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An Integrated Approach to the Construction of Energy-Saving Trigeneration Systems for Objects of the Agro-Industrial Complex

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Abstract

This work is devoted to a comprehensive approach to the construction of energy-saving systems for agro-industrial complex objects as well as their mathematical description and consideration of possible approaches to analysis. The general problem of energy saving is identified and its special relevance for the agro-industrial complex (AIC) is noted. The prospects of an approach to solving this problem based on the principle of trigeneration, based on the simultaneous generation of electricity (using the direct photoelectric method), as well as heat and cold (using the thermoelectric method), are shown. Using the proposed approach, a block diagram of an energy-saving system is developed and its mathematical description is given, which sufficiently fully and accurately describes the heat exchange processes occurring in it.It is noted that in some cases, the presented expressions are not convenient enough to use, and therefore the image of the principle of microclimate regulation of the trigeneration system in the form of a functional scheme in relation to temperature changes and its subsequent analysis using the methods of automatic control theory is relevant. In addition, for cases when there are several agro industrial complex objects in the general climate control system, and in each of them a set of point sources and sensors, it is proposed to use its representation on the basis of a generalized hierarchical model, which is a structural approximation of this microclimate control system.

Keywords: agro-industrial complex, energy-saving systems, energy trigeneration, thermoelectric, Peltier effect, thermoelectric modules, hierarchical model.

1. INTRODUCTION

On a global scale, every year the problems of reducing energy costs and saving energy [1-6] become more and more urgent. These problems are exacerbated by the transition to market relations in many developing countries, as well as by the global shortage of energy resources and a sharp increase in their cost. As a result, the competitiveness of manufactured products in various sectors of the economy largely depends on the economical use of energy resources.

The problem of energy saving is relevant for all spheres of the economy, but especially for the branches of the agro-industrial complex [7] and is becoming more acute in modern political and economic conditions. At the same time, it should be noted that AIC objects are characterized by a special item of energy consumption, determined by the need to create a special microclimate of production [8] (due to the generation of low-temperature heat), which in some industries is spent more than 50% of the total cost of purchasing energy resources.

Solving the problem of energy saving in the agro-industrial complex will reduce the energy intensity and, consequently, the cost of agricultural products. That is why one of the main goals of the development of modern agricultural industries is their intensification by increasing production efficiency through better use of resource potential, especially energy. To do this, in particular, it is necessary to solve a number of scientific and technical tasks for the installation of energy-saving equipment and/or technical re-equipment of energy supply systems for AIC objects which is already being successfully implemented in many countries of the world.

1.1. Application of the principle of trigeneration for building energy-saving systems for agro-industrial complex objects

A promising approach to solving the problem of energy saving at AIC objects can be the use of the principle of trigeneration [9], based on simultaneous generation of electricity (to power electronic devices), as well as heat and cold (to create the necessary microclimate of premises). It is proposed to use the direct photovoltaic method (obtaining electrical energy from Solar energy) and the thermoelectric method (obtaining heat and cold from electrical energy) as the basis for building multifunctional systems that implement this principle.

The direct photovoltaic method is based on obtaining electrical energy from the energy of the Sun using photovoltaic cells, the principle of operation of which is based on obtaining the potential difference inside the solar cells when sunlight hits them. The main advantages of this method of obtaining electric energy include its theoretically complete environmental safety for the environment (no harmful emissions), inexhaustibility of the energy source in the long term and low cost of energy received in the conditions of constant growth in prices for traditional types of energy carriers. These advantages encourage an increasing number of countries to develop solar energy, which is currently most actively used in countries such as Germany, Japan and China. At the same time, according to forecasts, it is expected that the energy obtained from solar radiation will hypothetically be able to provide 20-25% of humanity's electricity needs by 2050 and reduce carbon dioxide emissions into the atmosphere.

The thermoelectric method of obtaining heat and cold from electrical energy is based on the use of thermoelectric modules (TEM), the principle of operation of which is based on the Peltier effect [10-17]. The essence of this effect is that when a constant electric current flows through an electrical circuit made up of dissimilar conductors, a certain amount of heat is absorbed or released at the junction, and, accordingly, this part of the circuit is cooled or heated depending on the direction of the current. Modern TEMs based on the Peltier effect are devices consisting of two ceramic plates-insulators, with series-connected thermocouples located between them (Fig. 1), and the design is made in such a way that each side of the module, depending on the polarity, contacts either *p-n* or *n-p* transitions.

