Journal of Theoretical and Applied Information Technology
15th June 2020. Vol.98. No 11

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

FUZZY MODELING AND CONTROL OF THE CATALYTIC CRACKING UNIT ON VARIOUS TYPES OF INFORMATION

BATYR ORAZBAYEV[1], DINARA KOZHAKHMETOVA[2], AIGUL SHAIKHANOVA[3], ROZA BEKBAEVA[4], ALEKSANDR ZOLOTOV[5]

[1,2]Department of system analyses and control, Eurasian National University Named after L.N.Gumilyov, Nur-Sultan, Kazakhstan
[3,4,5]Department of automation and information technology, Semey State University Named after Shakarim, Semey, Kazakhstan

E-mail: [1]batyr_o@mail.ru, [2]dinara_kozhahmetova@mail.ru, [3]igul7@mail.ru, [4]31-roza@mail.ru, [5]azol64@mail.ru

ABSTRACT

In this paper, based on available information of various types, including fuzzy information, mathematical models of the reactor block installation in the fluidized bed of the catalyst at the Atyrau oil refinery in Kazakhstan are investigated and developed. The plant is designed to convert the residue of atmospheric distillation (AR, fuel oil), heavy gas oil, vacuum gas oil, heavy gas oil from the coking plant, heavy refined oil from the aromatics production complex and heavy aromatic compounds from the same complex into more valuable products, such as liquefied hydrocarbon gas, gasoline and light catalytic cracking gas oil. The version of such system with the help of MALAB was elaborated.

Keywords: *Mathematical Modeling; Fuzzy Information; Catalytic Cracking Reactors; Fuzzy Model*.

1. INTRODUCTION

Uncertainty problems connected with deficit and illegibility of initial information often occur when developing mathematical models for solving problems on control of working hours for real chemical and engineering systems. The most effective approach to solve these uncertainty problems is the use of system approach so this way available information may be applied. [1-3].

Processing units of oil refining industry consist of several interconnected installations. Therefore, it is necessary to have connected mathematical models of processing units built on the basis of system approach in order to maintain the process in optimal mode. These models should allow predicting the influence of parameters of installations on their processes, intermediate and final products as well as operation in general.

To formalize and solve problems on optimization and management of multi-criteria facilities such as system of oil refining units, it is necessary to:

1) identify working conditions of units and their connection with other facilities;
2) select local criteria of the facility, i.e. indicators of operating modes of units and systems that are to be optimized;
3) determine control parameters; you can achieve optimal values of criteria by changing control parameters;
4) formulate problem on decision making for selection of optimal operating modes of process facility;
5) develop system of mathematical models for process units that cover relationship of control actions to values of local quality criteria:

● collect data available (theoretical, experimental and statistical, expert, fuzzy);
● identify types of models that can be built for each process unit based on data collected;
● analyze and select type of models for installations (based on comparison and selection criteria).

Analysis of various methods on development of mathematical models for complex facilities within research papers was conducted. It was further revealed that the papers cover very few issues on system modeling for interconnected process units within reactor/regenerative block of catalytic cracking installation under the lack of quantitative data.

I propose to apply probability methods of modeling or simulation methods under conditions of fuzziness associated with the lack of initial data.

I propose a method on creation of system of models based on building of models for various interconnected process units (determined, statistical, fuzzy, combined) with the use of available quantitative and qualitative information where these are further combined into a single package.

I propose an algorithm for automatic search of configuration for logical conclusion of fuzzy system in order to solve approximation problems.

Development and debugging of control algorithms for the processes based on their mathematical models are effectively performed with the use of standard programming means. This paper includes MATLAB results on computational experiment conducted for mathematical model of reactor block of catalytic cracking unit for vacuum gas oil within moving catalyst layer.

When developing mathematical models and control of different chemical and engineering system, often problems connected uncertainty and shortage of information often occur. It is suggested to apply probability theory methods and mathematical statistics for uncertainty [4,5]. However, these methods can not be applied if uncertainty is connected with fuzziness of initial information and this is often the case in the real working conditions. In these conditions Statistical information is either not available or insufficient under such conditions and probability theory axioms (statistical stability of researched object, repeatability of experiments under identical conditions) are not performed. Available information is sometimes the uncertain information that is person's (person making decisions - PMD, expert) knowledge (experience, intuition, judgment). Effective formalization of uncertain information representing knowledge of experts on chemical and engineering system may be obtained based on methods for expert evaluations and fuzzy set theory (FST) [6–9].

If person making decisions, experts are competent and there is proper organization for their questioning, collecting and processing of uncertain information, models can be built that include all complex interrelations with various parameters and variable complex chemical and engineering system. Such models can be more informative than those developed via traditional methods plus they may accurately describe real chemical and engineering systems and problems.

Engineering objects of oil processing are considered to be complex chemical and engineering systems that incorporate engineering processing processes with raw materials and final products (e.g. oil products) that are measured by economical indicators. In the course of work these chemical and engineering systems affect the environment and in turn it requires some ecological criteria for evaluation of their performance [10]. Therefore, control of modes for such chemical and engineering systems should be performed taking into account economic and engineering criteria (maximize quantity of produced/made products, profit, improve engineering indicators to minimize product cost and etc.), and also criteria on ecological safety of production. In order to solve control multicriterial tasks with chemical and engineering system more effectively, it is necessary turn these criteria into extreme, i.e. it is required to make decisions on selection of optimal for operation of chemical and engineering systems. Such tasks are, as a rule, formalized in the form of problem with multicriterial choice in fuzzy environment [4,11,12], which are solved on the basis of knowledge of experts and mathematical models of object which are built taking into account illegibility of initial information [7].

