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Fuzzy Automatic Control of the Pyrolysis Process for the Municipal Solid Waste of Variable Composition

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Abstract:
This paper is devoted to the issues of the fuzzy automatic control of the pyrolysis process of municipal solid waste (MSW) of variable composition and moisture content. The fuzzy control method that is developed and studied makes it possible to carry out the proper automatic control of a pyrolysis plant with the determination of the optimal ratio of air/MSW for various types of waste and with different moisture content values to ensure high efficiency of the MSW disposal process. The effectiveness study of the proposed fuzzy control method is performed in this paper on a specific example, in particular, when automating the pyrolysis plant for MSW disposal with a reactor volume of 250 liters. The obtained simulation results confirm the high efficiency of the developed method, as well as the feasibility of its use for designing automatic control systems of various pyrolysis plants that operate under conditions of changes in the composition and moisture content of input waste.

Keywords: *Automatic control system, Fuzzy control method, Pyrolysis plant, Municipal solid waste disposal, Variable composition, and moisture content*

1. Introduction

Environmental pollution is one of the most urgent problems of our time, caused by the rapid development of industry and the growth of urbanization in many countries of the world [1, 2]. To date, to solve this problem, there have been proposed quite a lot of different ways to dispose of municipal solid waste, which is generated by the population, in industrial enterprises, trade institutions, and municipal services. The analysis of world experience has shown that the most affordable and cost-effective method of MSW disposal is through various thermal treatments [3]. The roadmap of the European Union for the disposal of municipal waste envisages no more than 10% of municipal waste by volume being buried in landfills by 2035. The rest of the volume would be recycled or incinerated. Spiegel [4] notes that currently only 16% of plastic waste is recycled. The two-stage pyrolysis process with subsequent use of the obtained combustible substances in energy equipment is considered to be an alternative to the incineration of MSW. However, for the successful application of this pyrolysis technology that obtains all its advantages, it is necessary to effectively control the process of waste thermal destruction in automatic mode.

Since modern equipment samples for the implementation of the two-stage pyrolysis technology are quite complicated control plants, then traditional control theory means are insufficient in most cases for adequate implementation of their reliable control [5, 6]. Additional difficulties are imposed when changing the composition of the input waste, as well as its moisture content during the operation of the pyrolysis plant. As some modern studies show, to automate complex thermal power and chemical facilities for increasing the efficiency of their operation and reliability, in many cases, it is necessary to develop new control methods [7-10]. Moreover, advanced research confirms that intelligent control principles can be applied quite effectively to automate complex plants of this type [11-13]. Namely, for the control of non-linear and non-stationary plants, the characteristics of which can be determined only approximately, and for which the parameters can change randomly, the most appropriate is the use of systems based on fuzzy logic [14-16]. The given fuzzy systems make it possible to effectively use expert information and experimental data, implement complex and flexible control and decision-making strategies with high logical transparency and interpretability, and they can also be effectively trained like neural networks based on training samples or objective functions [17-20]. Therefore, it is advisable to carry out the creation of advanced control systems for pyrolysis plants that operate under changing conditions in the composition and moisture content of the input MSW, based on the principles of fuzzy control.

This paper is devoted to the development of the method of fuzzy control for the pyrolysis process of municipal solid waste of variable composition and moisture content. The rest of the paper is organized as follows. The brief literature review of the studied area and the main purpose of this work are presented in section 2. Section 3, in turn, describes in detail the proposed method of fuzzy control of the pyrolysis process. Section 4 is an effectiveness study of the fuzzy control system for a specific pyrolysis plant designed based on the proposed method. Finally, section 5 concludes the work and suggests directions for future research.

2. Related Works

To date, many studies have been conducted that are dedicated to various technologies for waste disposal using pyrolysis, as well as automation of installation and technological complexes for their implementation [11, 21, 22]. In turn, papers [23, 24] present various algorithmic and circuit solutions, as well as developed software and hardware tools that allow automating both separate circuits and entire pyrolysis plants for MSW disposal.

Furthermore, sufficient attention has been paid to the development and research of mathematical and simulation models of various pyrolysis plants and their separate components (reactors, circulation systems, heat exchangers, etc.) [25-28], including the use of fuzzy logic, soft computing and other intelligent techniques [29, 30]. Also, currently, a sufficient number of examples of the successful application of intelligent and other advanced algorithms and devices for the implementation of effective control of certain technological variables of waste utilizing complexes have been presented [31, 32]. In particular, fuzzy self-tuning PID [33], robust [34], model reference adaptive [35], and other types of controllers [36] have been proposed.

These control means make it possible to solve mainly individual automation tasks (stabilization of temperature mode, reactor load level, MSW feed rate), but to significantly increase the efficiency of the MSW disposal process, it is necessary to carry out a comprehensive control of the pyrolysis plant with the provision of optimal values for several indicators. Namely, it is necessary to ensure the optimal ratio of air/MSW and the optimal temperature mode to supply the required flow rate of the output pyrolysis gas to the consumer with the maximum calorific value [37]. This problem becomes much more complicated when the composition and moisture content of the input raw materials changes [38]. The use of any type of extremal controller does not allow determining the optimal air/MSW ratio quite accurately due to large errors in determining the measured parameter when approaching the extremum point [39-41]. Additional difficulties are also imposed due to the possibility of only an approximate determination of the percentage ratio of certain components in the composition of raw materials. Thus, to successfully solve this problem, it is necessary to create a unified method for controlling the pyrolysis process of MSW of variable composition and moisture content based on fuzzy logic.

The main aim of this work is the development and research of the method of fuzzy control for the pyrolysis process of municipal solid waste of variable composition and moisture content.

