Automation and control of the vacuum block

Elchin Melikov*, *Tamella* Maharramova, and *Aygun* Safarova

Electronics and Automation Department, Azerbaijan State Oil and Industry University, Baku, Azerbaijan

Abstract. Based on a comprehensive study of technological processes occurring in the vacuum block for an installation of the ELOU-AVT type, the features of the complex technological complex under consideration as a control object were analyzed. In this regard, a statement for the optimization task of a block under study has been developed, taking into account restrictive conditions on control and input parameters. Taking into account the compiled mathematical models for the quantitative and qualitative characteristics of the process under consideration and the algorithm for their gradient adaptation, to numerically solve the problem of optimizing the functioning for this block, the classical Lagrange method multipliers is used. In a wide range of changing conditions in input disturbing factors in quantity and quality, as well as insufficient operational quality information on the selected petroleum products, the proposed method and principles of development algorithm for controlling the process under study allows for prompt preliminary local regulation modes correction and the selection of new optimal modes for adaptive control as a whole. This circumstance leads to an increase in the economic production efficiency as a whole.

1 Introduction

Technological unit for fractionating is an essential part of the petroleum branch [1]. Accordingly, in the experience of realizing optimal control structures for manufacturing units, the crucial part of the research phases is an integrated learning of these processes [2-4]. Raw material successively is exposed in these technological complexes to the primary distillation process, dividing the crude oil into fractions of different boiling point ranges. At the same time, as control objects, the above-mentioned units differ by the intricacy of including in their composition apparatuses, a lot of controlled and disturbance factors. In addition, it is necessary to make smart decisions on the management of technological objects in the lack of a full data-related process [5-6].

In the presented article, a vacuum block for primary oil processing of the ELOU-AVT installation is seen as a research object and development of an automated control system. In a vacuum block residual mazut is converted into various fractions. These fractions are used in lubricant production in machine building, as well as for combustion engines and other process equipment.

* Corresponding author: elchin03@mail.ru

Therefore, solving the actual problem of improving the quality of vacuum blocks automatic control in petroleum refining and, as a result, economic efficiency growth of petroleum products is of essential practical significance.

The presented article reviewed cybernetic principles of the solving control problem for the vacuum technological block of a primary oil processing unit and proposes principles for the development of an algorithm for an automated control system. This will improve the efficiency, profitability, and productivity of the production in question as a whole.

In the 1st stage, operative parametric control of the basic aggregates for the vacuum block is implemented. It is based on the synthesis of deterministic models together with optimization algorithms for process control.

In the 2nd stage, the problem of invariant stability for technological modes is solved under conditions of insufficient information about the state of the management object under study. A combined system using self-regulating regulators is proposed to obtain stable quality of final products. Let's look at the functional scheme of the automation for the vacuum block of the ELOU-AVT type installation, presented in Figure 1.

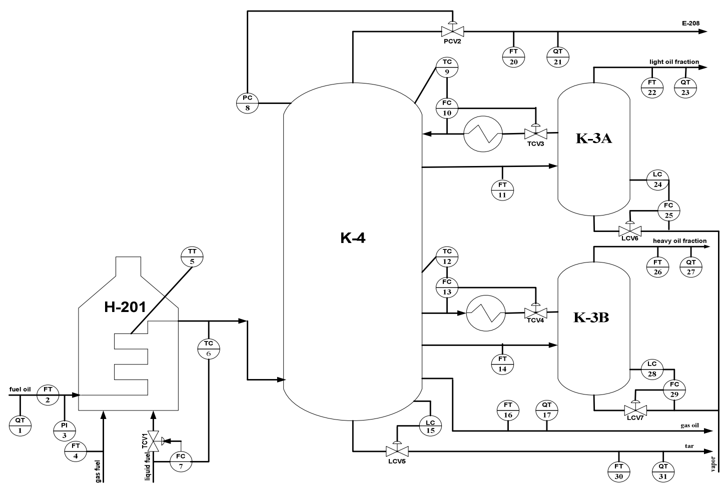

Fig. 1. Automation functional scheme of the vacuum block for a primary oil refining ELOU-AVT type installation.

The studies have shown that the main and significant for effective management of technological apparatuses of this block is a tubular furnace (it provides mazut heating), a vacuum mazut rectification column, and stripping columns.

Fuel oil is a residual product of the atmospheric block. It is heated in a tube furnace (H-201) to 405÷415 °C. Next, it enters the lower part of the K-4 vacuum column.

