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OPTIMIZATION OF HEAT PRODUCTION PROCESSES IN THE BIOFUEL VORTEX COMBUSTION SYSTEMS

Purpose. Improving the energy efficiency of heat generation processes in vortex combustion systems of uncertified fuel by streamlining the dosing regimes of fuel mixture components using an automated control system.

Methodology. The research process is based on mathematical modeling of the vortex combustion control system of uncertified fuel. A peculiarity of the study is the three-circuit interconnected proportional-integral-differential (PID) control of fuel and air dispensers taking into account their humidity and ambient temperature, as well as the implementation of correction of performance control devices (dispensers) on the basis of these data.

Findings. To determine the rational dosing regimes of the fuel mixture components, experimental studies on energy-efficient heat generation processes in vortex combustion systems of uncertified fuel are carried out. The research results will be used in the process of setting up a technology management system based on fuzzy logic. For the first time, a comprehensive simulation model of the thermal energy generation system with an integrated control system is developed, which allows investigating the parameters of the heat generator by using different types of crushed fuel, as well as testing the system in normal and critical modes. This confirms the need to use artificial intelligence to optimize energy-efficient heat generation processes in vortex combustion systems of uncertified fuel.

Originality. Based on the analysis of the characteristics of humidity, physicochemical and particle size distribution of uncertified solid fuel, temperature and humidity, as well as the percentage of oxygen in the flue gases, the effectiveness of rational dosing of combustion components is substantiated using controlled modes of fuel supply dispensers and pressure blowers to provide the required amount of air in the process of vortex combustion, which can be achieved through the use of intelligent control system.

Practical value. The application of the declared developments will allow solving the economic, energy, ecological and social problems in Ukraine to a large extent at the same time, namely: 1) reduction in natural gas consumption; 2) new jobs; 3) reduction in harmful emissions into the atmosphere. As a result of the study, an automated heat generation system based on vortex combustion of uncertified fuel is developed. There are no analogues of such development, as the main fuel used in the drying process is elevator waste, grain cleaning waste and biofuels, shredded waste.

Keywords: *uncertified fuel, bioremediation, heat generator, energy efficiency, diversification*

Introduction. It is well known that Ukraine takes one of the last places in the heat generation system working on biofuels. According to the State Statistics Service of Ukraine, the share of the natural gas in the total primary energy supply structure was high (28.9 %, 26 million tons), while the share of biomass, biofuels and wastes made only 2.2 % (2 million tons of oil equivalent). At the same time, European countries (including Lithuania, Sweden) have crossed the 50 % mark in this sector.

The new Energy Strategy of Ukraine until 2035 "Security, Energy efficiency, Competitiveness" dated August 18, 2017 No 605-p, which outlines the strategic guidelines for the development of the fuel and energy sector of Ukraine for this period, defines the scope of usage of renewable resources at the level of 25 %, including biomass, biofuels and wastes – 11.5 % [1]. The proposed study implementation is an integral part of the Energy Strategy of Ukraine. This Strategy cannot be implemented without introduction of energy efficient technologies for heat energy production in systems of the vortex combustion of uncertified fuel.

Drying of grain crops is the most energy-intensive seasonal technological process in the agricultural sector. It consumes about 2 billion m3 of natural gas, furnace fuel, diesel fuel, the use of which leads to a sharp increase in production cost, which is one of the main items of the state budged received as the foreign currency from export.

Fact-based research shows that the replacement of traditional fuel with renewable biological wastes of local origin contributes to a significant reduction (by 5–7 times) of gas consumption, creates almost zero burden on the environment, as well as provides additional work places.

Our state agricultural sector annually produces a technically available volume of biowastes in the amount of 25 million tons. Given that 2.5–3.0 tons of these wastes replaces 1000 m^3 of natural gas, the implementation of diversification efforts in primary heat generation systems can make up a value equivalent to the import of 9–10 billion m^3 of gas [2].

