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DEVELOPMENT OF CONTROL SYSTEM FOR WASTE PYROLYSIS UNIT OF AGRICULTURAL COMPLEX WITH THE APPLICATION OF FUZZY LOGIC

The object of research is the control system for the pyrolysis reactor of agricultural waste (plant biomass). The subject of research is the stability and the value of the calorific value of synthesis gas formed by pyrolysis of plant biomass. The biggest problem of the technological object (the pyrolysis reactor of agricultural waste) is the high sensitivity of the heating value of synthesis gas to disturbances in the composition of plant biomass. This sensitivity is expressed as a square law of the amount of oxidant required to achieve a high calorific value. Another problem is the deviation of certain time constants of the control object, caused by changes in the chemical composition of the plant biomass.

The built control system provides a high calorific value of the generated syngas by determining the composition of the waste, pyrolysis by determining the composition of the generated syngas in a separate isoenthalpic device, and stabilizes it. Information on the composition of raw materials allows to calculate the optimal parameters for the pyrolysis process, and, accordingly, update the controller's task. This information also makes it possible to compensate for changes in the time constants of the control object caused by changes in the chemical composition of raw materials, which made it possible to achieve a high robustness of the system. Compensation for these changes was carried out by training a regression polynomial. The training was carried out on test sets of time constant deviations. The resulting polynomials were used for convolution with membership functions of a fuzzy controller. Such a convolution made it possible to obtain the following membership functions that ensure compliance with the control quality parameters close to those obtained without deviations in the time constants.

Simulation of the constructed control system showed a significantly reduced sensitivity of the calorific value to the composition of raw materials, and also revealed a low sensitivity of the control quality from the deviations of the time constants of the control object caused by disturbances in the chemical composition of the waste.

The method by which the control system for the pyrolysis reactor was built differs from the existing ones in that the use of information on the composition of the pyrolyzed substance is used to accurately calculate the optimal values of the pyrolysis parameters, as well as to mutate the membership functions of the fuzzy controller. The method can be used in other similar systems designed for the pyrolysis of organic substances in order to expand their scope. In particular, for the integration of such systems into technological objects, they are more sensitive to deviations in the calorific value of the gas used as fuel.

Keywords: *pyrolysis reactor, control system, fuzzy controller, system robustness, control quality.*

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1. Introduction

The whole pyrolysis process is the process of decomposition of molecules into lighter ones under the influence of temperature. According to the oxidant excess ratio, the pyrolysis process occupies an intermediate position between the gasification process, according to which the oxidant excess ratio is 0, and the combustion process, is characterized by high oxidant excess values, close to, and sometimes even larger than 1. Pyrolysis is classified into fast and slow by its classification. As a rule, fast pyrolysis is characterized by a higher temperature – 1500–2000 degrees Celsius, and higher – against 500–900 degrees with slow pyrolysis. To date, there is an active development of research on fast pyrolysis. Despite this, a slow pyrolysis reactor is still a standard technological solution for the conversion of a wide range of materials. Such materials include raw materials with a low calorific value, or are of little use for energy use for other reasons. With the help of pyrolysis, such raw materials are obtained into materials with a high calorific value, such as synthesis gas, artificial coal, artificial gasoline. It should be noted that the ratio between volatile, solid and liquid pyrolysis products, as well as the chemical properties of these products, are determined by exhaustive factors. These factors include: the configuration and internal structure of the pyrolysis reactor, the process mode – temperature, moisture in the reactor, the rate of material feeding into the reaction zone (heating), the oxidizer excess ratio in the reactor, etc. Another factor is the physical properties of the raw material – its temperature, humidity as well as its chemical composition. In matters of energy security and energy security, the development of technologies that allow to fully realize the potential of the above resources by pyrolysis is becoming important. Today there is a wide range of raw materials suitable for pyrolysis in order to obtain more energy products – from household waste, used tires, to waste of agro-industrial technologies. Taking this into account, the development of technologies that make it possible to fully realize the potential of the above resources by pyrolysis is becoming important. One of the measures to improve the energy efficiency of pyrolysis technologies is the conversion of pyrolysis reactors into the class of controlled ones. In general, the specificity of the task of controlling the pyrolysis process lies in the need to regulate certain technological parameters of the process (temperature, oxidizer excess ratio, etc.). The control problem is solved depending on the measured or estimated qualities of the feedstock and the desired ratio between the initial pyrolysis products, taking into account the configuration, of the reactor. In the case of using waste of agro-industrial technologies – biomass – as a raw material for pyrolysis, a number of new problems arise. First of all, the chemical composition of the substance is not known exactly. Another problem is that this composition is constantly changing. Such problems significantly complicate the assessment of the qualities of the composition, and, accordingly, complicate the solution of the management problem with high quality indicators. The presence of such complications leads to significant fluctuations in the properties of the obtained products. So, for example, in the system that controls the reactor for pyrolysis of agricultural waste (biomass), which is optimized for the release of volatiles – sieve gas, fluctuations in the chemical composition of raw materials will lead to fluctuations in the composition of synthesis gas, and therefore to fluctuations in its calorific value. The value of the calorific value of gas is used in the calculations of controllers and other components of technological systems for various purposes that use the energy of gas combustion, and fluctuations in this value complicate the design of such systems. So, such a property of synthesis gas obtained from pyrolysis of wastes of technologies of the agro-industrial complex makes its use in subsequent technological links problematic or undesirable. Thus, studies in the direction of constructing control systems for a pyrolysis reactor for the waste pyrolysis of the agro-industrial complex, providing a high and constant value of the heating value of synthesis gas, will increase the energy efficiency of such reactors, and expand their scope of use, and therefore are relevant.