When formalizing and solving control tasks for chemical and engineering systems, number of problems connected with set of inconsistent and uncertainly described quality criteria may occur. When solving problems on selection of optimum operating modes and development of mathematical models for chemical and engineering systems, main sources of information are, as mentioned above, people, expert, person making decisions i.e. their knowledge, experience and intuitions which are expressed unclearly. It led to emergence of new methods for the solution of the considered problems that rely on uncertain information obtained from experts in the form of their judgments about functioning of object and which incorporates their preferences in the process of decision making related to optimal control of object [12–14].

Successful problem resolution connected with modeling and control of chemical and engineering systems under uncertain conditions requires development of methodology on creation of fuzzy models, further development of formalization methods and solving problems related to control of working modes for sistem in the fuzzy environment, that are actual problems of chemical technology, engineering systems and processes [2].

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

The purpose of work is to develop methods for construction of mathematical models for chemical and engineering system in the conditions of uncertainty, formalization of definitions for multicriterial problems related to optimal modes of object in the fuzzy environment and development of heuristic algorithms for their solving.

2. PROBLEM DEFINITION

Let us formulate control problem related to operating modes in the form of multicriterial optimization task using classical terms: it is necessary to maximize target function (criterion) $f(x)$ taking into account different restrictions $\varphi(x) \geq 0$, and $x \in X$, that is:

$$\min_{x} f(x),$$

$$\varphi(x) \geq 0, x \in X$$

where $f(x) = f_1(x),..., f_m(x)$ vector of criteria, $\varphi(x)$ – restriction functions, $x = (x_1,...,x_n)$ – variables for conditions of object. Definition range for $f(x)$, $\varphi(x)$ and x are: $0 \leq f(x) \leq f_{est}(x)$ ($f_{est}(x)$ –presetvalue);

$\varphi(x)^{\min} \leq \varphi(x) \leq \varphi(x)^{\max}$; $x = [x^{\min}, x^{\max}]$, where $\varphi^{\min}, \varphi^{\max}$ – minimum and maximum restriction values, $x_i^{\min}, x_i^{\max}$ – lower and upper limits for change of variables *x*.

Let us consider chemical and engineering system of production of high-quality gasoline as the conrol object – reforming block of catalytic cracking unit LG-35-11/300-95 in Atyrau Oil Refinery (OR). The task is to create mathematical models, modeling, problem definition for multicriterial control of chemical and engineering system in the conditions of uncertainty and development of heuristic algorithm for its solving.

Let us formulate specific main parameters of control problems for object of research.

Results of work of any chemical and engineering system may generally be estimated via vectors of criteria of two types: volumes of produced products (oil products in our case) and quality indicators of target products. Volumes of products are defined by different indicators: general, sent, normative net product, etc. In our case volume of target product-catalysate is measured in m^3/hour within the interval of [64÷80]. Some problems occur while assessment of quality of target product. Quality assessment of catalysate by one number is very difficult or is impossible. In the problem below, quality of catalyst is defined by the following indicators:

- octane number of a catalysate (according to motor method is *not less than* $\tilde{\geq}$ 86, i.e. fuzzy restriction):
- fractional composition of catalysate - 10% and 50% refine, and respectively at *approximately* 70 and 115 °C;
- pressure of saturated steam – *no more than* $\tilde{\leq}$ 500 mm of mercury;
- resin content in 100 ml. of gasoline – *no more than* $\tilde{\leq}$ 5.0 mg.

As we can see quality indicators of target products are assessed via fuzzy criteria or restrictions such as "not less than", "about, approximately" or "no more than". During decision making and control processes at production place, as a rule, we want that volume of target products to be *more*, and product quality to be *better*. These criteria are often controversial, i.e. after determination of Pareto set it is impossible to improve them at the same time. Thus while control of chemical and engineering system taking into account the situation at production place and production schedule it is necessary to find compromise solution that satisfies requirements of person making decisions.

Thus, we formalize problem on selection and control for operational modes of chemical and engineering system for reforming block and set it in mathematical way as follows.

Let $f(x) = \varphi^1(f(x)) = \mu_0^1(x)$ be normalized criterion that assesses output (volume) of target product of reforming block – catalysate. Let us assume that membership function of accessory $\mu_q(x), q = \overline{1,5}$ for each fuzzy restriction $\varphi_q(x) \tilde{\geq} (\tilde{\approx}, \tilde{\leq}) b_q, q = \overline{1,5}$, are built and they describe quality indicators of catalysate. A number of priorities for restrictions or vector of scales showing mutual importance of these restrictions $\beta = (\beta_1, \beta_2, \beta_3, \beta_4, \beta_5)$ is known.

In the conditions of multicriteriality and illegibility, formalized problem can be set in the form of problem of uncertain/fuzzy mathematical programming (FMP):

$$\max_{x \in X} \mu_0(x), \mu_0(x) = \mu_0^1(x) \text{ or}$$

$$\mu_0(x) = \log \mu_0^1(x), \quad (1)$$

Journal of Theoretical and Applied Information Technology
15th June 2020. Vol.98. No 11

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

$$X = \{x : x \in \Omega \wedge \arg\max_{x \in \Omega} \sum_{q=1}^{5} \beta_q \mu_q(x) \wedge \sum_{q=1}^{5} \beta_q = 1 \wedge \beta_q \geq 0, q = \overline{1,5}\} \quad (2)$$

The optimal solution for this problem is the vector regime, entrance parameters $x^* = (x_1^*, x_2^*, ..., x_5^*)$, which provides extreme values of criterial at compliance with imposed restrictions that consider and satisfy preferences of person making decisions.

