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Synthesis of Robust Fuzzy System of Automatic Regulation Of The Temperature Regime Of The Chemical Reactor

Marakhimov Avazjon Rakhimovich, Khudaybergenov Kabul Kadirbergenovich, Sherboboeva Gulruh Bakhtiyorovna, Ohundadaev Ulugbek Rahimjonogli

Doctor of Science, Professor, Department of Mathematics, National University of Uzbekistan, Tashkent, Uzbekistan
PhD Student, Department of Mathematics, National University of Uzbekistan, Tashkent, Uzbekistan
Tashkent University of Information Technologies Karshi Branch, Karshi, Uzbekistan
Master's Student, Department of Mathematics, National University of Uzbekistan, Tashkent, Uzbekistan

ABSTRACT: This article discusses the methods of fuzzy-system modelling and intelligent control of technological objects in conditions of vagueness and fuzziness of the initial information. The results of the synthesis of a fuzzy system for controlling the temperature regime of a chemical reactor, invariant to parametric and external perturbation are presented.

KEY WORDS: Classification, Data Mining, Machine Learning, Predictive analysis, Social Networking Spam, Spam detection.

I.INTRODUCTION

Analysis of state of the problem on designing control systems with complex technological objects shows that traditional methods for constructing models of objects and their control systems do not lead to satisfactory results when the original description of the problem to be solved is certainly inaccurate and incomplete [1,2,7,9].

As a rule, these weakly-structured or poorly defined objects possess such properties as uniqueness, nonstationary structure and parameters, incompleteness or absence of formal description of control object [1, 6, 8, 12]. Controlling objects of this class represents from the point of view of the classical theory of automatic control (TAC) is quite complicated, in most cases, unsolvable problem. This is because when building a traditional control system (CS), it is necessary to formally describe the object of control in advance and form control criteria based on a certain mathematical apparatus that operates in quantitative categories. If it is impossible to give an exact mathematical description of the object and criteria for its control in quantitative terms, the traditional control theory is inapplicable [4,11,13,15]. In these cases, it is advisable to use the methods of intelligent control, specifically focused on the construction of models that take into account the incompleteness and imprecision of the initial data.

II.ANALYSIS OF THE EXISTING CONTROL SYSTEM AND PROBLEM STATEMENT

Let us consider a chemical reactor for the production of fiber "Nitron", in which the process of polymerization of the reaction mixture takes place. This chemical reactor is a vertical welded apparatus with a spherical lid, equipped with a frame stirrer and a steam jacket. The reaction mixture in the reactor is fed from the bottom, and is taken from the top into the dope. The polymerization process takes about 1.5-2 hours. The processes occurring in the reactor depend on the temperature in the reactor, the percentage of all components and the consumption of the reaction mixture.

The main input parameters of this process are: consumption of steam and desalinated water; initial temperature in the jacket and the reactor; initial concentration of components of the reaction mixture. The rest of the effects are perturbing, pressure of heating steam can be considered as the main perturbing influence.

Under certain assumptions and on the basis of the equations of material balance [3,8], it can be represented as following form (Fig. 1):

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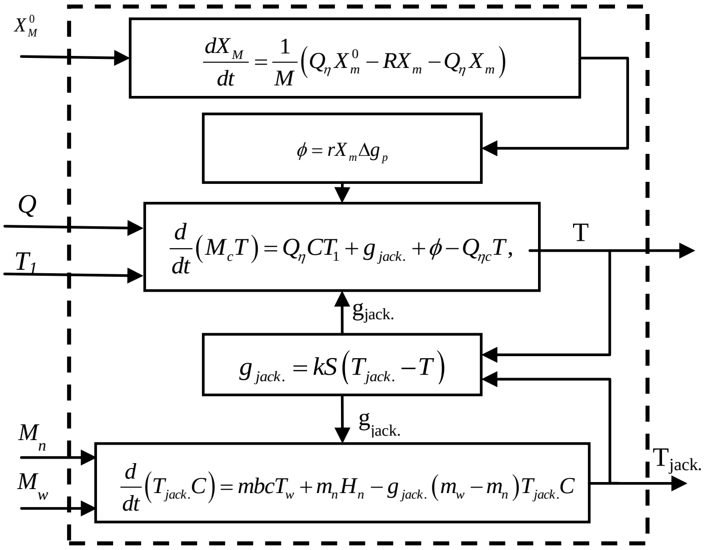

Fig. 1. Structural-functional model of chemical reactor with a steam-jacket

where,M – mass of reactor contents; M_c - mass of the reaction mixture ; X_m – monomer concentration in the reactor; Q_1 –consumption of the reaction mixture at input to the reactor; Q_2 –consumption of output flow; X_m^0 – monomer concentration; R – constant of reaction rate; Δg_p – thermal effect of the reaction; C – reactor heat capacity; $T_{jack.}$ – temperature in the jacket; T –reactor temperature; T_w – water temperature; H_n – enthalpy of steam; S - surface area of jacket heat transfer; $g_{jack.}$ –heat flow from the jacket; k – heat transfer coefficient from the jacket to the reactor; φ – generating heat; m_w – consumption of water supplied to the jacket; m_n – steam consumption at the entrance to the jacket.

The input regulating effect for the reactor temperature is the heating steam consumption, and the rest are perturbing [3,9].