2. The object of research and its technological audit

2.1. The object of research and the scheme of the reactor for pyrolysis of agricultural waste. *The object of research* is the control system of the reactor for pyrolysis of agricultural waste (plant biomass). The subject of research is the stability and the value of the calorific value of synthesis gas formed by pyrolysis of plant biomass. The diagram of the reactor of the pyrolysis reactor of agricultural waste is shown in Fig. 1.

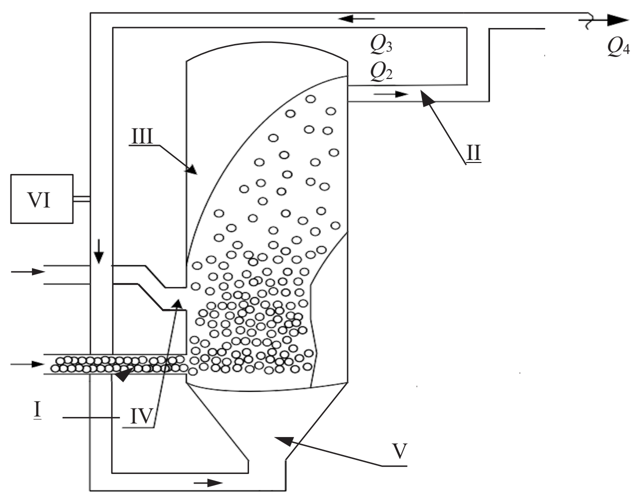

Fig. 1. Diagram of the pyrolysis reactor of the agro-industrial complex waste: I – collector of synthesis gas supplied to reverse; II – synthesis gas collector; III – reactor; IV – oxidizer (air) supply pipe; V – gas inlet as fuel; VI – controller of oxidant flow rate and synthesis gas supplied to reverse; Q_2 – flow rate of the generated synthesis gas; Q_3 – consumption of synthesis gas supplied to reverse; Q_4 – syngas costs to the consumer

Hot synthesis gas enters the common system through collector II at the outlet of the reactor with a flow rate Q_2. This synthesis gas is divided into two streams with flow rates: Q_4 – to the consumer; Q_3 – reverse synthesis gas to inlet V. Inlet V receives gas as a fuel for the reactor for drying and heating the feedstock, the required amount of air is supplied to the collector IV at a flow rate Q_1.

2.2. Characteristics of the control object. In the control object, it is considered, there are the following connections between inputs and outputs:

- air flow rate Q_1 – synthesis gas flow rate Q_2;
- consumption of the feedstock G_1 – consumption of synthesis gas Q_2;
- consumption of recycled synthesis gas Q_3 – consumption of synthesis gas Q_2;
- air flow rate Q_1 – pyrolysis temperature t;
- waste costs of the agro-technological complex G_1 – pyrolysis temperature t;
- consumption of recirculated synthesis gas Q_3 – pyrolysis temperature t;
- air flow rate Q_1 – composition of synthesis gas Q^p.