Criterion $f_i(x), i = \overline{1,m}$ and restrictions $\varphi_q(x), q = \overline{1,5}$ depend on vector of entrance, regime parameters $x_i, i = \overline{1,5}$: $x_1 -$ volume of raw materials; $x_2, x_3 -$ temperature and pressure in reactors of reforming R-4, R-4a; $x_4 -$ rate of volume flow for raw materials: $x_5 -$ relation of hydrogen/hydrocarbon. These dependences are defined on the basis of mathematical models of reforming process that are developed taking into account shortage and illegibility of initial information. Let us consider suggested system approach on development of models and modeling chemical and engineering system where we take reforming block of catalytic reforming unit in the Atyrau Oil Refinery as an example. One of the main tasks of upgrading the Atyrau oil refinery is the construction of a deep oil refining Complex, which allows to significantly increase the production of high-quality light oil products. The deep oil refining complex, which will be integrated with the existing plant installations, consists of several installations:

- Reactor unit;
- Flue gas fine cleaning and recovery unit;
- In the rectification unit;
- Gasoline stabilization and gas fractionation unit.

The plant is designed to convert the residue of atmospheric distillation (AR, fuel oil), heavy gas oil, vacuum gas oil, heavy gas oil from the coking plant, heavy raffinate from the aromatics production complex and heavy aromatic compounds from the same complex into more valuable products such as liquefied petroleum gas, gasoline and light catalytic cracking gas oil.

Catalytic cracking of oil residues (figure 1) provides conversion of hard-to-crack raw materials with high Conradson coking properties (8-10 %) and / or metal concentrations (up to 50 mg / kg). The "R2R" section process is, for the most part, a typical catalytic cracking process in a fluidized catalyst bed. The raw material is sprayed at the bottom of the Elevator reactor, where it is mixed with an ascending stream of hot regenerated catalyst. The upper part of the Elevator reactor enters the separator hopper for rapid separation of vapors from the catalyst. After separating the catalyst, the cracking products are sent to the fractionating column, where they are separated into gas, gasoline, and gas oil. The coked catalyst is sent for regeneration.

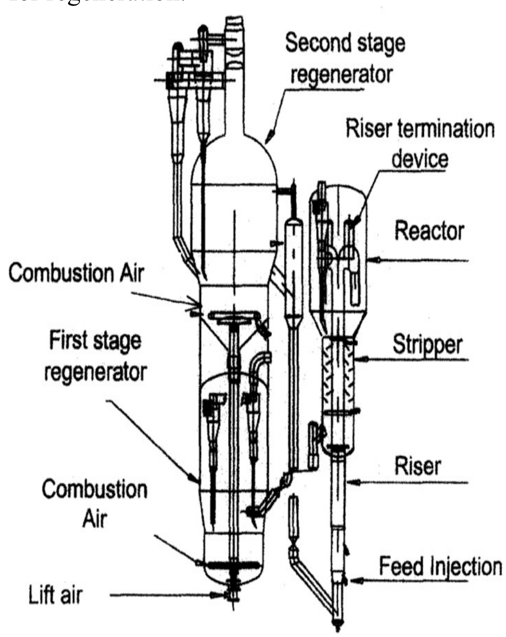

Figure 1. Schematic diagram of a FCCU

A distinctive feature of the R2R process is the presence of two regenerators with separate air supply and flue gas removal. In the first stage regenerator, operating at a temperature not higher than 700 °C, there is a partial (~50-80%) burning of carbon and almost complete burning of hydrogen. From the first stage regenerator, the catalyst is fed into the second stage regenerator, where because of the virtual absence of water vapor can be maintained at a temperature up to 900°C. At such temperatures and excess air is almost complete burning of coke from the catalyst surface. The second regenerator is

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

equipped with a remote cyclone and a zone for blowing off the catalyst from the flue gases.

Another feature of the "R2R" process is the supply of cooled circulating gas oil (fraction 360-420 °C) to the Elevator reactor above the point of entering the raw material, which makes it possible to regulate the temperature in the Elevator reactor regardless of the temperature in the mixing node. The temperature in the reactor is about 510 °C, the contact time is about 1 second.

2.1 Metod for mathematical modeling of chemical and engineering system based on various sources of information, development of models for reforming reactor

Let us consider mathematical statement for every local criterion $f_i(x), i=\overline{1,m}$, i.e. method for building mathematical model [3,7,15,17] that describes dependence of output parameters of chemical and engineering system for production of gasoline on its mode parameters where we consider available information. Suggested method for modeling of chemical and engineering system on the basis of available information consists of the following points:

1. Research of chemical and engineering system elements, connections between elements, collecting available informandtion and its processing, determination of purpose of modeling;
2. Determination of assessment criteria and comparison of models which are possible to be built for elements of system taking into account purpose of modeling;
3. By the chosen criteria to Carry out expert evaluation of possible models for each chemical and engineering system element based on selected criteria and determine optimal type of model for each element;

3.1 If theoretical data are sufficient for description of operation of chemical and engineering system element and summarized assessment criteria for building a model are effective, determined models are built for such unit based on analytical method;

3.2 If statistical data are sufficient for description of operation of chemical and engineering system element or collecting of such data is possible and statistical model is effective based on summarized assessment criteria and comparison, then statistical models of this element are built based on experimental and statistical methods;