One of the most important parameters characterizing the quality of the technological process is the concentration and working viscosity of the spinning solute at the outlet of the reactor. Measurement of these parameters is possible only by laboratory method. Analysis of the references [3,8,9,14,16] and experience of industrial operation showed that in order to obtain a spinning solute of a given quality, it is necessary to maintain a certain temperature regime. Therefore, the reactor temperature $T_{peak.}$ is selected as the output parameter. The temperature of the reactor, in turn, is a controlled parameter, and it is controlled by the temperature of the reactor jacket $T_{jack.}$.

Figure 2 shows the structural diagram of the existing cascade system of automatic control (SAC) of the temperature of a chemical reactor. According to this scheme, the temperature in the reactor is controlled by the temperature of the jacket, which can be changed by supplying cold water or hot steam to it. For this purpose, control valves installed on the water and steam supply lines are controlled by a signal from the secondary temperature controller of the jacket, which is installed in relation to the first one in a cascade scheme. Setting the temperature of the controller jacket is generated by the primary reactor temperature controller.

As regulating devices in the primary and secondary regulators, proportional-integral (PI) regulators were used.

$$u_{T_{jack}}^{prev.}(t)=k_n^1e_1(t)+\frac{1}{T_u^1}\int_0^\infty e_1(t)dt\,,\quad u_{Qn}\ (t)=k_n^2e_2(t)+\frac{1}{T_u^2}\int_0^\infty e_2(t)dt\,, \tag{1}$$

where

$e_1(t)=T_p^{prev.}(t)-T_p(t),\quad e_2(t)=T_{jack.}^{prev.}(t)-T_{jack.}(t)$ - regulation errors, respectively in the reactor and in the jacket;

$k_n^1,\ T_u^1,\ k_n^2,\ T_u^2$ - Adjustment parameters of the primary and secondary regulators.

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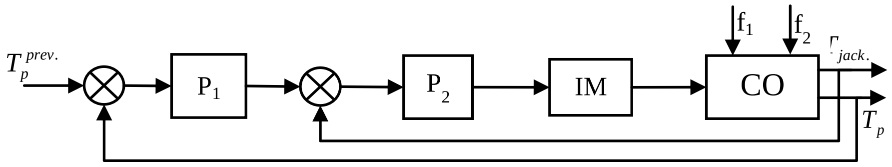

Fig.2. Structural diagram of the cascade SAC temperature of a chemical reactor

As it is known, for a given regulator structure, the calculation of the SAC is reduced to determining the optimal (from the point of view of any quality criterion) tuning parameters of the regulator taking into account the fulfillment of constraints on the system stability margin.
As a quality criterion, the integral quadratic criterion is used:

$$J(t) = \int e\ (t)dt \to \min_{K_n, T_u} \tag{2}$$

Optimum tuning parameters $k_n^1,\ T_u^1,\ k_n^2,\ T_u^2$ of regulators can be found on the basis of minimizing the functional (2).
During the optimization cycle, the following values of the parameters of the primary and secondary regulators were obtained:

$$k_n^1 = 0.51,\quad T_u^1 = 0.37;\quad k_n^2 = 0.41,\quad T_u^2 = 0.19.$$

Further, taking into account these values of the tuning parameters of the regulators, we built a simulation model of a cascade SAC of a chemical reactor temperature in the MatLab environment (Fig. 3).

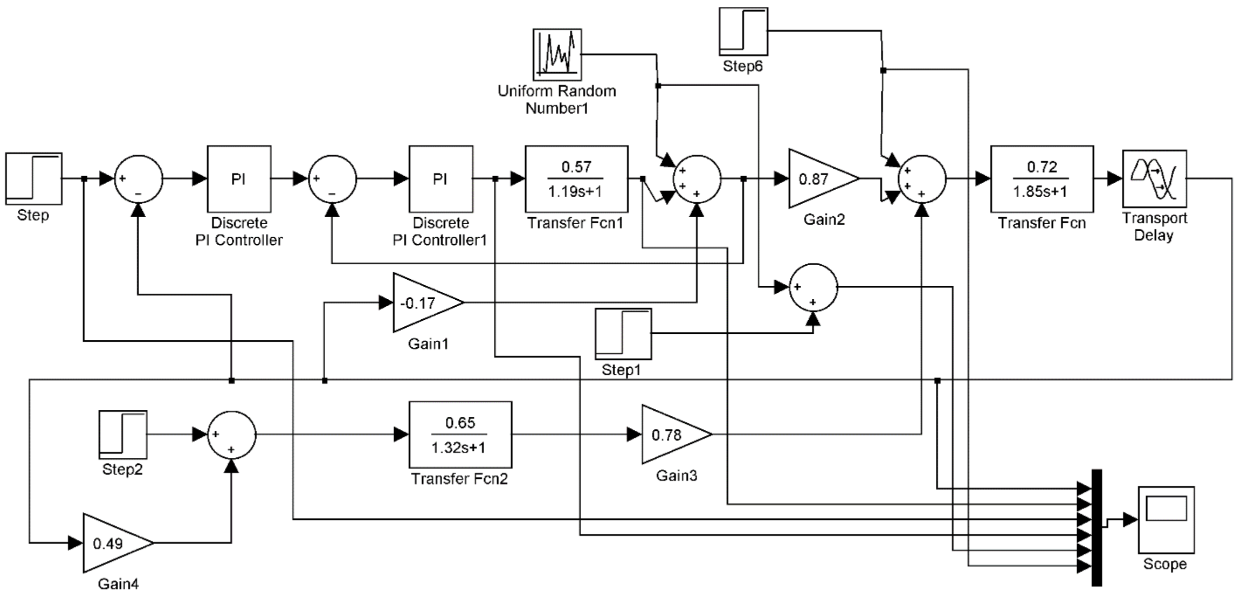

Fig.3. Simulation model of a cascade SAC temperature of a chemical reactor in MatLab environment

