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DEVELOPMENT OF THE SIMULATION MODEL OF THE INTERACTION OF AUTOMATIC CONTROLLERS IN THE CONTROL SYSTEM OF THE ENERGY COMPLEX

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Представлена розроблена імітаційна модель системи керування енергетичною установкою, що працює за різних режимах. Була проведена робота по розробці системи керування енергетичною установкою, фізичне управління якою буде здійснюватися за допомогою автоматичних регуляторів, які компенсують вплив зовнішніх факторів і, таким чином, приводять величини параметрів до заданих значень. Зокрема, були вибрані оптимальні регулятори для управління основними складовими частинами енергетичної установки.

Моделювання режимів роботи було зроблено для мінімізації похибки керування, а також для відповідності усталеним величинам витрати, температури пари та інших параметрів заданим (номінальним) значенням. В результаті проведеного моделювання було встановлено, що регулятори (П- і ПІ-типу) досить добре справляються з завданнями стабілізації параметрів при будь-яких збуреннях, незважаючи на взаємний вплив відхилень одних параметрів на інші. Динамічні відхилення від усталених значень таких величин, як витрати: димових газів, пари на турбіну і на перетіканні в конденсатор, а також тиску пари на виході з парогенератора, не перевищують ±0,1. Час заспокоєння коливань витрати пари на турбіну не перевищує 5 хв. Коливання інших витрат практично повторюють коливання витрати пари на турбіну.

Проведені дослідження будуть корисні для ефективного і якісного (точного) керування різними енергетичними комплексами, призначеними для вироблення електричної енергії і тепла. Управління такими складними енергокомплексами, як правило, здійснюється автоматичними системами, для яких потрібні правильні інструменти та оптимальні регулятори. Дана стаття присвячена імітаційного моделювання взаємодії даних регуляторів

Ключові слова: мікроенергетичний комплекс, турбоустановка, енергетична установка, імітаційна модель системи керування, оптимальний регулятор

1. Introduction

One of the essential needs of the world community today is the recycling and disposal of waste. In the world practice, waste incineration plants (which can be attributed to thermal power plants) that not only burn waste but also process the generated heat into energy are widely used. In [1], it is shown that steam-turbine power plants are the most preferable in terms of operational and economic characteristics. The considered micro-energy complex (MEC) is intended to use the heat of exhaust gases from municipal solid waste disposal plants (MSWDP) and to generate electric energy and heat on their basis for heating and hot water supply systems.

The flue gas from the MSWDP enters a waste-heat boiler (steam generator), where water is heated and turned into steam with specified parameters. This steam is fed to a turbine, jointed with an electric generator, which generate electric energy directed to the power grid. The steam spent in the turbine goes to the network water heater (condenser), where the water circulating in the heat supply system is heated. The condensate from the network water heater is returned to the steam generator.

The control of such installations consists in the stabilization of at least three parameters:

1) turbine rotor speed, by varying the steam supply to the turbine;

2) steam pressure at the steam generator outlet, by varying the supply of flue gases from the MSWDP to the boiler;

3) water temperature at the condenser outlet, by varying the condenser flow and also regulating the boiler supply, which consists in maintaining the equality of the feedwater and steam flow.

This control is carried out by means of automatic controllers that compensate for external influencing factors and thus bring the deviated parameters to the set values. The most important of these factors are the generator electric load and heat consumption, depending on the time of day, weather, season, etc.

The urgency of developing such an energy complex is dictated primarily by the fact that the analysis of current trends in the waste processing industry has shown that new technological solutions are needed in this area. According to the average statistical data, from 1 to 1.4 cubic meters of MSW per each resident of Russia a year are formed. At the same time, the volume of municipal waste is increasing, and the territorial opportunities for disposal are decreasing. The problem of waste disposal lies not only in the lack of an optimum, safe and fast method, but also in economic efficiency. Thus, the development of an energy complex for waste processing with efficient and high-quality management of operating modes is an urgent task at the moment.

2. Literature review and problem statement

In [2], waste disposal is directed, first of all, on waste processing by «fermentation» in places of formation by the method of anaerobic digestion. That is, there is no mobility of the plant operating in this way, such disposal «is tied» to the place of waste formation. There can be very different reasons for this approach. For example, the presence of a single stationary organic waste landfill in a particular locality. However, often cities have landfills different in size and hazard level. The solution to this problem is the creation of a mobile energy complex for waste processing, which can be easily moved by a tractor.

