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Frequency Characteristics of a Climate Control System Based On Thermoelectric Modules for Objects of the Agro-Industrial Complex

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Abstract

The thermoelectric method of converting electrical energy into thermal energy has a number of unique advantages, which makes it possible to consider it as a promising option for the implementation of climate control systems, one of the areas of application of which is their integration into energy-saving trigeneration systems for objects of the agro-industrial complex, which makes it possible to reduce the energy intensity of production and the cost price manufactured agricultural products. To describe the functioning of the climate control system based on the thermoelectric method and study its characteristics, the Peltier effect for a single thermocouple, as well as the main characteristics of thermoelectric modules, are considered. The simplest structural diagram of the climate control system for an arbitrary object of the agro-industrial complex, a single point source of heat/cold and a single climate sensor was developed, on the basis of which an equivalent functional model was obtained with respect to temperature changes and describing its transfer functions for the main influences, with the help of which modeling can be carried out its characteristics and quality indicators. The advantage of the proposed system is the use of the deviation control principle, which provides selective suppression of disturbing influences in a given range of the frequency spectrum, to assess the effectiveness of which the frequency characteristics were studied. On the basis of the obtained graphical dependencies, generalized conclusions are drawn that can be used in the practical implementation of the microclimate control system.

Keywords: climate control, energy saving, thermoelectricity, agro-industrial complex, trigeneration, Peltier effect, automatic regulation.

Introduction

A climate control system is one or more devices that are generally designed to create the desired microclimate at an arbitrary object by maintaining a given temperature, humidity level and chemical composition of the air. At the same time, its main task is, first of all, to mix flows of cold and warm air so that it meets a given temperature. Microclimate control is carried out under the influence of control values, which are functionals of the desired values of temperature, humidity, chemical composition of air and the results of measurements of similar values using climate sensors.

In view of the widespread tightening of requirements for the production of various types of energy from the point of view of the environmental friendliness of this process [1-6], recently there has been a great interest in thermoelectric energy conversion [7, 8]. Along with environmental friendliness, this type of thermal energy production is characterized by exceptional reliability of components; possibility of very fast cooling; high precision temperature control; independence of the parameters of thermoelectric modules from gravity and orientation in space; low sensitivity to high mechanical stress and no need for maintenance.

The indicated advantages of the thermoelectric method allow us to consider it as a promising option for the implementation of climate control systems based on it. In particular, one of the areas of application of such systems can be their integration into energy-saving trigeneration systems [9-11] for objects of the agro-industrial complex (AIC) [12, 13], which are characterized by a significant part of energy consumption for creating a microclimate of production. In this case, in the general case, the principle of trigeneration implies the simultaneous receipt of electricity (to power electronic devices), as well as heat and cold (to create the necessary microclimate).

The use of such an integrated approach to solving the problem of energy conservation at agro-industrial complex facilities will reduce the energy intensity of production and, consequently, the cost of agricultural products.

Thermoelectric method and characteristics of thermoelectric modules

To describe the functioning of the climate control system based on the thermoelectric method and the subsequent study of its characteristics, we will consider the idea of this method of energy conversion, as well as the main characteristics of thermoelectric modules.

One of the known thermoelectric phenomena is the Peltier effect, which consists in the fact that when direct current is passed through a thermocouple consisting of two semiconductors, a certain amount of heat is released or absorbed at the point of their contact (junction) (depending on the direction of the current) [9, 10,14,15]. When electrons pass through electrical contact from a material with electron conductivity (p-type) to a material with a hole conduction (n-type), they have to overcome the energy barrier and take energy from the crystal lattice (cold junction). Conversely, when passing from an n-type material to a p-type material, the electrons give up energy to the lattice (hot junction).

Modern thermoelectric modules (TEM) based on the Peltier effect are a set of thermocouples electrically connected to each other, as a rule, in series using a copper connection plate - Fig. 1. Semiconductors based on bismuth, tellurium, antimony and selenium are traditionally used as materials for Peltier elements. In this case, the number of thermocouples can vary in a wide range - from units to hundreds of pairs, which makes it possible to create a TEM with a capacity from tenths to hundreds of watts. If efficient heat removal from the hot side of the TEM is ensured (for example, using a radiator), then on the cold side it is possible to obtain a temperature that will be tens of degrees lower than the ambient temperature, and the degree of cooling will be proportional to the value of the flowing current. Moreover, to increase the temperature difference, it is possible to cascade the Peltier thermoelectric modules [9], which makes it possible to obtain a significant temperature difference by relatively simple means and to provide effective cooling.

