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MODELING AND OPTIMIZATION OF OPERATING MODES OF OIL HEATING TUBE FURNACES

Abstract. Mathematical modeling and optimization of parameters and operating modes of production facilities is the most effective and promising direction for solving many production problems. Mathematical model, multicriteria optimization, fuzzy information, (DM) - decision maker, heuristic algorithm, oil heating furnace. But, with the development of technology and an increase in the number of complex, mathematically difficult to formalize, described indistinctly and by the vector of criteria for technological objects of oil refining and other industries, the processes of developing their mathematical models and optimizing their operating modes become more complicated. In this regard, at present, the study and solution of the problems of developing mathematical models and multicriteria optimization problems characterized by the fuzziness of technological objects of oil, for example, oil heating furnaces, and other enterprises is a very urgent task of science and practice.

In this paper, to develop models and optimize the operating modes of fuzzy oil heating furnaces, experimental-statistical methods and methods of expert assessments and fuzzy set theories are used, which make it possible to use the available information of a statistical and fuzzy nature. The hypothesis is accepted that there are sources of reliable fuzzy information, i.e. experts on the object of study, which is confirmed in the practice of collecting and processing expert fuzzy information about the operation of oil heating furnaces of the Atyrau Oil Refinery and the oil heating station. Based on expert evaluation methods and fuzzy set theories, an algorithm for developing fuzzy models is proposed, with the help of which a fuzzy model of the investigated oil heating furnace is synthesized, fuzzy estimating its performance. To optimize the operating modes of the oil heating furnace based on the developed models, modifying the principles of Absolute concession and Pareto optimality for operation in a fuzzy environment, a heuristic algorithm for solving the problem of multicriteria optimization with fuzzy constraints was developed. The proposed algorithms for model development and multicriteria optimization in a fuzzy environment can be used in practice for modeling and optimizing the operation modes of complex, quantitatively difficult to describe objects of various industries.

Key words: Mathematical model, multicriteria optimization, fuzzy information, (DM) - decision maker, heuristic algorithm, oil heating furnace.

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ҚҰБЫРЛЫ МҰНАЙ ҚЫЗДЫРУ ПЕШТЕРІНІҢ ЖҰМЫС РЕЖИМІН МОДЕЛЬДЕУ ЖӘНЕ ОПТИМИЗАЦИЯЛАУ

Аннотация. Өндірістік объектілердің параметрлері мен жұмыс режимдерін математикалық модельдеу және оңтайландыру көптеген өндірістік есептерді шешудің ең тиімді және перспективалы бағыты болып табылады. Алайда, технологияның дамуымен және күрделі, математикалық формализациялануы қиын, айқын емес және критерийлер векторы бойынша сипатталатын мұнай өңдеу және басқа да өндірістік салалардың технологиялық объектілерінің сандары артуымен, олардың математикалық модельдерін құру және жұмыс режимдерін оптимизациялаау процестері күрделене түседі. Осыған байланысты қазіргі уақытта мұнай өңдеу зауыттарының технологиялық объектілерінің, мысалы мұнай қыздыру пештерінің және басқа да кәсіпорындардың айқынсыздықпен сипатталатын объектілерінің математикалық модельдерін құру және көпкритерийлі оптимизациялау есептерін шешу мәселелерін зерттеу ғылым мен практиканың өте өзекті мәселе болып табылады.

Бұл жұмыста айқынсыздықпен сипатталатын мұнай қыздыру пештерінің модельдерін құру және жұмыс режимдерін оптимизациялау үшін статистикалық және айқын емес сипаттағы қолжетімді бастапқы ақпараттарды қолдануға мүмкіндік беретін, экспериментменттік-статистикалық және эксперттік бағалау мен айқын емес жиындар теориясы тәсілдері қолданылады. Сенімді айқын емес ақпарат көздері, яғни зерттеу объектісі бойынша эксперт-мамандар бар деген гипотеза қабылданған. Бұл гипотеза Атырау мұнай өңдеу зауытының мұнай жылыту пештерінің және мұнай жылыту пунктісінде олардың жұмысы туралы эксперттік айқын емес ақпаратты жинау және өңдеу практикасында расталды. Эксперттік бағалау мен айқын емес жиындар теориясының тәсілдері негізінде айқын емес модельдерді құру алгоритмі ұсынылады, оның көмегімен зерттелетін мұнай қыздыру пешінің өнімділігін айқынсыздықта бағалайтын айқын емес моделі синтезделген. Құрылған модельдер негізінде маұнайды қыздыру пешінің жұмыс режимдерін оптимизациялау үшін Абсолютті концессия және Парето оптималды принциптерін айқынсыздықта жұмыс жасауға модификациялай отырып, айқын емес шектеулері бар көпкритерийлі оптимизациялау есебін шешудің эвристикалық алгоритмі әзірленді. Айқынсыздықпен сипаттаталын объектілердің жұмыс режимдерін модельдеу және оптимизациялау үшін ұсынылған айқын емес тәсілдеменің тиімділігі көрсетілген. Айқын емес ортада модельдерді құру және көпкритерийлі оптимизациялау үшін ұсынылған алгоритмдер күрделі, сандық жағынан қиын сипатталатын түрлі өндірістік сала объектілерінің жұмыс режимдерін модельдеу және оптимизациялау үшін практикалда қолданылу мүмкіндігі зор.

Түйін сөздер: математикалық модель, көпкритерийлі оптимизациялау, айқын емес ақпарат, (ЩҚТ) – шешім қабылдаушы тұлға, эвристикалық алгоритм, мұнайды қыздыру пеші.