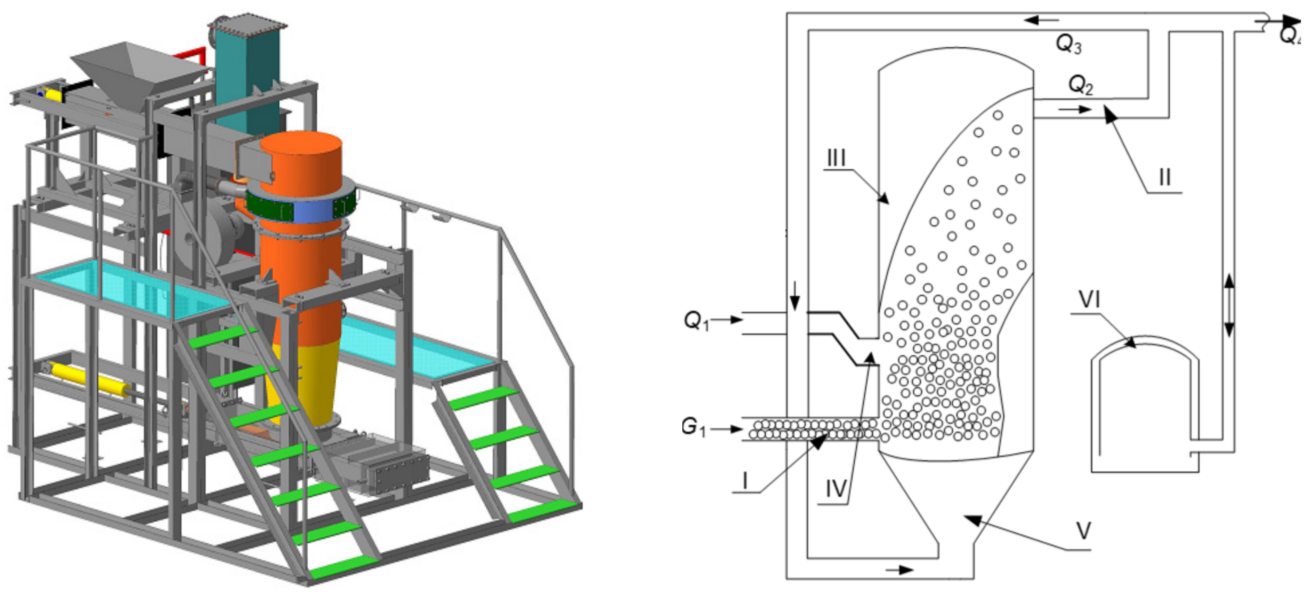
3. Method of Fuzzy Control of the Pyrolysis Process for the MSW of Variable Composition

Before presenting the main aspects of the proposed fuzzy control method, it is advisable to consider a brief description of the operation features, and main control tasks of the generalized pyrolysis plant used for MSW thermal disposal.

3.1. Features and Control Tasks of the Generalized Pyrolysis Plant for MSW Thermal Disposal

Figure 1 shows a 3D model (a) and a schematic diagram (b) of the generalized pyrolysis plant, which is used for the thermal disposal of municipal solid waste.

The pyrolysis plant shown in Fig. 1 operates as follows [37]. The MSW with the flow rate G_1 is supplied to the reactor inlet through collector I. In turn, the required amount of air with the flow rate Q_1 is fed through the collector IV, to carry out the pyrolysis process in a certain mode. The main pyrolysis process takes place in reactor III, as a result of which the py-



(a) (b)

Fig. 1. Generalized pyrolysis plant: (a) 3D model; (b) schematic diagram

rolysis gas is produced with the flow rate Q_2, which exits through collector II at the outlet of the reactor. Furthermore, the generated pyrolysis gas is divided into 2 streams: with flow rate Q_4, which is supplied to the consumer; with flow rate Q_3, which enters through the recirculation line to the inlet V to the reactor for the MSW drying and preheating. In addition, the gasholder VI is installed after the pyrolysis plant, which makes it possible to ensure the presence of a buffer capacity for smoothing the pyrolysis gas flow in the event of sudden changes in its consumption.

Thus, in the stationary operation mode, the presented pyrolysis plant gives the opportunity to completely gasify the organic component of the MSW with a defined composition, while calculating the minimum required amount of air and regulating its supply. For the most efficient processing of waste and the production of pyrolysis gas with the highest calorific value, it is necessary to ensure the supply of such an amount of air that the ratio of air/MSW is optimal. Moreover, the optimal value of this ratio significantly depends on the type of waste being processed. In turn, the considered pyrolysis plant (Fig. 1) can process 4 main types of MSW: 1) hydrocarbon (CH_m); 2) hydrocarbon that contains oxygen (CH_nO_f); 3) hydrocarbon that contains oxygen and nitrogen ($CH_wO_qN_k$) and 4) hydrocarbon that contains active elements that form "sour gases" (CH_aF_x, CH_bCl_y, CH_dS_z) [37]. However, since in practice the exact sorting of waste is rather difficult, any one type of MSW from the above may contain small impurities of MSW of other types. For example, incoming waste may consist of more than 90% of the first type and up to 10% in total of the second, third and fourth types. There may also be mixtures between the main composition of some two types of MSW and small impurities of two other types. For example, such an MSW mixture may consist of more than 45% of the first type, more than 45% of the third type, and up to 10% in total of the second and fourth types. Also, the efficiency of the disposal process is significantly affected by the MSW moisture content for some of their respective types and their mixtures.

To ensure high efficiency of waste disposal, it is necessary to carry out proper automatic control of the pyrolysis process with the determination of the optimal ratio of air/MSW for various ratios of the 4 types of considered MSW that have different moisture content values.

Thus, the following main tasks of automatic control of this pyrolysis plant can be distinguished:

1) control of MSW G_1 and air Q_1 supply to ensure the production of the required amount of pyrolysis gas Q_4 for the consumer;
2) control of the air/MSW ratio α for the MSW of variable composition and moisture content to maximize the calorific value Q_i^r of the obtained pyrolysis gas;
3) stabilization of the required temperature mode of the pyrolysis process;
4) stabilization of the required level value L_G in the gasholder.

To implement the above tasks of multi-connected control for the pyrolysis plant, it is necessary to apply the highly efficient fuzzy control method developed by the authors, which is presented in the next subsection.

3.2. Main Aspects of the Fuzzy Control Method of the Pyrolysis Process for the MSW of Variable Composition

In the stationary operation mode of the pyrolysis plant, the amount of the produced pyrolysis gas Q_4 is defined by the sum of the flow rate values of MSW and air that are fed to the reactor [38]:

$$Q_4 = G_1 + Q_1 \tag{1}$$

Thus, to ensure the desired value of the pyrolysis gas flow Q_4 required by the consumer, it is necessary to control the MSW supply G_1 and air flow Q_1 in such a way that equation (1) is fulfilled.

At the same time, for the optimal disposal of waste of various compositions, a certain ratio between the MSW supply G_1 and air flow Q_1 must also be observed. To do this, it is advisable to introduce a specific coefficient K_α that will determine the consumption of MSW and air, depending on the required amount of pyrolysis gas Q_4 at the outlet. Using the coefficient K_α, the equation (1) takes the form

$$Q_4 = G_1 + Q_1 = Q_4 k_\alpha + Q_4(1 - k_\alpha), \tag{2}$$

where K_α theoretically can take values from 0 to 1.

