ІНФОРМАТИКА, ОБЧИСЛЮВАЛЬНА ТЕХНІКА ТА АВТОМАТИЗАЦІЯ

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COMPARISON OF EXTREME PYROLYSIS PLANT CONTROL SYSTEMS

Currently, the task of recycling household waste to obtain secondary energy resources is a very urgent task. This problem can be solved by using pyrolysis plants that process organic municipal solid waste into synthesis gas. The synthesis gas is then used as a fuel. The main problem with pyrolysis is the change in the composition of the raw material being processed. Changing the composition of the feedstock affects the composition of the synthesis gas and, consequently, its calorific value. Extreme control systems are used to ensure the production of synthesis gas in a given amount and with a maximum calorific value. The research and implementation of extreme control systems has been carried out for a long time, but no recommendations have been found on the use of such systems at a particular facility. The article considers typical extreme control systems when applied to a pyrolysis plant. Four control schemes are compared with each other. Each of them maintains a given pyrolysis temperature, providing the best conditions for the decomposition of organic compounds of different composition. A single-circuit system without determining the composition of the synthesis gas, a cascade system with correction for the composition of the synthesis gas, and two extreme control systems with direct determination of derivatives and with memory of the extreme are considered. The main advantages and disadvantages of each control system are identified. The advantage of control systems without measuring the calorific value of synthesis gas and cascade ACS is their simple adjustment and the absence of additional technical devices. The main disadvantage is the low quality of maintaining the calorific value of the synthesis gas. The advantage of a derivative-measuring ECS is the absence of control influence in the absence of perturbations in the feedstock composition. The disadvantage is the presence of differentiators that are highly sensitive to noise and interference. The advantage of a controller with extreme memory is a smaller deviation of the regulated parameter. The disadvantage is constant fluctuations in the system as a result of the search algorithm.

Key words: *pyrolysis plant, automatic control, extreme control system, simulation modeling.*

Formulation of the problem. The process of processing household waste into useful products by pyrolysis has attracted a lot of attention in recent years. Pyrolysis is a thermal decomposition process that converts organic materials into valuable products such as bio-coal, bio-oil and synthesis gas. The efficiency and productivity of pyrolysis systems largely depends on the control and regulation of various parameters. One of these is the composition of raw materials [1, 2].

The composition of raw materials means the types and proportions of organic materials used as raw materials in the pyrolysis process. It can vary greatly depending on the desired end products and the availability of biomass resources. Common types of raw materials include wood, agricultural waste, and household waste, including plastics. Each raw material has its own unique chemical composition, which affects the pyrolysis process and the properties of the resulting products.

The composition of raw materials has a significant impact on the properties of the pyrolysis plant as a control object. It affects the thermal behavior of raw materials and chemical reactions occurring during pyrolysis. Understanding these effects is critical to optimizing the pyrolysis process and maximizing the yield of the desired products.

The non-linear properties of the pyrolysis plant mean the non-linear dependence between the composition of raw materials and process variables, such as temperature, residence time and heating rate [4, 5, 6]. These properties are important for optimizing the pyrolysis process and maximizing the yield of the desired products. For example, the heating rate affects the distribution of products and the quality of bio-oil. A higher heating rate can lead to an increase in the yield of bio-oil, but a decrease in its quality.

Analysis of recent research and publications. As a result of the systematization of sources of information about automatic control systems of pyrolysis plants, it was found that the synthesis and research of optimal, particularly extreme control systems has been carried out for a long time. Many types of extreme control systems for non-linear objects have been developed, including pyrolysis installations.

The most complete statement of the principles of extreme regulation is given in the book by Draper and Lee [3]. This book proposes the classification of ECS according to the principle of receiving the input signal of the control device.

In order to solve the problems of low speed of gas production, low quality, low level of automation, complex furnace temperature control, and high energy consumption in the process of biomass gasification, the article [7] presents a system of automatic control of the furnace for the pyrolysis of gas mixture of carbon from biomass based on PLC. The control system implements a neural network and a fuzzy algorithm for processing data during its operation, as well as for adjusting parameters on the PLC online.

