quantity passive experiment, regression coefficients.

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1. Introduction

One of the most important technological facilities among the enterprises being included in the leading industries is the refining facilities that ensure primary oil refining. The purpose of these facilities is to ensure the production of a wide range of high-quality oil fractions from crude oil. Requirements for the quality indicators of various oil products produced through these technological facilities require the creation of more modern and perfect control systems [1]. Most of the catalytic processes in the chemical, petrochemical and oil refining industries are refers to the number of non-stationary complex and multi-stage processes. For optimal control of such processes, due to the large dimensionality of the initial problem, decomposition approaches are mainly used.

Currently, each of the technological processes existing in the petrochemical and oil refining industries requires the research of technological equipment composition used in them, as well as, technical means of automation and control systems as complex systems in terms of operating characteristics. As it is known, in order to evaluate the current status of such technological processes, it is necessary to be based on the data about hundreds of technological parameters. However, it should be noted that the final data on the current status of each technological parameter, as a rule, depends more on the technical parameters of the transmitters, converters, communication channels and technical indicators of other technical means in the operation mode. On the other hand, technical characteristics of both technological equipment and each automation tool change according to the regularities which are not always predictable in the operating condition [2].

Many studies consider the issue of static optimization of petrochemical processes. The main attention in these studies is given to the study of problems associated with experimental and statistical methods [3, 4]. The results obtained when solving the problem of mathematical modeling of a specific technological process are correlated with the results obtained when applying the regression analysis method [5–7]. In [8], the authors studied the problems of mathematical modeling of non-stationary processes and explored ways to solve the problems that arise in this regard.

[9, 10] describes in detail the main elements and functions of stochastic modeling.

Modeling of technological processes is usually based on the use of kinetic models that reflect their physical and chemical properties. However, the use of mathematical models of this class does not always allow one to obtain the expected results, since the parameters of the modes usually change according to random laws during the functioning of real technological processes operated in production conditions.

Given the above, the main goal of the study is the development of mathematical models that can be used in control systems for industrial technological processes that carry out primary oil refining, operating under conditions of stochastic uncertainty. To do this, primary data were collected empirically, carrying more complete information about the object. Adequate mathematical models have been built that allow compensating for disturbance factors by regression analysis, determining the optimal operating modes of individual devices, and as well as coordinating the operating modes of these devices.

Based on the above-mentioned reasons, it should be noted that the data which is available to the control system about the status of technological processes cannot be considered complete. Thus, in a particular case, it is more reasonable to consider each technological system and its control system, consisting of a set of automation tools, as a system operating in conditions of uncertainty in terms of dataware, both physically and technically.

2. Materials and methods

Based on the above-mentioned, it can be concluded that in the real operating condition of technological systems, both outside and inside, as well as in the dataware channels, random events, the change of which is not unpredictable, occur. Due to these random events probabilistic models must be developed that can more adequately record these random events in order to be used in the decision-making process in changing situations in technological processes.

To solve the issue of physically based optimization of the technological complex for primary oil treatment, after the formation of typical mathematical models of its main devices, conditions of limitations and optimality criteria, it is necessary to build mathematical models that reflect the features of this technological complex.

It is known that probability theory, which is a classical mathematical apparatus for the study of random processes, is an integral part of modern mathematics and records such events and the regularities of their occurrence on the basis of any pre-selected mathematical model.

A legitimate event is an event that definitely occurs under certain conditions. However, in technological systems, there are such events that their occurrence is random. As a rule, the selected mathematical model plays an important role in predicting such events. It should be noted that probability theory is in fact considered one of the most developed areas of classical mathematics, being the area which studies the models of random events. In other words, mathematical models based on probability theory allow to determine such relationships between the probabilities of random processes so that the probabilities of complex events can be calculated as a set of probabilities of relatively simple events [6, 7].

It is known that the methods used in many areas of classical mathematics are widely used in the development of probability theory. Moreover, probability theory has its own methods of studying.

Now let's give a brief explanation of the simplest concepts to be used in the process of mathematical modeling of events occurring in oil refining systems through probability theory and the main features that characterize random processes.

In the modeled technological process, the number characterizing their occurrence opportunities can be considered the probability of the occurrence of this event in order to quantify and compare the values that can be obtained by output coordinates during the process.

If the discrete ξ random quantity of any output coordinate controlled by technological processes obtains its value with the corresponding probability P_i, then a set of (x_i, P_i) pairs of real numbers is called the distribution law of the random quantity ξ.

The probability that a random quantity ξ obtains a value less than x, in other words, the probability of an event $(\xi < x)$ is called the quantity distribution function and is denoted as follows:

$$F(x) = P(\xi < x), \ -\infty < x < +\infty.$$

The value determined by the expression $\gamma_2 = \left(\mu_4/\mu_2^2\right) - 3$ of a random process is called its excess. Where,

$$\mu_2 = D\xi = M(\xi - M\xi)^2,$$

is a process dispersion from the second order moment, and μ_4 characterizes its fourth order moment.