Being a residual product of the atmospheric block, mazut is heated in the H-201 furnace to a temperature of 405÷415 °C and then enters the bottom of the K-4 vacuum column. The light oil fraction is removed from the top of the K-4 column at a temperature of 155÷185°C. Some of it is used here for irrigation. The main flow is supplied through the K-5A stripping column to the product section of the installation under study. The heavy petroleum fraction obtained from the middle part of the K-4 with a temperature of 290÷310 °C is also used for irrigation. The main flow of the fraction itself flows through the lower part of the K-5B stripping column into the product compartment.

Finally, heavy vacuum gas oil is allotted from the bottom of the K-4, and residual tar with a temperature of 340÷345 °C is given out from the bottom. Table 1 shows the regulatory indicators of the vacuum block mode parameters.

Note that the fuel oil vacuum distillation column K-4 has the greatest influence on the quality of the resulting target products. In this case, the important controlled coordinates of the technological object under consideration are the matrices of temperature modes and remaining pressure. The disturbing impacts of this object are changes in the quantitative as well as qualitative characteristics of the mazut which comes from the atmospheric block.

Table 1. Regulatory indicators of the vacuum block mode parameters.

Technological parameters	Unit of measurement	Range of variation	
		Lower limit	Upper limit
Raw materials quality	-	Not measured	
Raw materials consumption	kg3/h	60	100
Temperature at the outlet flow from the furnace H-201	°C	390	400
Temperature of the K-4 column cube	°C	385	395
Temperature of the vacuum column top K-4	°C	72	88
Level in vacuum column K-4	%	40	60
Residual pressure in vacuum column K-4	mmHg	60	80
Temperature of the plate from which the light oil fraction is taken	°C	155	185
Temperature of the plate from which the heavy oil fraction is taken	°C	290	310
Light oil consumption	m3/h	10	-
Heavy oil consumption	m3/h	15	-
Light vacuum gas oil	m3/h	45	-
Vacuum residue – tar	m3/h	10	-

2 Statement of the problem

According to the amount of a priori data about the controlled and control parameters, as well as on the disturbing influences of the process being studied, the vacuum block is classified as a deterministic and partly uncertain system.

Besides this, difficulties in synthesizing a complex of models that most comprehensively describe the features of the ongoing processes in this block are related to the efficiency and measurement error of process parameters.

The operation of such units shows that for this process plant type, the important indicator is to maximize the output and quality of the petroleum fractions (specific gravity of resulting product, flash temperature, kinematic viscosity, etc.) with a minimum of energy costs. The solution to this problem lies in consistently optimal control of the technological process under consideration.

Thus, taking into account, a generalized mathematical statement of the optimal control task for a vacuum block, taking into account regulatory indicators:

$$Y_{l.o.f} = f_1(F_{f.o}, T_b, T_t, P, T_{K-3A}) \rightarrow max \, , \quad (1)$$

$$G_{l.o.f}^{s.g} = f_2(F_{f.o}, T_b, T_t, P, T_{K-3A}) \geq 0.877 \, , \quad (2)$$

$$G_{l.o.f}^{k.v} = f_3(F_{f.o}, T_b, T_t, P, T_{K-3A}) \leq 8.5 \, , \quad (3)$$

$$G_{l.o.f}^{f.p} = f_4(F_{f.o}, T_b, T_t, P, T_{K-3A}) \geq 135 \, , \quad (4)$$

$$Y_{h.o.f} = f_5(F_{f.o}, T_b, P, T_{K-3B}) \rightarrow max \, , \quad (5)$$

$$G_{h.o.f}^{s.g} = f_6(F_{f.o}, T_b, P, T_{K-3B}) \leq 0.907 \, , \quad (6)$$

$$G_{h.o.f}^{k.v} = f_7(F_{f.o}, T_b, P, T_{K-3B}) \leq 6.5 \, , \quad (7)$$

$$G_{h.o.f}^{f.p} = f_8(F_{f.o}, T_b, P, T_{K-3B}) \geq 205 \, . \quad (8)$$

Limitations on control and input variables of the block:

$$60\ \frac{m^3}{h} \leq F_{f.o} \leq 100\ \frac{m^3}{h}, \quad (9)$$
$$72\ ℃ \leq T_b \leq 88\ ℃, \quad (10)$$
$$385\ ℃ \leq T_b \leq 395\ ℃, \quad (11)$$
$$60\ mmHg \leq P \leq 80\ mmHg, \quad (12)$$
$$155\ ℃ \leq T_{K-3A} \leq 185\ ℃, \quad (13)$$
$$270\ ℃ \leq T_{K-3B} \leq 285\ ℃. \quad (14)$$