The parametric model of the control object is shown in Fig. 2.

The pyrolysis reactor of the agro-industrial complex wastes by the inertial link with a delay along the indicated channels.

The dynamic characteristics of the control object are represented by a matrix of transfer functions. The matrix of transfer functions is presented in Table 1.

The time constants and delays for this reactor are as follows: T_1=50 s, T_2=50 s, T_3=70 s, T_4=40 s, τ=5 s.

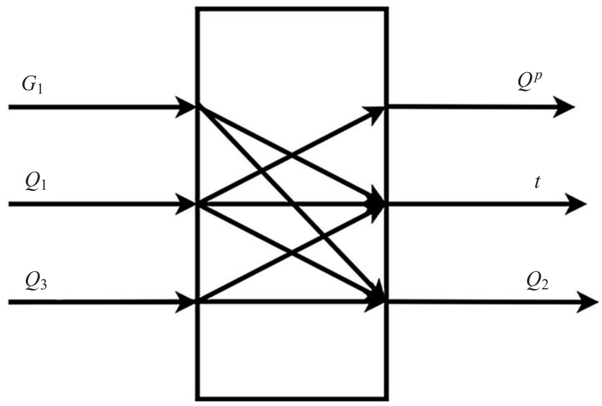

Fig. 2. Parametric model of the pyrolysis reactor of the agro-industrial complex waste: G_1 – expenditure of the agro-technological complex waste; Q_1 – air flow; Q_3 – consumption of recycled synthesis gas; Q^p – composition of synthesis gas; t – pyrolysis temperature; Q_2 – synthesis gas consumption

Table 1

Matrix of transfer functions of the pyrolysis reactor of agricultural waste

System in/out	Air consumption Q_1, mol/s·50	Raw material consumption G_1, mol/s	Recycle gas consumption Q_3, mol/s·70	Calorific value of raw materials Q^P, n
Product gas consumption Q_2, mol/s	$W(s)=\frac{1}{T_1s+1}e^{-\tau}$	$W(s)=\frac{1}{T_2s+1}e^{-\tau}$	$W(s)=\frac{1.83}{T_3s+1}e^{-\tau}$	–
Pyrolysis temperature t, °C	$W(s)=\frac{600}{T_1s+1}e^{-\tau}$	$W(s)=\frac{300}{T_2s+1}e^{-\tau}$	–	–
Calorific value of product gas Q^P, n	$W(s)=\frac{k}{T_1s+1}e^{-\tau}$	–	–	$W(s)=\frac{1}{T_4s+1}e^{-\tau}$

2.3. Control object model. The matrix of transfer functions, which is given in Table 1, represents a ready-made model for conducting research, but such a model itself is not complete. Considering that the subject of the study is the stability and the calorific value of synthesis gas formed by pyrolysis of plant biomass, the presence of only a dynamic characteristic of the behavior of the calorific value is a disadvantage. To eliminate this drawback, it is necessary to supplement the model with an expression that connects the calorific value, gas consumption, and the chemical composition of raw materials. In the study [1] it was shown that the value of the calorific value can be estimated by the following expression:

$$Q_I^d = Q_{I0}^d\left(1-k\left(Q_1-G_0V_0\right)^2\right), \quad (1)$$

where Q_I^d – calorific value of the resulting synthesis gas; Q_{I0}^d – coefficient of the theoretically maximum possible calorific value of the gas depending on the feedstock; V_0 – volume of air required for pyrolysis of 1 mol of raw material – depends on the chemical composition of the raw material; k – coefficient of proportionality, determined analytically or experimentally for each raw material. Since the amount of the oxidizing agent directly depends on the controlled value of the oxidant (air) consumption, and the volume in expression (1) is also directly related to the amount of the oxidizing agent, expression (1) satisfies the requirements of the model. It should also be noted that changes in the composition of agricultural waste also lead to fluctuations in the variable time T_1. In this work, the vibration limits are ±5 s.