Domestic and foreign scientists have studied the modes of operation of distributed heat generation systems in terms of the use of renewable sources and the nature of the distribution of energy from them, developed autonomous heat supply systems and their automation systems and analyzed the energy potential of renewable biofuels [3, 4]. The research highlights the general design features of boilers fired with biofuels and gaseous fuels [5]. Chopped wood, straw, energy plants can be used as a fuel [6]. Foreign experience in the use of biofuels as a source of thermal energy for different consumers is considered [7, 8]. However, in the above installations there is a dissipation of low-potential heat energy, which negatively affects their efficiency factor. Therefore, to solve the problem of creating systems based on heat generators scientific communities more often consider the question of using a decentralized heat supply system, through the use of generators-utilizers fired with solid biofuels.

The issue of using an adjustable electric drive on solid fuel fired boilers is also insufficiently considered. After all, these systems use fuel with unstable parameters of humidity, density, calorific value, which determines the use of neuro fuzzy systems to control the fuel combustion process. Insufficiently studied by foreign and domestic scientists' models or the complete absence of the models for control systems in these technologies based on artificial intelligence [9, 10].

Purpose. Improving the energy efficiency of heat generation processes in systems of vortex combustion of uncertified fuel by streamlining the modes of dosing fuel mixture components using an automated control system

Materials and methods of research. The study provides comprehensive automation of the processes of heat energy production from uncertified fuels based on artificial intelligence systems, controlled by adjustable asynchronous electric drives, specially adapted sensors of: temperature, humidity, speed, pressure levels, etc. Given the undetermined nature of changes in technological parameters, it is foreseen the creation of process models, the development of adaptive control algorithms, software, which in complex will streamline the combustion of uncertified fuel in continuous vortex furnace, coordinate the supply of combustion products to the heat exchanger, to determine the range of air supply for heating to the required inlet temperature. It is necessary to take into account the type of fuel, its calorific value, humidity, particle size distribution for the possibility of controlling the regulated supply with the dosing fan. Adjustable fans of the vortex combustion chamber provide an optimal combustion zone for uncertified fuel, preventing its movement to the upper part of the heat generator, where the exhaust fan is primary mixing combustion products with atmospheric air and the temperature at the top of the furnace is reducing to 650–700 °C, to prevent overheating of the primary chamber of the heat exchanger.

The research is aimed at the development a control system that will ensure the coordination of all the above undetermined parameters of the technological process to optimize energy-efficient heat production modes in systems of vortex combustion of uncertified fuel.

Theoretical research was based on the thermodynamics laws, heat transfer theory and was accompanied by the development of a mathematical model, which was performed using the theory of identification, experimental theory and computer modeling. Mathematical models of thermal processes in systems of heat energy production in systems of vortex combustion of uncertified fuel, taking into account the influence of external factors, have been developed using the theory of thermal processes.

Heat generators based on vortex continuous combustion of uncertified crushed fuel are used in the research (Fig. 1). Fuel supply into them is carried out by means of the screw dispenser with the frequency-regulated asynchronous electric drive and the aspiration fan.

To increase the energy efficiency of heat energy production systems, an automated control system has been developed, which will take into account a number of nondeterministic factors, including that which are influencing its operation: calorific value of a fuel, temperature and humidity of the air supplied to the combustion chamber.

Fig. 1. Exploratory prototype of a 2500 kW heat generator-utilizer with the principle of vortex combustion of uncertified fuel

Studies performed show that to determining of the optimal modes of operation of heat energy production systems that use uncertified fuel, it is necessary to take into account its calorific values. The efficiency of the fuel combustion process ensures the cost efficiency of the heat generator' operation and helps to reduce environmental pollution. The process of vortex combustion requires regulation of air supply, in accordance with the humidity, heat and technical properties of the fuel, in particular, taking into account the excess air coefficient value.

In addition, for efficient combustion of solid fuel, it is necessary to ensure coordinated control of specific modules of electricity technological complex of the heat generator, in particular solving the problem of regulating the speed of electric drives of fans and a screw, which determine the dosing volumes of fuel mixture components and vortex combustion modes.