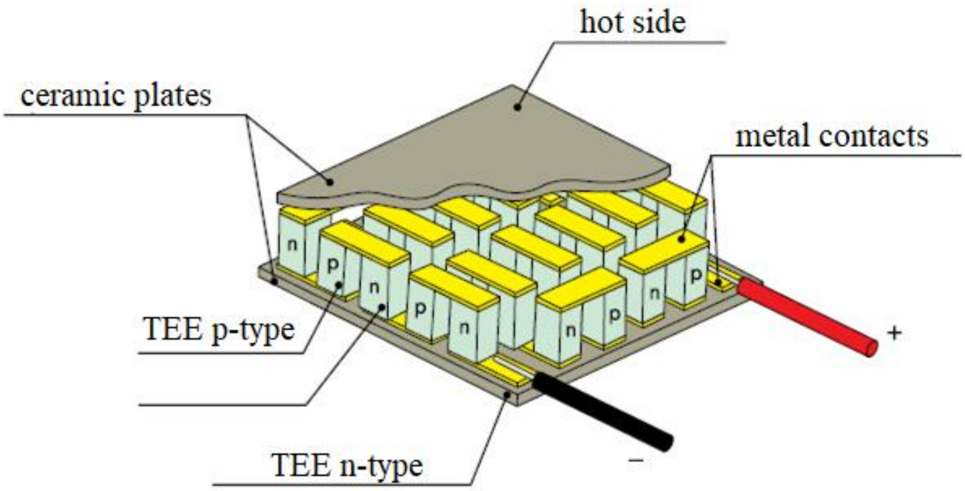


Figure 1 - The structure of the thermoelectric module based on the Peltier effect

The most important energy characteristic of any Peltier thermoelectric module is its refrigerating coefficient [9, 10], which is determined by the ratio of refrigerating capacity to the work expended. It is directly related to the figure of merit of the material used, which depends on the Seebeck coefficient, electrical conductivity and thermal conductivity of the material used.

Refrigeration coefficient of the thermoelectric module based on the Peltier effect is defined as

$$\varepsilon = \frac{\alpha \mathrm{T}_c I - 0{,}5 I^2 R - \lambda(\mathrm{T}_h - \mathrm{T}_c)}{I^2 R + \alpha I(\mathrm{T}_h - \mathrm{T}_c)}, \quad (1)$$

where α is the coefficient of differential thermoEMF, which depends on the physical properties of the material and its temperature; I is the strength of the current flowing through the module; R is the internal resistance of the module; λ is the average specific coefficient of thermal conductivity of the module; T_h and T_c are the temperatures of the hot and cold junctions.

From (1) it follows that this coefficient depends on the magnitude of the current flowing through the thermoelectric module. Moreover, its maximum value is reached at a current

$$I = \frac{\alpha(\mathrm{T_r} - \mathrm{T_x})}{R[\sqrt{1 + 0{,}5Z(\mathrm{T_r} + \mathrm{T_x}) - 1}]}, \quad (2)$$

where Z is the figure of merit of the material (thermoelectric), determined by its physical properties: thermal conductivity k, electrical conductivity σ and coefficient of thermoEMF α, which are related by the formula

$$Z = \frac{\sigma\alpha^2}{k}. \quad (3)$$

Climate control system based on thermoelectric Peltier modules for agro-industrial complex facilities

Thus, depending on the value of the control current flowing through the Peltier thermoelectric module, one or another temperature profile is formed on its junctions. Based on this principle [16-18], a simple structural diagram of the climate control system has been developed for an arbitrary object of the agro-industrial complex, a single point source of heat/cold and a single climate sensor, which directly includes the thermoelectric Peltier module (TEM) itself, its temperature controller (TC), ventilation system (VS), temperature sensor (TS) and inertia compensator (IC) for this sensor - Fig. 2. The following designations are also adopted in the diagram: T_d - desired temperature; I_c - control current for Peltier thermoelectric module; T_{PS} is the temperature of the point source of heat/cold; T_S - temperature at the outlet of the temperature sensor; T_{Scomp} - temperature at the outlet of the temperature sensor after passing through the inertia compensator.