The paper [8] presents a fuzzy model of a predictive regulator for small-sized grate furnaces based on a biomass burning model. The resulting local predictive regulators are combined with membership functions to form a global nonlinear fuzzy control structure. The results of the closed circuit modeling of the fuzzy model of the predictive controller, the linear model of the predictive controller, and the PI control algorithm are presented and compared. Based on the results of the proposed fuzzy controller, its application, advantages and disadvantages are discussed.

The purpose of the study [9] is to study the behavior of thermal destruction and kinetics of microwave pyrolysis of biomass, which was improved and verified using a fuzzy PID control algorithm. Compared with the traditional PID control, the use of fuzzy PID control algorithm greatly improved the response speed of the system. Thus, more accurate temperature control using the fuzzy PID algorithm can reduce the experimental error and increase the efficiency of energy use during biomass conversion.

Research [10] is devoted to the development of a control system for the production of biomethanol by the method of thermochemical pyrolysis. The dynamic control system was designed and modeled using *Matlab*. The developed reference control model with a neural controller made it possible to achieve better control in manipulating the reaction temperature for a batch pyrolysis reactor.

The paper [11] considered the synthesis of automatic extremum search systems for a single-channel object, the model of which can be represented as a sequential connection of a nonlinear dynamic component and a static quality function with a well-defined minimum or maximum. The possibility of finding the extremum by the method of localization using the largest derivative of the output variable of the dynamic part of the object in feedback is discussed. Depending on the version of the implementation of such feedback, two main types of extreme systems are distinguished: single-circuit, in which the controller receives data about the gradient of the static characteristic, and two-circuit. In the latest systems, it is proposed to use regulators based on the localization method for preliminary stabilization of processes in the internal circuit containing the dynamic part. In the external circuit, the integral control law is used and the movement to the extremum with the specified dynamic quality is implemented, taking into account the gradient data. The simulation shows the features of the considered extreme systems.

An approach to the design of extremum-seeking control systems based on the localization method is given in [12]. A class of settings that represent a combination of nonlinear input dynamics and static nonlinearity with an extremum is considered. A feature of this work is the proposed approach to the design of a two-circuit system, in which the internal subsystem includes the dynamic part of the installation. The controller for this subsystem is based on the localization method and uses the derivatives of the output variable. This allows you to ensure processes according to the linear desired model. The external circuit contains a stabilized dynamic part ("equivalent" linear dynamics) and a static nonlinear map. Next, it is proposed to organize a gradient proportional regulator in the external circuit of the circuit. The search for the defining influence (extreme value of the non-linear initial static map) occurs with the required dynamic quality. The proposed system design approach is illustrated by a short simulation study.

In [13], an extremum-seeking control algorithm for discrete systems is given, applied to a class of installations that are a sequential combination of linear input dynamics, static nonlinearity with extremum, and linear output dynamics. Using the theory of two-time averaging, we derive a soft sufficient condition under which the output of the installation exponentially converges to $O(\alpha^2)$ around an extreme value, where α is the magnitude of the modulation signal. The sufficient condition is related to the positive materiality of the linear parts of the installation, but only at the modulation frequency. The algorithm is illustrated by a short simulation study.

The analysis of literary sources shows that it is necessary to use multi-loop extreme control systems to control pyrolysis plants. But all studies are devoted to only one system proposed by the researcher. And the comparison is made only with typical regulation laws and there is no comparison between different extreme systems.

Task statement. In this way, the task of comparing typical extreme regulation systems is set with the aim of developing recommendations for use in managing the pyrolysis process of solid household waste.

Outline of the main material of the study. A conventional automatic control system (ACS) cannot solve the optimization problem. This happens because in a conventional ACS, the set value of the regulated parameter is always known and, therefore, it is always known in which direction it is necessary to change the regulating influence in order to eliminate the system error: the difference between the set value and the current value of the regulated parameter.

