POWER SUPPLY TECHNOLOGIES

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ENHANCING THE EFFICIENCY OF ENERGY GENERATION SYSTEMS BASED ON SOLID BIOFUELS: TECHNICAL AND ECONOMIC ASPECTS

Purpose. Comparison of the efficiency of uncertified fuel use in a bioenergy complex of a new type and traditional thermal energy generation systems.

Methodology. The research is based on mathematical modeling of the bioenergy complex. Indicators of efficiency of application of continuous solid-fuel heat generators for drying process were studied using experimental and analytical methods.

Findings. It has been established that for efficient burning of solid fuel, it is necessary to ensure coordinated control of individual modules comprising the electrotechnological complex of the solid-fuel heat generator, in particular, to solve the problem of controlling the rotation frequency of the fan and the dosing screw feeder electric drives, determining the volumes of dosing the combustion components. The principal task of ensuring energy efficiency of the solid-fuel heat generator by identifying regulated biofuel dosage regimes, based on the analysis of oxygen percentage in flue gases, has been solved.

Originality. The efficiency of combustion components rational dosing ensured by implementing regulated modes of a dosing screw feeder and fan operation has been substantiated by the analysis of flue gases composition, which made it possible to increase the energy efficiency of solid-fuel heat generators.

Practical value. The regularities of biofuel components rational dosage are determined in terms of flue gases composition and the physical and chemical properties of the processes in the fuel mixture. The economic expediency and efficiency of drying various materials are considered in the context of biodegradable energy generation systems.

Keywords: *solid-fuel systems bioresources, diversification, heat generator, energy efficiency*

Introduction. One of the ways to improve the situation on the energy market of Ukraine is the replacement of traditional energy sources with renewable sources, primarily with agriculture-based bioenergy [1]. European experience shows that with a properly built energy system, this segment can make up to 40–50 % in the energy balance of our country.

In the whole range of energy-intensive technologies, the use of lump fuel from wood, uncertified fuel (straw, energy willow, elevator waste, sawdust, wood chips) successfully competes with natural gas and electricity. According to the National Academy of Agrarian Sciences of Ukraine, enterprises of the Agricultural-Industrial Complex of Ukraine can become fully self-sufficient in generating heat energy for the rural population using biomass. In conjunction with the production of biofuels for internal combustion engines, this can be a significant contribution to the energy balance of Ukraine and will create thousands of additional jobs [2].

Numerous examples of European partners show a real opportunity for our energy sector to reduce the dependence on hydrocarbon sources in time. It is possible to solve current economic, energy, environmental and social problems in a short time and diversify the generation system by using traditional biomass, various wastes and novel biomass. Today, 7 % of the territory of Ukraine is occupied by unauthorized dumps, while disorderly roadside plantation shocks visitors from other countries. Hence, ignoring this trend will lead to catastrophic environmental consequences [3, 4].

It is well-known that Ukraine ranks last in the field of generating heat from biofuels (below 1 %), while EU countries (Lithuania, Sweden, Croatia) have passed 50 % mark. Factorial studies indicate that the replace-

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ment of traditional fuels with renewable non-certified biofuels of local origin will lead to a revolutionary 5–10-time reduction of the heat energy cost, produce a practically zero load on the environment, and create additional employment opportunities.

The project implementation provides a transition to a promising energy-saving technology, which fully corresponds to world trends – a closed bioresource cycle: the waste becomes a source of thermal energy generation. Also, the technologies of utilization and cogeneration of energy are being developed.

Objectives of the article. The aim of the research is to compare the efficiency of uncertified fuel use in a new type of bioenergy complex and traditional thermal energy generation systems, including those for drying of grain.

Methods. The research is based on the performance indicators of continuous solid-fuel heat generators for drying technology.

The proposed technology is widely used in systems of thermal energy consumption. The use of continuous solid-fuel heat generators in such technology allows the use of uncertified fuel for drying various products (building materials, sand, sawdust, bulk materials, and others).

Having considered the problems of controlling the drying process, we established that for the implementation of energy efficient operating modes of the stationary dryer, it is necessary to determine the optimum power of the heat generator electric drives, which would be able to maintain the temperature in the dryer, taking into account the moisture content of the drying product, and provide the necessary efficiency of the fan to supply air to the boiler and dose screw feeder depending on the oxygen content in the flue gases.