3.3 If theoretical and statistical data are insufficient for description of operation of chemical and engineering system elements, collecting of such data is economically impractical, collecting of uncertain information that describes operation of unit and its processes is possible, uncertain model is effective according to summarized assessment/comparison criteria, then uncertain models should be built for such units based on FST; for these purposes see point 4;

3.4 If theoretical data, statistical data and uncertain expert information for the description of operation of object are insufficient and collecting of such data is useless, *combined model* should be built for such unit on the basis of combined information (theoretical, statistical, unclear) and other data that are available. For description of different parameters of specific element of chemical and engineering system that depend on nature of information, see 3.1–3.3 or 4;

4. Determination and selection of model with uncertain input (mode) $\tilde{x}_i \in A_i, i=\overline{1,n}$ and output $\tilde{y}_j \in \tilde{B}_j, j=\overline{1,m}$ parameters. $\tilde{A}_i \in X$, $\tilde{B}_j \in Y$ – uncertain subsets, *X, Y* – universal sets. Input parameters can be accurate (determined) i.e. $x_i \in X_i$, $i=\overline{1,n}$;

5. If $x_i \in X_i$, i.e. input parameters of object (element of CES) are determined, determination of structure of uncertain equations for multiple regression (polynomial equations) are $\tilde{y}_j = f_j(x_1,...,x_n,\tilde{a}_0,\tilde{a}_1,...,\tilde{a}_n)$, $j=\overline{1,m}$ (solution of problem for structural identification);

6. On the basis of expert methods for description of chemical and engineering system element and determination term sets of uncertain parameters $T(X_i, Y_j)$;

7. Building of membership function (MF) of uncertain parameters $\mu_{A_i}(\tilde{x}_i)$, $\mu_{B_j}(\tilde{y}_j)$. For building of membership function, e.g. output parameters of object, it is suggested to use the following formula (3)

$$\mu^p_{B_j}(\tilde{y}_j) = \exp(Q^p_{B_j}\left|(y_j - y_{mdj})^{N^p_{B_j}}\right|) \qquad (3)$$

where $\mu^p_{B_j}(\tilde{y}_j)$ – membership function (MF) of uncertain input parameters $\tilde{y}_j$ that belong to uncertain set $\tilde{B}_j$; p – quantum number (interval); $Q^p_{B_j}$ – parameter which is defined at identification of membership function and characterizing degree of fuzziness; $N^p_{B_j}$ – coefficient that changes range of definition of terms and form of schedule for membership function fuzzy parameters; y^p_{mdj} – fuzzy variable that is most corresponding to set

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

term (in quantum p) for such value $\mu^p_{B_j}(y_{mdi}) = \max_j \mu^p_{B_j}(y_j)$;

8. If input and output parameters of chemical and engineering system element are fuzzy, we need to formalize fuzzy R_{ij} that define connections between $\tilde{x}_i$ and $\tilde{y}_j$. Build linguistic models and see point 10;

9. If conditions of point 5 are followed, then estimate values of fuzzy coefficients $(\tilde{a}_0, \tilde{a}_1, ..., \tilde{a}_n)$ identified in point 5 of models $\tilde{y}_j$ (solution of problem with parametric identification) and see point 11;

10. If conditions of point 8 are followed, then based on rules of composition input $B_j = A_i \circ R_{ij}$, carry out determination of fuzzy parameter values for the object:

$$\mu^p_{B_j}(\tilde{y}^*_j) = \max_{x_i \in X_i}\{\min[\mu^p_{A_i}(\tilde{x}^*_i), \mu^p_{R_{ij}}((\tilde{x}^*_i, \tilde{y}_j)]\} \quad (4)$$

If $\tilde{x}^*_i$ – parameter values of object estimated by experts, then set of current values of input parameters is defined as fuzzy set consisting of maximal values of membership function $\mu_{A_i}(\tilde{x}^*_i) = \max(\mu_{A_i}(\tilde{x}_i))$.

Membership functions of p-quantum (interval) of fuzzy values for output parameters of modelled object $\mu^p_{B_j}(\tilde{y}^*_j)$ are calculated according to formula (4)

Numerical values of output parameters of object $\tilde{y}^{**}_j$ are defined out of set of fuzzy solutions according to the following formula: $\tilde{y}^{**}_j = \arg\max_{\tilde{y}^*_j} \mu^*_{B_j}(\tilde{y}^*_j)$, i.e. parameters for membership function that reached maximum values.

11. Checking sufficiency of model. If sufficiency condition is satisfied: i.e. $R = |y_m - y_e| \le R_D$, where R, R_D, criterion and its allowed value y_m and y_e, respectively, values of output parameters received according to the model and experimentally, at identical values of input parameters, then developed models are recommended for research and determination of optimum operating modes for chemical and engineering system elements and system in general. Otherwise, it is necessary to find out the reason of insufficiency and return to corresponding points for solving the issue with sufficiency of the model.