Simulation modeling theory was used to create computer models and the Matlab/Simulink software environment was used; graphical presentation of modelling results was performed using MS EXCEL and Matlab environment.

The Fig. 2 presents a block diagram of the control system for technological modes of operation of the bioheat generator. It is performed by means of computer simulation modelling in MATLAB environment (Simulink).

A specific feature of this model is the three-circuit interconnected proportional-integral-differential (PID) control of fuel and air with dispensers taking into account their humidity and ambient air temperature, as well as making corrections of productivity control of operating devices (dispensers) basing on these data.

Such an approach enables to reduce the error of regulation in the dynamic of the equipment transient operation modes, especially obvious during the occurrence of stochastic changes in humidity of uncertified fuel.

The PID_T1 controller maintains the set temperature (1000 °C) in the combustion chamber (furnace) until the set temperature of the heat transfer agent T2 (120 °C) is set at the exit from the heat generator, then it switches to the output value limiting mode and, thus, does not affect the control process. The temperature in the furnace is reduced, and the temperature of the heat transfer agent (T2) is maintained constant by introducing of the controller PID_T2 into the control process. The signals from the controllers PID_T1 and PID_T2 are fed to the summing unit, which also receives the correction signals $K=f(W_{bio}, T_{atm})$, functionally related to the humidity of biofuel W_{bio} and the air ambient temperature T_{atm}. The corresponding control signals generated in this way are fed to the control channel of the screw dispenser Out Shn.

To ensure the completeness of the fuel combustion and, at the same time, to increase the energy efficiency of the heat generator in the system, the control of the percentage concentration of oxygen (O_2) in the flue gases by using a λ-probe is foreseen. Information from this sensor is fed through the comparison ele-

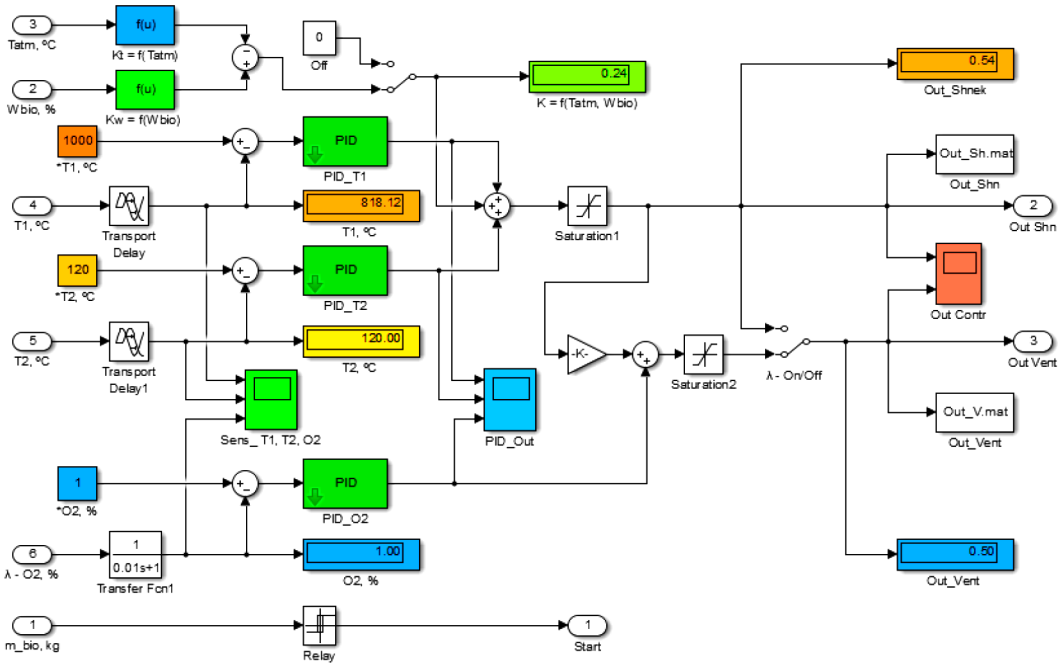

Fig. 2. Heat generator control system with three-circuit interconnected PID control

ment to the entrance of the PID_O2 controller and the corresponding control signals from it through the summing unit are fed to the control channel of the air fan-dispenser Out Vent. The productivity of the dispensers for the fuel mixture components is controlled by the frequency-regulated asynchronous electric drives with energy consumption optimization functions.