The papers [3–5] describe the operation of control systems of various power plants. However, the problem of inconvenient adjustment of parameters, as well as problems of a complex, hardly adaptable control system are revealed in these works. In view of the inaccurate setting of parameters, low plant performance is suggested. There are no solutions in the works reviewed that can effectively implement the process of regulating the micro-energy complex operating on the Renken cycle, which should probably be based on the P and PI controllers of their own control system. The technical solutions considered in [3–5] are unable to solve the problem of parameter stabilization under any perturbations, despite the mutual influence of deviations of parameters.

The papers [6, 7] deal with the simulation of power plants that have computers with special software. However, the problem of the dependence of the entire energy complex on a certain program, which can be written and controlled only by a narrowly focused specialist is revealed there. Thus, the control system of the power plant, operating with proven and efficient controllers is more reliable.

In [8–10], the researchers focus on minimizing the risk of hazardous waste management. However, it is obvious that the main problem now is the elimination of existing huge landfills, as well as minimization of the environmental impact in electric and heat energy production. The publications [11, 12] describe the concept of waste disposal in the reactor, but this installation lacks a very significant capability, namely, the production of useful thermal and/or electric energy from waste products.

Thus, an obvious niche of research is revealed, the development of an energy complex with a high-quality independent software and hardware control system for processing of sorted waste, with the possibility of auxiliary consumption of the generated energy, and also supply to the external consumer of thermal and electric energy. For this energy complex, an effective, high-quality and reliable control system, which allows operating in different modes is needed.

3. The aim and objectives of the study

The aim of the work is to select control methods based on simulation of the processes occurring in the system of the micro-energy complex, ensuring the mobility of the installation, as well as to estimate the mutual influence of individual automatic controllers and identify possible excess dynamic deviations of the controlled parameters resulting from this interaction. The aim is achieved by accomplishing the following objectives:

– to develop a block diagram of the control system of the micro-energy complex;

– to develop block diagrams of algorithms for the calculation of dynamic processes of interaction of automatic controllers in the MEC control system;

– to construct graphs of transients in the turbine, steam generator and condenser with a step variation of the turbine load;

– to analyze the quality of control when switching to various types of P or PI controllers with or without disturbance compensation.

4. Simulation of dynamic processes in the micro-energy complex control system

Fig. 1 shows the schematic diagram of the considered MEC with the designation of the corresponding control circuits. In Fig. 1, the following designations are accepted: 1 – steam generator controller (SG); 2 – SG outlet steam pressure controller; 3 – turbine controller (T); 4 – turbine rotor speed controller; 5 – SG outlet steam flow sensor (G_0+G_2); 6 – SG outlet (turbine inlet) steam pressure sensor p_0; 7 – turbine regulator; 8 – turbine steam space capacity V_1; 9 – turbine (T); 10 – turbine speed sensor φ; 11 – electric power sensor of the electric generator N_T; 12 – electric generator; 13 – condenser regulator; 14 – condenser (C); 15 – sensor of cooling water temperature at the condenser outlet t_2; 16 – circulating pump of the condenser cooling system (heating and hot water supply system); 17 – regulator of flue gas supply from the MSWDP to the SG; 18 – regulator of excess flue gas emission into the atmosphere; 19 – SG feedwater flow sensor; 20 – condensate pump; 21 – condenser controller; 22 – controller of cooling water temperature at the condenser outlet t_2.

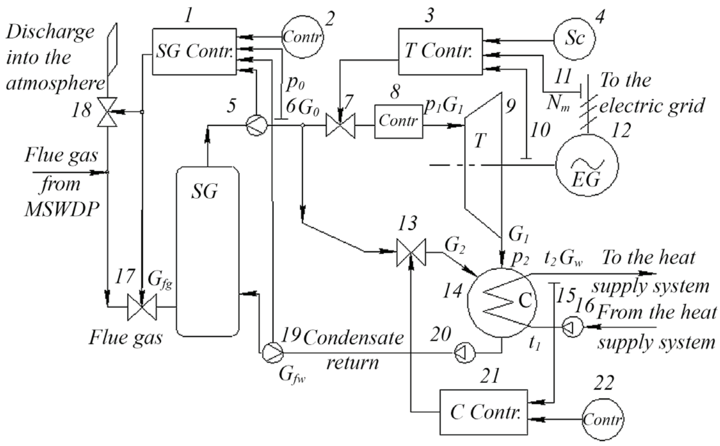

Fig. 1. Block diagram of the MEC-5 control system

G_{fg}, G_0, G_1, G_2, G_w – flows of flue gases from the MSWDP at the SG inlet, steam flow at the control valve inlet and turbine flow, condenser flow, condensing water flow, respectively.

p_0, p_1, p_2 – steam pressure at the SG outlet (in front of the turbine control valve), at the turbine inlet, at the turbine outlet (in the condenser).

t_1, t_2 – cooling water temperatures at the condenser inlet and outlet.