Thus, according to the proposed method, based on equation (2), the required values of the flow rate of MSW and air are calculated using equations (3) and (4), respectively:

$$G_1 = Q_4 k_\alpha; \tag{3}$$

$$Q_1 = Q_4(1 - k_\alpha). \tag{4}$$

Moreover, the specific coefficient K_α correlates with the value of the air/MSW ratio α as follows

$$k_\alpha = \frac{1}{1+\alpha}. \tag{5}$$

Since for the effective implementation of the pyrolysis process of the organic waste, the ratio α must be in the range from 0.3 to 0 [38], depending on the type of MSW, then the coefficient K_α can vary from 0.769 to 1 following the equation (5).

Thus, to solve the first two tasks of automatic control of the pyrolysis plant, the control signals for the flow of MSW u_{G1} and air u_{Q1} should be calculated using equations (6) and (7), as follows:

$$u_{G1} = u_{Q4} k_\alpha; \tag{6}$$

$$u_{Q1} = u_{Q4}(1 - k_\alpha), \tag{7}$$

where u_{Q4} is the signal corresponding to the set value of the pyrolysis gas flow Q_4 required by the consumer.

In turn, the signal u_{Q4} should be set by the operator of the control system at the upper level. The optimal values of the coefficient K_α should be calculated for MSW of certain compositions and depend on the moisture content, based on the mathematical model of the pyrolysis process developed in the paper [38].

The implementation of such control actions based on equations (6) and (7) will allow effective control of the pyrolysis plant in a stationary mode. In turn, to ensure the efficient automation of the pyrolysis process in transient modes, it is necessary to solve tasks 3 and 4 in addition to the 1st and 2nd control tasks.

To stabilize the temperature mode of the pyrolysis process (task 3), it is necessary to carry out additional control of the air flow in the transient modes.

In turn, to stabilize the required level value L_G in the gasholder (task 4), it is necessary to carry out additional control of the MSW supply to the reactor in the transient modes.

Thus, equations (6) and (7) will take the form:

$$u_{G1} = u_{Q4}k_\alpha + u_{LC} = u_{Q4}k_\alpha + f(\varepsilon_L); \quad (8)$$

$$u_{Q1} = u_{Q4}(1-k_\alpha) + u_{TC} = u_{Q4}(1-k_\alpha) + f(\varepsilon_T), \quad (9)$$

where u_{LC} and u_{TC} are the control signals of the level controller (LC) and the temperature controller (TC) that should stabilize the required level value L_G in the gasholder and the reactor temperature in the transient modes; ε_L is the level control error, which is determined by the deviation of the real level value L_R in the gasholder from the set one L_{GS}, $\varepsilon_L = L_{GS} - L_R$; ε_T is the temperature control error, which is determined by the deviation of the real temperature value T_R in the reactor from the set one T_S, $\varepsilon_T = T_S - T_R$.

The set value of the gasholder level L_{GS} should be set by the operator of the control system at the upper. The temperature value T_S must be set in such a way that it corresponds to the optimal value of the coefficient K_α, depending on the MSW composition and moisture content.

The specific coefficient K_α should be determined in such a way as to provide the maximum possible value of the calorific value Q_i^r of the obtained pyrolysis gas and, at the same time, the highest temperature T in the reactor to intensify the pyrolysis process.

In the stationary mode of the pyrolysis plant operation, the calorific value Q_i^r of the obtained pyrolysis gas and the temperature T of the pyrolysis process, depending on the MSW supply G_1 and air flow Q_1, can be calculated based on expressions (10) and (11), respectively [38]:

$$Q_i^r = Q_{i0}^r \left(1 - k_C \left(\frac{Q_1}{G_1 V_0}\right)^2\right); \quad (10)$$

$$T = k_G G_1 + k_Q Q_1, \quad (11)$$

where Q_{i0}^r is the calorific value of the MSW; V_0 is the volume of air required for the pyrolysis of 1 mol of MSW. k_C, k_G, and k_Q are the proportionality coefficients, which depend on the MSW's specific composition and its moisture content,

$$k_C = f(Q_{W1}, Q_{W2}, Q_{W3}, Q_{W4}, h_W); \quad (12)$$

$$k_G = f(Q_{W1}, Q_{W2}, Q_{W3}, Q_{W4}, h_W); \quad (13)$$

$$k_Q = f(Q_{W1}, Q_{W2}, Q_{W3}, Q_{W4}, h_W), \quad (14)$$

where Q_{W1}, Q_{W2}, Q_{W3}, Q_{W4} are the percentage of the 1st, 2nd, 3rd, and 4th types of MSW in the mixture; h_W is the MSW moisture content wherein,

$$Q_{W1} + Q_{W2} + Q_{W3} + Q_{W4} = 100\%. \quad (15)$$

In turn, the dependencies (12)-(14) are determined using the mathematical model presented in [38]. For example, for the case in which the mixture consists of 100% waste of the 2nd type with 15% moisture content (Q_{W1} = 0%; Q_{W2} = 100%; Q_{W3} = 0%; Q_{W4} = 0%; h_W = 15%), the coefficients take the following values: k_C = 0.27; k_G = 300; k_Q = 570.

As can be seen from equations (10) and (11), the calorific value Q_i^r of the resulting pyrolytic gas increases when decreasing the air flow Q_1 in the pyrolysis process, and the maximum value Q_{i0}^r can be achieved at Q_1 = 0. However, with a decrease in air flow, the temperature T in the reactor also decreases, and with its zero value (Q_1 = 0), there will not be enough energy to carry out the pyrolysis process. Therefore, it is advisable to choose the value of the coefficient K_α in such a way that a compromise is observed between the calorific value Q_i^r and the temperature T of the pyrolysis process. It is advisable to introduce the objective function J (16), the optimal value of which will correspond to the optimal value of the coefficient K_α for a certain composition of the MSW and its moisture content.

$$J = Q_i^r(K_\pm) + 0.3\frac{T(K_\pm)}{T_{max}} \rightarrow \max, \quad (16)$$

where T_{max} is the maximum temperature value corresponding to the maximum values of the flow rate of MSW and air for a certain composition and moisture content.