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МОДЕЛИРОВАНИЕ И ОПТИМИЗАЦИИ РЕЖИМОВ РАБОТЫ ТРУБЧАТЫХ ПЕЧЕЙ ПОДОГРЕВА НЕФТИ

Аннотация. Математическое моделирование и оптимизация параметров и режимов работы производственных объектов является наиболее эффективным и перспективным направлением решения многих производственных задач. Однако с развитием технологии и увеличением числа сложных, математический трудно формализуемых, описываемых нечетко и вектором критериев технологических объектов нефтепереработки и других отраслей производства усложняются процессы разработки их математических моделей и оптимизации их режимов работы. В этой связи в настоящее время исследование и решение проблем разработки математических моделей и задач многокритериальной оптимизации, характеризуемых нечеткостью технологических объектов нефтяных, например, печей подогрева нефти и других предприятий является весьма актуальной задачей науки и практики.

В работе для разработки моделей и оптимизации режимов работы нечетко описываемых печей подогрева нефти используется экспериментально-статистические методы и методы экспертных оценок и теорий нечетких множеств, позволяющие использовать доступную информацию статистического и нечеткого характера. Принята гипотеза о том, что источники достоверной нечеткой информации, т.е. специалисты-эксперты по объекту исследования имеются, которая подтверждена на практике сбора и обработки экспертной нечеткой информации о работе печей подогрева нефти Атырауского НПЗ и пункта подогрева нефти. На основе методов экспертной оценки и теорий нечетких множеств предложен алгоритм разработки нечетких моделей, с помощью которого синтезирована нечеткая модель исследуемой печи подогрева нефти, нечетко оценивающая ее производительность. Для оптимизации режимов работы печи подогрева

нефти на основе разработанных моделей модифицируя принципов Абсолютной уступки и Парето оптимальности для работы в нечеткой среде разработан эвристический алгоритм решения задачи многокритериальной оптимизации с нечеткими ограничениями. Показана эффективность предложенного нечеткого подхода для моделирования и оптимизации режимов работы нечетко описываемых объектов. Предлагаемые алгоритмы разработки моделей и многокритериальной оптимизации в нечеткой среде могут быть использованы на практике для моделирования и оптимизации режимов работы сложных, количественно трудноописываемых объектов различных производств.

Ключевые слова: математическая модель, многокритериальная оптимизация, нечеткая информация, (ЛПР) - лицо, принимающее решение, эвристический алгоритм, печь подогрева нефти.

Introduction. One of the most important problems of oil companies is optimization of large oil reserves of Kazakhstan on the basis of modeling of operating modes of tubular oil heating tube furnaces in the processes of oil refining and transportation applied in the development of the country's economy and efficient exploitation. From the practical point of view for effective solution of problems of optimal management of such complex technological systems as oil heating furnaces it is necessary to apply the latest achievements of mathematical approaches and new information technologies, which are based on the system approach. Besides, many complex production systems including tubular oil heating furnaces frequently used in oil refining and transportation processes are characterized by deficit and uncertainty of the initial information. All this complicates formalization and solution of tasks for studying of tubular oil heating furnaces, development of mathematical models and optimization of operation modes thereof (Abakumov et all., 17 (1). 2014:209- 218., Orazbayev et all 2021: 2(114)). Thus, to effectively solve the above problems of the oil heating system in oil refining, transportation technologies it is necessary to take into account the economic, environmental and technological criteria for assessing the effectiveness of the system operation, i.e, the vector of criteria, the large number of limitations, the lack and uncertainty of the initial information. Under these conditions optimization of the operation modes of such a complex system as tubular oil heating furnaces is impossible without application of the modern mathematical approaches and computer aided technologies. (Muhammad, et all 2021: 2712. 1–24., Chen, et all 2018: 109. 216-235).

Many process oil production facilities including oil heating stations (tubular furnaces) are a complex of balancing units. Therefore it is necessary to create a complex of models, i.e. a system of models, in which these units interact with each other. Under the conditions of uncertainty due to randomness, uncertainty of initial information, the construction of mathematical models of interconnected objects such as oil heating furnaces, setting of tasks of multi-criteria optimization of process complex operation and their solution are still referred to a number of issues, which are insufficiently studied and completely unresolved within the scientific-research work (Valiakhmetov, et all 2018: 329(2) 159-167., Orazbayev, et all 2020: 54(6), 1235–1241). Due to these reasons the most relevant subject of this work is development of mathematical models of oil heating furnaces in oil refining and transportation technologies under the conditions of uncertainty and multi parameter nature of the studied initial information, approaches to multi-criteria optimization of optimal facility operation modes on basis thereof.