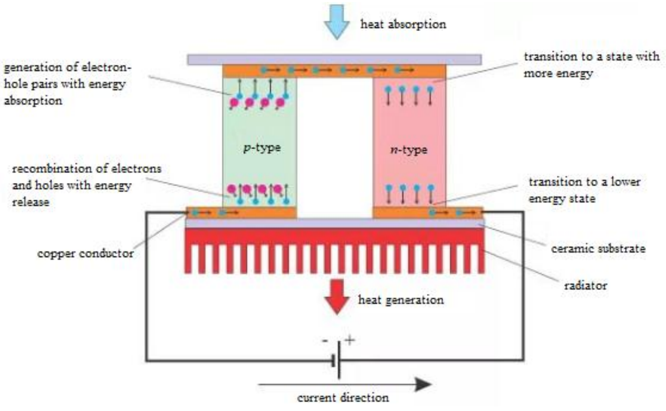

Fig. 1: The design of thermoelectric module based on the Peltier effect

Currently, there is a surge in interest in thermoelectric energy conversion, and the production of thermoelectric equipment is actively developing around the world. So in recent years, the average growth in global production of TEMs and thermoelectric devices for various purposes is about 14-15%. This is due to the key advantages of this method of obtaining energy: environmental cleanliness; the ability to smoothly and accurately regulate the temperature regime; almost unlimited resource of operation; the absence of moving and wearing parts, as well as working fluids and gases; quiet operation; small dimensions of TEM; arbitrary orientation of the source of cold or heat in space and independence from the presence of gravitational forces; resistance to dynamic and static overloads; structural and technological versatility, and others.

1.2. Block diagram of an energy-saving trigeneration system for agro-industrial complex objects and its mathematical description

Using the proposed principle of trigeneration, a block diagram of an energy-saving system for AIC objects was developed, shown in Fig. 2. The main modules of this system are directly *n*-th objects of the agro-industrial complex (n=1...N) and the power supplysystem (PSS), which is common to them. In the diagram the following notation: SC_m - *m*-th solar cell (m=1...M), BP - battery pack, PS - power supply, ACSPS - automatic control system of power supplies, CCS_n - *n*-th climate control system, $TEMS_n$ - *n*-th thermoelectric modulessystem, VS_n - *n*-th ventilation system, PST_{ni} - *ni*-th point source of temperature (heat or cold), CS_{nj} - *nj*-th climatesensor, $I_{CONTRnl}$–*nl*-th managing influence for thermoelectric modules, T_{PSTni} - temperature *ni*-th point source of temperature (heat or cold), T_{CSnj}- temperature recorded *nj*-th climate sensor.

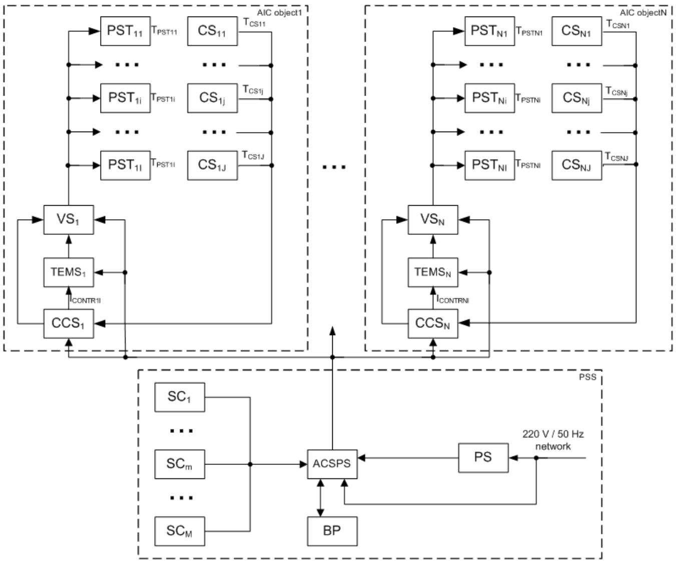

Fig. 2: Block diagram of an energy-saving trigeneration system for agro-industrial complex objects

Let's consider the principle of operation of this diagram in more detail.

The core of the power supply system is an automatic control system of power supplies, which includes a charge controller, an inverter, and a power supply switch. The system charge controller is designed to automatically control the process of charging the battery pack batteries from solar panels. For example, if the Sun is not present, the charge controller is in "sleep mode" and continues to remain at rest until the incoming voltage from the solar panels reaches a certain level (for example, 10 V). After this, the charge controller goes into "operating mode" and begins to transmit electric current to the battery pack batteries until their charging level reaches a limit value (for example, 14 V), after which it stops supplying current until the batteries begin to discharge.The inverter in this system is designed to convert direct current from batteries to alternating current and increase the voltage level to the standard values used by energy consumers (220 V / 50 Hz).