In contrast to conventional ACSs, the set value of the regulated parameter is not known in extreme control systems (ECS). Therefore, the task of ECS is fundamentally more difficult and consists in automatically finding such a value of the regulating influence that ensures the maximum (minimum) of the regulated value. In contrast to conventional automatic control systems, in ECS, the analysis of the state of the object at this moment in time does not make it possible to determine in which direction the control influence should be changed in order to obtain the desired result.

The task of ECS is to automatically find such a value of the adjustable parameter, about which only the features that distinguish this value from others are known in advance: either it is the maximum or the minimum of all possible values.

Extreme control systems are divided according to the principle used to determine the direction of movement to the extreme into the system:

1. Systems with extremum memory that respond to the difference between the largest output value reached at previous moments of time and the current output value y.

2. Systems responding to the sign or magnitude of the derivative dy/dx or dy/dt .

3. Systems with auxiliary modulation, which determine the direction of movement to the extremum based on the phase shift between the input and output oscillations of the object.

4. Step-type systems responding to the sign of output increments y.

According to the impact of the actuator (ACT) on the object, the ECS can be of continuous or discrete action. In continuous-action systems, during the operation of the regulator, the executive mechanism continuously changes the input x of the object. In discrete ECSs, the executive mechanism changes the input of the object after certain intervals of time. There are ECS s of a mixed type, which combine the properties of different systems of the above classification.

A characteristic feature of an extreme control system is continuous automatic monitoring of the mode parameters of the object that change (according to the value of the input value, which corresponds to the extremum of the output value), in the form of the result of an automatic search.

The magnitude of the system's "wobbling" in the process of searching for the extreme value of the initial value is an indicator of the ECS's operation in a stable mode. In the unstable mode, the time of entry into the zone of the specified yaw serves as an indicator of ECS operation.

Comparison of typical ECS s when controlling a pyrolysis plant

In order to achieve the goal, a simulation model of a pyrolysis plant [14, 15, 16, 17] with a variable structure of the ACS was created, which is shown in Figure 1.

Switches were used to study the ECS, which allow to observe the transient processes of regulation in the following modes:

1 – maintenance of the set pyrolysis temperature without the use of a feedback signal based on the quality of the pyrolysis synthesis gas;

2 – a cascade system for regulating the set temperature of pyrolysis using a proportional signal of the quality of pyrolysis synthesis gas;

3 – a cascade system for regulating the set temperature of pyrolysis using a ECS with measurement of the derivative function of the quality of the pyrolysis synthesis gas from the air consumption for pyrolysis;

4 – ECS with memorization of the extremum of the pyrolysis synthesis gas quality signal;

5 – ECS with measurement of the derivative function of the quality of pyrolysis synthesis gas from air consumption for pyrolysis.