Characteristic features of the current level of drying automation are:

- application of control schemes only for indirect quality indicators (e.g. drying product temperature);
- development of the automation system for a specific type of dryer without the possibility of changing the technological scheme in order to increase productivity.

At present, the dryers control the input and the output temperature of the heat carrier, as well as the temperature of the drying product heating (the main controlled parameter). The adjustment of the drying process according to the parameters is carried out manually by the operator and allows one only to avoid overheating the drying product to the extreme temperature. With this approach, the productivity of the dryer depends on the qualifications of the operator. Thus, there is a topical necessity to develop universal systems and automation schemes using serially produced block elements which allow changing the control scheme not only of the same dryer but also of the whole class of the most common types of dryers, taking into account variants of their possible reconstruction [5].

The automation of control and management of the drying process ensures high efficiency of dryers and preservation of the necessary qualitative parameters of the drying product. As a result of automation, the operation factor of dryers and reliability of their work increase, while the consumption of fuel and electric power is reduced, and so is the number of auxiliary personnel.

Therefore, increase in the efficiency of energy generation systems can be achieved through the complete automation of the process using controllers, regulated asynchronous electric drives, specially adapted sensors measuring temperature, pressure, humidity, speed, level, and others.

Taking into account nondeterministic character of input parameters change, the adapted algorithms of management and software have been worked out, which together give an opportunity to rationalize the process of burning of the uncertificated fuel in the continuous vortex furnace, co-ordinate feeding of combustion products into the heat-exchanger and define the range of cold air supply for its heating up to the consumer-specified input temperature. In this case, it is necessary to take into account the type of fuel, its calorific value, humidity, granulometric composition of the dry product for the regulated control of its feeding fan through the cleaning separator. Simultaneously, the control system must take into account the temperatures of the environment, of the dried material in the combustion chamber, at the output of continuous solid-fuel heat generator, in drying and cooling zones. The regulated fans of the vertical combustion chamber provide the optimum zone of uncertified fuel combustion, preventing it from moving to the upper part of the heat generator, where, with the help of the exhaust fan, the primary mixing of combustion products with atmospheric air occurs at the temperature of 650–700 °C.

The proposed technology involves using continuous solid-fuel heat generator and is based on vortex continuous combustion. The fuel is supplied with the help of a regulated asynchronous electric drive, which makes it possible to fully automate the operation modes of the complex. In real time, the process controller supports the parameters of combustion and the supply of hot air to the consumer [6].

Let us consider drying technology with a continuous solid-fuel heat generator using drying of grain as an example.

Grain-drying is the most energy intensive seasonal technological process in the agricultural industrial complex of Ukraine. About 2 billion m^3 of natural gas, stove fuel and diesel fuel are consumed for this purpose, which results in a sharp increase in the price of products, the main sources of currency earnings in the state budget [7].

The technological process identifies the following interdependencies and conditions:

1) the process of grain drying occurs in a flow at variable ambient temperatures;

2) uncertified waste has unstable (random) physical and mechanical parameters (humidity, temperature, granulometric composition, calorific values, and others);

3) cereals come with different temperature and humidity, which affects the temperature of the drying agent and the drying time;

4) cereals dry at different temperatures of the drying agent;

5) grain loading into the drying machine is related to a continuous drying process (Fig. 1).

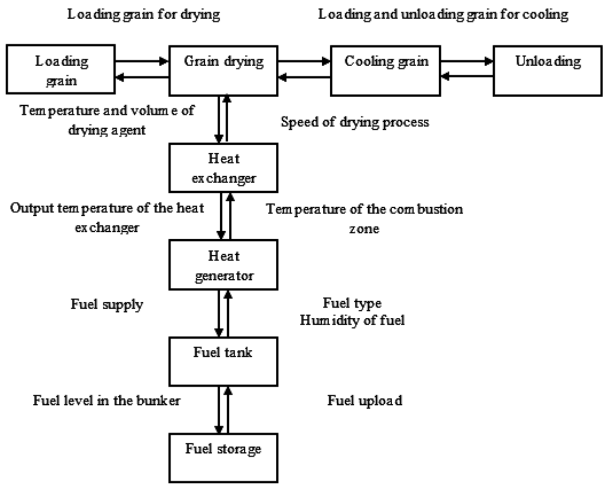

Fig. 1. Structural diagram of the drying complex

For efficient combustion of fuels, it is necessary to ensure the coordinated management of individual modules of bio heat generator electrotechnological complex. In particular, it is important to solve the task of controlling the frequency of the fan and screw electric drives rotation, because these devices determine the volumes of the combustion components dosage [1].