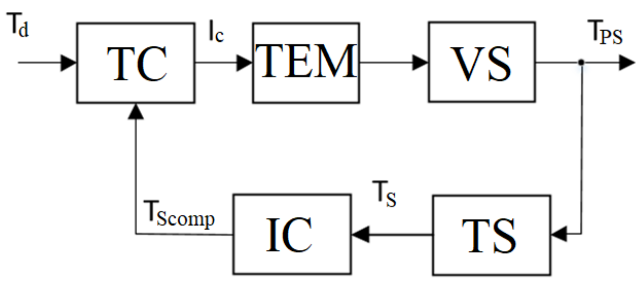


Figure 2 - Block diagram of the climate control system based on Peltier thermoelectric modules

According to this scheme, control over the microclimate at the AIC facility is carried out by a temperature regulator that generates the control current I_c for the thermoelectric module, which is a functional of the desired temperature of the T_d and the result of temperature measurements by the temperature sensor T_S. This control action has a direct impact on the temperature values of the sides of the Peltier thermoelectric module. The ventilation system in the circuit is used to ensure effective air exchange at the agro-industrial complex facility and is based on the convection principle of cooling, supplemented by the possibility of cold and heat removal from the thermoelectric module junctions to create a certain three-dimensional unsteady temperature field using point heat/cold sources. Control over the temperature regime installed at the agro-industrial complex is carried out using a temperature sensor. To reduce its inertia, a special compensator is used at the sensor output.

On the basis of the proposed structural diagram, an equivalent functional model with respect to temperature changes (Figure 3) has been developed, with the help of which it is possible to simulate its characteristics and quality indicators. The following designations are adopted on the diagram: $T_{\text{int}}(p)$ - interference effect simulating the processes of heat exchange between the environment and the external sides of the TEM; $H_{\text{TC}}(p)$ - transfer function of the temperature controller; $H_{\text{AZ}}(p)$ - transfer function of the aperiodic link of the temperature controller (used to reduce the inertia of the Peltier thermoelectric module); $H_{\text{TEM}}(p)$ - transfer function of the Peltier thermoelectric module; $H_{\text{VC}}(p)$ - ventilation system transfer function; $H_{\text{S}}(p)$ - temperature sensor transfer function; $H_{\text{IC}}(p)$ - transfer function of the inertia compensator; p is the Laplace operator; k_{I} and k_{P} are the transfer coefficients of the integral and proportional components of the temperature controller.

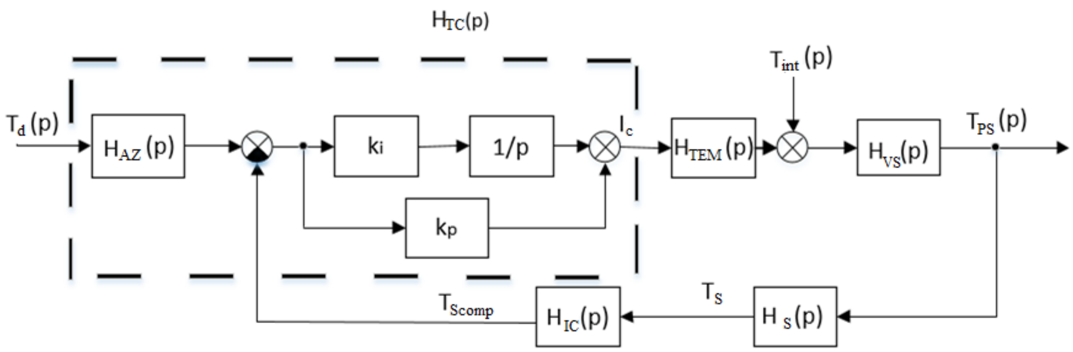


Figure 3 - Equivalent functional model of the climate control system based on Peltier thermoelectric modules

The transfer functions of the main structural links of the system are presented in table. 1