Experimental, statistical and expert data were collected and processed based on a method of consecutive inclusion of regressors using aprior information and the method mentioned above (points 2 and 3). Structure of model is defined (structural identification of models) for reforming reactors in the form of system of equations with multiple regression (5)–(7), (9) and system of fuzzy equations with multiple regression (8):

$$y_{R2} = a_0 + \sum_{i=1}^{5} a_1 x_1 + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ik} x_i x_k \quad (5)$$

$$y_{R3} = a_0 + \sum_{i=1}^{5} a_1 x_i + \sum_{i=1}^{5}\sum_{k=1}^{5} a_{ik} x_i x_k \quad (6)$$

$$y_{R4} = a_0 + \sum_{i=1}^{5} a_1 x_i + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ik} x_i x_k$$

$$y_{R4a} = a_0 + \sum_{i=1}^{5} a_1 x_i + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ik} x_i x_k \quad (7)$$

$$\tilde{y}_j = \tilde{a}_{0j} + \sum_{i=1}^{5} \tilde{a}_{ij} x_{ij} + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ijk} x_{ij} x_{kj},\ j = \overline{1,5} \quad (8)$$

$$y_j = a_{0j} + \sum_{i=1}^{5} a_{ij} x_{ij} + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ijk} x_{ij} x_{kj},\ j = \overline{6,7} \quad (9)$$

Here $y_{R2}, y_{R3}, y_{R4}, y_{R4a}$ – is volume of catalysate (target product) from output of reactors R-2, R-3 and R-4 and R4a respectively; $\tilde{y}_j, j = \overline{1,5}$ – is quality indicators of catalysate: octane number ($\tilde{y}_1$ – via motor method and not less than 86); fractional composition ($\tilde{y}_2$ – 10% refining – not less than 70°C, $\tilde{y}_3$ – 50% refining – no more than 115°C); pressure of saturated steams ($\tilde{y}_4$ – no more than 500 mm of mercury); resin content in 100 ml. gasoline ($\tilde{y}_5$ – no more than 5.0 mg.); $y_j, j = \overline{6,7}$ – volumes of dry gas (DG) and gas with hydrogen content (GHC); x_1 – raw materials, hydrogenate from output of hydrotreating block, m^3/hour; x_2 – volume speed in reactors, $hour^{-1}$; x_3 – temperature in reactors R-2, R-3, R-4 and R-4a at °C, x_4 – pressure in reactors R-2, R-3, R-4 and R-4a in kg/cm^2; x_5 – relation of N_2/raw materials, $nanometer^3$; a_{0j}, a_{ij}, a_{ikj} and $\tilde{a}_{0j}, \tilde{a}_{ij}, \tilde{a}_{ikj}$,

Journal of Theoretical and Applied Information Technology
15th June 2020. Vol.98. No 11

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

$i, k = \overline{1,5}$ – identified regression coefficients (~ – fuzziness sign), free member, coefficients of linear (x_{ij}), square and mutual correlation (x_{ij}, x_{kj}).

Thus, models describing products' volumes from output of reforming block are built via experimental statistical methods in the form of models of multiple regression, and the models describing quality indicators of products are built on the basis of uncertain information obtained from experts in the form of fuzzy equations with multiple regression [7,17]. Coefficients of models (5)–(9) are defined via known methods of parametric identification based on least squares method (using Regress software and MatLab system [18]).

The results of parametrical identification of models that define volumes of catalysate coming out from reactors ($y_{R2}, y_{R3}, y_{R4}, y_{R4a}$) and gas with hydrogen content (y_2) are mentioned in (10)–(13):

$$\begin{aligned}Y_{R2} &= 0.39848\,X_1 + 12.15385\,X_2 + 0.03211\,X_3 - 0.98375\,X_4 + \\ &+ 0.01975\,X_5 + 0.00494\,X_1^2 + 9.34911\,X_2^2 - 0.00007\,X_3^2 - \\ &- 0.03792\,X_4^2 + 0.00005\,X_5^2 + 0.22788\,X_1X_2 + 0.0001\,X_1X_3 + \\ &+ 0.00197\,X_1X_4 + 0.00049\,X_1X_5 + 0.03705\,X_2X_3 - \\ &- 0.48615\,X_2X_4 - 0.00064\,X_3X_4;\end{aligned} \tag{10}$$

$$\begin{aligned}Y_{R3} &= 0.39500\,X_1 + 12.10769\,X_2 + 0.03186\,X_3 - \\ &- 0.98375\,X_4 + 0.01967\,X_5 + 0.00504\,X_1^2 + \\ &+ 9.3136\,X_2^2 - 0.00006\,X_3^2 - 0.04099\,X_4^2 + \\ &+ 0.00005\,{}^2_5 + 0.22989\,X_1X_2 + 0.0001\,X_1X_3 + \\ &+ 0.00207\,X_1X_4 + 0.00049\,X_1X_5 + 0.03676\,X_2X_3 - \\ &- 0.50448\,X_2X_4 - 0.00066\,X_3X_4;\end{aligned} \tag{11}$$

$$\begin{aligned}Y_{R4,R4a} &= 0.39898\,X_1 + 11.07697\,X_2 - 0.03158\,X_3 - 1.02391\,X_4 + \\ &+ 0.01962\,X_5 + 0.00507\,X_1^2 + +9.28995\,X_2^2 - 0.00006\,X_3^2 - \\ &- 0.04452\,X_4^2 + 0.00005\,X_5^2 + 0.23018\,X_1X_2 + 0.0001\,X_1X_3 + \\ &0.00217\,X_1X_4 + 0.00049\,X_1X_5 + 0.03645\,X_2X_3 - \\ &- 0.52508\,X_2X_4 - 0.00068\,X_3X_4;\end{aligned} \tag{12}$$

$$\begin{aligned}Y_2 &= 500\,X_1 + 7142.857\,X_2 + 10.101\,X_3 - 1458.3333\,X_4 + \\ &+ 25.0\,X_5 + +6.25\,X_1^2 + +5102.0408\,X_2^2 + +0.0204\,X_3^2 - \\ &- 60.7639\,X_4^2 + 0.0625\,X_5^2 + +178.5714\,X_1X_2 + \\ &+ 0.2525\,X_1X_3 - 5.625\,X_1X_4 + +15.625\,X_1X_5 - \\ &- 297.619\,X_2X_4 - 2.5252\,X_2X_4 - -0.05051\,X_3X_5 - 1.0417\,X_4X\end{aligned} \tag{13}$$

Identification of fuzzy coefficients $\tilde{a}_{ij}, i = \overline{0,6}$ and $\tilde{a}_{ikj}, i,k = \overline{0,6},\ j = \overline{3,7}$, system of equations (9) is carried out on the basis of methods from the fuzzy set theory and α-sets for levels α=0.5, 0.75 (left and right) and 1.