The modelling was carried out in the time interval of 0–7200 s (2 hours). The results of the modeling of the system functioning are shown in the Fig. 3.

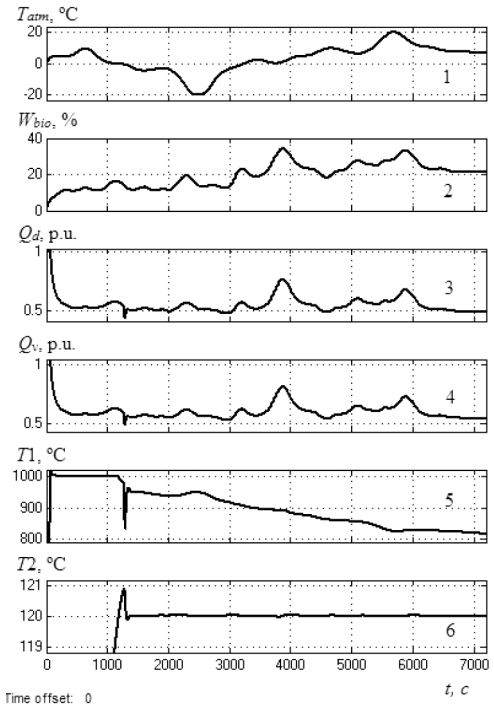

Fig. 3. Time dependences of heat generator operation:

1 – ambient temperature T_{atm}, °C; 2 – relative humidity of biofuel W_{bio},%; 3, 4 – performancei (in relative units) of the biofuel dispenser Q_d, and the fan Q_v, accordingly; 5 – temperature in the furnace of the heat generator T_1, °C; 6 – the temperature of the heat transfer agent at the exit of the heat generator T_2, °C

Graphical dependences 1, 2 illustrate stochastic changes in the operating conditions of the heat generator (ambient temperature and relative humidity of the biofuel) as input destabilizing effects, according to which the correction of control signals of the dispenser Q_d and the fan Q_v (dependences 3, 4), formed by the functional blocks $K_t = f(T_{atm})$ and $K_w = f(W_{bio})$ of the control system is carried out (Fig. 2). The Charts 5 and 6 show the temperature modes in the furnace and at the exit of the heat generator, respectively. The error of regulation of the set output temperature T_2, according to the Chart 6, taking into account the dynamic transient processes, does not exceed 1 %.

Analysis of the modelling results and experimental studies made it possible to obtain the dependence of the heat generator's energy efficiency indicator η on the relative humidity of the biofuel W_{bio} and the excess air coefficient (according to the indicator λ), the graphical interpretation of which is shown in the Fig. 4.

Graphical dependence gives grounds to make appropriate conclusions, which show, that the energy efficiency of a heat generator significantly depends on the humidity of the biofuel and the excess air coefficient during combustion, so these regularities must be taken into account when designing such heat

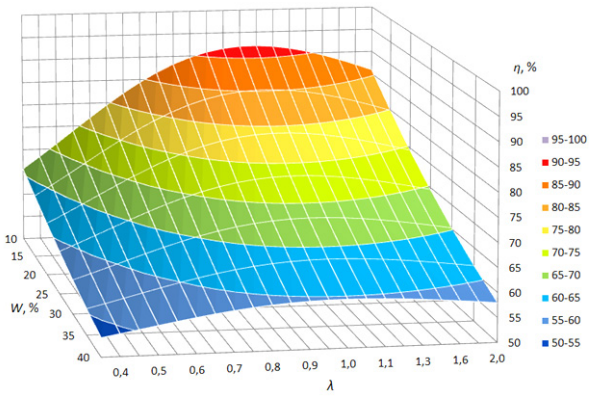

Fig. 4. Dependency of the heat generator's energy efficiency indicator η on the value λ and the relative humidity of the biofuel W

supply systems based on the processes of vortex combustion of uncertified fuel and are intended for operation in various sectors of the economy (economy of Ukraine).