Therefore, the topical task is to provide certain controlled fuel dosing modes based on the analysis of the percentage composition of oxygen in flue gases.

For this purpose, a simulation model of the technological process was created (Fig. 2). This model allows reproducing the dynamics of changes in the main parameters of the technological process and takes into account the above interdependences and conditions. Since the processes occurring in the system of heat generation are non-deterministic and unclearly defined, the tool of hybrid networks is used for implementation of some simulation model modules.

Matlab's Simulink environment toolkit is selected for the development of simulation models. The simulation model of the drying machine and solid fuel boiler with integrated control system contains several subsystems, executed by the means of the standard library Sim Power System, Sim Scape, and Thermal libraries.

The structure of the integrated *Biokotel* model (Fig. 2) comprises the following modules:

1. Control system module – *Control System.*

2. Boiler simulation model – *Biokotel* (*Q_vent* – fan combustion efficiency, *Q_bio* – screw feeder efficiency, *W_bio, %* – fuel humidity, *T_atm* – air temperature, *w_atm, %* – air humidity).

3. Subsystems of fans – *Vent_1* and *Vent*

4. Models of asynchronous motors *AIR56A4 (0,55kW)* and *AIR56A4 (0,25kW)*.

5. Subsystems of frequency converters *-3f-PWM1* and *-3f-PWM2.*

6. Dosing screw feeder model – *Bunker_Shnek*.

In the simulation model, according to the algorithm, combustion efficiency (*Q_vent*) of the fan which feeds air into the combustion chamber and the screw feeder efficiency (*Q_bio*) are calculated by the system, depending on the fuel humidity (*W_bio, %*), the air temperature (*T_atm,* °C), and the air humidity (*w_atm, %*). These efficiency indicators should provide the required temperature in the combustion chamber (*T1,* °C) and the temperature of the heat carrier (*T2,* °C). At the same time, the system must also support, according to the proposed method, the required percentage of oxygen in flue gases [2].

The developed model makes it possible to investigate the parameters of the heat generator when uncertified fuel is used, as well as check the operation of the system under normal and critical conditions.

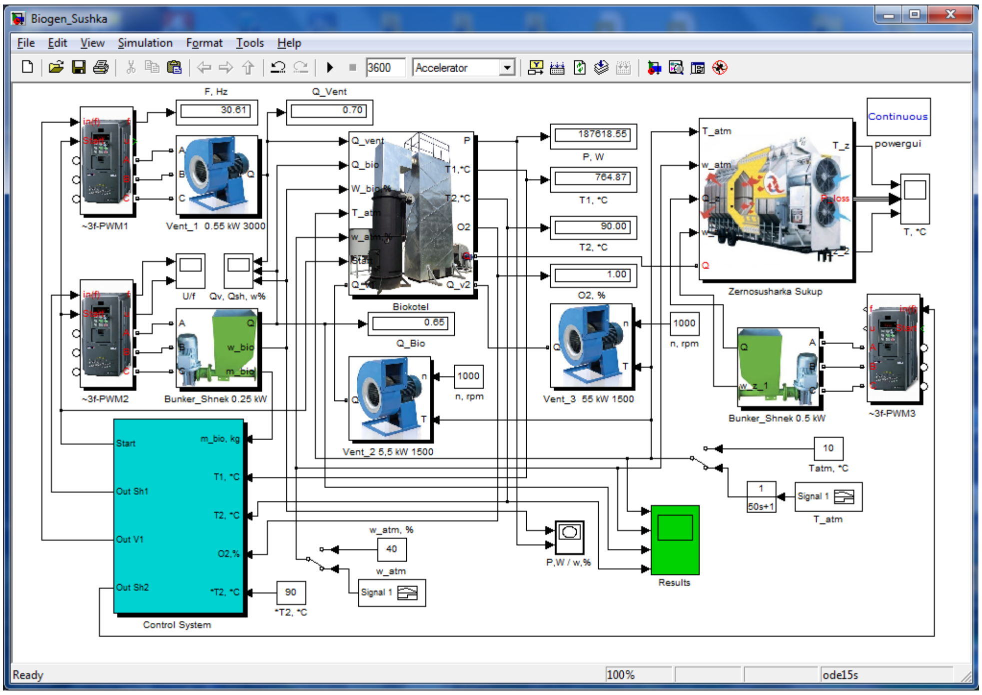

Fig. 2. Simulation model of grain drying complex

Frequency controlled electric drives of the fan and dosing screw feeder (*-3f-PWM1* and *-3f-PWM2)* provide a smooth adjustment of their working members rotation frequency by changing the frequency of the supply current of asynchronous motors within the range of 5–50 Hz.