The simulation results of this system show (Fig. 4) that the over regulation in the system does not exceed 20%, and the transient process time is 385 seconds.
In presence of external or parametric perturbing influences on the object (for example, a change in vapor pressure of more than 15%, a change in the concentration of the components of the reaction mixture by 10%), the quality indicators of the transition process deteriorate significantly. In the case of a wide range of changes in these parameters, this aspect may lead the control system to an unstable state. This is explained by the fact that in automatic control systems with fixed values of the controller parameters, the quality of the transient process varies depending on the disturbance and technological regimes of the chemical reactor [7, 9].

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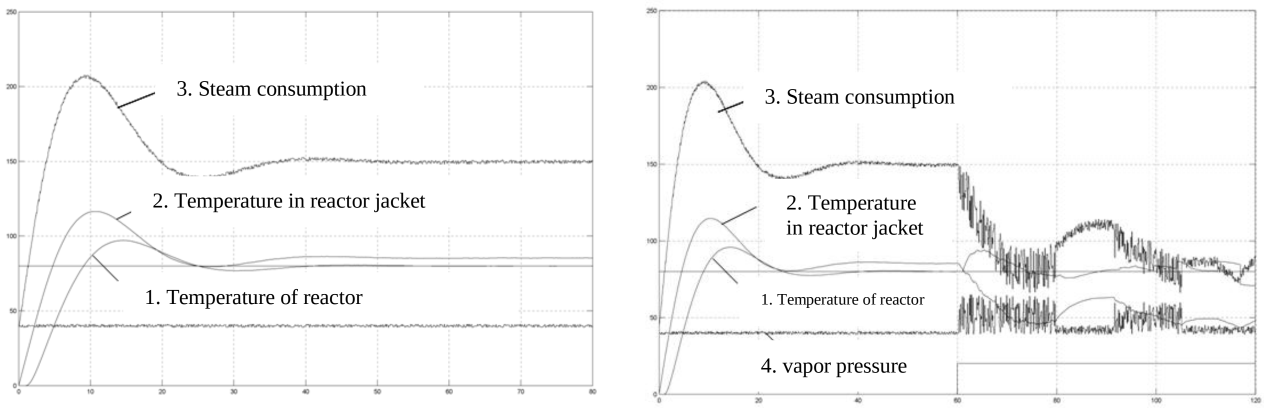

Fig.4. Results modeling of SAC temperature of a chemical reactor

Therefore, it is proposed to look for the solution of such problems using the theory of fuzzy logic, which allows operating with linguistic fuzzy statements, the values of which are interpreted as a fuzzy region of a variable, i.e. as a fuzzy set, which makes it possible to take into account the uncertainty and ambiguity of the source data, as well as assessing the quality indicators of the control object.
Thus, the problem is setting of synthesis a robust fuzzy system for controlling the temperature regime of a chemical reactor, invariant to external and parametric perturbations.

III.SYNTHESIS OF A FUZZY CONTROL SYSTEM, INVARIANT TO EXTERNAL AND PARAMETRIC PERTURBATIONS

To solve the problem, it is necessary [11,12]:
1. Description of the control object and the definition of its input and output parameters and perturbing influences.
2. The choice of the fuzzy inference algorithm, which most fully determines the decisions made under the given conditions of the course of the polymerization process in a chemical reactor.
3. Synthesis of a fuzzy controller, which is an integral part of an intelligent controller and provides the required qualitative and quantitative indicators of controlling the temperature regime of a chemical reactor in the presence of perturbing influences.
4. Investigation of the obtained response surfaces of a fuzzy regulator under the conditions of the presence of perturbing influences and a pure delay characterizing the technological process of heating for the consumer.
Let us consider a closed system of automatic temperature control of a chemical reactor with a fuzzy logic controller (FLC) (Fig. 5).