Having considered the problems of drying process control, it is established that to implement energy-efficient modes of the stationary dryer, it is necessary to determine the optimal power of bio-heat generator's electric drives, which could maintain the temperature in the dryer, taking into account the grain moisture and provide the necessary productivity of fans for supplying air into the heat exchanger as well as the boiler's furnace depending on the oxygen content in the flue gases and the screw dispenser of biofuel depending on the temperature of the heat transfer agent at the exit of the heat exchanger.

One of the methods for reduction the energy consumption for ventilation and dosing of raw materials is the introduction of frequency-regulated asynchronous electric drives based on the modern frequency converters with a built-in function of energy consumption optimization.

The control system of the dryer heat generator provides regulated air and biofuel supply depending on the necessary drying temperature. Therefore, the main tasks of the dosing control subsystem for the combustion components in the heat generator are aimed at maintaining of required temperatures at the exit of the heat exchanger T_2 and the temperature in the furnace T_1 at specified levels, oxygen concentration in flue gases – up to 1 %.

Taking into account these parameters and depending on the ratio of humidity and ambient temperature, type of biofuel, its density and humidity, the screw and fan production rate values are determined.

The operating algorithm of the subsystem for regulation of air and biofuel supply to the heat generator is as follows:

1. Processing of information from temperature sensors, fuel level, lambda probe, as well as air and fuel humidity values with a certain discreteness in time.

2. Calculation of the required productivity of the screw dispenser Q_{sd}

$$Q_{sd} = f(w_{fuel}, t_{out}),$$

where w_{fuel} – fuel humidity; t_{out} – required outlet temperature of the heat transfer agent.

$$Q_{sd} = f(t_{amb}, Q'_{sd}),$$

where t_{amb} – ambient air temperature.

3. Calculation of the required productivity of the fan Q_{fan}

$$Q_{fan} = f(w_{air}, Q_{sd}, \lambda),$$

where w_{air} – air humidity; λ – oxygen percentage in the flue gases.

To implement this algorithm, the *Control System* subsystem has been developed, which allows tracking the influence of input parameters on outputs both independently of each other and taking into account their interconnection.

According to the control algorithm, the screw productivity is determined at the first stage, depending on the required outlet temperature of the heat transfer agent, taking into account the influence of fuel humidity.

In our calculations of the screw productivity we rely on the following. Approximately 4 kWh of energy can be produced from 1 kg of standard fuel. Taking into account the heat power of the dryer heat generator is 2500 kW, the maximal screw productivity (kg/s) is as follows

$$Q_{sd,\max} = 2500/4/3600 \approx 0.17.$$

In the range of outlet temperature 60–120 °C and fuel humidity 7–50 % the dependency $Q'_{sd} = f(w_{fuel}, t_{out})$ on $Q_{sd,\max}$ in percentage with approximation reliability grater, than 0.98 can be described with the following equations

for $t_{out} = 120$ °C

$$Q'_{sd} = 0.0001 \cdot w_{fuel}^2 - 0.0019 \cdot w_{fuel} + 0.675;$$

for $t_{out} = 110$ °C

$$Q'_{sd} = 0.00005 \cdot w_{fuel}^2 - 0.0017 \cdot w_{fuel} + 0.5813;$$

for $t_{out} = 100$ °C

$$Q'_{sd} = 0.0004 \cdot w_{fuel}^2 - 0.0016 \cdot w_{fuel} + 0.52;$$

for $t_{out} = 90$ °C

$$Q'_{sd} = 0.0004 \cdot w_{fuel}^2 - 0.0012 \cdot w_{fuel} + 0.4963.$$

For further correction of the screw productivity taking into account the influence of ambient air temperature $Q''_{sd} = f(t_{air}, Q'_{sd})$ the following functional dependence established experimentally was used

$$Q''_{sd}(t) = -0.0057 \cdot t + 0.7507,$$

where Q''_{sd} – screw productivity, *v.u.*; t – ambient air temperature, °C.