The power plant under consideration consists of three main integrated blocks: steam generator (SG), turbine (T) with electric generator (EG) and condenser (C). Each of these blocks is equipped with an appropriate controller. The SG controller means a set of the steam pressure controller at the boiler outlet and the power controller. The pressure controller with the help of the regulator 17 changes the supply of flue gases to the boiler, and by means of the regulator 18 discharges excess flue gases from the MSWDP into the atmosphere. The turbine controller is the speed controller of the turbogenerator rotor. To improve performance, a double-circuit controller is used here. The additional circuit operates on the disturbance signal – the EG load, passed through the differentiator, and the main circuit – on the signal of speed deviation from the set value. This controller by means of the regulator 7 changes the turbine flow. The condenser controller is the controller of the cooling water temperature at the condenser outlet, which is changed by varying the condenser flow by the regulator 13. This water is used in the consumer heating system circuit. In the condenser, water is heated from t_1 to t_2 due to the condensation of the steam spent in the turbine 9, as well as the steam flowing through the overflow pipeline through the turbine.

Fig. 2 shows the block diagram of algorithms for the calculation of dynamic processes in the MEC control system, compiled by means of the SimInTech software [13]. This diagram corresponds to the block diagram in Fig. 1 and considers the interaction of the above controllers.

There are three sub-blocks corresponding to the main integrated blocks of the MEC block diagram, Fig. 1, designated as: «Steam generator model», «Turbine model» and «Condenser model». Double-click on a sub-block opens the diagram of the algorithms of the corresponding model.

Interaction of sub-blocks is carried out through shared memory. The calculation results in each sub-block (the output values shown to the right of the sub-block) are recorded in the shared memory, and input data required for the calculation (shown to the left of the sub-block) are read by each sub-block from the shared memory. All parameter calculations are performed in relative units, so the word «relative» in the designations is omitted. The designations of the input and output values of the sub-blocks are given in Table 1.

In the right part of the diagram (Fig. 2), the output block in the form of graphs of the results of the calculation of the above input and output parameters of the SG and the turbine is shown, as well as: *Mju*1 – the position of the turbine control valve and *r*1 – the steam pressure after the control valve. Under the «Condenser model» block, there is the output block in the form of graphs of the results of the calculation of the above input and output parameters of the condenser.

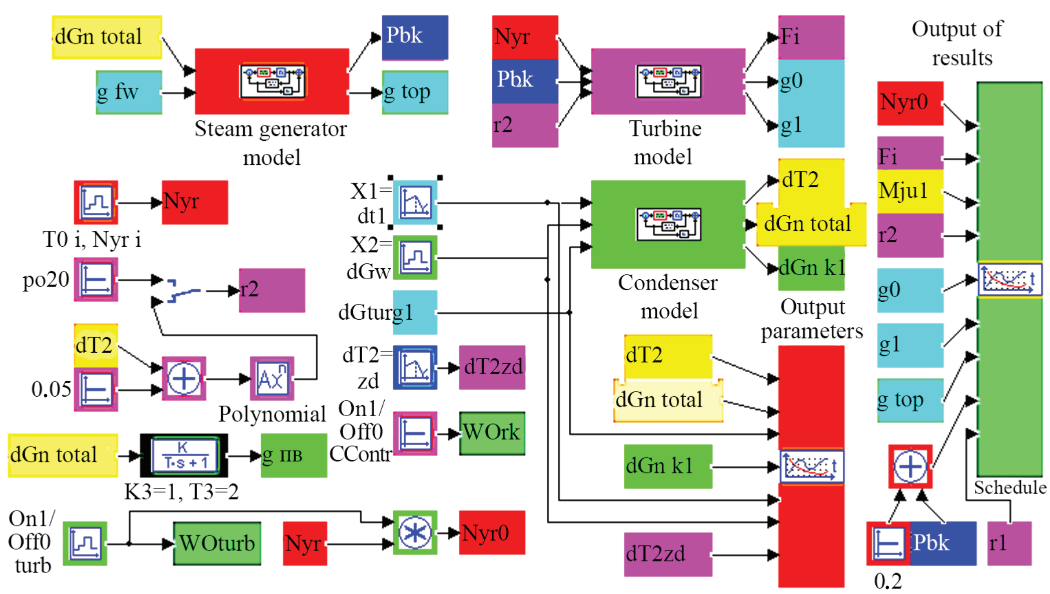

Fig. 2. Block diagram of algorithms for the calculation of dynamic processes of interaction of automatic controllers in the MEC control system