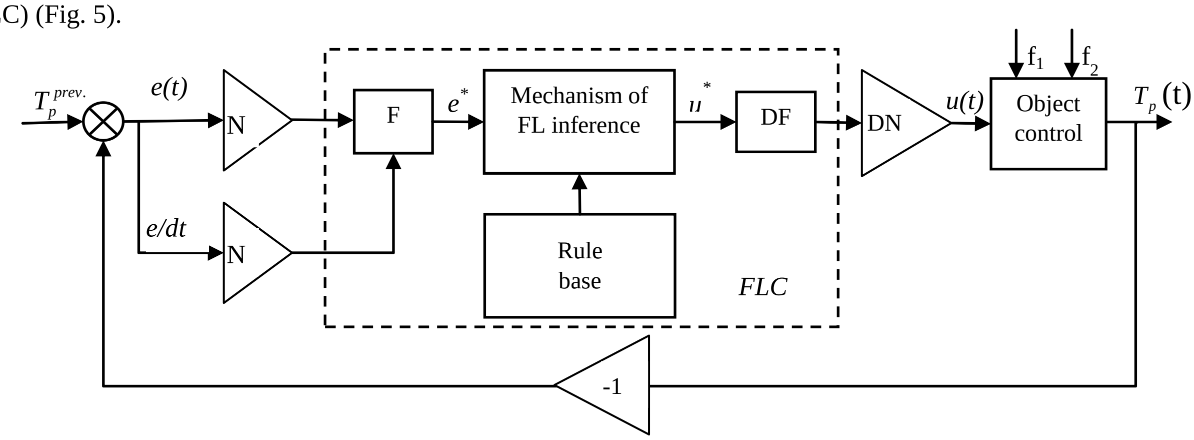

Fig. 5. SAC temperature of chemical reactor with a fuzzy logic controller

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This system differs from the previously considered cascade SAC with classical PI controllers in that there is one single fuzzy logic controller of the MISO type with two inputs and one output in the control loop. The fuzzy controller is assigned the task of generating a control changing in the range of variation of the dynamic regulation error and its derivative with respect to its threshold values.
According to this scheme, the input vector FLC is converted into a fuzzy form $E^* = (e_1^*, e_2^*)$ using fuzzificationblock F, then a fuzzy inference is performed in the rule base, resulting in a fuzzy output variable u^*. Transfer of control vector values u^* from fuzzy to clear u carried out by the defuzzification unit *DF*.
Block *N* is designed to preprocess the input error of the control and its derivative:

$$e_i^N = \begin{cases} e_i\ , & |e_i| < e_i^{\max}; \\ e_i^{\max} sign(e_i), & |e_i| \geq e_i^{\max}. \end{cases} \tag{3}$$

Post-processing of the output control signal is carried out by the DN block, where the problem of u denormalization is solved:

$$u = u_N DN = u_N |u_{\max}|, \tag{4}$$

where $u_{\max}$ – the maximum value of the control supplied by the object.
As a rule, the FLC knowledge base contains a description of terms of linguistic variables (LV), which must be defined in advance for each input and output variable.
For this, we introduce the following linguistic variables $e_1 = ("Control\ error", T_{e1}, E_1)$, $e_2 = ("Derivative\ error", T_{e2}, E_2)$ and $u = ("Control", T_u, U)$, where $T_{e_i} = \{T^1{}_{e_i}, T^2{}_{e_i}, \cdots T^k{}_{e_i}\}, i = \overline{1,k}$, $T_u = \{T^1{}_u, T^2{}_u, \cdots T^k{}_u\}$, - term set of linguistic variables e_1, e_2 and u with related membership functions (MF) $T^l{}_{e_i} = \mu_{ei}^l(e_i)$, $T_u{}^l = \mu_l(u), l = \overline{1,k}$, given respectively on universal sets $E_i = [E_{i\min}, E_{i\max}]$ and $U = [U_{\min}, U_{\max}]$.
Suppose, that each input and output linguistic variable $T_x = \{T_e, T_{e/dt}, T_u\}$ each has 7 terms: T_x ={'*NB'*, '*NM'*, '*NS'*, '*ZE'*, '*PS'*, '*PM'*, '*PB'*} with triangular membership functions:

$$\mu_{Tx}(x,a,b,c) = \begin{cases} 0 \quad if\ x \leq a \\ (x-a)/(b-a) \quad if\ a \leq x \leq b \\ (c-x)/(c-b) \quad if\ b \leq x \leq c \\ 0 \quad otherwise\ c \leq x \end{cases}. \tag{5}$$

Then, linguistic variables are the result of fuzzification:
e_1,=«*Error*» = [$\mu_{NB_e}(e)$ /NB_e, $\mu_{NM_e}(e)$ /NM_e , $\mu_{NS_e}(e)$ /NS_e, $\mu_{ZE_e}(e)$ /ZE_e, $\mu_{PS_e}(e)$ /PS_e, $\mu_{PM_e}(e)$ /PM_e, $\mu_{PB_e}(e)$ /PB_e];
e_2=«*Speed change of error* » = [$\mu_{NB_{e/dt}}(e/dt)$ /$NB_{e/dt}$, $\mu_{NM_{e/dt}}(e/dt)$ /$NM_{e/dt}$, $\mu_{NS_{e/dt}}(e/dt)$ /$NS_{e/dt}$, $\mu_{ZE_{e/dt}}(e/dt)$ /$ZE_{e/dt}$, $\mu_{PS_{e/dt}}(e/dt)$ /$PS_{e/dt}$, $\mu_{PM_{e/dt}}(e/dt)$ /$PM_{e/dt}$, $\mu_{PB_{e/dt}}(e/dt)$ /$PB_{e/dt}$];
u^*=«*Control* » = [$\mu_{NB_u}(u)$ /NB_u, $\mu_{NM_u}(u)$ /NM_u , $\mu_{NS_u}(u)$ /NS_u, $\mu_{ZE_u}(u)$ /ZE_u, $\mu_{PS_u}(u)$ /PS_u, $\mu_{PM_u}(u)$ /PM_u, $\mu_{PB_u}(u)$ /PB_u].
Next, we form the base rules of logical inference of the FLC in the form:

$$If\ \ (T_{e1}^{j} \times T_{e2}^{j})\ \ TO\ \ T_u^j\ ,\ j = \overline{1,7}, \tag{6}$$

where $(T_{e1}^{j} \times T_{e2}^{j})$ - cartesian product of fuzzy sets E_1 and E_2, given on scales E_1 and E_2, with the membership function:

$$\mu_{(T_{e1}^j \times T_{e2}^j)}(e_1, e_2) = \mu_{T_{e1}^j}(e_1) \wedge \mu_{T_{e2}^j}(e_2), \tag{7}$$