Within the oil industry the reduction of production costs, increase in productivity of process units, reduction of power consumption and oil losses is carried out by modeling and optimizing the operation modes of main process facilities such as oil heating furnaces. (Toloo, et all 2020: 10. 1796., Ospanov et all 2016: 978-1-4673-8414-8. 103-109). An important condition for functioning of computer aided simulation and optimization systems for this purpose is obtainment of the information necessary for building models, which adequately characterize the state and all relations of the object under research. The operation quality of such computer aided modeling and optimization systems essentially depends on metrological qualities of measuring instruments, statistical and dynamic properties of regulating and actuating devices (Zhao Zhi-Wen, et all 2012: 56(7-8). 152166). However, under production conditions some important parameters characterizing quality indicators of many complex systems, for example, oil reheating furnaces (environmental impact, productivity, etc.) are quantitatively, comprehensively measured or not measured, that is, their statistical properties are unknown. In most cases such measurable complex or immeasurable production indicators are best described in natural language by qualified specialists, i.e. by experts who have worked in this production for many years and have gained a lot of experience. Useful information in form of such a word, sentence, reasoning in the theory of fuzzy sets (fuzzy sets) is called implicit information and is converted into a format, which can be formalized and processed by the methods of this theory. (Ryzhov, et all 2017:115., Liu et all 2022., 10, 2368). Such implicit information is the knowledge, experience and intuition of expert specialists, i.e. their intelligence and is accumulated by means of special expert evaluation methods (Gutsykova et all 2017: 978-5-9270-0209-2., Sabzi et all 2017: 82(3). 145–163).

The purpose of the scientific article is to create mathematical models of tubular oil heating furnaces, for which there are some work quality indicators obtained as an object of research, and on the basis of the obtained models is to formulate the problem of optimization of the object operation mode (problem statement) and to offer a way of solution thereof.

To achieve the set goal the following main research objectives will be set forth and achieved:

- Collection and processing of available information of various nature, which characterizes the work of the objects under research, the study of modes of oil reheating furnaces operation of Atyrau oil refinery and at Atyrau point of Uzen-Atyrau hot oil pipeline;
- improvement of the methodology for building mathematical models of complex technological facilities on the basis of available information of different nature including fuzzy information and system approach and creation of mathematical models of oil heating furnaces on basis thereof;
- multi-criteria optimization under conditions of contradiction of optimization criteria and uncertainty of a part of the initial information, i.e. development of heuristic algorithm of decision-making and its realization under specific production conditions.

Research materials and methods. As science and technology are developing oil refinery process premises, oil transportation and other facilities are constantly improving and becoming complicated. Currently the specified technological systems are referred to a number of the complex systems characterized by lack and uncertainty of theoretical, statistical information under initial production conditions consisting of interconnected units (elements). Therefore, this work applies formal and informal approaches of system analysis (Boud et all 2019: 978-0-12-121851-5) as effective approaches for finding optimal operation modes of tubular oil heating furnaces most frequently used in oil refining and transportation processes: mathematical modeling (Abakumov et all 2014: 209-218., Orazbayev et all 2021: 6: 2(114)), 147–162., Leonenkov et all 2017: 787), multi-criteria optimization (Bekibayev et all 2022: 115., Chen et all 2018: 109. 216–235., Orazbayev et all 2019: 330(7).182-194., Kahraman et all 2008., 592–608), and also methods of expert evaluations and theory of fuzzy sets (Abakumov et all 2014: 17 (1). 209- 218., Ryzhov et all 2017: 115., Gutsykova et all 2017: 509., Sabzi et all 2017: 82(3). 145–163).

At the same time depending on the nature of available information different methods of developing mathematical models are used, for example: experimental-statistical, regression methods in developing of statistical models in the form of regression equations; fuzzy methods of developing mathematical models of the object under research based on expert fuzzy information. Methods of multi-criteria optimization are applied in the process of development of heuristic algorithm of decision-making tasks as to the choice of the optimal mode of oil heating furnace operation. To collect fuzzy information, i.e., knowledge and experience of experts the methods of expert evaluation are used, and to formalize, to process and to use the collected fuzzy information the methods of fuzzy sets theories are used.

When carrying out this study the structure, experimental and statistical data from G9P02B tubular furnaces, which are deployed as part of the oil heating station in Atyrau oil refinery (AOR) and at Atyrau point of Uzen-Atyrau hot oil pipeline, were viewed as study materials. Besides, expert, fuzzy information on estimation of productivity of oil heating furnaces and their influence on environment is used, which information is necessary for development of models and optimization of operation modes thereof.

Within technological processes of oil refining and transportation it is necessary to provide optimal temperature and process operation modes of heating furnaces as well as their accident-free and continuous operation.

Thus, by means of computer aided modeling of oil heating furnaces operation modes the following multi-criteria tasks can be resolved:

- minimizing the cost of oil heating and refining;
- maximizing the volume of heated oil and productivity;
- improving the environmental safety of the facility.

It is known that the above criteria practically contradict each other in the field of effective solutions such as increasing the productivity of the oil heating furnace, increasing its costs and increasing the impact on the environment. To solve these problems, it is necessary to make a solution for effective management of oil heating furnace operation modes, i.e. to formulate and solve the problem taking into account the contradictions of the criteria. And when solving such problems we need mathematical models describing connection between object output parameters to be received as criteria and input mode parameters therefore this research paper with application of fuzzy information builds up models of tubular oil heating furnaces being an object of research, and on the basis of these models the paper sets forth the task of multi-criteria optimization for managing operation modes of the facility and a heuristic algorithm for its solution is proposed.

The operation principle of tubular oil heating furnaces of G9P02B type is based on combustion of fuel in the burners inside of the radiation chamber. The flame arising from the combustion of fuel is directed to the smooth wall and dissipates heat in the tubes of the 4-way productive coil, in which the oil circulates (it gives off heat by the ray method). In the convection chamber of such furnaces the hot fume gases heat the furnace winding tubes (heat transfer by convection method).