To find the coefficient K_α corresponding to the optimal value of the objective function (16) for a certain MSW composition and moisture content, it is advisable to use the mathematical model of the pyrolysis process given in the paper [38]. So, for example, for the composition described above (Q_{W2} = 100%; h_W = 15%), the calculated dependence of the objective function J (16) on the coefficient K_α has the form shown in Fig. 2.

As can be seen from the graph in Fig. 2, the optimal value of the coefficient $K_{\alpha opt}$ for this MSW composition and moisture content is equal to 0.81. In turn, the temperature set value T_S that corresponds to the given optimal value of the coefficient K_α is equal to 703 °C.

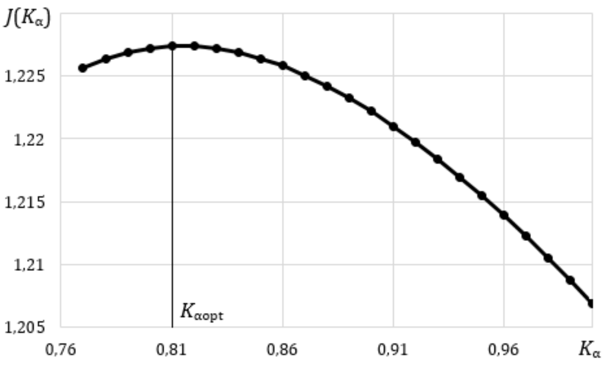


Fig. 2. Dependence of the objective function J on the coefficient Kα (QW2 = 100%; hW = 0.15%)

The mathematical model of the pyrolysis process [38], on which the optimal value of the objective function is calculated, includes the equations of chemical kinetics and requires significant computational resources and time costs to determine the required values of the coefficient K_α. This causes certain difficulties when using it in the real-time mode in the automation system of the pyrolysis plant in the control process. Therefore, it is advisable to perform a preliminary calculation of the optimal values of the coefficient K_α and temperature T_S for the main possible compositions of MSW and to use the given values in the control process. Since the composition of the waste can only be determined approximately, it is advisable to use a fuzzy subsystem to approximate the preliminary calculated data, which will determine the values of the coefficient K_α and temperature T_S at various percentages of waste and moisture content.

Thus, taking into account all of the above, for the implementation of the proposed fuzzy control method, the automatic control system of the pyrolysis plant will have the structure presented in Fig. 3.

In turn, Fig. 3 adopts the following designations: UCL is the upper-level control, SD is the setting device, FSS is the fuzzy subsystem, TS is the temperature sensor, LS is the level sensor, u_{LS} and u_{TS} are signals that correspond to the set values of level L_{GS} and temperature T_S, and u_{LR} and u_{TR} are signals that correspond to the real values of level L_R and temperature T_R, measured by the sensors LS and TS.

To determine the optimal values of the coefficient K_α and set temperature T_S in this system, a fuzzy subsystem of the Takagi-Sugeno type is used, which implements the following dependencies:

$$K_\alpha = f(Q_{W1}, Q_{W2}, Q_{W3}, Q_{W4}, h_W); \quad (17)$$

$$T_S = f(Q_{W1}, Q_{W2}, Q_{W3}, Q_{W4}, h_W). \quad (18)$$

Further, in subsection 3.3, the development of the fuzzy subsystem is presented, which determines the optimal values of the coefficient K_α and temperature T_S of the pyrolysis process, depending on the composition of MSW and moisture content.