Table 1

Input and output parameters of integrated sub-blocks

Input parameters	Output parameters
Steam generator model	
dGn total – total turbine flow and condenser flow	*Pbk* – boiler drum pressure
g fw – feed water flow	*g* fg – flue gas flow from the MSWDP to the SG
Turbine model	
Nyr – EG electric load is set in the form of step time variation with the help of a special block, designated as *T*0 *i*, *Nyr i*.	*Fi* – turbogenerator rotor speed
Pbk – boiler drum pressure	*g*0 – steam flow through the turbine control valve
*r*2 – condenser pressure	*g*1 – steam flow at the turbine outlet
Condenser model	
*X*1 = *dt*1 – cooling water temperature at the condenser outlet varying according to a given law	*dT*2 – cooling water temperature at the condenser outlet
*X*2 = *dG*w – cooling water flow in the condenser varying according to a given step law	*dGn* total – total turbine outlet flow and condenser flow
dT2zd – set value of the cooling water temperature at the condenser outlet varying according to a given law	*dGn kl* – condenser control valve flow, condenser flow

Fig. 3 shows the block diagram of the algorithm for the calculation of dynamic processes in the SG, presented in the diagram, Fig. 2, as the subblock: «Steam generator model».

Actually, the steam generator model is represented by the consecutive connection of three blocks: time-lag element *Tz* and two aperiodic elements, with parameters *K*1, *T*1 and *K*2, *T*2. To correct the result obtained in these blocks, the value *dGn* total, which passes through the aperiodic element with parameters *K*3, *T*3 is introduced into the sub-block from the outside and goes with the coefficient *K*0 to the adder *S*2 as an amendment reflecting the effect of steam flow on the SG outlet pressure – *Pb*, which is given to the output of the sub-block *Pbk*.

The value *Pb* is compared in the adder *S*3 with a given value *Pzd* and the error signal *Pb-Pzd* is fed to two types of controllers: «P controller *Kp*1» and «PI controller *Kp*3, *KpTi*3». The choice of a controller for estimating the quality of regulation is made with the help of the switch Sw.2.

The input signal to the SG model is formed with the help of the adder *S*1 from three signals: feedwater flow *g* fw, entering the sub-block from the outside; impact on the regulator in the manual remote control and the signal from the controller connected by the switch Sw.2. Thus, it is modeled that the flue gas flow from the MSWDP to the SG is basically proportional to the feedwater flow, adjusted for the manual impact on the regulator, and the controller corrects this flue gas flow from the MSWDP in order to restore the boiler drum steam pressure deviated from the set value.

The lower branch of the blocks is designed to allocate the MSWDP flue gas flow from the input SG signal, the value of which is output from the sub-block *g* fg.

The diagram of the algorithms of the «Turbine model» sub-block is presented and described in [1], and the diagram of the algorithms of the «Condenser model» sub-block – in [14]. The above two sub-blocks are part of the entire energy complex control system, which, due to changes in the purpose of the complex and the parameters of the working fluid, undergoes significant changes. The micro-energy complexes described in the previous works are designed for operation mainly on the electric load schedule, and the regulation is aimed at providing it. The main task and distinctive feature is maximum efficient, fast and environmentally friendly waste disposal, with a relatively constant electric load schedule (own needs), which leads to changes in the control system.

Fig. 4 shows the results of calculations in the form of graphs of transients:

a) in the turbine and steam generator;

b) in the condenser, with a step variation of the turbine load and the on-state of all controllers. Designations of the lines here correspond to the designations of parameters in Fig. 2.

This is the so-called winter operating mode of the cogeneration micro-energy plant, when both electric and thermal energy is simultaneously supplied to consumers.