The simulation process reproduces the operation of the boiler, the initial characteristic of which is provision of the necessary temperature for drying the grain.

Designs of modern solid-fuel heat generators include heat exchangers, and therefore the drying agent is environmentally friendly, which is important for the quality of dried grain.

The final cost of grain drying (P_{drying}) consists of the cost of fuel (P_{fuel}), electricity (P_{elect}), its transportation (P_{trans}), storage (P_{stor}) and the salaries of operators (P_{sal})

$$P_{drying} = P_{fuel} + P_{elect.} + P_{trans} + P_{stor.} + P_{sal}. \qquad (1)$$

The fuel cost component (P_{fuel}) essentially depends on the type of fuel. Diesel, propane-butane, natural gas are the most commonly used types of fuel in elevators for drying grains.

Let us consider the possibility of using pellets and grain wastes to reduce operation costs of drying. Compare the costs of fuel (Table 1). The table shows the market value of each fuel, the efficiency of boilers, the calorific value and fuel consumption at humidity reduced by 1 % for 1 ton of grain and the cost of fuel in UAH at humidity reduced by 1 % for 1 ton of grain.

From this table and Fig. 3, it can be seen that despite the lower efficiency of the boiler and the increase in fuel consumption, the cost of pellets and uncertified fuels (grain cleaning waste) is significantly lower. Thus, the total cost of grain drying will be reduced due to the cheap component of the P_{fuel}. And the use of regulated electric drives will reduce the consumption of electric power P_{elec}.

Considering the possibility of using a vortex solid-fuel heat generator as an object of rational investment (project), it is necessary to calculate the economic efficiency of its application and several indicators that characterize its expediency [8].

For example, the proposed solid-fuel heat generator can be used on elevators for drying grain, heating residential buildings, providing temperature regimes for various objects [1], which will enable to:

- abandon imported fuel (natural gas, coal) completely;
- reduce the burden on the environment;
- increase the competitiveness of Ukrainian enterprises;
- improve the investment attractiveness of Ukraine;
- create additional thousands of jobs.

To calculate the expediency of using a vortex solid-fuel heat generator in the case of using borrowed funds, the following definitions and mathematical tools may be introduced [9]: P – the amount of cash income from the economic activity of the investment object after putting it into operation; B_u – the amount of investment required for commissioning (investment costs); B_e – the amount of current expenses of the operating object, required for the production of goods or services, which produces the created object (operating costs); A_t – the size of the accrued depreciation of assets created at the expense of investments; T – the number of years of the investment project lifetime; t – index of each year of the investment object operation.

Net Present Value of the project (NPV)

$$NPV = \sum_{t=1}^{T} \frac{P_t - B_{ut} - B_{et}}{\left(1+r\right)^t}. \qquad (2)$$

The payback period of the project (T_k) is equal to the t ($T_k = t$), at which the following equality is true

$$B_u = \sum_{t=1}^{T_k} \frac{P_t - B_{et}}{\left(1+r\right)^t}. \qquad (3)$$

Ratio of Income and Expense (K)

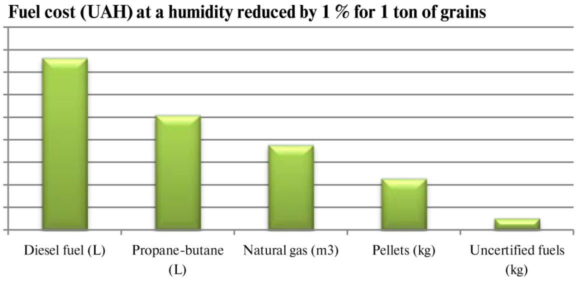

Fig. 3. Fuel cost (UAH) at humidity reduced by 1 % for 1 ton of cereals

Table 1

Comparison of costs for different types of fuel for drying cereals

№	Title	Diesel fuel (L)	Propane-butane (L)	Natural gas (m^3)	Pellets (kg)	Uncertified fuels (kg)
1	Heat generation (kW)	10.4	7.25	8.3	4	2.8
2	Boiler efficiency	0.89	0.92	0.92	0.85	0.85
3	Energy cost	25	12	10.2	2.8	0.5
4	Fuel consumption at humidity reduced by 1 % for 1 ton of grains	1.53	2.14	1.87	4.13	5.16
5	Fuel cost (UAH) at humidity reduced by 1 % for 1 ton of grains	38.31	25.67	19.06	11.56	2.58

$$K=\frac{\sum_{t=1}^{T}\frac{P_t}{(1+r)^t}}{\sum_{t=1}^{T}\frac{(B_{ut}+B_{et})}{(1+r)^t}}. \qquad (4)$$