Table 1

Climate control system link	**Transmission function**
Aperiodic link of the temperature controller	$$\mathrm{H}_{AZ}(\mathrm{p}) = \frac{1}{\mathrm{Tp}+1}, \quad (4)$$ where *T* is the desired time constant of the temperature transient
Thermoelectric Peltier module	$$\mathrm{H}_{TEM}(\mathrm{p}) = \frac{\kappa_{TEM}}{\mathrm{T}_1\mathrm{p}+1}, \quad (5)$$ where k_{TEM} is the transfer coefficient of the module; T_1 - module time constant (takes into account its inertia)
Ventilation system	$$\mathrm{H}_{VC}(\mathrm{p}) = k_{VS}, \quad (6)$$ where k_{VC} is the transmission coefficient of the ventilation system (close to 1 and taking into account the heat losses arising in it)
Temperature sensor	$$\mathrm{H}_{S}(\mathrm{p}) = \frac{\kappa_{S}}{\mathrm{T}_S\mathrm{p}+1}, \quad (7)$$ where T_S is a time constant that takes into account the inertia of the sensor; k_S - coefficient of transmission of the temperature sensor (close to 1 and taking into account its imperfection)
Inertia compensator	$$\mathrm{H}_{IC}(\mathrm{p}) = \frac{\mathrm{T}_S\,\mathrm{p}+1}{\mathrm{T}_f^2\mathrm{p}^2+2\mathrm{T}_f\mathrm{p}+1}, \quad (8)$$ where T_{f} is the time constant of the filter of the inertia compensator polynomial

Using the transfer functions of links (4) - (8) and an equivalent functional model (Fig. 3), the transfer functions of the climate control system based on Peltier thermoelectric modules were obtained for the main effects:

- for useful

$$\mathrm{H}_d(\mathrm{p}) = \frac{\mathrm{H}_{AZ}(\mathrm{p})\mathrm{H}_o(\mathrm{p})}{1+\mathrm{H}_o(\mathrm{p})\mathrm{H}_{FB}(\mathrm{p})}, \quad (9)$$

where $\mathrm{H}_o(\mathrm{p}) = \mathrm{H}_{VS}(\mathrm{p})\mathrm{H}_{TEM}(\mathrm{p})\left[\frac{\kappa_I}{p}+\kappa_p\right]$ is the transfer function of an open feedback loop, $\mathrm{H}_{FB}(\mathrm{p}) = \mathrm{H}_S(\mathrm{p})\,\mathrm{H}_C(\mathrm{p})$ - generalized transfer function of feedback links;

-for interference

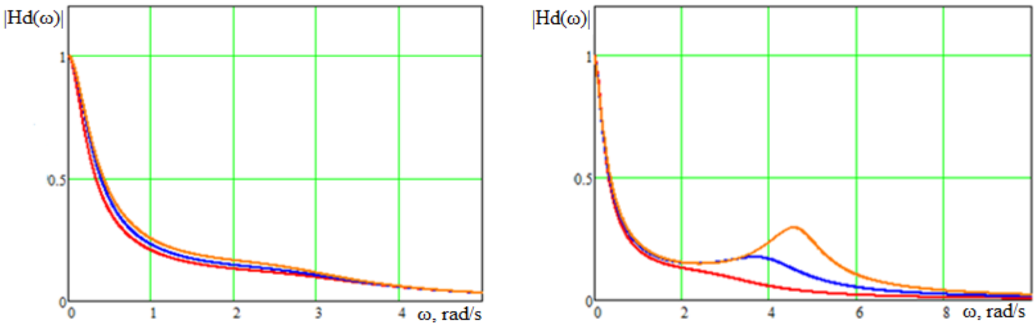
$$H_{int}(p) = \frac{H_{VS}(p)}{1 + H_o(p)H_{FB}(p)}. \quad (10)$$

The obtained expressions of the transfer functions of the system for various influences can be used to simulate its characteristics and quality indicators.

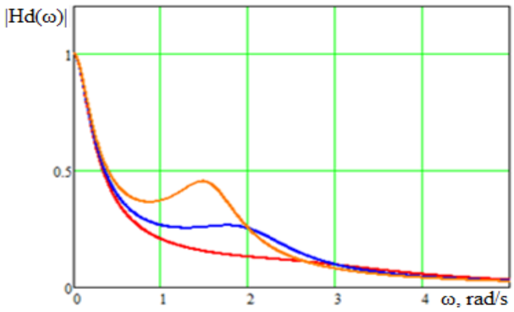
Frequency characteristics of the climate control system

The advantage of the proposed system is the use of the principle of control by deviation [19], which provides selective suppression of disturbing influences in a given range of the frequency spectrum, to assess the effectiveness of which it is necessary to conduct a study of the frequency characteristics of the device.