Models that cover the output of the unit have the form of multiple regressions which are identified via experimental and statistical methods. Models that access quality of catalyst have the form of fuzzy regression equations and are built on the basis of qualitative data obtained from specialists and experts.

3. PRACTICAL USE AND DISCUSSION OF RESULTS

As an example of implementation of the suggested approach we will consider definitions and problem solutions for control of operational mode of reforming block of chemical and engineering system that operates at Atyrau Oil Refinery. To determine optimum temperature for process of reforming based on suggested method of development of models for engineering complexes and various information, linguistic models were built for defining influence of reforming reactor's temperature on output of catalysate and stability of catalyst.

The main results of organizing and conducting expert evaluations in order to collect the necessary information for expert evaluation were to find out and select the most significant input, mode and output parameters of the object, for example, the installation of catalytic cracking of the Atyrau oil refinery. The expert survey was conducted among the expert specialists servicing the installation. Their roles were performed by the plant's process engineer, instrumentation engineer, head of the catalytic cracking plant.

Table 1: Fuzzy rules for catalyzate from the reactor

Temperature in the reactor	Temperature at the reactor outlet				
	PB	PM	PS	NS	NB
PB	PB	PS	PS	NB	NB
PS	PB	PS	SS	NB	NB
SS	PB	PS	SS	NS	NB
NS	PB	PS	PS	SS	NB
NB	PB	PB	PB	PS	SS

*Negative Big (NB), Negative Small (NS), Steady State (SS), Positive Small (PS), Positive Big (PB)

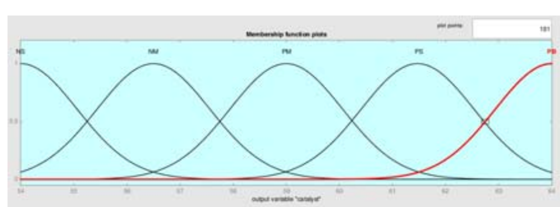

Figure 2: Method variable membership function

Journal of Theoretical and Applied Information Technology
15th June 2020. Vol.98. No 11

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

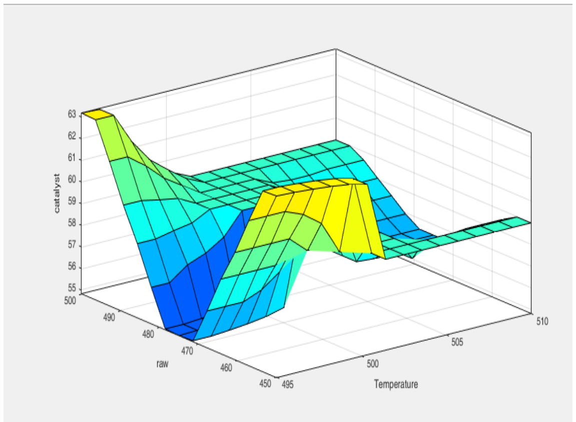

Figure 3: The surface of fuzzy inference

Results obtained by means of various methods were compared and a solution that matched the results the most accurately was selected.

In figure 4 the graph of the dependence of the output of the catalyzate on the reactor temperature is given.

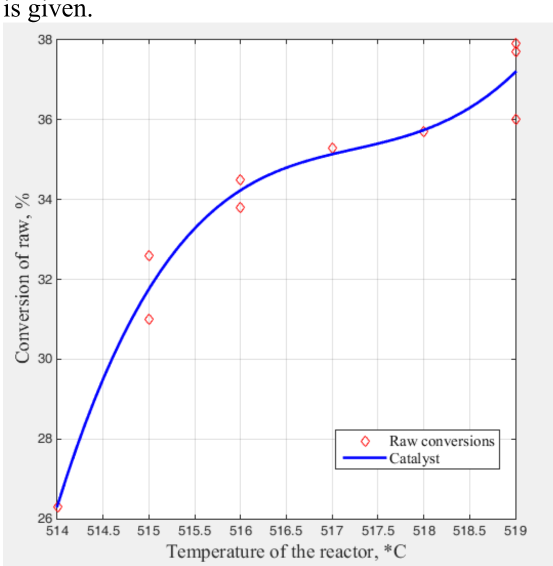

Figure 4: Graph of the dependence of the catalyst output on the reactor temperature

I proposed to regulate temperature of the process within the range of 515-520 ºC (temperature point would be selected based on composition of a processed raw material) in order to increase output of gasoline fraction. Increased output of gasoline fraction could be achieved by increasing the temperature of catalytic cracking process.

Calculations were made and study of the effect of temperature on catalyst after regeneration on output and composition of cracking products for the developed model in the course of the research. Calculations were made with consideration of the change in temperature of the catalyst. It, in turn, corresponds to regulatory values of the installation.

The influence of the main parameters of the reforming process on the quantity and quality of the produced catalyst products is studied. Based on the results of research and processing of the collected quantitative and qualitative information, statistical and combined models of the reactor are constructed.