Profitability ratio (q)

$$q=\frac{\sum_{t=1}^{T}\frac{P_t-B_{et}}{(1+r)^t}}{\sum_{t=1}^{T}\frac{B_{ut}}{(1+r)^t}}. \qquad (5)$$

Fund profitability of the project (f)

$$f=\frac{\sum_{t=1}^{T}\frac{(P_t-B_{et})}{T}}{\sum_{t=1}^{T}\frac{(B_{ut}-A_t)}{T}}. \qquad (6)$$

Internal rate of return (IRR)

$$IRR=NPV=\sum_{t=1}^{T}\frac{P_t-B_{ut}-B_{et}}{\left(1+r\right)^t}=0. \qquad (7)$$

The calculations were based on the output data presented in Table 2.

The calculation of the cost estimates for the drying complex modernization project are presented in Table 3.

Table 2

Output data for estimating the value of the drying complex modernization project for 2017 (SPA “Energy-saving Technologies”, Ternopil region)

№	Title	Unit	The value of the indicator as of 2017
1.	The amount of dried grain	ton/%	91 000
2.	The cost of drying grain services	UAH per ton/%	54
3.	Cost of drying on biofuel	UAH per ton/%	20.64
4.	Investment costs	UAH	5 000 000
	Depreciation costs	UAH	120 000
5.	Discount rate	%	20
6.	Index (serial number) of each year of the object operation	Absolute value	from 1 and beyond

Table 3

Estimation of the cost of the drying complex modernization project (SPA “Energy-saving technologies”, Ternopil region)

№	Title	Formulas for calculation	The result of the calculation
1.	Net Present Value of the project (NPV)	$NPV=\sum_{t=1}^{T}\frac{P_t-B_{ut}-B_{et}}{\left(1+r\right)^t}$	809.3 thousand UAH
2.	The payback period of the project (T_k)	($T_k = t$), for which equality is fulfilled $B_u=\sum_{t=1}^{T_k}\frac{P_t-B_{et}}{\left(1+r\right)^t}$	2 years
3.	The ratio of income and expenses (K)	$K=\frac{\sum_{t=1}^{T}\frac{P_t}{(1+r)^t}}{\sum_{t=1}^{T}\frac{(B_{ut}+B_{et})}{(1+r)^t}}$	1.4
4.	Profitability ratio (q)	$q=\frac{\sum_{t=1}^{T}\frac{P_t-B_{et}}{(1+\mathrm{r})^t}}{\sum_{t=1}^{T}\frac{B_{ut}}{(1+r)^t}}$	1.8
5.	Internal Rate of Return (IRR)	$IRR=NPV=\sum_{t=1}^{T}\frac{\left(P_t-B_{ut}-B_{et}\right)}{\left(1+r\right)^t}=0$	60.7 %
6.	Fund profitability of the project (f)	$f=\frac{\sum_{t=1}^{T}\frac{(P_t-B_{et})}{T}}{\sum_{t=1}^{T}\frac{(B_{ut}-A_t)}{T}}$	1.97 UAH/UAH

The data in Table 3 show that the main indicators of the project are: the Internal Rate of Return (*IRR*) and the Net Present Value of the Project (*NPV*). These indicators can fully characterize an investment project in terms of its economic efficiency. The Net Present Value of the project (*NPV*) amounted to 809.3 thousand UAH and the internal rate of return (*IRR*) 60.7 %, which gives a very high positive rating for the investment [10].

The vast majority of grain dryers are equipped with gas burners. For the use of pellets and the elevator waste, it is necessary to rebuild grain complexes implementing solid-fuel heat generators.

The estimated cost of rebuilding for 2000 kW grain dryer will be 3.5 million UAH. These costs will pay off in less than 100 days of operation of the complex using elevator waste, and in 150 days of operation on pellets.