T_u^j - corresponding output fuzzy set defined by fuzzy relation $R^j = (T_{e1}^{j} \times T_{e2}^{j}) \times T_u^j$, $j = \overline{1,7}$ with the membership function:

$$\mu_{R^j}((e_1, e_2), u^*) = (\mu_{T_{e1}^j}(e_1) \wedge \mu_{T_{e2}^j}(e_2)) \wedge \mu_{T_u^j}(u^*). \tag{8}$$

The combination of all the rules corresponding to fuzzy relation $R = \bigcup_{j=1}^{7} R^j$ with the membership function

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$$\mu_R((e_1,e_2),u^*) = \bigvee_{j=1}^{7}[(\mu_{T_{e1}^j}(e_1)\wedge\mu_{T_{e2}^j}(e_2))\wedge\mu_{T_u^j}(u^*)] \tag{9}$$

determines the knowledge base of the FLC and sets the law for the functioning of a fuzzy system.
Thus, given the values of the input linguistic variables T_{e1}^j and T_{e2}^j, the output value of the fuzzy-logic controller T_u^j can be determined on the basis of the following compositional rule [13]:

$$B^j = (T_{e1}^j \times T_{e2}^j)\bullet R, \tag{10}$$

with degree of membership:

$$\mu_{T_u^j}(u^*) = \bigvee_{e_1\in E_1, e_2\in E_2}[(\mu_{T_{e1}^j}(e_1)\wedge\mu_{T_{e2}^j}(e_2))\wedge\mu_R(e_1,e_2,u^*)]. \tag{11}$$

In case the linguistic variables of the input signal e_1 and e_2 take respectively fuzzy sets $T_{e1}^{'}$ and $T_{e2}^{'}$, fuzzy set $T_u^{'}$ the linguistic variable of the control signal u^* is defined as follows:

$$\mu_{T_u^{''}}(u^*) = \max_{e_1,e_2}\left\{\left[\prod_{i=1}^{n}\mu_{T_{e_i}^{'}}(e_i)\right]\cdot\left[\min_{j=1}^{m}\left[\prod_{i=1}^{n}\mu_{T_{e_i}^j}(e_i)\right]\cdot\mu_{T_u^j}(u^*)\right]\right\}. \tag{12}$$

Linguistic control law of the FLC can be presented in the form of table 1.

Table 1.

Extended table of rules for fuzzy-logical PD - regulator

$e_2=(de/dt)^*$	$e_1=e^*$						
	NB_e	NM_e	NS_e	ZE_e	PS_e	PM_e	PB_e
$NB_{e/dt}$	NB_u	NB_u	NB_u	NB_u	NS_u	NS_u	ZE_u
$NM_{e/dt}$	NB_u	NB_u	NB_u	NS_u	NS_u	ZE_u	PS_u
$NS_{e/dt}$	NB_u	NB_u	NS_u	NS_u	ZE_u	PS_u	PB_u
$ZE_{e/dt}$	NB_u	NS_u	NS_u	ZE_u	PS_u	PB_u	PB_u
$PS_{e/dt}$	NM_u	NS_u	ZE_u	PS_u	PB_u	PB_u	PB_u
$PM_{e/dt}$	NS_u	ZE_u	PS_u	PB_u	PB_u	PB_u	PB_u
$PB_{e/dt}$	ZE_u	PS_u	PM_u	PB_u	PB_u	PB_u	PB_u

u^*

After the fuzzy inference procedure, to obtain the real value of the output signal of the fuzzy controller, it is necessary to carry out the defuzzification process – converting the fuzzy value of the linguistic variable u^* to a clear value u.
For this, we use the center of gravity method [15]:

$$u = \sum_{n=1}^{9}u_n^*\mu_{T_u}(u_n^*)\bigg/\sum_{n=1}^{9}\mu_{T_u}(u_n^*). \tag{13}$$

If we consider the membership function of a fuzzy value $T_u^{'}$, it can be represented as:

$$\mu_{T_u^{''}}(u) = \begin{cases}\prod_{i=1}^{n}\mu_{T_{e_i}^j}(e_i), & u=\lambda^j \\ 0, & u\neq\lambda^j,\end{cases}, \tag{14}$$

where λ^j – discrete numerical values of the output signal.
Then the determining value of the output signal FLC at the stage of defuzzification can be calculated as follows:

$$u = \sum_{j=1}^{m}\lambda^j\left[\prod_{i=1}^{n}\mu_{T_{e_i}^j}(e_i)\right]\bigg/\sum_{j=1}^{m}\prod_{i=1}^{n}\mu_{T_{e_i}^j}(e_i), \tag{15}$$

or

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$$u(\bar{e},\bar{\lambda}) = \sum_{j=1}^{m} \lambda^j \zeta_j(\bar{e}), \quad (16)$$

where $\zeta_j(\bar{e}) = \prod_{i=1}^{n} \mu_{T_{e_i}^j}(e_i) \Big/ \sum_{j=1}^{m} \prod_{i=1}^{n} \mu_{T_{e_i}^j}(e_i)$.