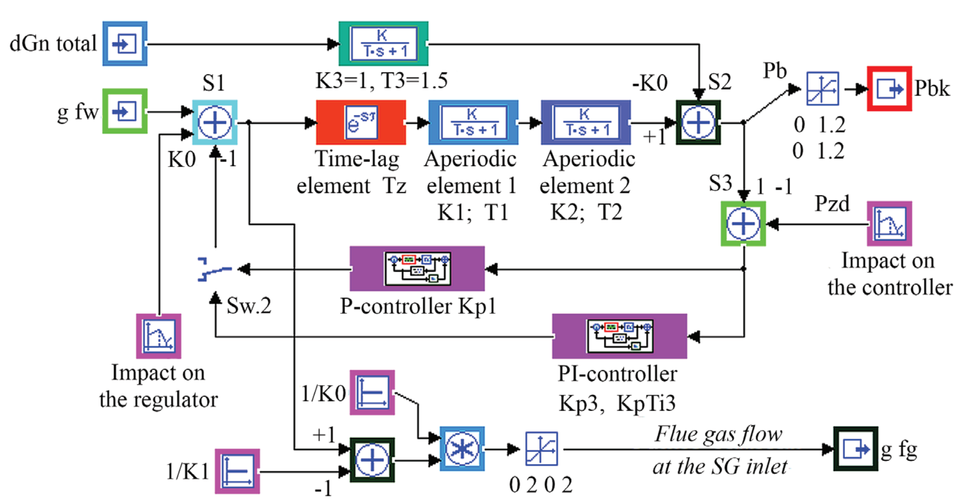

Fig. 3. Block diagram of algorithms for the calculation of dynamic control processes of the SG outlet steam pressure

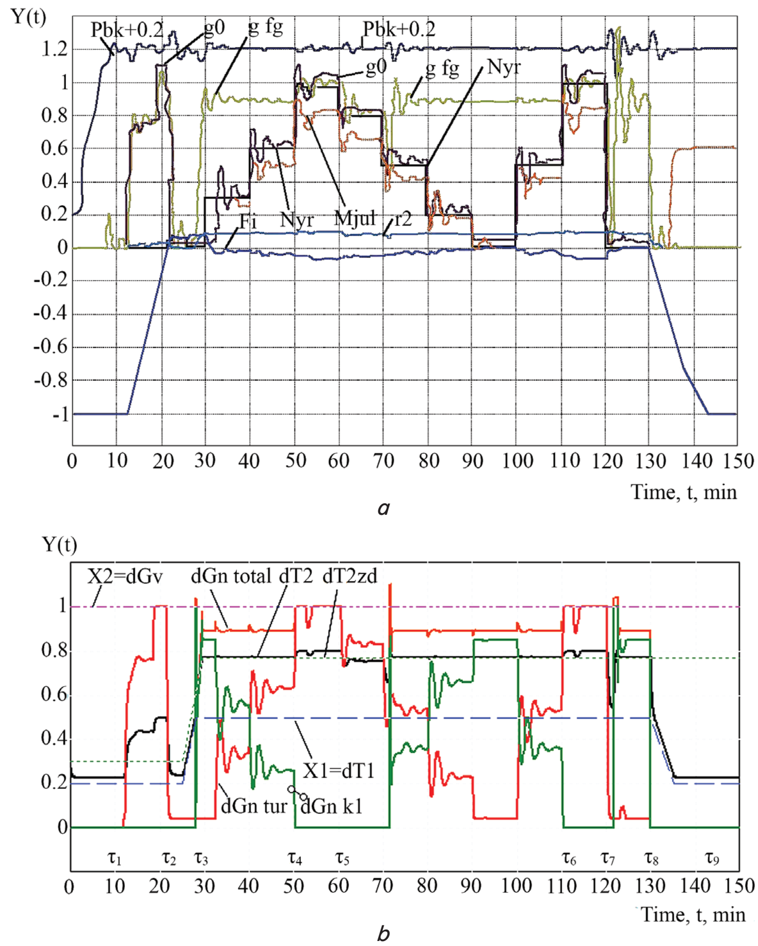

Fig. 4. Graphs of transients: *a* – in the turbine and steam generator; *b* – in the condenser, in the interaction of all controllers and step variation of the turbine load

In the time interval from 0.5 to τ_1, the boiler is started – steam pressure is increased due to the supply of a small amount of flue gases from the MSWDP in the absence of steam consumption. After reaching the rated steam pressure *Pbk*, in the period from τ_1 to τ_2, the turbine is started. First, the valve *Mju*1 of steam flow to the turbine *g*0 is manually opened, and then, when reaching a certain turbine rotor speed *Fi*, the automatic turbine speed controller is activated. When the rated speed *Fi* = 0 is reached, the controller almost completely closes the valve of steam supply to the turbine and maintains a near-rated constant speed.