2.4. Disadvantages of the technological object. As mentioned above, changes in the chemical composition are due to the unpredictable, and such that it is difficult to analyze, the nature of the waste of agro-industrial technologies. This leads to fluctuations in the calorific value of the resulting synthesis gas. It should be noted that the pyrolysis reactor system is extremely sensitive to such fluctuations in chemical composition. As it is possible to see, the expression $Q_1-G_0V_0$ of equation (1) squared. Thus, even a relatively small change in the composition of the raw material will lead to a mismatch in the value of the amount of oxidant (air), to one that corresponds to the value V_0 will lead to significant changes Q_I^d. The quadratic nature of this part of the expression also indicates that regardless of the direction in which the chemical composition has changed, and therefore the value Q_I^d – the calorific value of the resulting synthesis gas will begin to fall at a high rate. So, the control system of pyrolysis plants, provides a high and stable calorific value of synthesis gas, has, first of all, to compensate for the sensitivity of the system to disturbances in the chemical composition of the feedstock. Another problem of the system is fluctuations in certain time states of the control object. Such fluctuations can negatively affect the quality of control, and determine high requirements for the robustness of the system.

3. The aim and objectives of research

The aim of research is to develop a control system for a pyrolysis reactor that stabilizes the calorific value at the maximum possible value for the current composition of agricultural waste in the pyrolysis reactor. To achieve this aim, it is necessary to solve the following objectives:

1. Choose a control method that best suits the given control problem.
2. Develop a way to compensate for disturbances in the chemical composition of agricultural waste.
3. Integrate disturbance compensation into the system with the selected control method.

4. Research of existing solutions to the problem

To date, the theory of automatic control is known for such methods of constructing controllers as proportional (P), proportional-integral (PI), proportional-differential (PD), proportional-integral-differential (PID) control. Also well studied is state control by placing poles, linear-quadratic programming, etc. Fuzzy PID controllers, controllers based on artificial neural networks, as well as various variations and combinations of the methods described above, are also widely used. However, the specificity of biomass pyrolysis control imposes certain restrictions on the feasibility of using some methods. So, for example, in [2], the quality of control was improved by using a fuzzy PID controller, instead of the classical PID regulation when building a control system for a microwave pyrolysis biomass unit. The improvement was due to the construction of membership functions for the terms of the temperature of the reactor, taking into account its non-linear and non-stationary nature. Thus, a decrease in the activation energy of microwave pyrolysis of corn feed, lignin, cellulose and hemicellulose by about 15.2 %, 17.3 %, 19.9 % and 11.8 %, respectively, was achieved. Other method of taking into account the nonlinearities of the pyrolysis reactor is the use of a predictive model, as shown in [3]. In this work, using experimental data, a fuzzy model of the states of a pyrolysis reactor was constructed, which made it possible to use adaptive control over the state vector. In turn, this made it possible to significantly improve the average deviation of the controlled values in comparison with the classical PI controller. Another direction in the control of pyrolysis reactors is the use of artificial neural networks. So, in [4], the following network is presented with optimization using swarm algorithms. This made it possible to obtain a system with high robustness, and an indicator of control accuracy in all modes above 0.97. However, it should be noted that the model developed in [4] accepts accurately measured components of biomass as input. This nature of the input data requires certain additional computational, technological, and even organizational measures. For example, such events include the organization of measuring the mass fractions of agricultural waste, their weighted averaging when training a model on a reactor with a new configuration.

Separately, it is possible to consider methods of control using classical neural networks. For example, in works [5–7], classical neural networks were developed to solve the control problem. On the one hand, the obtained systems demonstrate extremely high control quality indicators, but on the other hand, to ensure their high performance, it is necessary to conduct extensive experimental studies of pyrolysis of various types and mixtures of plant biomass. Another disadvantage of such systems is their general technical complexity, and among the risks for such systems is the potentially insufficient speed of complex computations by the processor. Also, such disadvantages are inherent in fuzzy neural networks. In order to mitigate such shortcomings in [8], the use of PLDs for the direct implementation of an already trained neural network was proposed. It should be noted that the use of PLDs also significantly increases the cost of both the system itself and its maintenance.

On the contrary, in [9, 10], a model and a method for determining the composition of biomass are presented, the pyrolysis process takes place in the form of a gross formula of the form:

$$C_xH_yO_z. \quad (2)$$

The disadvantage, however, remains the need to develop an integrated computer system.