If we consider the basic equation of the PID controller can be written as

$$u(t) = u_0 + K\left(e(t) + \frac{1}{T_u}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right), \quad (17)$$

then, control law of the PID controller can be represented as a controller with a variable coefficient:

$$K_{PID} = K \cdot K^*, \quad (18)$$

where K^* is the variable part of the gain depending on the current value of the derivative and the integral of the control error.

This allows to implement a PID-type fuzzy-logic controller in the form of two successively connected modules: "FLC PD type" module and "fuzzy correction" module with adjustable coefficients α and β (Fig. 6).

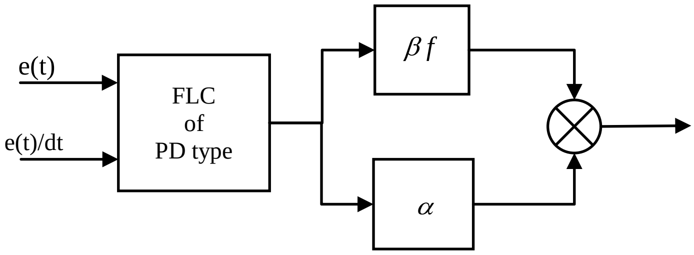

Fig. 6. Structural model of a fuzzy-logic PID-regulator

Thus, in the case of the completeness and consistency of the fuzzy inference rule base, the FLC operation law can be represented as sum of products of two functions determined by the type and distribution of the membership functions and the selected fuzzy inference algorithm.

Based on the above theoretical considerations, we can formulate the following algorithm for the synthesis of a fuzzy-logical PID controller:

1. Input and output linguistic variables of the FLC are determined by 7 terms - sets with uniformly distributed triangular membership functions.

2. Scaling and denormalization coefficients of the fuzzy controller (N, DN) are determined.

3. Rule bases of FLC logical inference are formed in the form of (12).

4. A standard linear FLC PD - type with 7 terms for each LV and 49 rules is sequentially included in the system, the task of which is to suppress oscillations.

5. The law of non-linear FLC functioning is formed by offsetting the centers of intermediate terms of the input LV "control error" to a linear FLC of PD type.

6. In order to reduce time of transition process, optimal parameters of the membership function of the term-sets of the linguistic variable e_1 are selected: $\mu_{Te}^j(x, a_j^*, b_j^*, c_j^*)$.

7. Selection of parameters α and β, allowing reduction of static error.

The considered algorithm for the synthesis of a fuzzy-logical PID controller is distinguished by simplicity, since it allows to use of a standard form for describing linguistic variables and the minimum set of control rules.

IV. RESEARCH OF QUALITY CHARACTERISTICS OF A FUZZY SAC TEMPERATURE OF A CHEMICAL REACTOR

Further, in order to study the efficiency of the synthesized law of fuzzy control, a simulation model of a fuzzy SAC temperature of a chemical reactor in the MatLab environment (Fig. 7) was constructed and a series of computational experiments were carried out.

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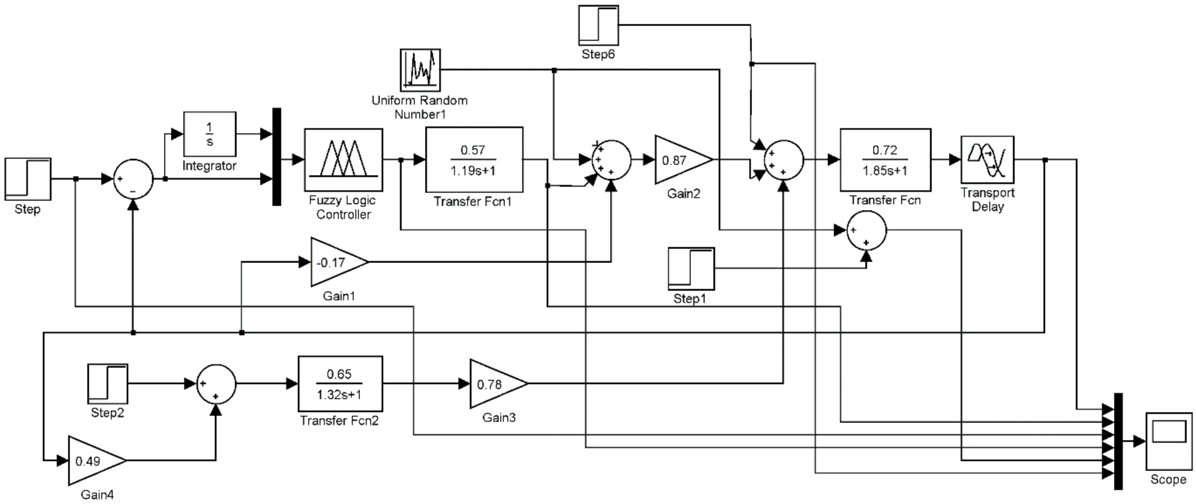