The basic scheme of tubular oil heating furnace of G9P02B type is shown in Fig. 1

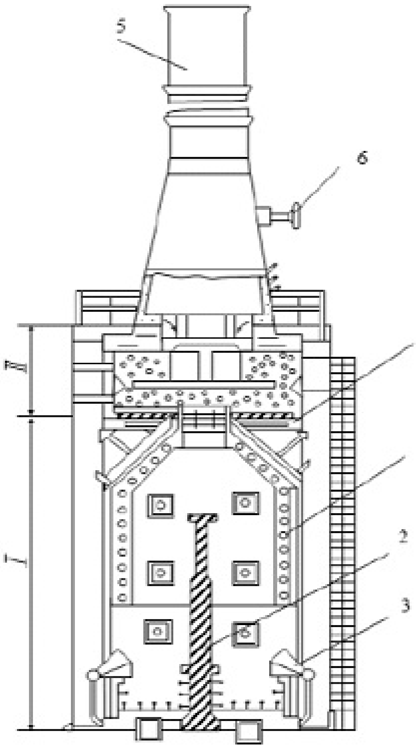

Figure 1 – The basic scheme of tubular oil heating furnace of G9P02B type
G9P02B oil heating furnace consists of the radiant I and convection II zones, separated by a metal frame 1.

The radiant zone I, in its turn, is divided into two parts by a wall made of refractory material 2. In the lower block of the furnace there are installed six nozzles 3 with air distribution of burning fuel. Oil or gaseous mixture are used as fuel. Also there are coils installed in this region 4. It heats the oil, in which the flare radiation energy is transported by oil.

In the convective zone II combustion products are heated by oil flowing through the pipes by force of convection. Chimney 5 is designed for emission of combustion products into the atmosphere. The draught in the furnace is regulated by means of slide gate 6.

The main parameters of the G9P02B tubular furnace: height - up to 10.5 m (excluding the chimney); capacity - 600 m3/h; heating oil - from 30°C to 70°C; pressure of heated oil at the coil input - not more than 6.5 MPa; heat output -10500 kW, efficiency ratio reaches 0.77.

Results. During practical application there is often an uncertainty of some important data required to study the production conditions of the facility and to optimize its operation modes. The source of non-obvious information in these cases is a person, for example, the operator who controls and manages the oil heating furnace, i.e. the person who makes the experienced decision (the decision maker - DM), the expert. Opinion, knowledge, experience and intuition of DM, experts transmitting the data in natural language about the state and operation of the facility can be formalized and used to build a model based on the mathematical apparatus of the fuzzy sets theory in the form of fuzzy information. Such models, structure of which is presented in the form of fuzzy regression equations, are built when input, operating parameters of the facility are obvious (quantifiable), whereas output parameters are not obvious (non-quantifiable). Also non-obvious will be the parameters (regression ratios) of such fuzzy models. In general the structure of fuzzy regression models can be written as follows:

$$\tilde{y}_j = \tilde{a}_{0j} + \sum_{i=1}^{n} \tilde{a}_{ij} x_{ij} + \sum_{i=1}^{n} \sum_{k=i}^{n} \tilde{a}_{ikj} x_{ij} x_{kj} + ..., \ j = \overline{1,m}$$

here $\tilde{y}_j$ – are fuzzy input parameters of the object to be modeled; as a rule such input parameters are considered as local criteria characterizing the facility operation quality; $x_{ij} x_{kj}$ – are measurable i.e. obvious input parameters of the facility being modeled; as a rule input operating parameters impacting the facility operation, a process going on therein are taken as these parameters, $\tilde{a}_{0j}, \tilde{a}_{ij}, \tilde{a}_{ikj}$ – non-obvious parameters of a model being assessed i.e. being identified are regression ratios. The proposed algorithm for building of a fuzzy model in form of multi-regression fuzzy regression equations consists of the following basic steps:

Step 1. Input necessary for building of $x_i \in X, i = \overline{1,n}$ model and uncertain output $\tilde{y}_j \in \tilde{B}_j$, $\tilde{B}_j \in Y, j = \overline{1,m}$ selection of parameters. In this step the input, operating parameters and output parameters of the object affecting the quality of object operation, output parameters assessing the quality of its operation are determined as a result of system analysis, whereas parameters not affecting the object operation or having weak influence, of low importance, are not considered in order not to complicate the model.

Step 2. Determination of thermal set, which characterizes the state and fuzzy parameters of the object, by means of expert evaluation methods.

$$\tilde{y}_j = f_j(x_1, ..., x_n, \tilde{a}_0, \tilde{a}_1, ..., \tilde{a}_n), \ j = \overline{1,m},$$

i.e., solving the structural identification problem, for example, based on the method of successive inclusion of regressors;

Step 4: Building the membership functions (membership functions) of fuzzy parameters of the object model. When building these functions based on practical experience it is recommended to use the following structure of the membership function with correction ratios (Orazbayev et all 2021: 2.114, 147–162):

$$\mu_{B_j}^p(\widetilde{y}_j) = \exp(Q_{B_j}^p \left| (y_j - y_{md_j})^{N_{B_j}^p} \right|).$$

here $\mu_{B_j}^p(\widetilde{y}_j)$ – $\widetilde{B}_j$ – $\widetilde{B}_j$ of fuzzy output parameter of object referred to the quantity of obvious, divisible by $\widetilde{y}_j$ membership function; p – quantum, i.e. the discretization value; $Q_{B_j}^p$ – ratio characterizing the level of uncertainty to be determined during identification of membership functions; $N_{B_j}^p$ – ratio, which changes (corrects) the area of therms of fuzzy parameters and the form of membership functions; $y_{md_j}^p$ – implicit variable that corresponds the most to a given therm (in p Quantum), for this value the following condition is satisfied $\mu_{B_j}^p(y_{mdi}) = \max_j \mu_{B_j}^p(y_j)$.