The asymmetry of a random process is determined by the expression $\gamma_1 = \mu_3/\sigma_\xi^2$.

Summarizing the concepts and expressions explained above, it is worth noting that the numerical characteristics of random quantities were determined from the following expressions when developing the mathematical models on the basic output coordinates in the uncertainty condition of K-1, K-2 and K-8 rectification columns being considered the main apparatus in terms of targeted product production of the atmospheric unit of ELOU-AVT-6 device:

1) average value:

$$x_{or} = \frac{\sum_{i=1}^{n} x_i}{n}; \quad (1)$$

2) dispersion:

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - x_{or})^2; \quad (2)$$

3) mean-square deviation:

$$\sigma = \sqrt{\sigma^2} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - x_{or})^2}; \quad (3)$$

4) average mathematical error:

$$M = \frac{\sigma}{\sqrt{n}}; \quad (4)$$

5) accuracy of the average mathematical value:

$$T = \frac{x_{or}}{M}. \quad (5)$$

Based on the above-mentioned expressions, the results of the reports on the main control coordinates and constraint conditions in K-1 rectification column are presented. The results of these reports were used in the modeling of each apparatus of the technological complex in the identification of distribution functions on the appropriate coordinates.

3. Research results

The mathematical formulation of the modeling problem, which expresses the regression dependence between unstable gasoline yield (volume consumption) of the atmospheric section and other parameters, and the sequence of solving the problem according to the formulation are as follows.

The diagram of the structural form of K-1 column as a modeling facility for the construction of a mathematical model is depicted in **Fig. 1.**

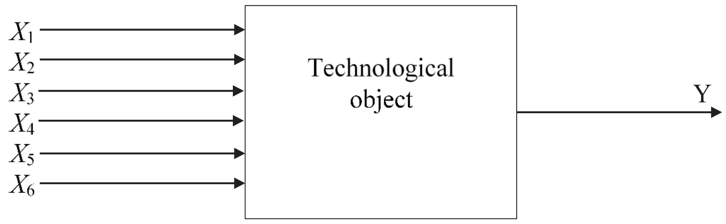

Fig. 1. Structural diagram of K-1 column as a modeling facility

Where:
– X_1 – volume consumption of raw material given to K-1, F, 160–175 m^3/hour,
– X_2 – pressure above K-1, P_{ab}, 65–110 atm,
– X_3 – temperature above K-1, T_{ab}, 72–88 °C,
– X_4 – residual pressure below K-1, P_{be}, atm,
– X_5 – temperature below K-1, T_{be}, 330–350 °C,
– X_6 – density of unstable gasoline, ρ, must be greater than 887 kg/m^3,
– Y – volume consumption of unstable gazoline with quality expectations, $F_{y.y}$, 28–32 m^3/h.

Why are these parameters so important to control process?

Consumption – it is possible to adjust the level and maintain temperature value by changing the consumption (irrigation), which makes it necessary to measure. Pressure **–** the pressure in the apparatus is also one of the factors affecting the process of separating raw materials into fractions. It affects directly the yield. Temperature – during the distillation of the crude oil, it is necessary to maintain the temperature at a certain value. Since the temperature is not at the proper level, this leads to a disruption in the process. The linear mathematical model of K-1 column is written as follows (with unknown coefficients):

$$y = b_0 + \sum_{i=1}^{n} b_i x_i \max, \tag{6}$$

where x_i are input $\left(i = \overline{1,n}\right)$ and y is output.

There are many ways to find the unknown regression coefficients of a mathematical model, one of which is to find the regression coefficients using the least squares method. This method is based on the fact that the square of the difference between the calculated value and the experimental one is very small:

$$\varepsilon = \Phi = \sum_{i=1}^{n} \left(y_i^* - y_i\right)^2 \to \min.$$

Here y_i^* – the calculated value of the function based on independent variables.

The initial statistical data obtained from the passive experiments required for modeling are as shown in **Table 1**.

Microsoft Office Excel (USA) software is applied since it is convenient to use software for determining the coefficients. The unknown coefficients of the linear mathematical model of our facility are determined by entering the statistical data in Excel and executing the relevant commands using least squares method (**Tables 1–3**).

The values of the coefficients found via the program are presented in **Table 2**.