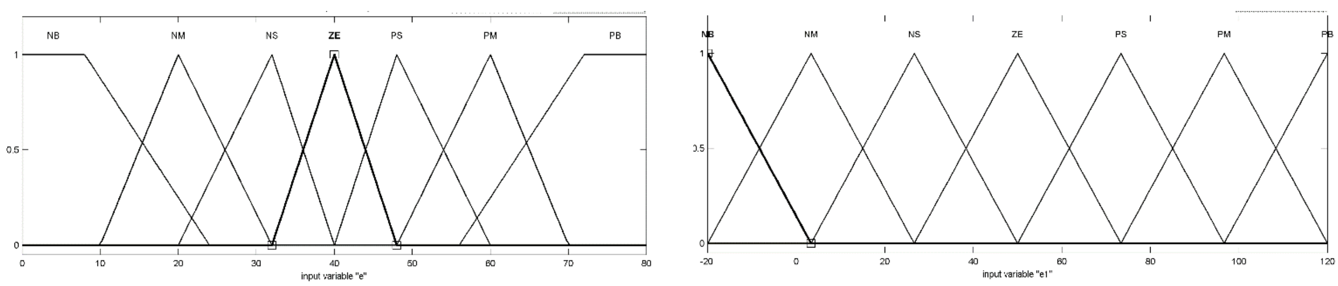
Fig.7. Simulation model of fuzzy SAC temperature of a chemical reactor in MatLab environment

Analysis of the simulation results of a fuzzy control system (FCS) with uniformly distributed triangular membership functions of the input linguistic variables showed that the qualitative characteristics of a FCS with an FLC are much better compared to the existing cascade SAC with a PI controller ($t_{nn}^{FLC_1} = 259 sec.$, $\xi_{nep.p}^{FLC_1} = 15.7\%$), but does not satisfy requirement in speed.

In order to improve the quality characteristics of this system, the parameters e_1^*, e_2^* and u^* of the membership function of linguistic variables have been optimized. For example, at several stages of an iterative search, the following parameters of the membership function of term sets are obtained T_{e1}={$'NB_e', 'NM_e', 'NS_e', 'ZE_e', 'PS_e', 'PM_e', 'PB_e'$} with different ranges of universes:

$$\mu_{NB_e}(e) = \mu_{NB_e}(e, -1.18, -1.02, -0.58);\ \mu_{NM_e}(e) = \mu_{NM_e}(e, -1.02, -0.58, -0.18);$$
$$\mu_{NS_e}(e) = \mu_{NS_e}(e, -0.58, -0.18, 0);\ \mu_{NS_e}(e) = \mu_{NS_e}(e, -0.18, 0, 0.18); \qquad (19)$$
$$\mu_{PS_e}(e) = \mu_{PS_e}(e,\ 0, 0.18, 0.58);\ \mu_{PB_e}(e) = \mu_{PB_e}(e,\ 0.58, 1.02, 1.18);$$

Figure 8 shows a graphical representation of the MF of e_1^*, e_2^* and u^* linguistic variables, as well as the response surface, illustrating the dependence of the output of a fuzzy logic regulator "*Degree of opening of a steam flow valve*" on the input variables "*Reconcilement temperature of the reactor*" and "*Error changing rate*".



a) input variable "e" *b)input variable "e1"*

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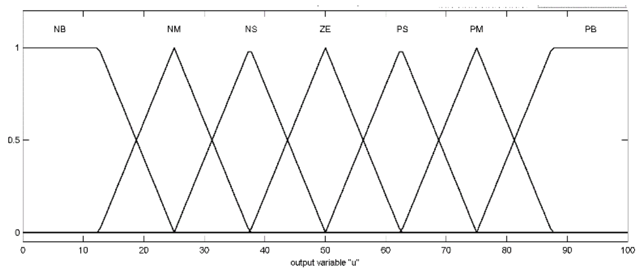
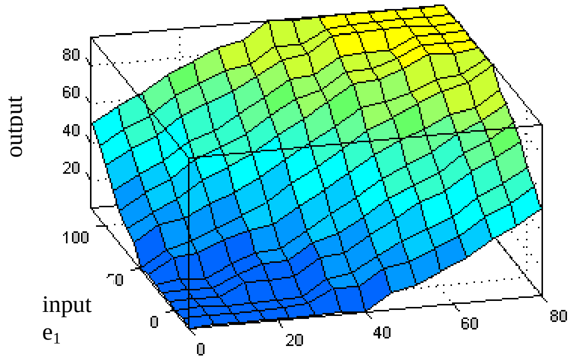


c)input variable "u"



d)

Fig. 8. Membership functions of term-sets of e_1, e_2 and u linguistic variables

Next, we repeat the computational experiments taking into account the optimized parameters of MF of linguistic variables for different values of the parameters of the transfer function of the control object and the levels of the perturbing signal (Fig. 9).