5. Methods of research

The research was carried out by means of a series of computer simulations of the model described in section 2.2. To simulate the dynamic behavior of the pyrolysis reactor, the Simulink software package was used, in which the model was implemented, in accordance with Table 1. To simulate changes in the biomass composition in the reactor, a disturbance signal was applied to the input of the Q^P model. The FuzzyLogic Toolbox software package was used to develop a fuzzy input-output system (controller). Mutations of the membership functions of the fuzzy controller were obtained by linear regression between the zero points of the terms of the variables of the fuzzy controller and the corresponding values of the deviations of the time constants.

6. Research results

6.1. General control scheme. As part of the research and solving the set tasks, a pyrolysis control scheme was developed, which is shown in Fig. 3.

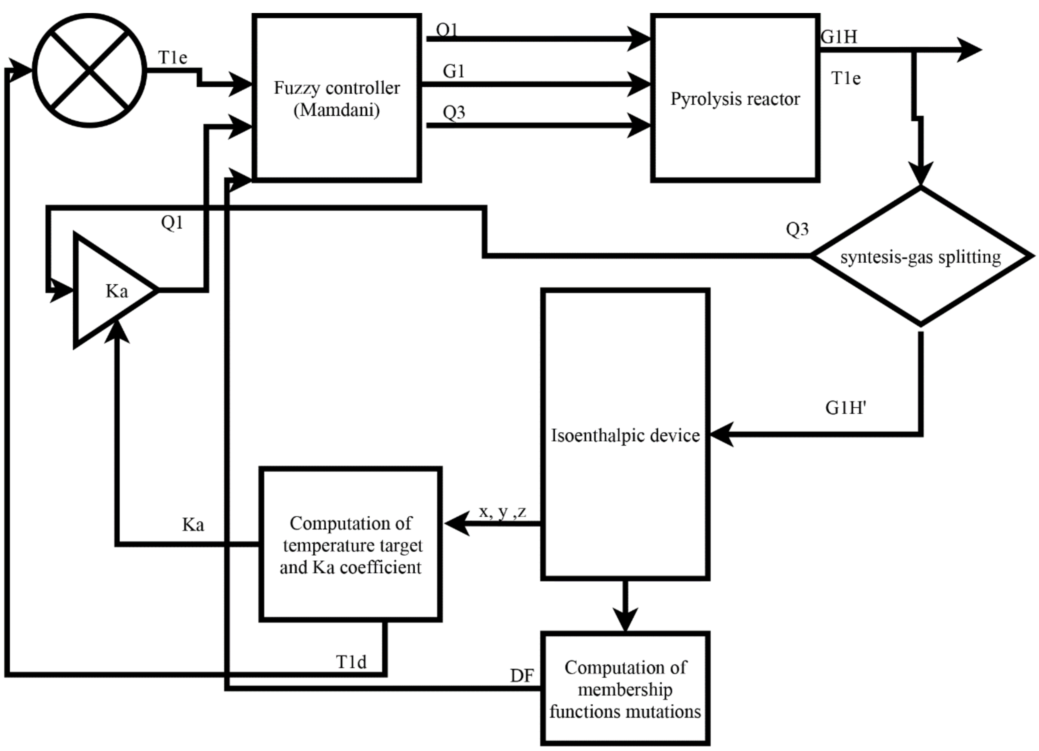

Fig. 3. Diagram of the pyrolysis control system

The diagram in Fig. 3 shows the computational blocks denoting the computation of mutations of membership functions, an isoenthalpic device [9, 10], a fuzzy controller, a multiplier, an adder, a block for computing tasks for a fuzzy controller. Arrows between computing units indicate the direction and type of data flow between logical parts of the software and hardware complex. The fuzzy controller (Mamdani) performs the actual control of the pyrolysis reactor in accordance with the reference influences received from the controller tasks calculation unit. Synthesis gas G1H from the reactor is the outlet of the system. Part of the gas is fed to the inlet of the reactor, and the other part is fed to the isoenthalpic device [9, 10]. The isoenthalpic device calculates the conditional gross formula and outputs the calculated composition in the form of a tuple *x, y, z*, where *x, y, z* are the corresponding coefficients of the conditional formula (2). Using the resulting gross formula, according to the table values, the optimal temperature and oxidizer excess ratio for the highest possible calorific value of synthesis gas are selected. The oxidizer excess ratio is recorded in Ka, and thus, when controlling the consumption of synthesis gas fed to the reverse, the optimal value in the reactor is ensured. The value of the current temperature in the reactor is compared with the optimal one, and thus an error signal is generated, used by the fuzzy controller, thus the control system is finally closed and degenerates into a classical error control system. The input and output variables of the fuzzy controller are weighted, thus the value of all input and output singals fluctuate in the range [–1; 1].