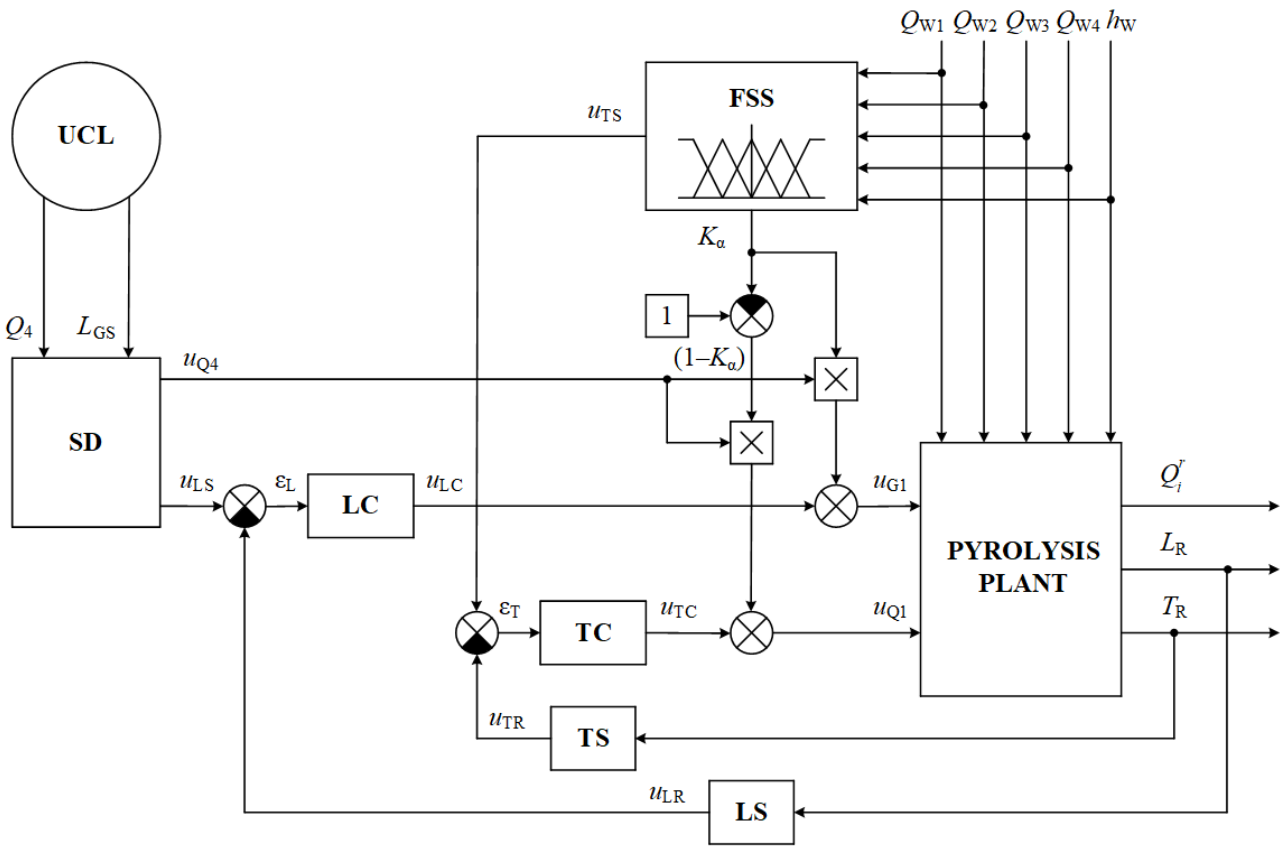


Fig. 3. Structure of the Automatic Control System of the Pyrolysis Plant

3.3. Development of the Fuzzy Subsystem for Determination of the Optimal Parameters of the Pyrolysis Process

The fuzzy subsystem of the Takagi-Sugeno type presented here has 5 input variables (Q_{W1}; Q_{W2}; Q_{W3}; Q_{W4}; h_W) and 2 output variables (K_α; T_S). To fuzzify the first four input variables (Q_{W1}; Q_{W2}; Q_{W3}; Q_{W4}), 3 linguistic terms are used: S – small; A – average; L – large. For the fuzzification of the fifth input variable h_W, 4 terms are used: L – low; A– average; AA– above average; H – high.

In turn, for all linguistic terms, a triangular membership function is chosen. The appearance of the given linguistic terms is shown in Fig. 4.

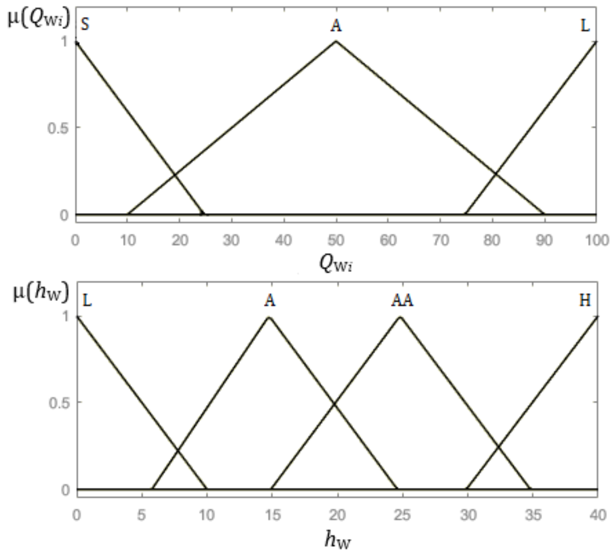


Fig. 4. Appearance of the Linguistic Terms for the FSS Input Variable (i = 1, 2, 3, 4)

Taking into account all possible combinations of the presented linguistic terms, the maximum number of rules of the rule base (RB) can be equal to 324. However, after analyzing all the actual operating conditions of the pyrolysis plant (taking into account condition (15) and the fact that not all types of MSW can have any percentage of moisture) it was determined that the number of rules is 31.

In general form, the r-th rule of this RB is represented by the expression:

$$\text{IF "}Q_{W1} = A_{W1}\text{" AND "}Q_{W2} = A_{W2}\text{" AND "}Q_{W3} = A_{W3}\text{" AND "}Q_{W4} = A_{W4}\text{" AND "}h_W = A_1\text{" THEN "}K_\alpha = K_{\alpha r}\text{" AND "}T_S = T_{Sr}\text{"}, \quad (19)$$

where A_{W1}, A_{W2}, A_{W3}, A_{W4}, and A_1 are the certain linguistic terms of the FSS input variables, and $K_{\alpha r}$ and T_{Sr} are the certain values of the output variables K_α and T_S for the r-th rule (r = 1, 2, ..., 31).

In turn, the developed rule base of the FSS is presented in Table 1.

Table 1. Rule Base of the FSS for Determination of the Optimal Parameters of the Pyrolysis Process

Rule number	Q_{W1}	Q_{W2}	Q_{W3}	Q_{W4}	h_W	K_α	T_S
1	L	S	S	S	L	0.83	1053
2	S	L	S	S	L	0.77	738
3	S	L	S	S	A	0.81	703
4	S	L	S	S	AA	0.85	666
5	S	L	S	S	H	0.88	646
6	S	S	L	S	L	0.92	924
7	S	S	L	S	A	0.93	918
8	S	S	L	S	AA	0.96	906
9	S	S	L	S	H	0.97	904
10	S	S	S	L	L	0.9	728
11	A	A	S	S	L	0.8	900
12	A	A	S	S	A	0.82	880
13	A	A	S	S	AA	0.84	857
14	A	A	S	S	H	0.85	846
15	A	S	A	S	L	0.87	978
16	A	S	A	S	A	0.88	970
17	A	S	A	S	AA	0.88	964
18	A	S	A	S	H	0.89	956
19	A	S	S	A	L	0.86	883
20	S	A	A	S	L	0.85	818
21	S	A	A	S	A	0.88	798
22	S	A	A	S	AA	0.91	777
23	S	A	A	S	H	0.92	770
24	S	A	S	A	L	0.84	720
25	S	A	S	A	A	0.86	707
26	S	A	S	A	AA	0.88	693
27	S	A	S	A	H	0.89	686
28	S	S	A	A	L	0.91	826
29	S	S	A	A	A	0.92	822
30	S	S	A	A	AA	0.93	815
31	S	S	A	A	H	0.94	812

The values of the output variables K_α and T_S for each RB rule (Table 1) are determined in the optimization process using the objective function (16) and the mathematical model of the pyrolysis process given in the paper [38].

Moreover, for this fuzzy subsystem, the "min" operation is used as an aggregation operation, and the discrete gravity center method is used as a defuzzification method.

The effectiveness study of the proposed fuzzy control method is performed in this work on a specific example, in particular, when automating the pyrolysis plant for the MSW of variable composition with a reactor volume of 250 liters.

4. Effectiveness Study of the Fuzzy Control Method of the Pyrolysis Process for the MSW of Variable Composition

The efficiency of the proposed fuzzy control method is studied when automating the pyrolysis plant with the reactor volume of 250 liters in a transient mode.