These calculations prove the economic feasibility of the complex conversion.

The project was tested and operated on four elevators of Kyiv, Ternopil and Chernihiv regions.

Conclusions.

1. The interdependences and conditions established during the analysis of the technological process allow defining the prerequisites for the development of an effective system of the bio-energy complex management.

2. The proposed technology allows 7-score reduction of grains drying cost on the condition that regulated modes of fuel delivery mechanisms operation be rationalized based on the analysis of flue gases composition.

3. In case of one's own working capital insufficiency, it is possible to consider the issue of vortex solid-fuel heat generator as an object of rational investment (project). Therefore, it is necessary to calculate the economic efficiency of its application and a number of indicators that characterize its expediency of investment at the expense of borrowed funds as an investment object and the possibility of their return.

4. The most objective indicators of the investment project feasibility are Internal Rate of Return (*IRR*) and Net Present Value (*NPV*) project cost. They give an objective characterization of the investment project in terms of its economic efficiency. The Net Present Value (*NPV*) of the project amounted to 809.3 thousand UAH and the Internal Rate of Return (*IRR*) 60.7 %, which gives a high positive rating for the investment.

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Підвищення ефективності біотвердопаливних систем генерації енергії: технічний та економічний аспекти

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Мета. Порівняння ефективності використання несертифікованого палива в біоенергетичному комплексі нового типу та традиційних системах генерації теплової енергії.

Методика. В основу процесу дослідження покладене математичне моделювання біотеплоенергетичного комплексу. Дослідження показників ефективності застосування твердопаливних біотеплогенераторів безперервної дії для процесу сушіння експериментальними й аналітичними методами.

Результати. Встановлено, що для ефективного горіння твердого палива необхідно забезпечити узгоджене керування окремими модулями електротехнологічного комплексу біотеплогенератора, зокрема, вирішення задачі регулювання частотою обертання електроприводів вентилятора та шнека, що визначають об'єми дозування компонентів горіння. Вирішена актуальна задача забезпечення енергоефективності теплогенератора шляхом визначення регульованих режимів дозування біопалива на основі аналізу відсоткового складу кисню в димових газах.

Наукова новизна. Обґрунтована ефективність реалізації раціонального дозування компонентів горіння з використанням регульованих режимів роботи шнека подачі палива та вентилятора на основі аналізу складу димових газів, що дало змогу підвищити енергоефективність твердопаливних теплогенераторів.

Практична значимість. Встановлені закономірності раціонального дозування компонентів біопалива залежно від аналізу складу димових газів і фізико-хімічних властивостей процесів у паливній суміші. Доведена економічна доцільність і ефективність сушіння різних матеріалів на базі біотвердопаливних систем генерації енергії.

Ключові слова: *твердопаливні системи, біосировина, диверсифікація, теплогенератор, енергоефективність*

Повышение эффективности биотвердотопливных систем генерации энергии: технические и экономические аспекты

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Цель. Сравнение эффективности использования несертифицированного топлива в биоэнергетическом комплексе нового типа и традиционных системах генерации тепловой энергии.

Методика. В основу процесса исследования положено математическое моделирование биотеплоэнергетического комплекса. Исследование показателей эффективности применения твердотопливных биотеплогенераторов непрерывного действия для процесса сушки экспериментальными и аналитическими методами.

Результаты. Установлено, что для эффективного горения твердого топлива необходимо обеспечить согласованное управление отдельными модулями электротехнологического комплекса биотеплогенератора, в частности, решение задачи регулирования частотой вращения электроприводов вентилятора и шнека, определяющих объемы дозирования компонентов горения. Решена актуальная задача обеспечения энергоэффективности теплогенератора путем определения регулируемых режимов дозирования биотоплива на основе анализа процентного содержания кислорода в дымовых газах.

Научная новизна. Обоснована эффективность реализации рационального дозирования компонентов горения с использованием регулируемых режимов работы шнека подачи топлива и вентилятора на основе анализа состава дымовых газов, что позволило повысить энергоэффективность твердотопливных теплогенераторов.

Практическая значимость. Установлены закономерности рационального дозирования компонентов биотоплива в зависимости от анализа состава дымовых газов и физико-химических свойств процессов в топливной смеси. Доказана экономическая целесообразность и эффективность сушки различных материалов на базе биотвердотопливных систем генерации энергии.

Ключевые слова: *твердотопливные системы, биосырье, диверсификация, теплогенератор, энергоэффективность*

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