Step 5. Solving the parametric identification problem, i.e. solving the fuzzy parameters of the $\widetilde{a}_0, \widetilde{a}_1, ..., \widetilde{a}_n$ model, definition (regression ratios);

Step 6. Checking for model consistency with actual data, i.e. adequacy of the developed model. The following condition can be obtained as an adequate criterion: $R = \min \sum_{j=1}^{m} \left(y_j^M - y_j^E \right)^2 \le R_D$, here y_j^M – are estimated (determined by means of the model) values of object output parameters, whereas, y_j^E – are experimental, i.e. true values of object output parameter; R_D – value of permissible deviation.

If adequacy condition is satisfied, it is recommended to use the model in tasks of determination of object's optimal modes. In the opposite case, i.e. when the adequacy condition is not satisfied, it is necessary to establish the cause of model inadequacy, afterwards in order to ensure model adequacy it is necessary to return to the above steps and repeat the procedure until the adequacy condition of the model is satisfied. Model inadequacy may happen due to various reasons, for example: non-inclusion of some parameters into the model, which parameters have significant influence on object operation, on the process going on in the object, wrong identification of model structure and/or parameters, etc.

Now, using the described algorithm of fuzzy model building, let's build models based on fuzzy information of the object under research. Models of G9P02B tubular oil heating furnace. To determine the effect of input mode related parameters of the oil heating furnace on its output parameters, i.e. to build its models under conditions of fuzzy part of the input information the generalized statistical data and unreliable information obtained from the experts have been used. Using the fuzzy regression model (1), which estimates the productivity of the oil heating furnace on the basis of the above proposed algorithm, and using the experimental-statistical approach the structures of the regression models (2), which characterize the dependence of the temperature and pressure at the furnace outlet on its input, operating parameters, have been identified as follows:

$$\tilde{y}_1 = \tilde{a}_{01} + \tilde{a}_{11}x_{11} + \tilde{a}_{21}x_{21} - \tilde{a}_{31}x_{31} + \tilde{a}_{41}x_{41} +$$
$$+ \tilde{a}_{51}x_{11}^2 + \tilde{a}_{61}x_{21}^2 - \tilde{a}_{71}x_{31}^2 + \tilde{a}_{81}x_{41}^2 + \tilde{a}_{91}x_{31}x_{41} \quad (1)$$

$$y_j = a_{0j} + a_{1j}x_{1j} + a_{2j}x_{2j} + a_{3j}x_{3j} + a_{4j}x_{4j} +$$
$$+ a_{5j}x_{1j}^2 + a_{6j}x_{2j}^2 + a_{7j}x_{1j}x_{2j},\ j = 2{,}3. \quad (2)$$

From the models taken: $\tilde{y}_1$ – non-obvious price of oil heating station performance; $y_j,\ j = 2{,}3$ – temperature and pressure at the outlet of oil reheating station; $\tilde{a}_{01}, \tilde{a}_{11}, \tilde{a}_{21} ..., \tilde{a}_{91}$ − fuzzy parameters (regression ratios) of the identified model (1) based on expert assessment; $x_{1j}, x_{2j}, x_{3j}, x_{4j}$ − in the order, temperature at the furnace inlet, pressure in the furnace and fuel and oil volume at the furnace inlet. To identify the fuzzy parameters of model (1), which characterizes the performance of the inbuilt oil heating furnace the method proposed in the research paper [1] is used. Thus, on the basis of modification of the least squares approach to the uncertain position and with the help of the method of fuzzy parameters identification the problems of identification of the unknown parameters (regression ratios) of oil heating furnace values identified as per the structure (1) of the fuzzy model are solved.

To identify the fuzzy regression ratios of the fuzzy model $\tilde{a}_{ij}$ of oil heating furnace (1), fuzzy sets (therm-quantity), which characterize fuzzy models, the following $\alpha = 0{,}5;\ 0{,}85;\ 1$ is characterized by a set of α level. According to the selected levels each $\alpha_q, q = \overline{1{,}3}$ level of the input object x_{ij} and $\tilde{y}_j$ output value of parameters are monitored and determined. The values of these parameters at different levels are given in deterministic form at each selected α_q level.

Then the fuzzy regression model (1) describing the performance of oil heating furnace in explicit form can be written for each level as follows:

$$y_1^{\alpha_q} = a_{01}^{\alpha_q} + a_{11}^{\alpha_q}x_{11} + a_{21}^{\alpha_q}x_{21} - a_{31}^{\alpha_q}x_{31} + a_{41}^{\alpha_q}x_{41} + a_{51}^{\alpha_q}x_{11}^2 + a_{61}^{\alpha_q}x_{21}^2 - a_{71}^{\alpha_q}x_{31}^2 +$$
$$+ a_{81}^{\alpha_q}x_{41}^2 + a_{91}^{\alpha_q}x_{31}x_{41},\ q = \overline{1{,}3}; \quad (3)$$

Since the obtained model (3) is a system of multi-regressive regression equations the problems of identification of their parameters (regression ratios) are reduced to the problems of identification of parameters of known multi-regressive regression equations. There fore to identify the unknown parameters of fuzzy model (3) it is possible to use the known methods of parametric identification, software package for the identification of regression ratios. In this paper to identify the regression ratios of the obtained model (3) we used the REGRESS package, in which the least squares method is implemented on programmable basis. This software package contains linear and nonlinear multi-regressive models, i.e. with any number of input parameters ($x_i, i = \overline{1,n}$), it allows to determine the regression ratios in the dialog mode.