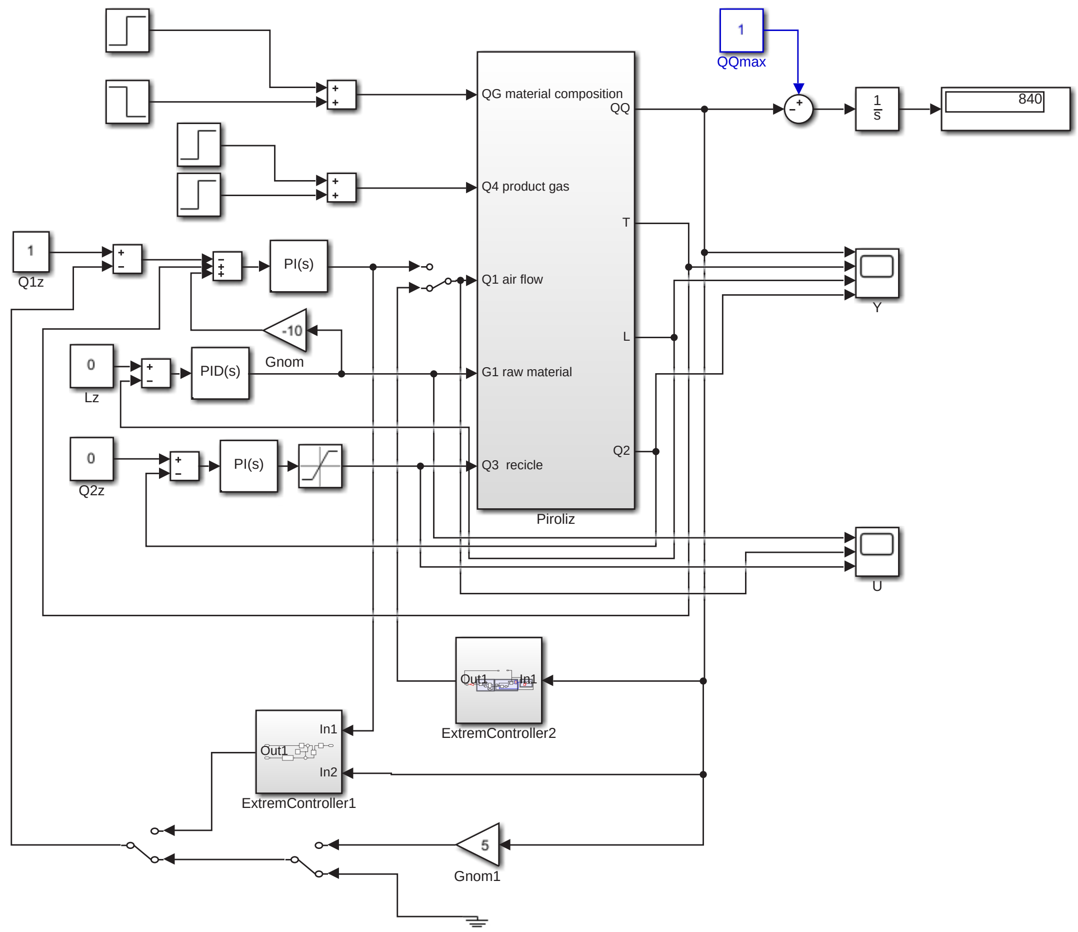

Fig. 1. Scheme of simulation modeling of a pyrolysis plant with a variable structure of the ECS

During the study, the following disturbances were applied to the input of the system:

– a change in the flow of pyrolysis synthesis gas (Q_2, mol/s), which is supplied for further use, i.e. a change in the load of the pyrolysis plant;

– change in the initial composition of the raw materials that are fed to pyrolysis (Q_G).

Since the pyrolysis plant is a non-linear object, during the research, disturbances were applied either alternately or simultaneously. The task of the ECS is to maintain the given load Q_2, while ensuring the maximum value of the quality of the pyrolysis synthesis gas, namely its calorific value Q_L^W. Also one of the important controllable parameters is the pyrolysis temperature T, as its change leads to a change in the composition of the product gas. Maintaining the correct temperature helps to maximize the yield of the target product, which has an economic value.

The simulation results are shown in Figures 2, 3 and 4.

As can be seen from Figure 6, the ECS provides the specified gas flow in any configuration.

$$J = \int_0^{t_p} \left(Q_{max} - Q\right) dt$$

Analysis of transient processes of pyrolysis temperature control shows that traditional systems, both single-circuit (1) and cascade (2), cope with the task of temperature maintenance. Short-term temperature deviations are observed when using ECS with derivative measurement (3). The increase in the deviation of the temperature from the zero value is explained by the change in the composition of the raw materials subject to pyrolysis.

It differs from other ECSs with extremum memory (4). For this system, the pyrolysis temperature deviation is maximum, on average up to 40°C. Also, constant fluctuations occur in the system, which is a characteristic feature of such systems.

The next indicator that was analyzed was the calorific value of synthesis gas, the transient processes of its regulation are shown in Figure 4.