The filling of the gasholder occurs when there is a difference ΔQ_G between the consumption of consumed pyrolysis gas and the supplied MSW and air. In turn,

$$\Delta Q_G = G_1 + Q_1 - Q_4. \quad (20)$$

To simulate transients of the gasholder filling for the pyrolysis plant with a given volume, it is advisable to use the following transfer function [37]

$$W_{LG}(s) = \frac{L_R(s)}{\Delta Q_G(s)} = \frac{5e^{-3s}}{s(50s+1)}. \quad (21)$$

To simulate transients of temperature T change and calorific value Q_i^r of the pyrolysis process for the plant with a given volume, it is advisable to use the following transfer functions [37]:

$$W_{TR}(s) = \frac{T_R(s)}{T(s)} = \frac{e^{-3s}}{(50s+1)}; \quad (22)$$

$$W_{QR}(s) = \frac{Q_{iR}^r(s)}{Q_i^r(s)} = \frac{e^{-3s}}{(50s+1)}, \quad (23)$$

where T_R and Q_{iR}^r are the real values of temperature and calorific value in the transient mode, and T and Q_i^r are the values of temperature and calorific value in the stationary mode calculated by the equations (11) and (10) respectively.

In this case, PD controllers are used as the level (LC) and temperature (TC) controllers for the pyrolysis plant control system, which have transfer functions:

$$W_{LC}(s) = \frac{u_{LC}(s)}{\varepsilon_L(s)} = k_{PL} + k_{DL}s; \quad (24)$$

$$W_{TC}(s) = \frac{u_{TC}(s)}{\varepsilon_T(s)} = k_{PT} + k_{DT}s, \quad (25)$$

where k_{PL}, k_{DL}, k_{PT} and k_{DT} are the controllers gains that are found in the process of parametric optimization, $k_{PL} = 48.8$; $k_{DL} = 43.4$; $k_{PT} = 0.015$; $k_{DT} = 0.054$.

Further, for the developed control system, based on the proposed method and using the presented transfer functions, the computer simulation of the pyrolysis plant operation for the various compositions, including moisture content, of the MSW is carried out.

The Fig. 5 (a, b) shows the transients graphs when controlling the temperature of the pyrolysis process and the level in the gasholder for the following composition of MSW and moisture content: $Q_{W1} = 44\%$; $Q_{W2} = 47\%$; $Q_{W3} = 4\%$; $Q_{W4} = 5\%$; $h_W = 20\%$.

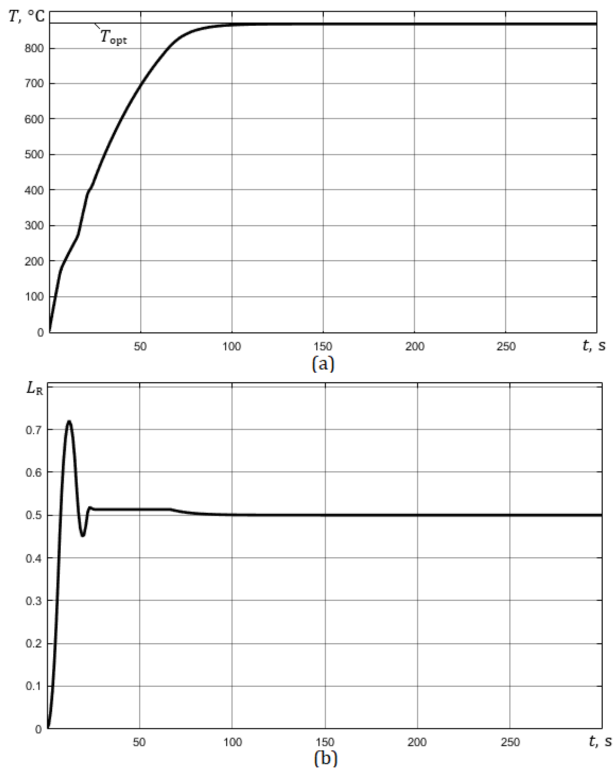


Fig. 5. Transients graphs of controlling: (a) temperature; (b) level in the gasholder ($Q_{W1} = 44\%$; $Q_{W2} = 47\%$; $Q_{W3} = 4\%$; $Q_{W4} = 5\%$; $h_W = 20\%$)

Also, for this composition, the graphs of transients for changing the calorific value Q_i^r of the obtained pyrolysis gas and the objective function (16) are presented in Fig. 6 (a, b). Herewith, using the fuzzy system, the required temperature value T_S was set at 868°C, which is optimal for the given waste composition and moisture content.

The specified value of the gasholder filling level L_{GS} was set in relative units as 0.5 of the maximum level value.

Moreover, in Fig. 6 the calorific value Q_i^r of the obtained pyrolysis gas is given in relative units from the maximum value, corresponding to the given composition of the MSW ($Q_i^r = 0.986$). Also, for the given waste composition and moisture content, the optimal value of the objective function J is 1.224.

Further, the similar graphs of transients were obtained for a completely different composition of MSW and moisture content: $Q_{W1} = 6\%$; $Q_{W2} = 45\%$; $Q_{W3} = 7\%$; $Q_{W4} = 42\%$; $h_W = 2.5\%$. In turn, Fig. 7 (a, b) shows the transients graphs for controlling the temperature T of the pyrolysis process and the level L_R in the gasholder, and the Fig. 8 (a, b) presents the graphs of transients for changing the calorific value Q_i^r of the obtained pyrolysis gas and the objective function (16).

For the given MSW composition and moisture content, the optimal values of the temperature T_S and ob-

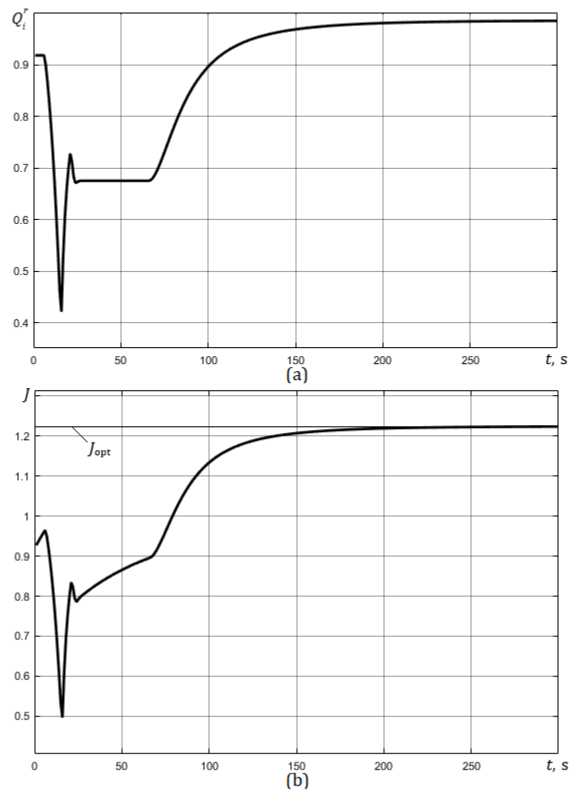


Fig. 6. Transients graphs for changing: (a) calorific value; (b) objective function (16) (Q_{W1} = 44%; Q_{W2} = 47%; Q_{W3} = 4%; Q_{W4} = 5%; h_W = 20%)