At the moment τ_3, the load is applied to the turbine generator *Nyr* = 0.3 step by step and the condenser controller is switched on simultaneously and the value *dT*2*zd* = 0.77 for it is set – the cooling water temperature at the condenser outlet should be 77 °C. Since the turbine controller is delayed and has not yet opened the valve of steam supply to the turbine, the condenser controller opens the turbine overflow valve, delivers steam to the condenser at the flow *dGn kl*, and thus brings the temperature *dT*2 to the set value *dT*2*zd*. Due to the increase in *dT*2, the return network water temperature *dT*1 also increases to the value equal to 0.5. To ensure the set steam flow *dGn kl*, the SG controller supplies the appropriate amount of MSWDP flue gases *g* fg to the boiler. The controller T opens the inlet valve and, after some fluctuations, sets the turbine flow *g*0 corresponding to the load *Nyr*. Due to the steam flow from the turbine to the condenser, the controller *K* reduces the steam overflow *dGn kl*, so that the total steam flow to the condenser *dGn* total and the network water temperature at the condenser outlet *dT*2 remain constant.

Similar variations of the parameters occur with a stepwise increase in the EG load – *Nyr* to 0.6 and 0.97. In the period from τ_4 to τ_5 (as well as in the period from τ_6 to τ_7), the EG load is almost equal to rated. Here, the turbine flow *g*0 = *dGn tur* exceeds the flow necessary for heating the cooling water to the set temperature *dT*2*zd*, therefore the steam overflow *dGn kl* = 0, and the temperature *dT*2 is not much higher than the set value *dT*2*zd*.

Further, a stepwise decrease in the EG load – *Nyr* to 0.8, 0.5, 0.2, and 0, and then the increase in *Nyr* to 0.5 and 0.97 were simulated. At the moment τ_7, an instantaneous drop of the EG load – *Nyr* from rated to 0 occurs. At all these steps, the controller *T* after some fluctuations sets the turbine flow *g*0 = *dGn tur* corresponding to the set load, the SG controller sets the required flue gas flow from the MSWDP to the boiler, and the controller K adjusts the steam overflow *dGn kl*, so that the total condenser flow *dGn* total and the network water temperature at the condenser outlet *dT*2 remain constant. At the time of a sudden load drop, the greatest fluctuations in the steam flow *g*0 = *dGn tur*, *dGn kl* and the flow of MSWDP flue gases *g* fg are observed.

At the time τ_8, the turbine inlet and turbine overflow valves are completely closed, the controller K is switched off. The turbogenerator rotor speed gradually decreases and at the time τ_9 the turbine is completely stopped (*Fi* = –1). The SG controller continues to operate and maintain the SG outlet steam pressure equal to the set value.

Similarly, transients in the step variation of the turbine load for the summer mode, when the condenser controller is switched off and the cooling water temperature at the condenser inlet remained unchanged and equal to 0.2 (20 °C) were simulated. Due to the switched off controller *K*, the condenser flow valve does not open, i. e. additional steam to adjust the cooling water temperature at the condenser outlet to the set value is not supplied. Therefore, there is a decrease in the water temperature at the condenser outlet, and, accordingly, the lower absolute steam pressure in the condenser.

In addition to the above options of the MEC operating modes, switching to various types of P or PI controllers was performed, or disturbance compensation was switched on or off to compare the quality of regulation. Moreover, perturbing effects were also modeled by varying the cooling water temperature at the condenser inlet (return network water temperature) and cooling (network) water flow. These variations are typical for the heating and hot water supply system at different times of the year and day, and also depending on weather.

In all cases, the simulation showed that the controllers cope quite well with the problems of parameters stabilization under any perturbations, despite the mutual influence of deviations of parameters. Dynamic deviations of such quantities as the flow of flue gases from the MSWDP, turbine flow and condenser flow, and also the SG outlet steam pressure from the established values (maximum amplitudes) do not exceed ±0.1. The settling time of the turbine flow fluctuations does not exceed 5 minutes. The fluctuations of the remaining flows are almost similar to, with a small delay, the turbine flow fluctuations. The largest fluctuations in the condenser flow and the flow of flue gases from the MSWDP to the SG are observed with an instantaneous load drop from rated to zero. However, the controllers «damp» the fluctuations quite quickly and the so-called «overspeeding», which could be expected in this case, does not occur. The static error (deviation of the established value from the set value) for the turbogenerator rotor speed does not exceed +0.07 at idle and –0.07 at the rated load.

5. Discussion of the results of the study of the simulation of the micro-energy plant for waste recycling

Simulation of the energy complex was carried out using the «Simulation In Technic» software, which allowed estimating the operation of various controllers in different modes. The micro-energy complex and the automatic control system were developed taking into account the principles of mobility, adaptability to external energy demands and conditions for disposal of used organic waste. The energy complex control system was developed taking into account the operation on the proven and efficient controllers.