Thus, the efficiency of the oil heating furnace $\tilde{y}_1$ its input, operating parameters $x_i, i = \overline{1,4}$ after the result of parametric identification of the model characterizing the fuzzy relation, taking into account each α level, can be written as follows:

$$\tilde{y}_1 = \left(\frac{0.5}{2.000254727} + \frac{0.85}{2.007525117} + \frac{1}{2.088235294} + \frac{0.85}{2.175725157} + \frac{0.5}{2.787515357} \right) x_{11} +$$
$$+ \left(\frac{0.5}{7.0010} + \frac{0.85}{7.01000} + \frac{1}{7.10000} + \frac{0.85}{7.101523567} + \frac{0.5}{7.156572378} \right) x_{21} -$$
$$+ \left(\frac{0.5}{5.005700} + \frac{0.85}{5.025000} + \frac{1}{5.680000} + \frac{0.85}{5.750000} + \frac{0.5}{5.950000} \right) x_{31} +$$
$$+ \left(\frac{0.5}{0.003700} + \frac{0.85}{0.055000} + \frac{1}{0.400000} + \frac{0.85}{0.450000} + \frac{0.5}{0.500000} \right) x_{41} +$$
$$+ \left(\frac{0.5}{0.0003787} + \frac{0.85}{0.0077253} + \frac{1}{0.0614187} + \frac{0.85}{0.0997334} + \frac{0.5}{0.1344578} \right) x_{11}^2 +$$
$$+ \left(\frac{0.5}{0.600000} + \frac{0.85}{0.650000} + \frac{1}{0.710000} + \frac{0.85}{0.760000} + \frac{0.5}{0.820000} \right) x_{21}^2 -$$
$$- \left(\frac{0.5}{0.180300} + \frac{0.85}{0.2001000} + \frac{1}{0.227200} + \frac{0.85}{0.247200} + \frac{0.5}{0.267200} \right) x_{31}^2 + \qquad (4)$$
$$+ \left(\frac{0.5}{0.0000037} + \frac{0.85}{0.0000775} + \frac{1}{0.0005634} + \frac{0.85}{0.0037355} + \frac{0.5}{0.0125574} \right) x_{41}^2 +$$
$$+ \left(\frac{0.5}{0.006000} + \frac{0.85}{0.007000} + \frac{1}{0.008000} + \frac{0.85}{0.009000} + \frac{0.5}{0.010000} \right) x_{31} x_{41}$$

For computer aided modeling the values of oil heating furnace model (4) determined at the levels of $a_{ij}^{\alpha_q}, i = \overline{0,7}, j = \overline{1,3}, q = \overline{1,3}$, regression ratios are combined as per following equations of fuzzy sets theory:

$$\tilde{a}_{ij} = \bigvee_{\alpha \in [0.5,1]} a_{ij}^{\alpha_q} \text{ or } \mu_{\tilde{a}_{ij}}(a_{ij}) = \sup \min_{\alpha \in [0.5,\,1]} \{\alpha, \mu_{a_{ij}^{\alpha}}(a_{ij})\}$$

here $a_{ij}^{\alpha_q} = \{a_i \mid \mu_{\tilde{a}_{ij}}(a_{ij}) \geq \alpha\}$

Then the model describing heating furnace efficiency, which is convenient for computer aided modeling, will be obtained as follows:

$$y_1 = 2{,}08957x_1 + 7{,}100257x_2 - 5{,}704050x_3 +$$

$$+ 0{,}40558x_4 + 0{,}07055x_1^2 + 0{,}7727357x_2^2 -$$

$$- 0{,}22755x_3^2 + 0{,}001735x_4^2 - 0{,}00805x_3x_4. \qquad (5)$$

From the last given model, to simplify it, we excluded either repressors, which do not affect the productivity of oil heating furnace, or ratios, which are close to 0, and secondary lower indices corresponding to the number of output parameter of input, operating parameters, i.e., index 1.

Figure 2 given below shows a graph of the dependence of the productivity of a tubular oil heating furnace on temperature, provided that the values of other input, operating parameters of the furnace are constant.

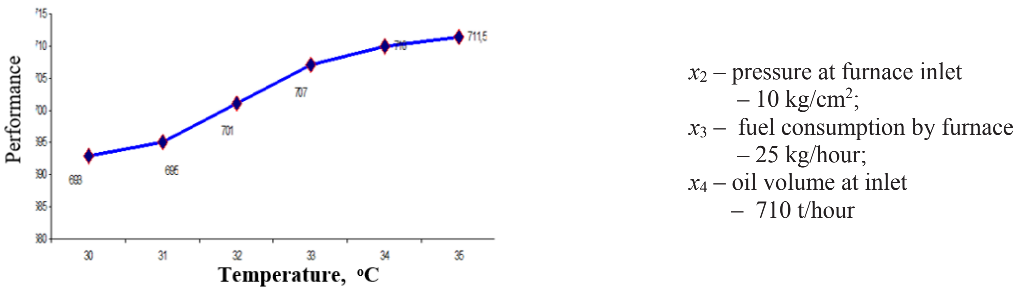

Figure 2 Dependence of oil heating furnace efficiency on temperature under constant x_2, x_3, x_4