Here and respectively are the outputs of light and heavier petroleum fractions: $G^{s.g}_{l.o.f}$, $G^{k.v}_{l.o.f}$, $G^{f.p}_{l.o.f}$, $G^{s.g}_{h.o.f}$, $G^{k.v}_{h.o.f}$ and $G^{f.p}_{h.o.f}$ accordingly, the specific gravity, viscosity and flash temperature of light and heavier petroleum fractions; $F_{f.o}$ - flow of masut entering the vacuum block for processing; P - remaining pressure in K-4; T_b, T_t, T_{K-3A} and T_{K-3B} – temperature conditions at control K-4 points.

3 Modelling and development algorithm of control problem

As a result of the process analysis under study, it was established that with the mathematical formalization of our block, it is more expedient to construct mathematical models that characterize the quality parameters of the target products of light and heavier petroleum fractions in a non-linear form, and models that describe the quantity parameters of the products in a linear type.

In addition, the control system applies a gradient adaptive algorithm, which allows iteratively to maintain the adequacy of the obtained mathematical models to the real process.

Here it is proposed to use a well-known postulate, under which the system can be considered adaptive if the deflection of the output parameter actual meaning from its expected value is minimized by any small amount ε:

$$M|y_m - y_{ac.m}| \geq \varepsilon,$$

where, y_m - output coordinate obtained based on linear or non-linear model (9) or (10), $y_{ac.m}$ - current meaning for the output coordinate obtained at the object output under study, ε – a value characterizing technological accuracy in the mathematical models development.

Here, to adapt mathematical models of the vacuum technological komplex to current situations, it seems more appropriate to use an adaptation algorithm based on the gradient method, since in this proposed adaptation algorithm, unlike other algorithms, gradients of input technological parameters are used to adapt mathematical models.

The advantage of this adaptation algorithm compared to other algorithms is that each of the mathematical models coefficients is adjusted depending on the direction of their gradients and the corresponding model error. This, in turn, makes it possible, based on a smaller operations number, to construct the most adequate mathematical models that have the required quality indicators.

Adaptation of mathematical models to current situations based on this algorithm is carried out in the following way:

- for linear models:

$$B_i^{m+1} = B_i^m + a^m\left[y_{real} - \left(B_0 + \sum_{p=1}^{k} B_p^m x_{preal}\right)\right] \cdot \left(\frac{\partial y_m^*}{\partial x_i}\right)_{x_i = x_{ireal}} \quad (15)$$

- for non-linear models:

$$B_i^{m+1} = B_i^m + a^m[y_{real} - (B_0 + \sum_{p}^{k} B_p^m x_{preal} +$$

$$+\sum_t^k \sum_p^k B_{tp}^m x_{treal} x_{preal})] \left(\frac{\partial y_m^*}{\partial x_i}\right)_{x_i = x_{ireal}} \tag{16}$$

$$B_{ij}^{m+1} = B_{ij}^m + a^m[y_{real} - (B_0 + \sum_p^k B_p^m x_{preal} +$$

$$+\sum_t^k \sum_p^k B_{tp}^m x_{treal} x_{preal})] \left(\frac{\partial^2 y_m^*}{\partial x_i \partial x_j}\right)_{x_i = x_{ireal}} \tag{17}$$

$$i = 1,2, \dots, k; j = 1,2, \dots, k; j \geq i$$

Here y_{real} , x_{ireal} $(i = \overline{1,k})$ - accordingly, the current values of the output and input parameters of the object under study; $\left(\frac{\partial y_m^*}{\partial x_i}\right)_{x_i = x_{ireal}}$, $\left(\frac{\partial^2 y_m^*}{\partial x_i \partial x_j}\right)_{x_i = x_{ireal}, x_j = x_{jreal}}$ - partial derivatives calculated values according to the corresponding input parameters of the model at points $\{x_{1real}, x_{2real}, \dots, x_{kreal}\}$ on the m-th tact, a^m - a positive number that satisfies certain conditions; y_m^* - calculated value of the output technological parameters at the m-th cycle, m – tacts.

