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Principles of Construction of Microclimate Control and Management Systems in Agro-Industrial Production Based on Identification Algorithms

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Abstract

One of the key problems in the agro-industrial complex (AIC) is the reduction of energy consumption. In order to increase the energy efficiency of agricultural production, the use of thermoelectric systems as microclimate control systems is promising. The quality of such systems largely depends on the level of applied technical and technological solutions and control and control algorithms. A generalized structure for the construction of energy-saving cooling and thermoelectric regenerative systems (TRS) to ensure the microclimate at agricultural facilities has been developed. The operator identification model of the TRS is constructed on the basis of parametric approximation of the temperature dependences of the system. The control algorithm of the TRS operation based on the identification method for multidimensional objects is developed. In order to test the proposed algorithm, a full-scale simulation of the control of a simplified TRS cooling module, namely a separate Peltier module RMT thermoelectric 1MS06-030-05, operating in active cooling mode, was carried out. The experiment has shown a significant difference between the transient's duration of a correct (0.7 s) and defective (0.42 s) module RMT thermoelectric 1MS06-030-05 with a standard error of 0.068 s and a significance level <0.001 (t-value=13.622 for sample size 20). At the same time, the measurement of static parameters (resistance and Q-factor) did not reveal a significant difference between a correct and defective module. In further research, it is planned to validate the proposed method by testing a wide variety of Peltier thermoelectric modules.

Keywords: Agro-industrial complex, thermoelectricity, trigeneration system, microclimate management, identification algorithm

Introduction

Nowadays, the growth of agricultural production is closely related to the pace of scientific and technological progress in the agro-industrial complex (AIC), which is largely determined by the efficiency of its energy supply. The most significant consumers of energy resources in the agro-industrial complex are livestock, poultry complexes and enterprises associated with food storage [1-3]. In animal farm, energy costs occupy the second largest place after feed, and more than 30 % of energy consumption is accounted for by creating a microclimate of production [4,5]. The task of creating a microclimate for storing finished products is particularly important. Accordingly, the energy intensity of production, especially for maintaining the microclimate, has an important impact on the quality and competitiveness of products.

Among the scientific and technical activities, developments on adaptive power management of heating, ventilation and air conditioning systems are of interest. A promising energy-saving direction is the development of electrotechnological methods, equipment and technical means that ensure the production of high-quality food, seed material and animal feed [6]. Currently, thermoelectric modules are widely used in energy-saving systems. They are actively used in such high-tech areas as telecommunications, space, precision weapons, medicine, etc. Today, microclimate support devices for agro-industrial enterprises for the creation, storage and transportation of agricultural products have been developed and presented on the market [7,8].

Cooling devices in the agroindustrial complex based on thermoelectric modules perform the same functions as traditional compression or absorption units of refrigerators operating on the basis of refrigerants [9, 10]. The usual method of cooling equipment and devices with the help of radiators consists in the general case of the radiator receiving the heat released by the cooled object, distributing the received heat over its internal volume of the radiator and dissipating heat from the surface. To intensify the heat exchange, the possibility of obtaining the temperature of the cooled object below the ambient temperature is given by thermoelectric modules that perform the function of heat pumps [11]. It should be noted that an important feature of the use of thermoelectric modules in the formation of the microclimate at agricultural enterprises is the possibility of distributed formation of local features of the microclimate in the selected areas of objects. This makes it possible to significantly increase the energy efficiency of production with the use of distributed thermoelectric elements built on the basis of the use of distributed control and control systems [12]. However, one should take into account the need for precise adjustment and correction of the operating modes of all distributed parts of the thermoelectric system for maintaining the microclimate in real time with a built-in self-diagnosis system [13].

In this case, the efficiency of energy supply and energy consumption largely depends on the level of applied technical and technological solutions and control algorithms. In this paper, we study the principle of monitoring microclimate systems with thermoelectric batteries in agro-industrial production based on identification algorithms.

Structure of the control system and control of trigeneration modes

Thermoelectric energy converters based on the Seebeck and Peltier effects are distinguished by their design and operational characteristics, such as the absence of mechanical moving parts and, as a result, they have high operational reliability [14]. This makes it possible to operate them at agricultural facilities for a long time with minimal costs for periodic maintenance. At the same time, distributed systems for creating a microclimate based on low-power thermal power plants with the use of thermoelectric batteries provide an additional opportunity for regenerative use of heat from any sources of thermal energy and have the ability to work independently of the spatial position of the cooling zones and the environment. However, it requires fine-tuning of the entire system through the use of predictive control algorithms with a built-in self-diagnosis subsystem. One of the approaches to solving this problem is the use of identification methods [15].