1. The problem on selection of optimal operational mode for reforming block in the conditions of single criteria which is based on RC-EP algorithm may be solved by applying above-stated results of research and on the basis of modified method of *relative concession* (RC) and *equality principle* (EP): As in our cases there is only one criterion, weight vector $\gamma = (\gamma_1,...,\gamma_m)$, $\sum_{i=1}^{m} \gamma_i = 1, \gamma_i \geq 0, i = \overline{1,m}$ is defined as $\gamma = 1$;

2. Let us introduce such values of weight vector as $\beta=(\beta_1, \beta_2, \beta_3, \beta_4,\beta_5)$ for restrictions that satisfy requirements of equality principle, i.e. $\beta_1\mu_1(x)=\beta_2\mu_2(x)=\beta_3\mu_3(x)= \beta_4\mu_4(x)=\beta_5\mu_5(x$: β= (0.2, 0.2, 0.2, 0.2, 0.2);

3. As in the considered problem $\mu_0(x) = \mu_0^1(x_1,x_2,x_3,x_4,x_5)$ or $\mu_0(x) = \log \mu_0^1(x_1,x_2,x_3,x_4,x_5)$, here $\mu_0(x)$ output (volume) of catalysate is accurate and $\gamma = 1$, therefore there is no need to determine term set and build membership function. The criterion is determined according to above-stated model (12) $\mu_0(x) = y_{R4,R4a} = f_1(x_1,x_2,x_3,x_4,x_5)$.

4. Let us define term set describing uncertain restrictions and for assessment of their degree of application; we build membership functions for their application: $\mu_q(x), q = \overline{1,5}$. As a result of expert assessment and with the help of person making decisions, experts, the following fuzzy descriptions are selected for describing restrictions: $\mu_1(x) =$ (octane number of catalysate according to motor method *is not less* than $\gtrsim$ 86); $\mu_2(x) =$ (fractional composition of catalysate, 10% refining, at *approximately* $\approx 70^o$ C); $\mu_3(x) =$ (fractional composition of catalysate, 50% refining, at *approximately* $\approx 115^o$ C); $\mu_4(x) =$ (pressure of saturated steam – is *no more*

than $\tilde{\leq}$ 500 mm of mercury); $\mu_5(x) =$ (resin content in 100 ml. gasoline – is *no more* than $\tilde{\leq}$ 5,0 mg) in which term-set is identified. Now by applying identified sets we will build membership functions describing extents of accomplishment of fuzzy restrictions $\mu_q(x), q=\overline{1,5}$. These membership functions are built using formula (3) on the basis of the method suggested in the paper [19]:

$$\mu_1(x) = \exp(0.83\,|\,y_1 - 87\,|^{0.75});$$

$$\mu_2(x) = \exp(0.75\,|\,y_2 - 69\,|^{0.85});$$

$$\mu_3(x) = \exp(0.12\,|\,y_3 - 114\,|^{0.50});$$

$$\mu_4(x) = \exp(0.51\,|\,y_4 - 500\,|^{0.25});$$

$$\mu_5(x) = \exp(0.15\,|\,y_5 - 5\,|^{1.50}).$$

where y_1, y_2, y_3, y_4, y_5 – assessed values of quality indicators of the model (8) after defuzzification; 87, 69..., 5 – parameter values that most corresponding to the selected term and in which membership function is the maximum value (1); 0.83, 0.75..., 0.15 and 0.75, 0.85..., 1.50 are coefficients for identification of membership function, for "fast" and "slow" change of a form of membership function chart.

5. We select formula describing relative concession, for example: $\mu_0(x) = \prod_{i=1}^{m}(\mu_0^i(x))^{\gamma_i}$ or $\mu_0(x) = \sum_{i=1}^{m}\gamma_i \log \mu_0^i(x)$; in our case, the problem has only one criterion, i.e. it will be m =1, $\gamma_1 = 1$, $\mu_0(x) = \mu_0^1(x_1, x_2, x_3, x_4, x_5)$ or $\mu_0(x) = \log \mu_0^1(x_1, x_2, x_3, x_4, x_5)$, and for definiteness we take the first option. We maximize criterion $\mu_0(x) = \mu_0^1(x_1, x_2, x_3, x_4, x_5)$ (18) on set (19). Fuzzy restrictions are based on results of the previous points and on set of level α are brought to system of accurate restrictions. Thus, fuzzy problem is brought to defining of single criteria problem with normal (accurate) restrictions where it can be solved with modification or by use of known methods for their solution. As a result, current results of solution appear in dialogue mode which depend on weight coefficients of restrictions: $x(\beta)$, $\mu_0^1 x(\beta)$, $\mu_1 x(\beta), \mu_2 x(\beta), \mu_3 x(\beta)$, $\mu_4 x(\beta), \mu_5 x(\beta)$.

6. The obtained current solutions are presented to person making decisions. The results did not satisfy person making decisions until the fifth cycle and he/she applied new values for vectors β and made return to point 3. On the 6th cycle with the received results of person making decisions was satisfied with the results at the sixth cycle and he/she turned to point 7.

Searching for solution is stopped, person making decisions selected final solutions:

- $x^*(\beta)$, values of input-mode parameters depending on weight vector of orestrictions that provides optimal value of criterion;

- optimal value of criterion $\mu_0^1(x^*(\beta))$ which is reached at $x^*(\beta)$.

- maximal values for membership functions for adherence to restrictions $\mu_1(x^*(\beta)), \mu_2(x^*(\beta)), \mu_3(x^*(\beta), \mu_4(x^*(\beta)), \mu_5(x^*(\beta))$.