Studies of transient processes, which are shown in the figure, show that the maintenance of the

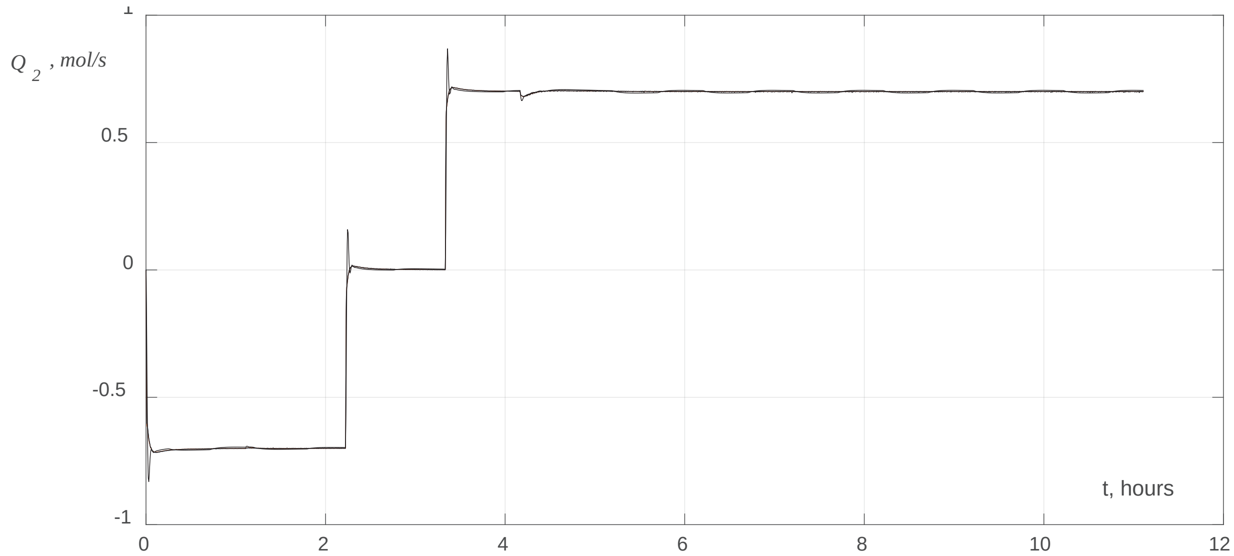

Fig. 2. Change in flow rate of pyrolysis synthesis gas (set load)