The value of the expected results of this study is that a variety of solid fuels: shredded wastes, fuel of biological origin with an annual complete recovery cycle (corn cobs, straw, sunflower husks, industrial wood production wastes, etc.) can be used as a fuel. The transition to alternative, renewable energy sources, accounting for the potential of Ukraine, will significantly reduce our country's dependence on imported energy and provide an opportunity to obtain cheap heat and electricity as well as a partial solution of the environmental problem of household waste utilization.

Studies performed show that in the process of designing heat generators for combustion of solid uncertified fuel it is necessary to take into account its basic physical and chemical properties. The combustion process requires regulation of air supply, in accordance with the humidity and physicochemical properties of raw materials, i.e. taking into account the air excess coefficient value. The optimal value of the air excess coefficient also depends on the combustion technology and fuel type. The efficiency of the fuel combustion process ensures the efficiency of the heat generator operation and helps to protect the environment from pollution.

In the process of conducting research basing on the mathematical and computer models created by us, the results were obtained, which will allow to determine a number of regularities:

- dependences of the movement speed of the working bodies of the dispensers and energy consumption in them in the process of preparation of the fuel mixture in the vortex combustion systems of heat generators, accounting for stochastic changes of uncertified fuel properties;
- establishing of relationships between uncertified fuel properties and the main parameters of the technological process of production heat under the influence of non-deterministic external factors;
- a neuro-fuzzy system for automatic control of vortex combustion processes of uncertified fuel for a solid fuel generator has been developed.

Conclusions.

1. The efficiency of rational dosing of combustion components with the use of regulated operational modes of the fuel supplying screw and fans is substantiated for the first time, which will increase the energy efficiency of solid fuel heat generators, reduce harmful emissions into the atmosphere, ensure safe fuel supply into the combustion chamber.

2. Rational modes of dosing the fuel mixture components are determined, experimental researches of energy-efficient heat generation processes in the systems of the vortex combustion of uncertified fuel were carried out. The research results are used in the process of setting up the technology control system based on the fuzzy logic.

3. A heat generator control system with three-circuit interconnected PID-control was developed for the first time, which allows to provide the necessary parameters of its operation using different types of crushed fuel, as well as to investigate and

check the system operation in normal and critical modes. This confirms the need to use artificial intelligence means to optimize energy-efficient heat production processes in the systems of vortex combustion of uncertified fuel. The produced energy is 5–7 times cheaper than that produced using gas, oil and coal.

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Оптимізація процесів теплогенерації в системах вихрового горіння біопалива

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Мета. Підвищення енергоефективності процесів теплогенерації у системах вихрового горіння несертифікованого палива шляхом раціоналізації режимів дозування компонентів паливної суміші із застосуванням автоматизованої системи керування.

Методика. В основу процесу дослідження покладено математичне моделювання системи керування вихрового горіння несертифікованого палива. Особливістю дослідження є триконтурне взаємозв'язане пропорційно-інтегрально-диференціальне (ПІД) регулювання дозаторами палива й повітря з урахуванням їх вологості та температури оточуючого повітря, а також здійснення на підставі цих даних корекції регулювання продуктивності виконавчих пристроїв (дозаторів).

Результати. Для визначення раціональних режимів дозування компонентів паливної суміші проведені експериментальні дослідження енергоефективних процесів теплогенерації в системах вихрового горіння несертифікованого палива. Результати досліджень використані у процесі налагодження системи керування технологією на базі нечіткої логіки. Уперше розроблена комплексна імітаційна модель системи генерації теплової енергії з інтегрованою системою керування, що дає змогу дослідити параметри теплогенератора при використанні різного виду подрібненого палива, а також перевірити функціонування системи у штатному та критичному режимах. Це підтверджує необхідність застосування засобів штучного інтелекту для оптимізації енергоефективних процесів теплогенерації в системах вихрового горіння несертифікованого палива.