By analysing data in the table 2 we may make the following conclusions:

1) Suggested heuristic algorithm *RC-PR* is more effective in comparison with the determined and other known methods;

2) When searching of optimum operating modes for chemical and engineering system by means of the offered algorithm, for the account and use of additional quality (uncertain/fuzzy) information in the form of knowledge, experience and intuition of person making decisions, experts who allow, without idealizing, to describe correctly real production situations, the accuracy of the solution increases;

3) Suggested algorithm of optimization in fuzzy environment allows to define values of membership function for fuzzy restrictions, i.e. to check correctness of obtained solutions taking into account applied restrictions.
4) Results of modeling show that increased quality requirements to products lead to reduction of its volume, person making decisions selects compromise solution between quality and quantity of catalysate.

Table 2. Comparison of results of suggested algorithm with results of other algorithms and with experimental data obtained from the object of control

No.	Criterion and restriction	Deterministic method (literature data) [20]	Heuristic algorithm *RC-PR* [21,22]	Algorithm of optimization in fuzzy environment	Experimental data (Atyrau Oil Refinery)
1.	Output (volume) of catalisate – criterion $y_{R4,4a}$, m^3/ hour	77.2	77.6	77.8	77.5
2.	Octane number of catalysate according to MT ($\widetilde{y}_1$)	86	87	87	(86)[1]
3.	Fractional composition of catalysate; 10% refining, ºC ($\widetilde{y}_2$);	70	70	70	(70)[1]
	50% refining, ºC ($\widetilde{y}_3$).	115	114	114	(114)[1]
4.	Pressure of saturated steams, mm of mercury ($\widetilde{y}_4$)	500	500	500	(500)[1]
5.	Resin content in 100 ml. gasoline, mg ($\widetilde{y}_5$)	5.0	4.8	4.7	(5.0)[1]
6.	Membership function (MF) with adherence to restrictions $\widetilde{y}_1$ – $\mu_1(x^*(\beta))$	-	1.0	1.0	-
7.	MF with adherence to restrictions $\widetilde{y}_2$ – $\mu_2(x^*(\beta))$	-	1.0	1.0	-
8.	MF with adherence to restrictions $\widetilde{y}_3$ – $\mu_3(x^*(\beta))$	-	0.97	1.0	-
9.	MF with adherence to restrictions $\widetilde{y}_4$ – $\mu_4(x^*(\beta))$	-	0.98	1.0	-
10.	MF with adherence to restrictions $\widetilde{y}_5$ – $\mu_5(x^*(\beta))$	-	1.0	1.0	-
11.	$x^* = (x_1^*, x_2^*, x_3^*, x_4^*, x_5^*)$ – optimal values of input-mode parameters x_1^* - raw materials volume; m^3/ hour.	80	80	80	80
12.	x_2^* – rate of volume flow in the reactor; hour^{-1}	1.7	1.3	1.3	1.5
13.	x_3^* – temperature in reactors R-4, R-4a, ºC	500	497	494	495
14.	x_4^* – pressure in reactors R-4, R-4a; kg/cm^2	26	25	25	25
15.	x_5^* –ratio of hydrogen/hydrocarbon	415	400	400	400

Note: $()^{l}$ means that corresponding quality indicators are defined via laboratory analysis and require a lot of time; (-) means that corresponding indicators are not defined by this method. In compared methods time for search of solution is about the same taking into account input of necessary data or their adjustment is about a minute.

The results given in the table show efficiency of the suggested algorithm for solution problems related to control of chemical and engineering system operating modes in uncertain environment as it shows not worse results in comparison with the known methods and production - experimental data in all aspects plus catalysate discharge results are better. Furthermore RC-PR algorithm allows to consider uncertain restrictions, define extent of accomplishment of uncertain restrictions. As we can see while solving uncertain problem on control, full delivery of uncertain restrictions is reached: membership functions $\mu_1(x^*(\beta)),\ldots, \mu_5(x^*(\beta))$ are equal to 1, delivery level for uncertain restrictions $\tilde{y}_3$ and $\tilde{y}_4$ is improved. Optimum modes are achieved at lower temperature in reactors R-4, R-4a (464 ^{o}C), than in other methods.

Presented data prove that developed models allow increase of output of the catalysis and improve its quality (octane number increases). Moreover, the models are applicable within a fuzzy environment that allows assessing quality of the products.

4. CONCLUSION

System approach on development of mathematical models for chemical and engineering system elements which is based on various information is presented and justified. Definitions of problems for control of chemical and engineering system operational modes under uncertain environment were obtained in the form of problem for selecting optimal operational modes of elements of system based on the models and via adapting optimality principles for work in uncertain environment. Mathematical definitions of initial problem are set in the form of problems with uncertain mathematical programming. Heuristic algorithm for solving formulated problem on control in uncertain environment has been developed based on principles of relative concession and equality. Novelty of the results is that tasks on selection of optimum operating modes for the object are set and solved in uncertain environment without their preliminary transformation to determinated equivalent problems. In turn it allows to describe industrial situations under uncertain environment in a more accurate way and obtain effective solutions for problems related to control of operating modes of the object. The presented approaches are implemented at creation of mathematical models and solving of problems related to selection of optimum operating modes for reforming reactors of chemical and engineering system used for production of high-octane gasoline under uncertain conditions.

Results of the research are considered to be theoretically promising, they widen the boundaries for solvable practical tasks, allow modeling and managing operating modes of complex chemical and engineering system taking into account multicriteriality and uncertainty of initial information.

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