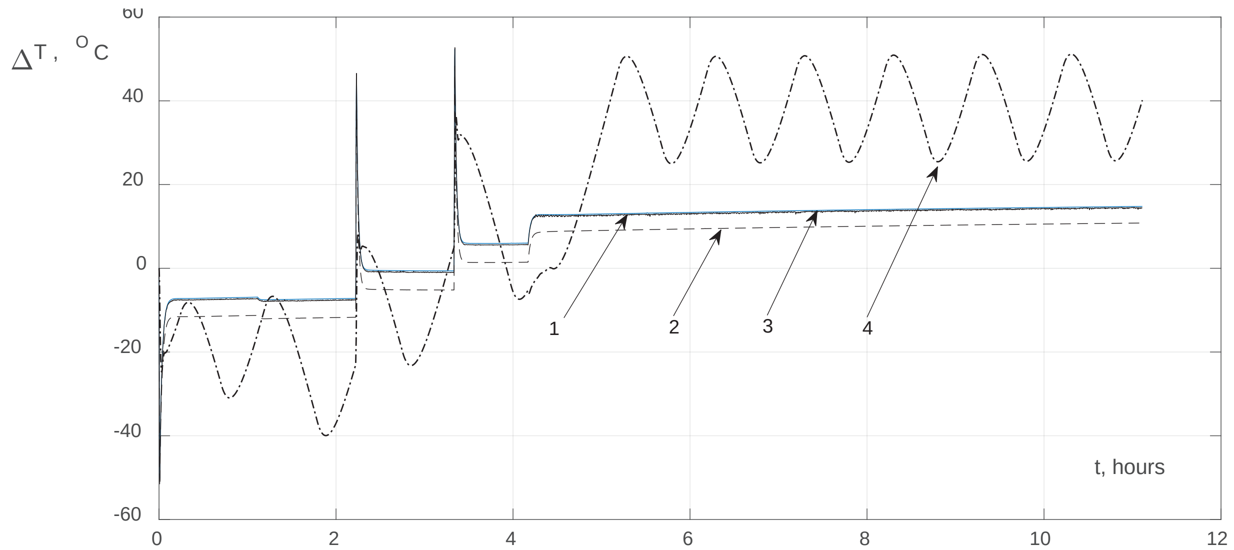

Fig. 3. Change in pyrolysis temperature

highest quality of synthesis gas takes place in the ECS with memory of the extremum (4). At the same time, a clear advantage of this system is observed when the composition of raw materials is changed. Control systems with other algorithms (1, 2, 3) compensate well only for load disturbances. At the same time, short-term deviations of the regulated parameter by rather large values (by 20–25%) are observed in the ECS with the measurement of derivatives (3).

As expected, the single-loop control system (1) shows the worst result of 10% static control error. For other systems, the static error is 7%.

The time of entry into the specified yaw zone for all systems can be considered the same because in this case it is determined by the dynamic properties of the control object.

For a quantitative comparison of control systems, an integral quality indicator was determined:

Table 1

Comparison of integral quality indicator for different systems

System	The value of *J*
Single-circuit (without measuring the calorific value of synthesis gas)	1980
Cascade without ECS	1166
ECS with measurement of derivatives	1976
ECS with extremum memory	243

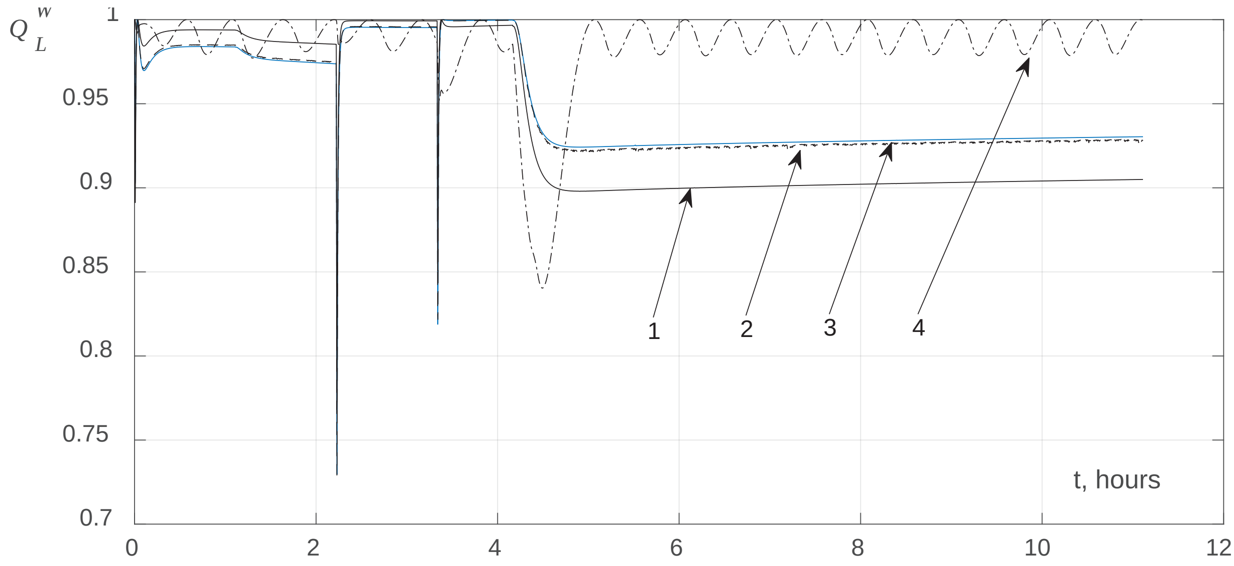

Fig. 4. Deviation of calorific value of synthesis gas

Conclusions. From the comparison of the considered control systems, it is clear that each of the ACSs has its own strengths and weaknesses.