Table 1

Statistical data table

No.	Parameters						
	X_1	X_2	X_3	X_4	X_5	X_6	Y
1	167	69.33	75.97	113.4	337.01	894.07	29.91
2	167.2	69.42	76.09	113.65	337.18	893.04	30.18
3	167.4	69.56	76.31	114.04	337.52	892.5	30.39
4	167.6	69.82	76.61	114.59	337.94	892.4	30.61
5	167.3	69.61	76.18	114.01	337.46	890.02	30.28
6	167	69.19	76	113.44	336.94	893.01	30.03
7	167	69.17	75.97	113.52	337.08	892.79	30.11
8	167.2	69.35	76.19	114.16	337.26	892.33	30.22
9	167.5	69.71	76.57	114.79	337.72	892.12	30.49
10	167.9	69.98	76.88	115.02	338.03	892.13	30.56
11	167.6	69.66	76.63	114.81	337.78	892.09	30.47
12	166.8	69.01	75.78	113.9	336.67	891.01	29.99
13	166.5	68.93	75.53	112.75	336.62	891.19	29.82
14	166.4	68.86	75.35	113.64	336.51	891.24	29.8
15	167	69.13	76.01	113.64	337.12	892.01	30.16
16	167.4	69.58	76.29	114.16	337.54	891.98	30.64
17	167.3	69.52	76.22	114.09	337.44	891.91	30.59
18	167.9	70.15	76.81	114.91	338.21	892.03	30.97
19	168.5	70.83	77.14	115.54	338.83	889.97	31.36
20	169	71	77.91	116	338.99	893.05	31.35
21	169	71.11	77.82	115.9	339.07	892.86	31.42
22	168	70.54	76.99	114.88	338.39	892.83	31.01
23	168.6	70.79	77.26	115.01	338.79	892.91	31.14
24	167.9	70.02	76.74	114.63	338.16	893.39	30.88
25	167.7	69.87	76.59	114.46	338.12	893.24	30.72
26	167.1	69.19	76.14	113.97	337.38	892.99	30.35
27	167.4	69.66	76.39	114.55	337.65	893.08	30.64
28	167.7	69.75	76.68	114.83	338	891.18	30.79
29	168.1	70	77.34	115.18	338.74	892.06	31.06
30	168.3	70.63	78	115.29	338.91	890.66	31.17

Table 2

Values of coefficients

b_0	b_1	b_2	b_3	b_4	b_5	b_6
–178.6	0.0477	0.0898	–0.244	0.0933	0.6279	–0.01

Table 3

Adequacy indicators of the mathematical model

	Adequacy index of the mathematical model	The value obtained from the analysis
1	Fisher criterion (F)	98.12
2	Set correlation coefficient (R)	0.98
3	Residual error ε	0.103

If to replace these values of unknown coefficients b_i in the model, then the linear mathematical model for the consumption of the unstable gasoline fraction of column K-1 in terms of density constraint is as follows.

Using coefficients obtained from **Table 2** in the (6) the regression equation in a linear form is formulated as follows:

$$Y = -108.6003558 + 0.344066235X_1 + 0.240099864X_2 + 1.144391904X_3 - 0.081228097X_4. \quad (7)$$

Let's assess adequacy of the model.

The experimental value of Fisher criterion (F_{exp}) must be greater than its table value (F_{tab}) for the mathematical model to be adequate:

$$F_{exp} < F_{tab}. \quad (8)$$

When checking the adequacy according to set correlation coefficient, the closer the coefficient R is to the unit ($0 \leq R \geq 1$), the more adequate the mathematical model is.

In order to check the adequacy of the developed linear mathematical model, its analysis should be carried out, which can also be performed using Excel. The results of the analysis of the data of the linear regression model performed via the program are as shown in **Fig. 2, *a–c***. Regression and dispersion analysis of the mathematical model developed through Excel was performed. The results of the analysis include residual error, set correlation coefficient, Fisher criterion, residual dispersion and other adequacy criteria of the mathematical model (**Table 3**). The program also shows the optimal values of the coefficients of the developed mathematical model.