The following fuzzy rules have been developed for the controller:

IF temperature IS low THEN shaft IS go_fast AND gas IS valve_open_strong
IF temperature IS high THEN shaft IS go_slow AND gas IS valve_open_weak
IF alpha IS too_high THEN valve IS open_weak
IF alpha IS too_low THEN valve IS open_strong,

where *temperature, alpha* – input variables; *shaft, valve, gas* – output. *Low, high too_high, too_low, go_fast, go_slow, open_weak open_strong, valve_open_strong valve_open_weak* – corresponding terms. The form of the membership functions of the input and output variables is triangular.

6.2. Mutation of membership functions. In order to compensate for the deviations of the time constants described above in the control object, a convolution was developed that modifies the membership functions of the terms of the variables of the fuzzy controller. Since the type of input variables is triangular functions, they can be described by a vector of tuples of the form:

$$[k_1, k_2, k_3, ...k_n, k_{n+1}, k_{n+2}], \quad (3)$$

where $k_1, k_3, ...k_n, k_{n+2}$ – points of the zeros of the function, and $k_2, ...k_{n+2}$ – vertices of the triangle. Each input variable is assigned a polynomial of the form:

$$a_1 + a_2 + a_{n+2}, \quad (4)$$

where $a_1...a_{n+2}$ – coefficients, are trained by linear regression. The input data for training the coefficients has the value of the deviation of the time constant within [–5; 5].

The initial values are the values of the tuples (3) obtained by manually adjusting the fuzzy controller at the points belonging to the training dataset.

In the course of research, it has been found that it is sufficient to modify only the input variables of the fuzzy controller.

6.3. Simulation results. The simulation was performed by applying a disturbance signal to the parameter corresponding to the change in the chemical composition of the waste of the agro-industrial complex.

Fig. 4 shows the reaction of calorific value of gas synthesis by 20 % stepwise reduction of the parameter corresponding to the chemical composition of the raw material.

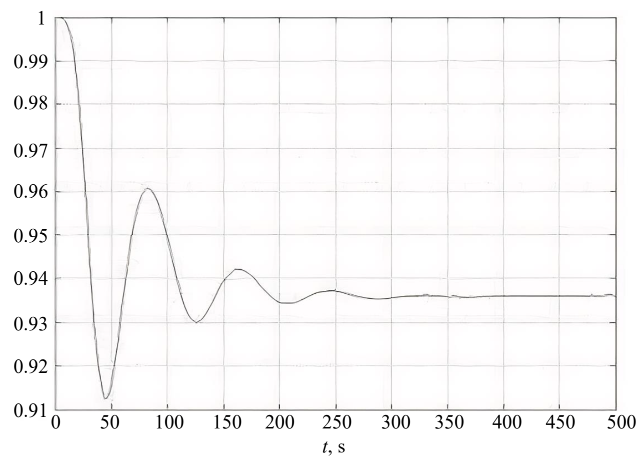

Fig. 4. Reaction of the heating value of synthesis gas by 20 % stepwise decrease in the parameter corresponding to the chemical composition of the feedstock. The ordinate shows the weighted value of the calorific value of synthesis gas, the abscissa shows the time in seconds

As can be seen from Fig. 4, the calorific value of the product-gas perturbing the product-gas flow rate is set at the maximum value, and for perturbing the composition of the raw material, namely, by reducing the calorific value by 20 %, it decreases by 6 %.

The second round of modeling consisted of plotting a deviation on the time constant from the test dataset, and removing the characteristics of the control quality – the amount of overshoot and the control time. The results are listed in Table 2.

Table 2

The values of the deviation of the time constant and obtained in accordance with the characteristics of the quality of control

Time constant deviation/control quality index	–3.9	–1	0	2.7	4.1
Overshoot, %	3.78	3.25	3	2.99	3.5
Regulation time, s	257	255	250	249	256

As it is possible to see from the Table 2, 6 % deviation of the time constant leads to 2.8 % change in the quality of control, with obvious retention of stability.