values, i.e., , i.e. $\tilde{y}_1 = f_1(x_1)$ graph

Temperature at the outlet of the tubular oil heating furnace **(y_2)** and temperature **(y_3)**at the furnace inlet, $x_i, i = \overline{1,4}$ operating parameters, results of parametric identification of the model based on statistical data and on the method of least squares to be defined by equation (4), which characterizes the relation (regressors with almost zero regression ratios not to be considered due to their very weak influence), are given below:

$$y_2 = 0.0000001 + 0.588235294x_{12} - 0.500000000x_{22} + 0.400000000x_{32} -$$
$$- 0.007042254x_{42} + 0.021626298x_{12}^2 - 0.050000000x_{22}^2 + 0.029411765x_{12}x_{22}. \qquad (6)$$

$$y_3 = 0.000000001 - 0.023529412x_{13} + 0.320000000x_{23} - 0.032000000x_{33} +$$
$$+ 0.002253521x_{43} - 0.001384083x_{13}^2 - 0.040000000x_{23}^2 + 0.007058824x_{13}x_{23}. \qquad (7)$$

Further we show the results of setting the problem of optimization of G9P02V tubular furnace operation modes and development of heuristic algorithm for its solution based on modification of absolute concession and Pareto optimality principles. The proposed heuristic algorithm for solving the problem of optimizing the modes of oil heating furnace operation will use the furnace models (6)-(7) developed above and is based on the interactive operation mode between the decision maker (DM) and the computer, in which the developed furnace models and the proposed heuristic algorithm for solving the task of optimization of operation modes of the research object are implemented on a programmable basis.

By modifying the principles of Absolute Concession (AC) and Pareto Optimality (PO) we will obtain the following mathematical statement of the problem of optimizing the modes of oil heating furnace operation:

$$\max_{\mathbf{x}\in X} \mu_0(\mathbf{x}),\ \mu_0(\mathbf{x}) = \sum_{i=1}^{m} \gamma_i \mu_0^1(\mathbf{x}), \tag{8}$$

$$X = \left\{ \mathbf{x} : \mathbf{x} \in \Omega \wedge \max_{\mathbf{x}\in\Omega} \sum_{q=1}^{L} \beta_q \mu_q(\mathbf{x}) \wedge \sum_{q=1}^{L} \beta_q = 1 \wedge \beta_q \geq 0, q = \overline{1,L} \right\}, \tag{9}$$

here A – is the logical "and" requiring truth of all statements, which are related through this sign; $\boldsymbol{\gamma} = (\gamma_1, \gamma_2, ..., \gamma_m)$, $\boldsymbol{\beta} = (\beta_1, \beta_2, ..., \beta_L)$ – are, respectively, weight vectors describing mutual importance of local criteria and fuzzy constraints; $\mu_q(\mathbf{x}), q = \overline{1,L}$ – membership functions of performance level of fuzzy constraints.

To solve the obtained problem of multi-criteria optimization of operating modes of tubular oil heating furnaces on the basis of the developed models, on the basis of adaptation of principles of optimality of absolute concession and Pareto optimality the AC+PO heuristic algorithm consisting of the following basic steps is offered:

Step 1. By involving the DM enter values of weight vector of $\boldsymbol{\gamma} = (\gamma_1, \gamma_2, ..., \gamma_m)$, local criteria importance, by observing the conditions: $\sum_{i=1}^{m} \gamma_i = 1, \gamma_i \geq 0, i = \overline{1,m}$.

Step 2. Define therm sets and build membership functions in case of fuzziness of criteria and/or of their weight ratios with the purpose of describing them.

Step 3. DM, experts shall define therm sets describing fuzzy constraints of the optimization problem.

Step 5. With participation of DM, experts the membership functions, which evaluate the degree of their fulfillment, shall be built for fuzzy constraints $\mu_q(x), q = \overline{1,L}$

Step 5. DM shall enter the values of the $\boldsymbol{\beta} = (\beta_1, \beta_2, ..., \beta_L), \sum_{q=1}^{L} \beta_q = 1, \beta_q \geq 0, q = \overline{1,L}$ weight vector, which reflects their mutual importance, for fuzzy constraints.

Step 6. By using mathematical models, which describe the dependence of the criteria on the input operating parameters, maximize the $\mu_0(\mathbf{x}) = \sum_{i=1}^{m} \gamma_i \mu_0^i(\mathbf{x})$ criterion integrated as per the principle of absolute concession on the acceptable solutions X, which is defined as per expression (9) on the principle of Pareto optimality. Determine the **x(γ, β)** – current solutions: the vector of input, operating parameters of the object, $\mu_0(\mathbf{x}(\boldsymbol{\gamma},\boldsymbol{\beta})) = \sum_{i=1}^{m} \gamma_i \mu_0^i(\mathbf{x}(\boldsymbol{\gamma},\boldsymbol{\beta}))$ – values of integrated local criteria and $\mu_1(\mathbf{x}(\boldsymbol{\gamma},\boldsymbol{\beta})),...,\mu_L(\mathbf{x}(\boldsymbol{\gamma},\boldsymbol{\beta}))$ – degrees of ensuring fuzzy constraints, which are achieved with the selected solution **x(γ, β)**.

Step 7. Obtained current solutions shall be submitted to DM for analysis and selection of the final solution. If submitted current solutions are not acceptable to DM, he changes the values of weight vectors of local criteria and/or constraints to improve the solution, and the search for the best solution is repeated starting from step 6. If the DM is satisfied with the current solution, the next step shall be taken.