Another element of the automatic control system is a switch that automatically switches between available power sources (batteries and industrial network 220 V / 50 Hz, connected in addition to the power supply to form a highly stable DC power supply, for example, also at the level of 14 V), while giving priority to connecting consumers to power from alternative energy sources (solar panels). The main consumers of AC voltage 220 V from the power supply system are climate control systems and power units of ventilation systems, and the consumers of DC voltage are thermoelectric modules based on the Peltier effect.

Microclimate control at each agro-industrial complex object is carried out by a climate control system that generates control values for thermoelectric modules in the form of $I_{\mathrm{CONTR}nl}$ currents, which are functions of the desired temperature $T_{\mathrm{D}nl}$ and the results of measurements of climate sensors $T_{\mathrm{CS}nj}$

$$I_{CONTRnl} = f(T_{Dnl}, T_{CSnj}).$$

These control actions directly affect the temperature values of the sides of Peltier thermoelectric modules, which can contain up to several hundred thermoelements in their composition to provide the necessary cooling or heating power. According to research [11], the power of thermoelectric modules of the order of kilowatts can be expected in the foreseeable future. This will be possible due to the use of multi-tiered structures of thermoelectric modules based on the cascading principle, composite branches, and the use of advanced semiconductor and ceramic materials with improved characteristics [13-17].

One of the features of the proposed system is the use of a combined (hybrid) ventilation system based on the convection cooling principle, supplemented by the possibility of both cold drainage from cold junctions of thermoelectric modules to create the necessary microclimate of the main areas of AIC objects, and the possibility of heat removal from hot junctions of thermoelectric modules to create an acceptable temperature regime, for example, in the administrative premises of AIC objects. As a result of using this approach to creating a microclimate, a certain non-stationary temperature field is created at agricultural facilities, described as

$$T = f(x, y, z, t),$$

where x, y, z - spatial coordinates, t - time,

which is controlled climate control system and is formed with point sources of temperature (heat or cold) $T_{\mathrm{PST}ni}$, each of which in general case is described in accordance with the differential equation (differential equation of Fourier) for three-dimensional unsteady temperature field in the presence of the internal temperature sources [18] of the form

$$\frac{\partial T}{\partial t} = a\nabla^2 T + \frac{q_V}{c\rho}, \tag{1}$$

where $a = \frac{\lambda}{c\rho}$ is the coefficient of temperature diffusivity, λ - coefficient of thermal conductivity, c - specific heat, ρ - density, $\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}$ - Laplace operator, q_V - the amount of heat generated per unit volume of the medium per unit of time.

A special case of equation (1) is the convective heat exchange observed in the case under consideration, in which the processes of convection and thermal conductivity run together [18]. This type of heat transfer is described by a differential equation that establishes a relationship between spatial and temporal changes in temperature

$$\frac{\partial T}{\partial t} + w_x \frac{\partial T}{\partial x} + w_y \frac{\partial T}{\partial y} + w_z \frac{\partial T}{\partial z} = a\nabla^2 T, \tag{2}$$

where w_x, w_y, w_z is the projection of the velocity vector on the *X*, *Y*and *Z* axis.

Control of the temperature regime installed at the AIC objects is carried out using climate sensors that register the temperature values of $T_{\mathrm{CS}nj}$, which differ from the values of $T_{\mathrm{PST}ni}$temperatures formed by point sources. The relationship between the values of these temperatures can be described with the help of the coefficient k_{nij} using a differential equation that takes into account the inertia of an arbitrary sensor in relation to the process of temperature field formation

$$T_{CSnj} + \tau_{nij} \frac{dT_{CSnj}}{dt} = k_{nij} T_{PSTni},$$

where τ_{nij} is the value that serves as a measure of the inertia of the climate sensor.

Transforming this equation with regard to the temperature, and after replacing $\frac{d}{dt}$ to the differential operator *p*, we write the transfer function for an arbitrary climate sensor relative to an arbitrary point source of temperature *n*-th AIC object in the operator form

$$H_{nij}(p) = \frac{T_{CSnj}}{T_{PSTni}} = \frac{k_{nij}}{1 + \tau_{nij} p}, \tag{3}$$

which corresponds to an aperiodic dynamic link.

1.3. Analysis of energy-efficient trigeneration system using the methods of automatic control theory

The mathematical expressions presented above describe the heat exchange processes that occur in the proposed energy-saving trigeneration system for AIC objects quite fully and accurately. However, they are not convenient enough to use in cases where it is necessary to evaluate the stability of an arbitrary climate regulation system, the dynamic properties of thermoelectric modules in the transition mode when the desired temperature of the agro-industrial complex object changes, or to optimize the mode of operation of these modules for one of the key parameters.