It should be noted that the optimization speed of the adaptation algorithm, performed on the expressions basis (15)-(17), depends on several factors, the most important of which is the sequence a^m choice. When developing adaptive mathematical models, it is desirable to choose such a^m coefficients that the deviation of the model coefficients current values from their desired values at each stage is minimal [7].

In accordance with the above, mathematical models adapted to the present situation regarding the exit coordinates in the upper section of the vacuum block were obtained:

In accordance with the above, mathematical models have been obtained that have been adapted to the current situation relative to the output coordinates in the vacuum block upper part and have the following form:

$$Y_{l.o.f} = -4501.1558 + 5.7527F_{f.o} + 8.8673T_b + 45.9481T_t + 3.0525P + 8.76462T_{K-3A} + \ + 0.0432F_{f.o}^2 - 0.0044F_{f.o}T_b - 0.164F_{f.o}T_t - 0.0079F_{f.o}P + 0.0018F_{f.o}T_{K-3A} - 0.127T_b^2 - 0.127T_b^2 - 0.085T_bT_t + 0.055T_bP - 0.06T_bT_{K-3A} + 0.106T_t^2 - 0.036T_t\,P - \ -0.0856T_tT_{K-3A} - 0.0024P^2 + 0.0019P\,T_{K-3A} - 0.00292T_{K-3A}^2 \tag{18}$$

$$G_{l.o.f}^{s.g} = 0.9236 - 0.00012F_{f.o} - 0.00117T_b - 0.00517T_t - \ -0.000106P - 0.00000177T_{K-3A} \tag{19}$$

$$G_{l.o.f}^{k.v} = 0.0213 - 0.04616F_{f.o} + 0.02752T_b - 0.1339T_t - \ -0.003585P + 0.05854T_{K-3A} \tag{20}$$

$$G_{l.o.f}^{f.p} = 31{,}3126 - 023486F_{f.o} + 0.1164T_b - 0.3665T_t - \ -0.000773P + 0.259T_{K-3A} \tag{21}$$

$$Y_{h.o.f} = -339.998 + 8.8025F_{f.o} + 2.3294T_b + 11.961P + 15.7958T_{K-3B} + 0.00798F_{f.o}^2 - \ - 0.008F_{f.o}T_b - 0.0599F_{f.o}P + 0.00189F_{f.o}T_{K-3B} - 0.0112T_b^2 + 0.00247T_bP - \ 0.03949T_bT_{K-3B} + 0.0024P^2 - \ 0.03193PT_{K-3B} - 0.004949T_{K-3B}^2 \tag{22}$$

$$G_{h.o.f}^{s.g} = 0.885 + 0.000455F_{f.o} + 0.00002T_b - 0.000022P - 0.000041T_{K-3B} \tag{23}$$

$$G_{h.o.f}^{k.v} = 0.3416 + 0.002496F_{f.o} - 0.00175T_b + \ 0.0385P + 0.0010854T_{K-3B} \tag{24}$$

$$G_{h.o.f}^{f.p} = 120.25 - 0.26975F_{f.o} - 0.02962T_b - \ 0.046579P + 0.433051T_{K-3B} \tag{25}$$

Thus, the mathematical statement of the optimizing task the functioning for the vacuum technological complex (1)-(14), built on the mathematical models basis (18)-(25) is by its nature a non-linear programming problem. Based on the scientific publications analysis, it has been established that to numerically solve the optimization task, it will be effective to apply the Lagrange multiplier method.

Based on the scientific publications analysis, it has been established that to numerically solve the above optimization problem, it is more rational and efficient to use the classical Lagrange multipliers method, since to solve this large-dimensional optimization problem, this method makes it possible to reduce it into a relatively simple subtasks complex that make it up.

For the task under consideration, the Lagrange function looks like this:

$$L = f_1(F_{f.o}, T_b, T_t, P, T_{K-3A}) + f_5(F_{f.o}, T_b, P, T_{K-3B}) + \lambda_1[f_2(F_{f.o}, T_b, T_t, P, T_{K-3A}) - 0.877] + \lambda_2[8.5 - f_3(F_{f.o}, T_b, T_t, P, T_{K-3A})] + \lambda_3[f_4(F_{f.o}, T_b, T_t, P, T_{K-3A}) - 135] + \lambda_4[0.907 - f_6(F_{f.o}, T_b, P, T_{K-3B})] + \lambda_5[6.5 - f_7(F_{f.o}, T_b, P, T_{K-3B})] + \lambda_6[f_8(F_{f.o}, T_b, P, T_{K-3B}) - 25] + \lambda_7[T_b - 385] + \lambda_8[395 - T_b] + \lambda_9[T_t - 72] + \lambda_{10}[88 - T_t] + \lambda_{11}[P - 60] + \lambda_{12}[80 - P] + \lambda_{13}[T_{K-3A} - 155] + +\lambda_{14}[185 - T_{K-3A}] + \lambda_{15}[T_{K-3B} - 270] + \lambda_{16}[285 - T_{K-3B}], \quad (26)$$

where λ_i $(i = \overline{1,16})$ are the Lagrange multipliers.