Step 8. Make the final decision acceptable to and chosen by DM as the best one: the values of the vector of input, operating parameters – **x*(γ, β)** , which ensure maximum value of the integrated criterion – $\mu_0(\mathbf{x}^*(\boldsymbol{\gamma},\boldsymbol{\beta})) = \sum_{i=1}^{m} \gamma_i \mu_0^i(\mathbf{x}^*(\boldsymbol{\gamma},\boldsymbol{\beta}))$ and the maximum values of the membership functions of the fuzzy constraints – $\mu_1(\mathbf{x}^*(\boldsymbol{\gamma},\boldsymbol{\beta})),...,\mu_L(\mathbf{x}^*(\boldsymbol{\gamma},\boldsymbol{\beta}))$.

The results of solving the problem of optimizing the oil heating station operation mode by means of three criteria and two fuzzy constraints with application of the developed models and on the basis of the proposed AC+PO heuristic algorithm are listed in Table 1 given below. The provided table contains the results of DM's selection of the final best solution acceptable to him after the 5th cycle of the algorithm application.

Table 1 – Comparison of the results of optimization of oil heating furnace operation modes as per the proposed heuristic algorithm, as per deterministic method [20] and real data obtained from the object under research

Criteria, fuzzy constraints and input, operating parameters	AC+PO heuristic algorithm	Known determined method	Real production data
Oil heating furnace efficiency, kg/s – criterion $\tilde{y}_1$;	$\approx$0,1968	0,1960	0,1963
Temperature at oil heating furnace outlet, K, criterion y_2;	323,15	322,03	323,15
Pressure of oil heating furnace, kPa, criterion y_3;	96,57	97,55	96,70
Membership function of compliance with the 1st fuzzy constraint - $\mu_1(\mathbf{x}^*(\beta))$	1.0	-	-
Membership function of compliance with the 2nd fuzzy constraint - $\mu_2(\mathbf{x}^*(\beta))$	0.99	-	-

Optimal values of vector of input, operating parameters $\mathbf{x}^* = (x_1^*, x_2^*, x_3^*, x_4^*)$:			
x_1^* – optimal temperature at oil heating furnace inlet, K;	306,00	308,10	307,15
x_2^* – optimal pressure at oil heating furnace inlet, kPa;	118.03	123,35	119,42
x_3^* – optimal consumption of raw materials for oil heating furnace, kg/s;	0,0070	0,0075	0,0072
x_4^* – optimal oil volume at inlet into oil heating furnace, kg/s.	0,1970	0,1970	0,1970

Note: (-) are not measurable parameters. The time required to solve the problem is approximately the same in the compared methods.

Discussion. On the basis of analysis and discussion of the obtained results of optimizing the operation modes of tubular oil heating furnace by using the developed models and the AC+PO heuristic algorithm, we can make the following conclusion:

– The results obtained in multi-criteria optimization of oil heating furnace operation modes on the basis of models and AC+PO heuristic algorithm developed with consideration of fuzziness of certain part of initial information are mostly consistent with the actual production data in comparison with the results of deterministic method of the optimization problem;

– Since fuzzy information received from DM, experts on the basis of their knowledge and experience allows to take into account complex, non-formalized relations between the parameters of the optimization object, the models adequacy and efficiency of the obtained results of solving the problem of optimizing the oil heating furnace operation modes in a fuzzy environment increases;

– The advantages of the proposed heuristic approach to the solution of the set optimization problem can also include the fact that it provides estimates of the execution of fuzzy constraints.

Difficulty of obtaining initial reliable fuzzy information might be the disadvantage or limitation of the proposed approach to model development and multi-criteria optimization. This limitation can be overcome by the proper organization and conduct of expert evaluation. Whereas the sources of reliable fuzzy information, i.e. experienced specialists-experts, DM, as it is evidenced from practice, are available at all objects that have been functioning for a long time.

Conclusion. In the process of the conducted research aimed at solving problems of modeling and optimization of fuzzily described objects, by the example of tubular oil heating furnaces used in oil processing and pumping technologies, the following results have been obtained:

– Based on the methodology of system analysis, expert evaluation methods and fuzzy sets theories the algorithm for building fuzzy models in the form of fuzzy regression equations has been developed and described;

– On the basis of the proposed algorithm and experimental-statistical approach the models of oil heating furnace, which estimate its efficiency in a fuzzy way, have been developed;

– Based on the modification of Absolute Concession and Pareto Optimality principles for working in a fuzzy environment a heuristic algorithm for solving multi-criteria optimization problems with fuzzy constraints has been developed. The results of optimization of operation modes of the object under research have been given and analyzed by means of the proposed algorithm and the developed models of oil heating furnace.

As opposed to the well-known approach to fuzzy problem solving, which is based on the replacement of the initial fuzzy problem with a set of clear problems, which leads to the loss of the collected fuzzy information, the proposed fuzzy approach sets and solves a fuzzy problem in a fuzzy environment. This allows to maximize the use of available fuzzy information and to receive a more adequate and efficient solution to the set problem in a fuzzy environment, which is the novelty and originality of the obtained results.

The example of application of the proposed fuzzy approach to solving modeling and optimization problems in a fuzzy environment of complexly formalized objects allows practical application of the obtained results to solving modeling and optimization problems of many complex, fuzzily described objects. The potential for further research within the field of research is quite high since methods of expert evaluations, fuzzy sets theories and means for implementation thereof are currently being intensively developed.

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