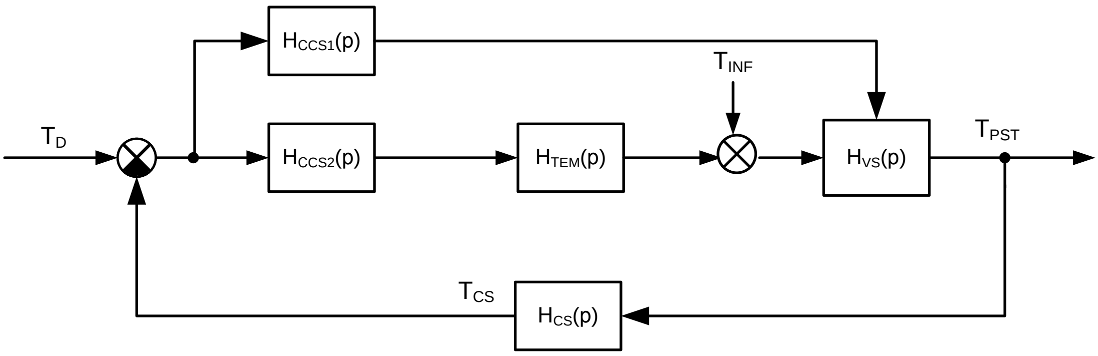

Fig. 3: Example of image of the principle of microclimate regulation using the trigeneration system under study based on the simplest functional scheme

In this aspect, the image of the principle of microclimate regulation using the trigeneration system under study in the form of a functional diagram with respect to temperature changes and its subsequent analysis using the methods of automatic control theory is relevant. An example of such a simple functional scheme for an arbitrary AIC object, a single point source of temperature and a single climate sensor is shown in figure 3. In the diagram the following notation: $H_r(p)$ - transfer function of the r-th block of the functional diagram, T_D - the desired temperature, T_{INF} - interference effects that mimic the processes of heat transfer between the environment and outer sides of TEMs, T_{PST} - the temperature of a point source of temperature, T_{CS} is the temperature registered by the climate sensor.

The resulting expression (3) can be used as a model of the transfer function of the climate sensor, and for the other parts of the functional scheme, mathematical models are presented, for example, in [19-21]. They were used to obtain expressions corresponding to the transfer functions of an open and closed microclimate control system for input and interference effects, which are typical and are not given in this paper. With their help, a study of the proposed functional scheme was carried out. So in fig. 4 shows as an example the dynamic characteristics of the microclimate control system for the input action on the system in the form of a change in the desired temperature in the form of a meander.

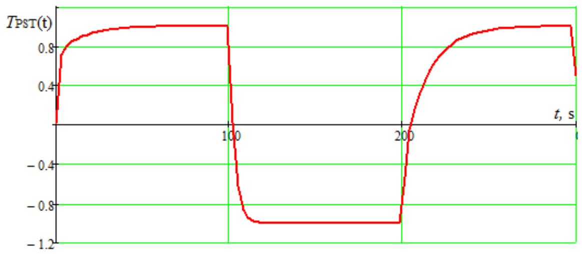

Fig. 4: An example of the dynamic response of a microclimate control system for an input action on the system in the form of a change in the desired temperature in the form of a meander

The results obtained are consistent with both the simulation results presented in [19-21] and the typical characteristics of thermoelectric modules presented in the reference literature.

2. CONCLUSION

The presented approach to the image of energy-saving trigeneration systems based on functional schemes and their analysis using methods of automatic control theory can serve as a fairly simple and convenient tool for studying their characteristics, quality indicators, and also be used to solve optimization and synthesis problems, which is confirmed by the research conducted by the authors. However, in cases where it is necessary to assess the presence of several AIC objects in the overall climate regulation system and in each of them a set of point sources and sensors, in this case, the task of obtaining the resulting transfer functions and their analysis will become more complicated.

To overcome this disadvantage, we can use the representation of microclimate control systems based on a generalized hierarchical model presented in [22-25], which allows for a uniform representation of various variants of systems to ensure their analytical description and subsequent analysis, in particular, taking into account nonlinear effects and characteristics (for example, nonlinear amplitude characteristic of TEM - the dependence of junction temperatures on the value of the control current). This model is built on the basis of a minimum number of similar structural blocks with the possibility of their arbitrary increase, but the integrity of the general forward, backward, and channel connections must be preserved. This model is a structural approximation of the general microclimate control system and contains an arbitrary number of parallel, dependent channels - "rows", which form a" frame "and can be expanded in a raster way both along" rows "(opening by levels) and along a" frame "with arbitrary lengths of" rows " and their number.

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