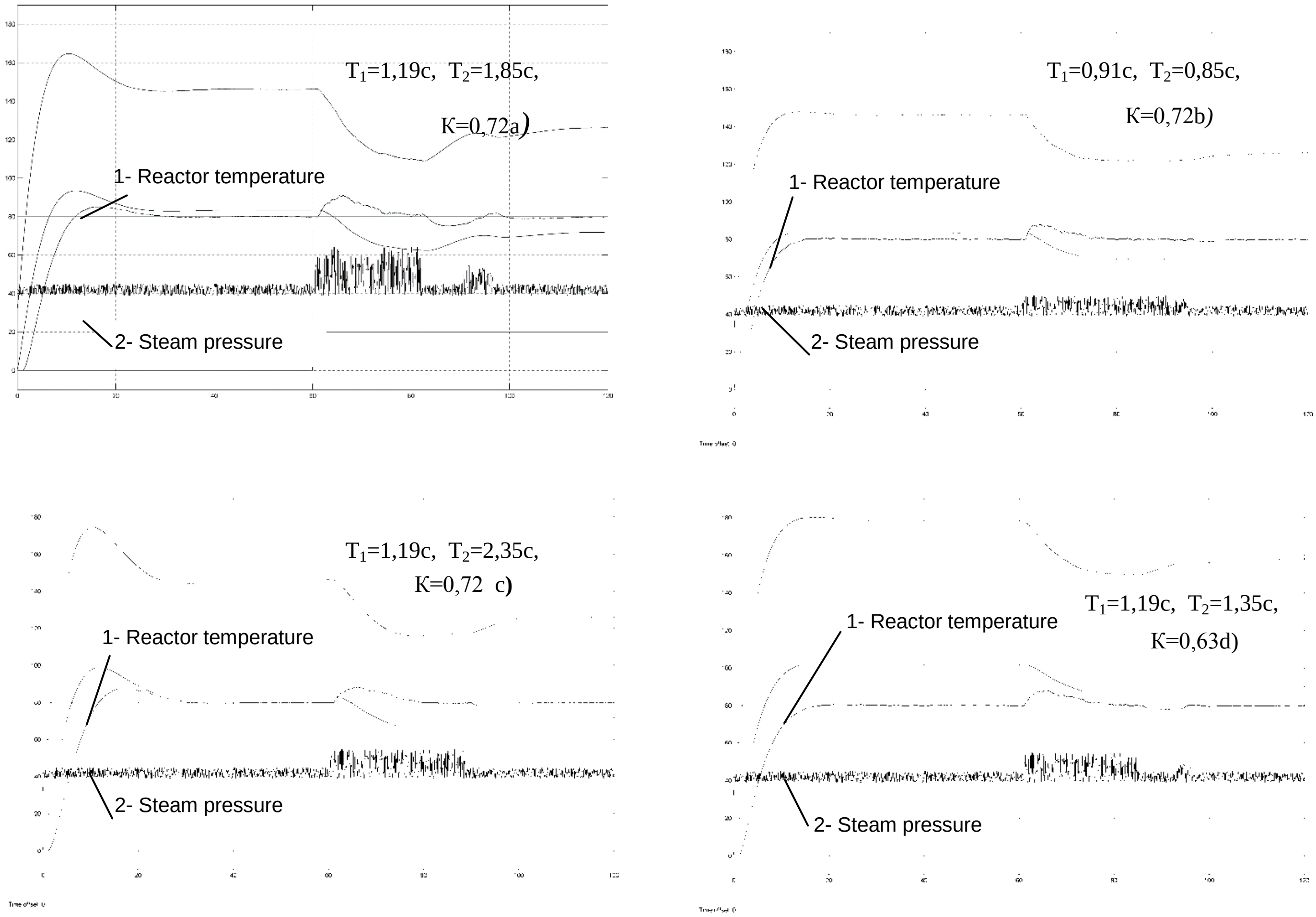


Fig.9. Simulation results of a fuzzy SAC temperature of a chemical reactor at different values of the transfer function parameters and levels of an external perturbation signal

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As can be seen from the graphs of the transition process (Fig. 9, a, b, c and d), in the presence of a noisy external perturbing signal in the system and its level changes up to 30%, as well as changes in the parameters of the control object (amplification factor K_1^{OY}, K_2^{OY} and constant time T_1^{OY}, T_2^{OY}) up to 25% (in the direction of increasing and decreasing), fuzzy system holds stability properties. At the same time, the quality characteristics of FCS varies sufficiently small range: $t_{nn}^{FCS_z} \in [231 \div 259] sec.$, $\xi_{nep.p}^{FCS} \in [0.0 \div 12]\%$.

V. CONCLUSION

Thus, based on the conducted computational experiments, it can be concluded that the synthesized fuzzy logic controller has the robustness feature and gives the entire automatic control system, the ability to maintain the reactor temperature at a given level in the presence of external perturbing influences, and also to qualitatively control the polymerization process with a wide range of changes in its parameters over time.

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AUTHOR'S BIOGRAPHY

Marakhimov Avazjon Rakhimovich
Affiliation: Doctor of Sciences, Professor, Department of Mathematics, National University of Uzbekistan, Uzbekistan. Rector of the National University of Uzbekistan. He is a excellent specialist in the research area of intelligent control systems and information technology. His last researches are devoted to the problems of fuzzy modeling, synthesis fuzzy control system and Intelligent Transportation Systems. He has more than 70 published research papers and 3 monographs.
1990-1993 Ph.D in Control systems and Automation of technological processes, Tashkent State Technical University, Uzbekistan
1978-1983 Graduated Applied Mathematics (Software engineering), Tashkent State Technical University, Uzbekistan

K.K. Khudaybergenov is pursuing a PhD in the National University of Uzbekistan. He was bornin1985,His research interests include issues related to computational intelligence, hybrid algorithms, fuzzy neural networks and complex system modeling.

G.B.Sherboboeva is a senior teacher in Tashkent University of Information Technologies Karshi Branch. She was born in 1984, graduate degree, Research direction: Control systems and Soft Computing, Fuzzy math.

U.R.Ohundadaev is graduate student at the National University of Uzbekistan. He was born in 1994, Research direction: Artificial Neural Networks, Control systems and Soft Computing.