Figure 1 shows a generalized structure for energy-saving cooling and thermoelectric regenerative systems to ensure a microclimate at agricultural facilities. In the given structure, the operating mode of a thermoelectric regenerative system is set by the input vector of parameters $\bar{X}$ and the optimization and stability conditions of the system $\bar{E}^*$ formed by the energy saving mode block in accordance with the specified conditions $\bar{E}$. Dynamic control of the thermoelectric regenerative system (TRS) is carried out in real time by a control system with feedback, consisting of three main blocks – the execution unit, the control unit and the subsystem measuring the main parameters of the whole system.

In this case, the control vector $\bar{U}$ is formed as a functional of the input vector of parameters, the selected climate mode, taking into account the energy saving $\bar{X}_E$, and the vector of mismatch of the object's climatic parameters:

$$\bar{U} = F_a(\bar{X}_E, \Delta\bar{E}, \bar{\Delta}_L), \tag{1}$$

where $\bar{\Delta}_L$ is the error vector of the mismatch caused by the application of linear control functions.

It should be noted that the measurement information received by the measurement subsystem has a limited and spatial discrete character:

$$\{\bar{T}\ ,\bar{E}^{*}\} = F_m(\bar{T}_c,\bar{T}_h,\bar{E}_T,\bar{\Delta}_m), \tag{2}$$

where $\bar{T}_c,\bar{T}_h,\bar{E}_T$ are vectors of trigenerative parameters, $\bar{\Delta}_m$ is the measurement error. At the same time, it is necessary to take into account the dynamic and stochastic nature of trigeneration parameters caused by technogenic factors $\bar{\xi}_T$ and natural factors $\bar{\xi}_p$.

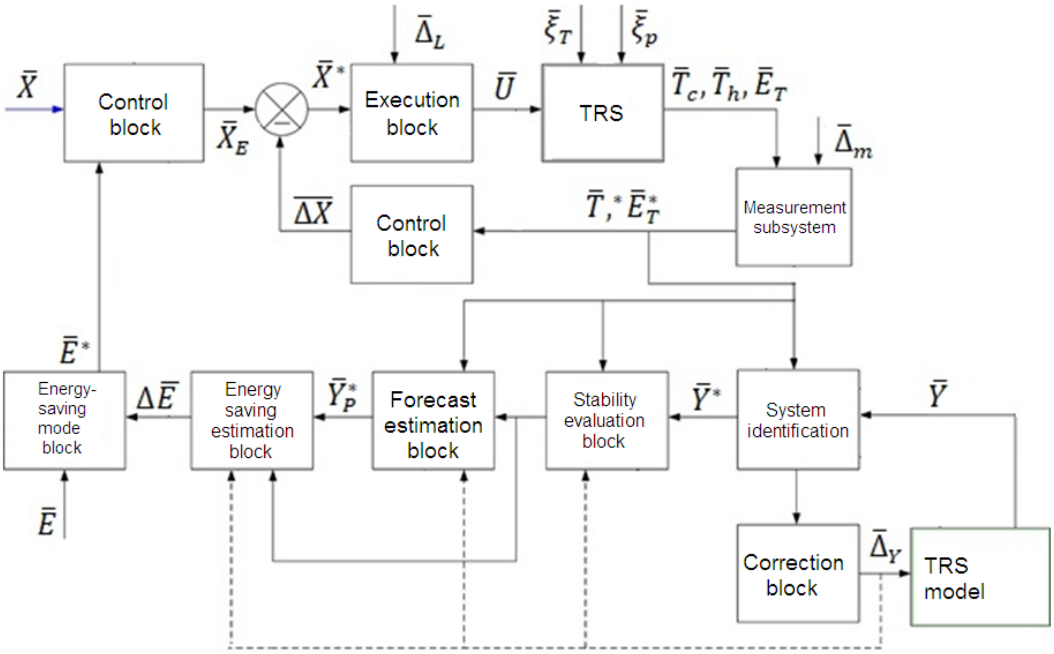

Figure 1-Generalized structure of energy-saving cooling and thermoelectric regenerative systems for providing microclimate at agricultural facilities

To construct algorithms for adaptive control of a thermoelectric installation, it should be taken into account that the temperature gradient has a time dependence that determines the transient nature of the process of thermoelectric transformations in Peltier modules [16]. In this structure, it permits to apply the TRS model and identification algorithms that implement self-monitoring of the system as a whole and its individual parts. In addition, on the basis of these algorithms, it is possible to conduct a stability assessment and a regression predictive assessment of the state of the system.