The progress of the scientific research begun in [1] is that the present model made it possible to test two new, not described earlier, alternative methods of turbine performance stabilization: either by withdrawal of some unclaimed flue gases into the atmosphere or by simultaneous impact on the turbine control valve and condenser control valve. In both cases, a new simulation has shown that the interaction of these controllers fully ensures the stabilization of turbine performance under arbitrary fluctuations in the performance of the disposal plant. Withdrawal of a part of unclaimed flue gases in a chimney from a practical point of view can cause some difficulties due to the high temperature of the gases. This will require the development and creation of special high-temperature controllers and a chimney with increased heat resistance.

Thus, logical development of earlier studies described in [1, 14–17] is clearly seen. The similarity is only that, like in earlier works, simulation, performed by means of the «Simulation In Technic» software is used to achieve the results [13].

The paper [15] describes the process of developing a wet-steam microturbine plant for distributed power generation systems based on the combined use of conventional and non-conventional energy sources for low-rise buildings. The following is also given:

– development of an optimum flow diagram of the micro-energy complex with a useful electric power of 5 kW and thermal – up to 65 kW;

– development of a method for independent control of the thermal and electric load of the energy complex;

– development of a vertical wet-steam microturbine with an electric power of 5 kW and thermal – up to 65 kW;

– development of an optimum flow diagram of the steam generation system using a combination of conventional fuel and solar energy for the micro-energy complex with an electric power of 5 kW and thermal – 65 kW.

When creating a pilot sample of this micro-energy complex, the problem was revealed: somewhat unpredictable behavior of the gas-dynamic bearings used in the turbine. Therefore, a number of additional studies, the results of which were published in [16], and subsequently in [15] have been carried out. In particular, it is specified that the problem of providing a small coefficient of friction in vertical turbomachines can be solved using different types of bearings. In [17], the analysis and comparison of gas-dynamic sliding bearings and ceramic friction bearings, which showed the efficiency of gas-dynamic bearings in the rated operating mode of vertical power plants have been performed. However, the rotor shaft does not immediately emerge in the axial thrust gas-dynamic bearing. At the initial shaft speed, in the start-up mode, there is active friction between the rotor shaft and the bearing foil. Also, to determine the convergence of the mathematical model and experimental data, the maximum relative error of the mathematical calculations of the vertical turbine, which does not exceed 14.7 %, was calculated. This error is caused by the error of measuring instruments (oscillograph and other equipment), as well as approximation of calculations in the software used [13]. In [17], the moments of emersion of the rotor shaft in gas-dynamic foil bearings of domestic production are determined by the method of mathematical modeling.

The basis of the control system was the scheme obtained in [1]. The additional difference between the model described in [1] and the model given in the present paper is that the first one describes the power plant with the steam generator, which uses fuel supplied to the furnace as a heat source, and in the second case the source of heat is flue gases obtained during waste recycling and disposal. The peculiarity of this case is that the disposal plant cannot be adjusted as fast as necessary to the constantly changing turbine performance, which depends on the generator load. Here, the method of performance stabilization of the steam generator by varying the fuel supply to the furnace cannot be used. Therefore, it is advisable to continue the research and to test other alternative algorithms of stabilizing the parameters of the plant under fluctuations in the performance of the heat source by simulation.

Among the advantages of the research, the indisputable convenience of simulation of various processes occurring in the steam turbine, steam generator and condenser can be identified. The convenience of simulation consists in a wide range of controlled parameters of the plant. Any researcher or heat-power design engineer can simulate the behavior of a similar turbine, obtain output parameters from the given input ones without designing a natural model.

The shortcomings of the study include the fact that this simulation model has not yet been tested on a real object, since the turbine and the energy complex as a whole are currently being designed.

The conducted studies of the operating modes of the energy complex will be useful to design engineers when designing waste recycling and incineration plants. Such waste recycling energy complexes will soon replace the currently popular waste incinerators. In such incinerators, there is no withdrawal of thermal or electric energy, on the contrary, these installations need energy from the outside, usually fuel energy and electric energy. The developed energy complex is mobile and will be useful in any country of the world.

The present study is a continuation of the previous study within the framework of the «Development of a wet-steam microturbine plant for distributed power generation systems based on the combined use of conventional and renewable energy sources» project. Previously, the simulation of dynamic characteristics of the vertical wet-steam microturbine with an electric power of 5 kW was carried out. The simulation model was supported by experimental studies that showed good convergence (the maximum relative error does not exceed 14.7 %) [16].

6. Conclusions

1. The block diagram of the micro-energy complex control system was developed. The developed diagram includes three basic integrated blocks: the steam generator, the turbine with the electric generator and the condenser. Each of these blocks is equipped with the appropriate controller.