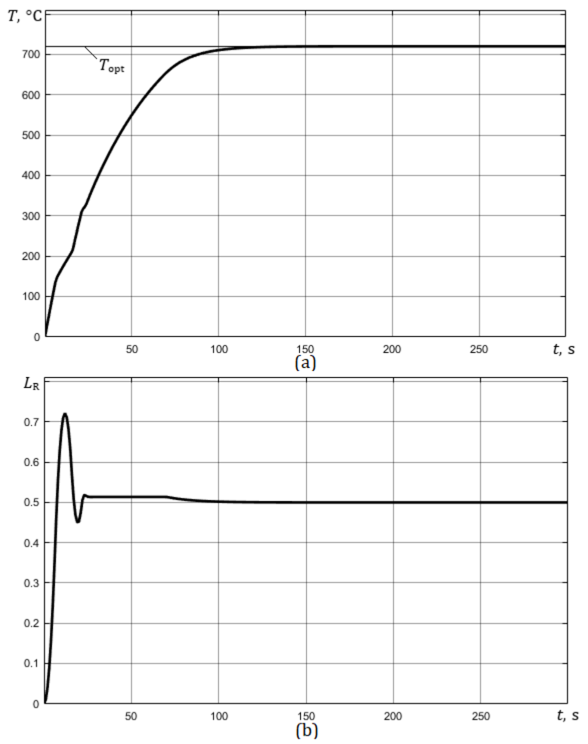


Fig. 7. Transients graphs of controlling: (a) temperature; (b) level in the gasholder (Q_{W1} = 6%; Q_{W2} = 45%; Q_{W3} = 7%; Q_{W4} = 42%; h_W = 2.5%)

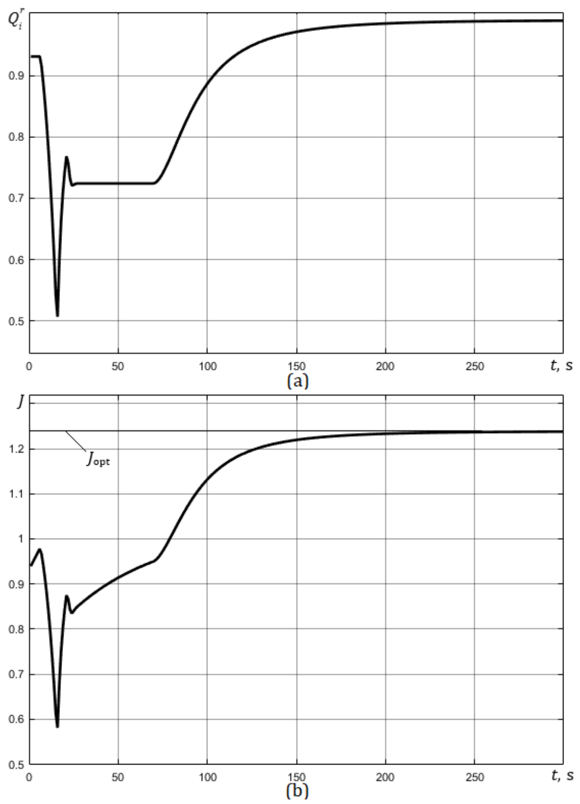


Fig. 8. Transients graphs for changing: (a) calorific value; (b) objective function (16) (Q_{W1} = 6%; Q_{W2} = 45%; Q_{W3} = 7%; Q_{W4} = 42%; h_W = 2.5%)

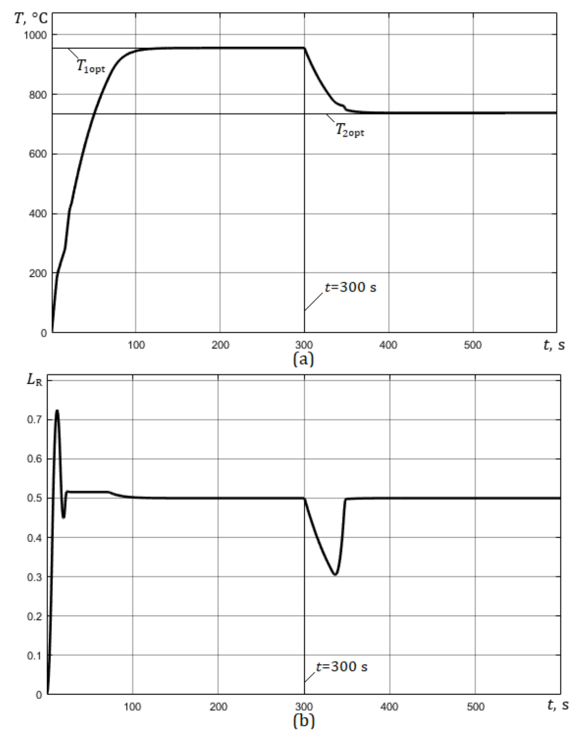


Fig. 9. Transients graphs of controlling: (a) temperature; (b) level in the gasholder (Changing of MSW composition and moisture content during the operation of the plant)

jective function J are 720 °C and 1.238, respectively. Moreover, the calorific value Q_i^r of the obtained pyrolysis gas is equal to 0.99 (Q_i^r = 0.99).

As can be seen from Fig. 5-8, the developed system makes it possible to effectively control the pyrolysis plant under conditions of variable waste composition and moisture content. At the same time, all 4 tasks of automatic control, set in Subsection 3.1, are successfully solved.

The production of the required amount of the pyrolysis gas with the optimal value of the calorific value Q_i^r is ensured due to the effective control of the coefficient K_α, which determines the supply of MSW and the air flow rate. Also, stabilization of the required level value in the gasholder and the optimal temperature value, which corresponds to a certain composition and moisture content of the input waste, is carried out. When controlling these interrelated variables (T and L_G), sufficiently high-quality indicators are provided in particular, zero overshoot and static error with short enough regulating time (t_r = 81 s for the 1st case; t_r = 92 s for the 2nd case) for temperature control of the pyrolysis process. Also, 44% maximum overshoot and zero static error with short enough regulating time (t_r = 69 s for the 1st case; t_r = 73 s for the 2nd case) is required to control the gasholder level.