Наукова новизна. На основі аналізу характеристик вологості, фізико-хімічного та гранулометричного складу твердого несертифікованого палива, температури й вологості зовнішнього повітря, а також відсоткового вмісту кисню у димових газах обгрунтована ефективність реалізації раціонального дозування компонентів горіння з використанням регульованих режимів роботи дозаторів подачі палива та нагнітальних вентиляторів для забезпечення необхідної кількості повітря у процесі вихрового горіння, що може бути досягнуто шляхом застосування інтелектуальної системи керування.

Практична значимість. Застосування задекларованих розробок дозволить у значній мірі одночасно вирішити економічні, енергетичні, екологічні й соціальні проблеми в Україні, а саме: 1) зменшення споживання природного газу; 2) нові робочі місця; 3) зменшення шкідливих викидів до атмосфери. У результаті виконання дослідження розроблена автоматизована система теплогенерації, що базується на принципі вихрового горіння несертифікованого палива. Аналогів такої розробки не існує, оскільки основне паливо, що використовується у процесі сушіння – це відходи очистки зерна елеваторного господарства, подрібнені відходи деревини та біопаливо.

Ключові слова: *несертифіковане паливо, біосировина, теплогенератор, енергоефективність, диверсифікація*

Оптимизация процессов теплогенерации в системах вихревого горения биотоплива

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Цель. Повышение энергоэффективности процессов теплогенерации в системах вихревого горения несертифицированного топлива путем рационализации режимов дозирования компонентов топливной смеси с применением автоматизированной системы управления.

Методика. В основу процесса исследования положено математическое моделирование системы управления вихревого горения несертифицированного топлива. Особенностью исследования является трехконтурное взаимосвязанное пропорционально-интегрально-дифференциальное (ПИД) регулирование дозаторами топлива и воздуха с учетом их влажности и температуры окружающего воздуха, а также осуществление на основании этих данных коррекции регулирования производительности исполнительных устройств (дозаторов).

Результаты. Для определения рациональных режимов дозирования компонентов топливной смеси проведены экспериментальные исследования энергоэффективных процессов теплогенерации в системах вихревого горения несертифицированного топлива. Результаты исследований использованы в процессе отладки систе-

мы управления технологией на базе нечеткой логики. Впервые разработана комплексная имитационная модель системы генерации тепловой энергии с интегрированной системой управления, которая позволяет исследовать параметры теплогенератора при использовании различного вида измельченного топлива, а также проверить функционирование системы в штатном и критическом режимах. Это подтверждает необходимость применения средств искусственного интеллекта для оптимизации энергоэффективных процессов теплогенерации в системах вихревого горения несертифицированного топлива.

Научная новизна. На основе анализа характеристик влажности, физико-химического и гранулометрического состава твердого несертифицированного топлива, температуры и влажности наружного воздуха, а также процентного содержания кислорода в дымовых газах обоснована эффективность реализации рационального дозирования компонентов горения с использованием регулируемых режимов работы дозаторов подачи топлива и нагнетательных вентиляторов для обеспечения необходимого количества воздуха в процессе вихревого горения, которое может быть достигнуто путем применения интеллектуальной системы управления.

Практическая значимость. Применение задекларированных разработок позволит в значительной степени одновременно решить экономические, энергетические, экологические и социальные проблемы в Украине, а именно: 1) уменьшение потребления природного газа; 2) новые рабочие места; 3) уменьшение вредных выбросов в атмосферу. В результате выполнения исследования разработана автоматизированная система теплогенерации, которая базируется на принципе вихревого горения несертифицированного топлива. Аналогов такой разработки не существует, поскольку основное топливо, используемое в процессе сушки – это отходы очистки зерна элеватора, измельченные древесные отходы и биотопливо.

Ключевые слова: *несертифицированное топливо, биосырье, теплогенератор, энергоэффективность, диверсификация*

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