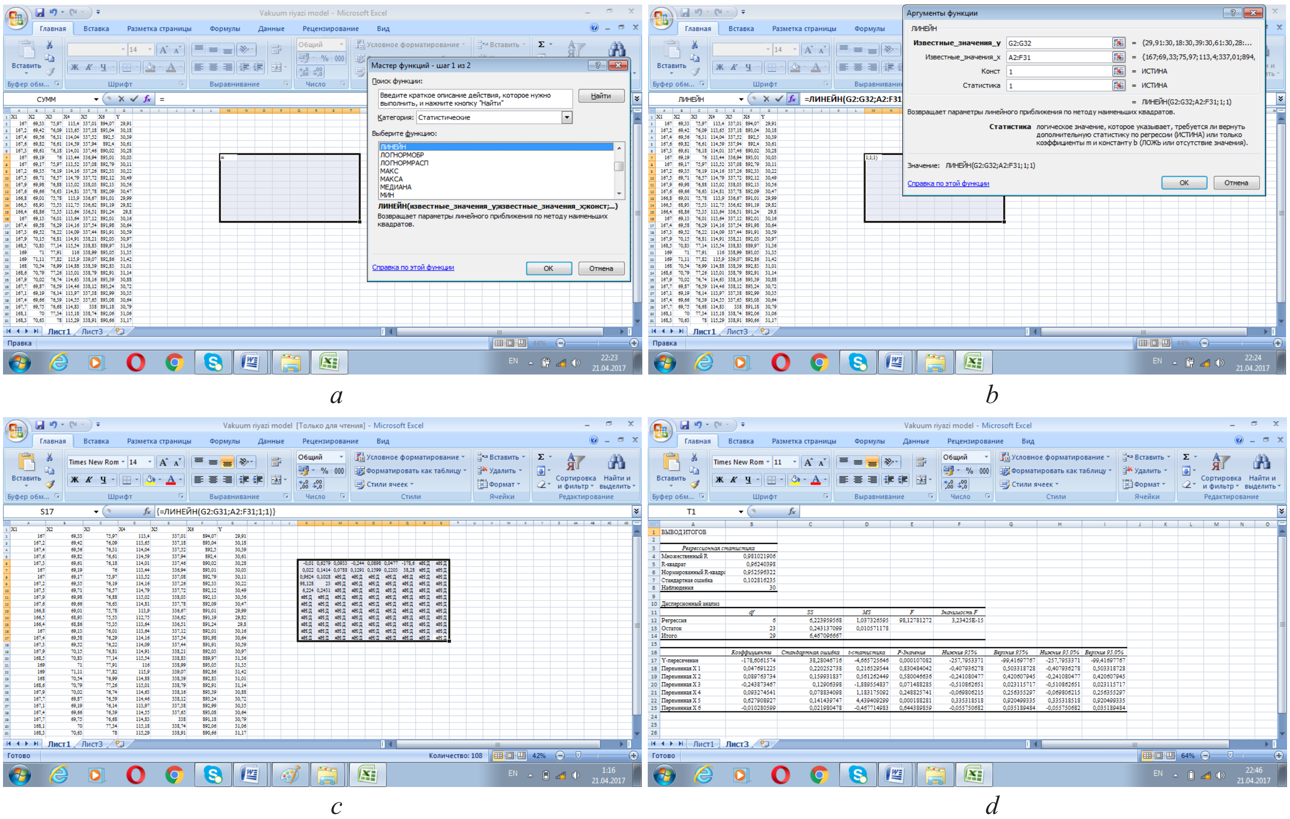

Fig. 2. Building of mathematical model in Excel:
a – selection of the section of the category for finding the coefficients of the model,
b – entering *x* and *y* values to find model coefficients, *c* – obtaining the coefficients
of a mathematical model, *d* – analysis of the adequacy of the model

Experimental value of Fisher adequacy index:

$$F_{exp} = 98.13.$$

Experimental value of set correlation coefficient: $R = 0.98$.

Table value of Fisher adequacy index corresponding to a mathematical model consisting of 30 experiments with 6 factors:

$$F_{tab} = 2.53.$$

Thus, since the numerical value of Fisher coefficient adequacy index of the mathematical developed model is greater than its table value ($F_{exp} > F_{tab}$), set correlation criterion R is close to the unit ($0.98 \approx 1$) and residual error ε is very small, the developed mathematical regression model is adequate.

The next stage of the study will to solve the optimization problem based on the obtained mathematical model. The optimization problem is to find the optimal value of the output parameter (objective function) according to the regime parameters in real production conditions under the following restrictions:

$$\begin{gathered} 160 \le X_1 \le 175, \\ 65 \le X_2 \le 11, \\ 75 \le X_3 \le 80, \\ 100 \le X_4 \le 130, \\ 330 \le X_5 \le 350, \\ X_6 \ge 887, \\ X_i \ge 0 \ (i = 1,6), \\ 28 \le Y \le 32. \end{gathered} \qquad (9)$$

X_i and Y are the parameters mentioned above. By finding the optimal values of X_i it will satisfy the maximum to the value of Y.

The practical significance of scientific results in paper is that it provides conditions for the operational management of the technological complex in cases where both external and internal state coordinates change according to random laws in the primary oil refinery unit under real production conditions.

4. Conclusions

The article deals with the research in terms of the control object of the atmospheric unit of oil refining technological complex and revealing the change of its input, controlling and controlled output coordinates according to random rules in production conditions.

A passive experiment was conducted through the equipment to collect the initial data of the object in order to develop mathematical models that can adequately record the real technological situations occurring in the operating modes of the primary oil refining equipment. Based on the statistical data collected as a result of the passive experiment for the main apparatus of the equipment, a mathematical model was developed in the form of a linear regression equation on the main output coordinate of K-1 rectification column and its adequacy was checked on the basis of mathematical statistics. As a result, a mathematical model was obtained that can adequately describe the real process.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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