First, it was found that, as an independent, ECS with the measurement of the derivative (5) was unsuitable due to large deviations of the regulated value under any disturbances. Therefore, in the future, this ECS was considered only as part of a cascade regulation system (3) for correcting the task of air consumption, which is supplied to pyrolysis.

The advantage of control systems without measuring the calorific value of synthesis gas and cascade ACS is their ease of setup, the absence of additional technical devices, both measurement and calculation. The main drawback is the low quality of maintaining the calorific value of synthesis gas, namely, a large static control error when the composition of raw materials is disturbed.

The advantage of ECS with measurement of derivatives is the absence of a controlling influence in the absence of disturbances in the composition of the raw materials. The disadvantage is the presence of differentiators that are highly sensitive to noise and interference.

The advantage of the ECS with memory of the extremum is a smaller deviation of the regulated parameter, namely the calorific value of the synthesis gas, a smaller value of the control influence (-0.8 ... 0.8 mol/s versus ± 20 mol/s in peak values and ± 0.7 mol/s in normal mode). The disadvantage is constant fluctuations in the system with a period of approximately 1800 seconds, as a result of the search algorithm.

Finally, it should be noted that the choice between these two extreme control systems depends on the specific requirements and limitations of the pyrolysis plant.

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Беглов Я.І., Тарахтій О.С. ПОРІВНЯННЯ ЕКСТРЕМАЛЬНИХ СИСТЕМ РЕГУЛЮВАННЯ ПІРОЛІЗНОЮ УСТАНОВКОЮ

У теперішній час задача переробка побутових відходів з метою отримання вторинних енергоресурсів є дуже актуальною задачею. Таку задачу можна вирішити за допомогою піролізних установок, які переробляють органічні тверді побутові відходи у синтез-газ. У подальшому синтез-газ використовується як пальне. Основною проблемою при піролізі є зміна складу сировини яка обробляється. Зміна складу сировини впливає на змінення складу синтез-газу і, відповідно, на його теплотворну здатність. Для забезпечення вироблення синтез-газу у заданої кількості та з максимальною теплотворною здатністю використовують системи екстремального регулювання. Дослідження та впровадження систем екстремального регулювання проводиться доволі давно, але не знайдено жодних рекомендацій щодо застосування таких систем на конкретному об'єкті. В статті розглянуто типові системи екстремального регулювання при застосуванні їх у піролізній установці. Між собою порівняні чотири схеми регулювання. Кожна з них підтримує задану температуру піролізу, забезпечуючи найкращі умови для розкладення органічних сполук різного складу. Розглянуті одноконтурна система без визначення складу синтез-газу, каскадна система з корегуванням за складом синтез-газу, та дві екстремальні системи регулювання з безпосереднім визначенням похідних та з запам'ятовуванням екстремуму. Визначені основні переваги та недоліки кожної системи регулювання. Перевагою систем керування без вимірювання теплотворної здатності синтез-газу та каскадної САР є їхня простота налагодження, відсутність додаткових технічних пристроїв. Основний недолік – низька якість підтримання теплотворної здатності синтез-газу. Перевага СЕР з вимірюванням похідних – відсутність керуючого впливу за відсутності збурень складом вихідної сировини. Недолік – наявність диференціаторів, які мають високу чутливість до шумів і перешкод. Перевага СЕР з запам'ятовуванням екстремуму – менше відхилення регульованого параметра. Недолік – постійні коливання в системі в наслідок роботи пошукового алгоритму.

Ключові слова: *піролізна установка, автоматичне регулювання, екстремальна система регулювання, імітаційне моделювання.*