7. SWOT analysis of research results

Strengths. The strengths of the developed control system are its high robustness, low sensitivity to disturbances in the chemical composition of agricultural waste, which are used as raw materials.

Weaknesses. The weak side of the developed control system is that it requires a source of information from an external relatively fuzzy controller. On the other hand, the device described in [9, 10] requires a minimum, but still a certain amount of produced synthesis gas for its operation. Over a sufficiently long period of time, this will lead to noticeable losses in the amount of synthesis gas produced. Another weakness of the developed control system is that its implementation is convenient only with the use of microprocessor technology.

Opportunities. An additional opportunity for this control system is the acquired possibility of using a pyrolysis reactor in technological processes that are more sensitive to fluctuations in the calorific value of the gas used as fuel.

Threats. The threat to the practical use of the developed control system is that its performance depends on a third-party factor. This factor is the accuracy of the method and the corresponding device described in [9, 10]. Ensuring this accuracy can entail separate engineering challenges and requires additional practical research.

8. Conclusions

1. To construct a control system for pyrolysis installations, a method of mutation of the membership functions of variables of a fuzzy controller is proposed, which consists in transferring the zeros of the terms of the membership functions of the terms of the controller.

2. The resulting control system provides the maximum value of the calorific value of the obtained synthesis gas for the current composition of agricultural waste, pyrolysis, and provides low sensitivity to disturbances in its chemical composition – 6 % fluctuations in response to 20 % disturbances.

3. Protrusion method of compensation of disturbances was integrated into the fuzzy controller to compensate for the deviation of the time variables of the control object arising from changes in the composition of raw materials – the composition of agricultural waste by mutations of the membership functions of the variables of the fuzzy controller. This confirms its high robustness indicators.

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THE IMPROVEMENT OF METHOD FOR THE MULTI-CRITERIA EVALUATION OF THE EFFECTIVENESS OF THE CONTROL OF THE STRUCTURE AND PARAMETERS OF INTERFERENCE PROTECTION OF SPECIAL-PURPOSE RADIO COMMUNICATION SYSTEMS

Military radio communication systems are the basis of special purpose control systems and the object of the enemy's primary influence. Therefore, the issue of increasing the noise immunity of military radio communication systems is important and needs further research. Thus, the object of the research was chosen to be a military radio communication system. Maintaining a given level of noise immunity for military radio systems is one of the key issues in radio resource management, the effective management of which allows the use of the entire suitable frequency range for the transmission (reception) of electromagnetic energy by radio electronic devices. A number of works have been devoted to the ways search for increasing the noise immunity of military radio communication systems. One such way is to develop new (improve existing) approaches for assessing the effectiveness of military radio interference management. This work solves the problem of improving the method of multicriteria management effectiveness evaluation of the structure and parameters of the military radio systems noise protection.

The scientific problem is solved by the devices of multicriteria estimation of the of noise protection level of the military radio communication system, graphic display of the executed and not executed tasks, the aggregation scheme of formation of the integrated estimation of noise protection. The research used scientific methods of analysis and synthesis, also the theory provisions of signal-code structures and the provisions of the complex technical systems theory.

The peculiarity of the proposed improvement of the methodology is the multi-criteria assessment of the noise immunity level of the military radio communication system in the conditions of radio electronic conflict. The proposed technique allows:

– *to evaluate the effectiveness of noise protection management;*

– *to substantiate the optimal configuration of the military radio communication system in solving the problems of noise protection management in the conditions of radio electronic conflict;*

– *to identify the ways to increase noise immunity at the stage of operational management of the military radio communication system in the conditions of electronic conflict.*

The results of the research should be used in assessing the effectiveness of management of noise protection of military radio communication systems and determining the optimal structure and parameters of military radio systems.

Keywords: *military radio communication, multicriteria evaluation, radio electronic conflict, destructive influence, noise protection, radio resource, signal-code constructions.*

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1. Introduction

Military radio communication systems (MRCS) are the basis of special purpose control systems and the primary priority of the enemy [1, 2]. Particular attention should be paid to the fact that the combat MRCS use takes place in conditions of shortage of various resources allocated for the organization of radio communication systems, as well as in the conditions of the use of radio electronic warfare by the enemy. Given all the above, the topical issue is the