The proposed algorithm for solving the non-linear problem of optimizing the functioning for the vacuum block in this case consists of the following steps:

1. the Lagrange function is found (26),
2. using the controlled coordinates of the block under consideration, the unconditional extremum of the resulting Lagrange function is formed,
3. by the Kuhn-Tucker theorem, necessary and sufficient conditions for the point of extremum are determined,
4. the coordinates of the extreme point are determined by the artificial basis method [8],
5. the optimal form for the original task is compiled and the values of the objective function are determined.

Below, the results of solving the optimization problem (1)–(14) for the block under consideration are presented in Table 2.

Considering various rectification processes from these concepts, it is worth noting that with a changes wide range of constantly acting disturbing influences at the entrance to the block under study, the stability of the quality of the resulting fractions, to one degree or another, depends on adequate, and most importantly, proactive regulation of irrigation and temperature regime in points of sampling of distillation products on the studied block.

Table 2. Results of optimization task for the vacuum block.

Parameter	**Real value**	**Optimal value**
Flow of raw materials (fuel oil), m^3/h	70.5	71.6
Temperature in the lower part of K-4, °C	388.4	385.0
Temperature at the top of K-4, °C	72.03	82.00
Remaining pressure in K-4, mmHg	64.18	62.00
Temperature on the plate for selecting light petroleum fractions of K-4 (line K-3A), °C	175.88	177.00
Temperature on the plate for selecting heavy petroleum fractions of K-4 (line K-3B), °C	276.13	285.00
Flow of light petroleum fraction, m^3/h	14.18	17.54
Specific gravity of light petroleum fraction, g/m^3	0.8770	0.8773
Viscosity of light petroleum fraction	7.71	6.46
Light petroleum fraction flash temperature, °C	132.00	135.24
Flow of heavy petroleum fraction, m^3/h	32.05	38.17
Specific gravity of heavy petroleum fraction, g/m^3	0.906	0.907
Heavy petroleum fraction flash temperature, °C	206	212

4 Conclusion

Thus, by providing a preliminary corrective signal depending on quantitative and qualitative changes in masut at the inlet and changes in the degree of irrigation, as well as the temperature gradient on the trays of the stripping column, it becomes possible to adapt the settings for local regulators. As a result, the greatest stability of the produced fractions quality and invariance to input disturbances of the entire system as a whole is achieved.

The main advantage of the approach described in this article to the proposed automatic control system development compared to existing traditional systems is the ability to maintain stability of the quality characteristics for the resulting fractions with sufficiently large changes in the quality and quantity of incoming fuel oil. The proposed principle of development algorithm for a two-level control system of the process under study provides for the corrective influences implementation at both levels. In this case, minor disturbances can be eliminated by self-tuning of installed local regulators. And significant changes at the input of the process are adjusted by selecting new optimal parameters for the management mode of the technological process under consideration.

References

1. V. Hesenli, E.A. Melikov, Scientific Discussion **73**, 35-38 (2023). https://doi.org/10.5281/zenodo.7626743
2. L.X. Wang, IEEE Transactions on Fuzzy Systems **6(1)**, 137-143 (1998).
3. A. Gupta, International Journal of Electrical, Electronics and Data Communication (IJEEDC) **1(9)**, 16-20 (2013).
4. V. Žilka, M. Halás, M. Huba, Lecture Notes in Computer Science **5717**, 618-625 (2009).
5. A. Khelassi, *Analysis and assessment of interaction in process control systems*, (UK, University of Nottingham, Nottingham, 1991).
6. P. Solatian, S.H. Abbasi, F. Shabaninia, American Journal of Intelligent Systems **2(5)**, 104-110 (2012).
7. N.M. Aleksandrovsky, S.V. Egorov, R.E. Kuzin, *Adaptive systems for automatic control of complex technological processes* (Energy, 2003).
8. I.L. Akulich, *Mathematical programming in examples and tasks* (Higher School, 2006).