In the two cases considered the composition of MSW and moisture content were established before the start of the pyrolysis plant and did not change during its operation. For a more detailed study of the developed system and the proposed fuzzy control method, we further consider the case in which the composition and moisture content of the input waste changes during the operation of the plant. Fig. 9 (a, b) shows the transients graphs for controlling the temperature of the pyrolysis process and the level in the gasholder.

In turn, these graphs are obtained when studying the case of changing the input MSW composition during the plant operation.

Also, the graphs of transients of changing the calorific value Q_i^r of the obtained pyrolysis gas and the objective function (16) for this case are presented in Fig. 10 (a, b).

Initially, before the plant was launched, the composition and moisture content of the MSW were as follows: Q_{W1} = 45%; Q_{W2} = 7%; Q_{W3} = 46%; Q_{W4} = 2%; h_W = 35%. For the given composition and moisture content, the optimal values of the temperature T_{1opt} and objective function J_{1opt} are 956 °C and 1.242, respectively.

Then, during the operation of the pyrolysis plant at the moment of time t = 300 s, the composition and moisture content of the waste changed in the following way: Q_{W1} = 5%; Q_{W2} = 90%; Q_{W3} = 3%; Q_{W4} = 2%; h_W = 0.5%. Herewith, the optimal values of the temperature T_{2opt} and objective function J_{2opt} are 738 °C and 1.228, respectively, for the given MSW composition and moisture content.

The obtained results of computer simulation in the form of graphs of transients (Fig. 9, 10) show that the system also allows quite effectively control of the pyrolysis process with changes in the composition and moisture content of the waste during the operation of the plant. Herewith, at the moment of time t = 300 s, when changing the composition and moisture content, the level value deviated by no more than 40% for up to 48 s. At the same time, for the temperature control channel, at the moment of changing the MSW composition and moisture content (t = 300 s), the transient was aperiodic with the regulating time of 48.

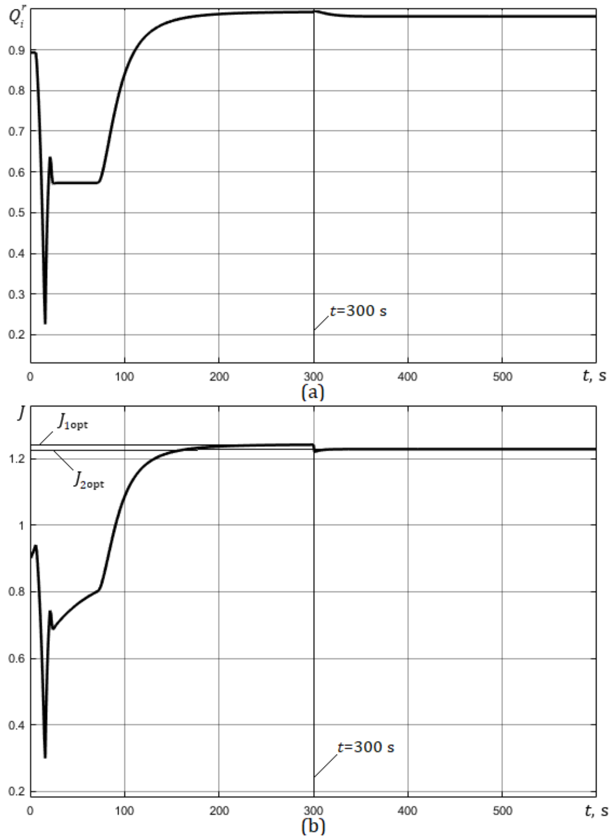


Fig. 10. Transients graphs for changing: (a) calorific value; (b) objective function (16) (Changing of MSW composition and moisture content during the operation of the plant)

Thus, the results obtained confirm the high efficiency of the proposed fuzzy control method and the feasibility of its application for the development of automatic control systems for various pyrolysis plants that operate under conditions of changes in the composition and moisture content of input waste.

5. Conclusion

The development and research for a method of fuzzy control for the pyrolysis process of municipal solid waste of variable composition and moisture content are presented in this paper. The obtained method makes it possible to carry out the proper automatic control of the pyrolysis plant with the determination of the optimal ratio of air/MSW for various types of waste and with different moisture content values to ensure the high efficiency of the MSW disposal process. Moreover, using this method, the tasks of stabilizing such interrelated controlled coordinates as the temperature of the pyrolysis process and the gasholder level in transients are successfully solved.

To evaluate the effectiveness of the proposed method, the development of the fuzzy control system for the pyrolysis plant for the MSW of variable composition with the reactor volume of 250 liters is carried out in this study. In particular, for detailed research, the computer simulation of the pyrolysis plant operation is performed for 4 various compositions and moisture content of the MSW: 1) Q_{W1} = 44%; Q_{W2} = 47%; Q_{W3} = 4%; Q_{W4} = 5%; h_W = 20%; 2) Q_{W1} = 6%; Q_{W2} = 45%; Q_{W3} = 7%; Q_{W4} = 42%; h_W = 2.5%; 3) Q_{W1} = 45%; Q_{W2} = 7%; Q_{W3} = 46%; Q_{W4} = 2%; h_W = 35%; 4) Q_{W1} = 5%; Q_{W2} = 90%; Q_{W3} = 3%; Q_{W4} = 2%; h_W = 0.5%. In addition, the case in which the composition and moisture content of the input waste changed during the operation of the plant is also studied.

The obtained computer simulation results confirm the high efficiency of the developed system and the fuzzy control method, which allows solving all 4 tasks of automatic control (set in Subsection 3.1) of the pyrolysis plant under conditions of variable MSW composition and moisture content. Namely, the production of the required amount of the pyrolysis gas with the optimal value of the calorific value Q_i^r is ensured due to the effective fuzzy control of the coefficient K_α, which determines the flow rate of the MSW and air. The stabilization of the optimal temperature value, which corresponds to a certain composition and moisture content of the input waste and the required level value in the gasholder, is performed with sufficiently high-quality indicators.

In further research, we plan to consider the issues of parametric and structural optimization of the proposed fuzzy subsystem for determining the coefficient K_α, as well as develop fuzzy level and temperature controllers to improve the quality indicators of the pyrolysis plant control.

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