Replacing the Laplace operator p in relations (9) and (10) by the complex frequency $j\omega$ of signal and taking the modulus and argument of the resulting complex transfer function, we obtained the amplitude-frequency (AFC) and phase-frequency (PFC) characteristics of the system when changing the transmission coefficients of the controller links and the time constant filter of the inertia compensator polynomial. Figures 4 and 5 show the results of the corresponding AFC simulation as an example. In numerical modeling, the following system parameters were used: T=4 s, $\kappa_I = 0{,}625$, $\kappa_p = 2{,}5$, T_I = 1 s, $\kappa_{TEM} = 1$, $k_{\text{св}} = 1$, $\kappa_S = 1$, $T_S = 2$ s, $T_f = 0{,}2$ s. In the figures, the graphical dependences are shown in red at the initial value of the varied parameters of the system, in blue - when they are doubled, and in orange - when they are increased by three times.

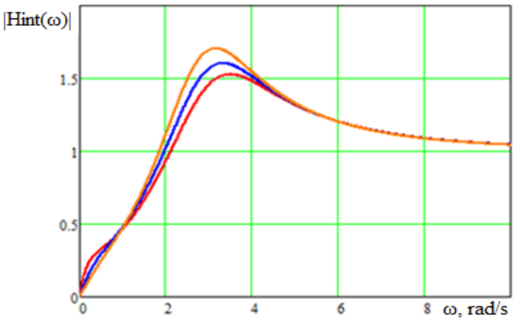


a) b)

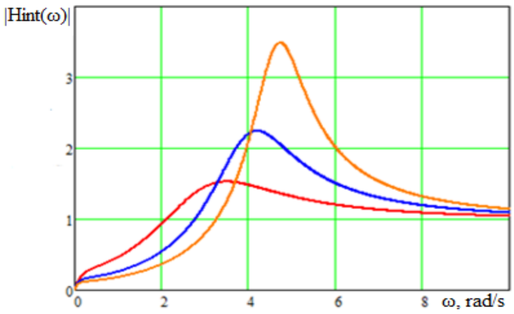


c)

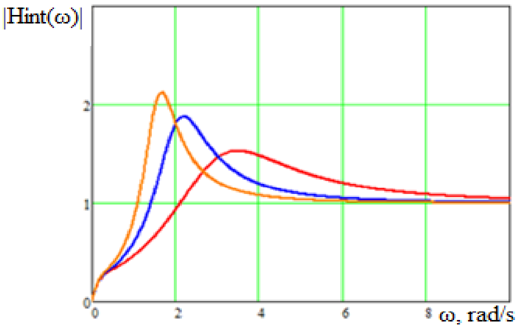
Figure 4 - AFC of the climate control system for a useful effect when changing the transfer coefficient of the integrating component of the controller (a), the transfer coefficient of the proportional component of the controller (b) and the time constant filter of the inertia compensator polynomial (c)



a)



b)



c)

Figure 5 - AFC of the climate control system for interference when changing the gain of the integrating component of the controller (a), the gain of the proportional component of the controller (b) and the time constant filter of the inertia compensator polynomial (c)

Conclusion

From the obtained graphical dependencies of the simulation results, the following generalized conclusions can be drawn:

- with an increase in the transfer coefficient of the integrating component of the temperature controller for both influences, an increase in the level of the frequency response of the system is observed while maintaining the shape;
- with an increase in the transmission coefficient of the proportional component of the temperature controller, an expansion of the system bandwidth for a useful effect and a narrowing for a noise one is observed, the frequency response level increases and becomes extreme;
- with an increase in the time constant of the filter of the polynomial of the inertia compensator, there is a narrowing of the system bandwidth for a useful effect and an expansion for a noise one, the frequency response level also increases and becomes extreme;
- the frequency response of the system for the beneficial effect corresponds to a low-pass filter, which in a given range of the frequency spectrum passes the useful effect to the system output, and for interference effects - to a high-pass filter, which suppresses the interference effect in a given range of the frequency spectrum.

The findings can be used in the practical implementation of a climate control system based on thermoelectric modules for objects of the agro-industrial complex to obtain a given quality of microclimate control.

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