2. Block diagrams of algorithms for calculating the dynamic processes of interaction of automatic controllers in the energy complex control system were developed. Various blocks and sub-blocks, such as aperiodic, integrating, amplifying, time-lag elements and others were selected. Based on the results of calculations, graphs of transients as time variations of parameters are constructed.

3. Simulation of the processes occurring both in the winter and in the summer period, when the temperature stabilization of the network water for heating purposes at the condenser outlet is not required, was carried out. In the simulation, options with two new, alternative methods for turbine performance stabilization were calculated: by withdrawing part of unclaimed flue gases to the atmosphere, or by simultaneous impact on the turbine control valve and condenser control valve.

4. The analysis of the control quality when switching to various types of P or PI controllers with or without disturbance compensation has shown that the controllers cope well enough with the problems of parameters stabilization under any perturbations, despite the mutual influence of deviations of parameters. Dynamic deviations of such quantities as the flow of flue gases at the steam generator inlet, turbine flow and condenser flow, and the SG outlet steam pressure from the established values (maximum amplitudes) do not exceed ±0.1. The settling time of the turbine flow fluctuations does not exceed 5 minutes.

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RESULTS OF RESEARCH INTO THERMAL-TECHNICAL CHARACTERISTICS OF SOLAR COLLECTOR

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Розроблено нову конструкцію повітряного геліоколектора, виготовленого у вигляді нероздільного енергетичного блока, що включає в себе каркас з теплоізольованими стінками, одинарним заскленням і селективною поверхнею на його днищі. Встановлено ряд узагальнювальних залежностей для знаходження теплової ефективності повітряного геліоколоектора, а саме впливу масової витрати повітря $q_{тн}$ на перепад температур теплоносія $t_{вих}$ та інсоляції E, на теплопродуктивність q і ККД η геліоколектора.

На підставі експериментальних даних отримано лінійно регресійні залежності середньої денної температури навколишнього середовища $t_{нсср}$ від енергетичної освітленості E та середньої температури теплоносія $t_{тнср}$ від середньої денної температури навколишнього середовища $t_{нсср}$. Отримані регресійні залежності мають різні коефіцієнти регресії, а саме $t_{нсср}$ дозволяє аналітично прогнозувати значення залежнозмінної середньо денної температури навколишнього середовища за допомогою незалежно змінної енергетичної освітленості E, що є хаотичною величиною. Крім цього, дає можливість виявляти і пояснити, на скільки та як змінюються середньо денні температури навколишнього середовища $t_{нсср}$ та теплоносія $t_{тнср}$ при зміні енергетичної освітленості E впродовж доби. З цього випливає, що найбільш суттєвим фактором, що впливає на роботу геліоколектора, є енергетична освітленість E. Здійснено перевірку адекватності результатів теоретичних і експериментальних досліджень.

З'ясовано, що максимальні значення ККД геліоколектора η – від 65 до 80,6 %, досягаються за температури вихідного потоку теплоносія $t_{вих}$ від 10 до 60 °C та масовій витраті повітря, $q_{тн}$ від 170 до 190 $м^3$/год. Визначено, що зростання рівня інсоляції E від 100 до 1000 Вт/$м^2$ дає змогу збільшити теплопродуктивність колектора q від 320 до 1260 Вт та температуру теплоносія на виході з колектора $t_{вих}$ від 10 до 60 °C.

Отримані результати можна використати під час розробки та вдосконалення технічних засобів сушіння фруктів, для підвищення технологічної та енергетичної ефективності процесу

Ключові слова: сонячний тепловий повітряний геліоколектор, селективне покриття, повітряна сонячна система опалення

1. Introduction

An air solar collector (ASC) is a device designed to collect energy of radiation of the Sun in the visible and infrared spectra and to convert it into thermal energy. ASC serves mostly as an additional heating element of a low-temperature source of heat, in particular at solar dry kilns during a low-temperature mode of fruits drying. ASC uses air as a heat-transfer agent. The basic heat engineering parameters of air are temperature, saturation φ, and psychrometric difference Δ*t* between temperatures of dry *t* and wet t_w thermometers of a psychrometer. The advantage of ASC is that it does not freeze and there is no boiling of a heat-transfer agent, unlike in liquid systems.

Currently ASCs are not commonly used in the energy market. Researchers developed most of ASC for countries with different types of subtropical climate, and they conducted research in laboratory or with a use of computer simulations. Thus, the fundamental problem of such devices is lack of methods for selection of elements and materials for construction and methods for calculation of heat engineering characteristics, which require additional research