In this case, the identification model estimate is made on the basis of regression relations for the registered and identified parameters $\overline{\overline{Y}^*}$, and the model parameters of the system $\overline{Y}$ with the correction $\bar{\Delta}_Y$.

Operator identification model of the TRS

The identification model of the TRS can be constructed on the basis of a system of basic thermal conductivity equations and the Poisson equation extended by the thermoelectric effects of Peltier and Seebeck [17,18]. Accordingly, the output parameter under control is the temperature *T*, and the control is set by the supply voltage of the thermoelectric module TRS *U*. In this case, let's assume that at the control points of the operating mode of the TRS, the temperature can be determined based on the following model

$$T(t,x) = \tilde{S}_E(x,\alpha,\sigma,k)F_a(\bar{X}_E,\Delta\bar{E},\bar{\Delta}_L,t), \quad (1)$$

where $\tilde{S}_E$ is the operator of the thermoelectric unit of the TRS, α, σ and k are the parameters that characterize the thermoelectric properties of the module (the Seebeck coefficient), electrical and thermal conductivity, respectively. It is necessary to take into account the temperature dependence of these parameters. When simplifying the models, it can be assumed that these parameters and properties of the material do not depend on temperature and have isotropic properties at constant external conditions. However, to conduct a qualitative analysis of thermoelectric transformations, it is necessary to take into account the temperature dependence. In this case, the temperature-dependent properties of materials used in thermoelectric systems are interpolated by cubic splines [19]. However, the best option is a quadratic approximation of these parameters, which makes it possible to significantly simplify the construction of the model and take into account the parametric temperature dependence of the thermoelectric parameters. Figure 2 shows as an example the parametric temperature dependences for bismuth telluride modules taken from [20, 21].

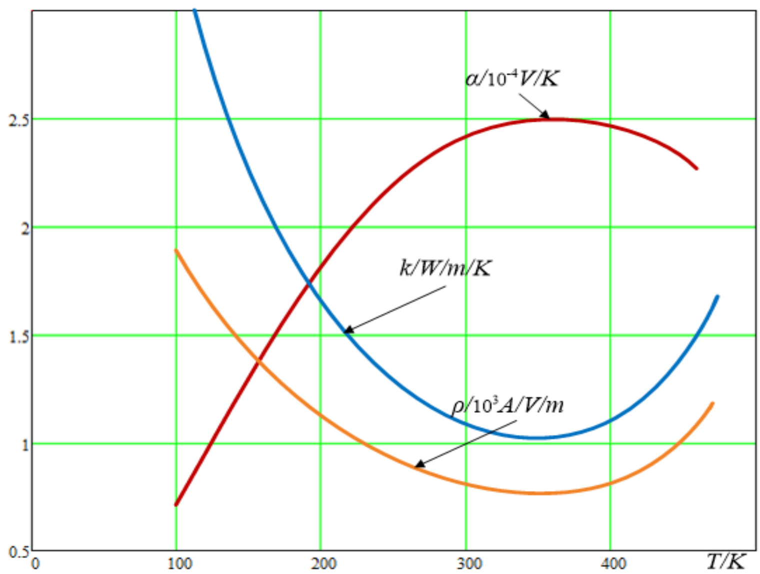

Figure 2-Parametric temperature dependences for bismuth telluride modules $(Bi_{0.5}Sb_{0.5})_2Te_3$: a) Temperature dependent Seebeck coefficient; b) Temperature

dependent thermal conductivity; c) Temperature dependent electric conductivity

In accordance with these assumptions, the parametric temperature dependences can be represented as

$$\vartheta(\alpha, k, \rho) == A_{(\alpha,\sigma,k)} + B_{(\alpha,\sigma,k)}T + C_{(\alpha,\sigma,k)}T^2,$$

$$T(t, x) = \tilde{S}_E(x, \alpha, \sigma, k) F_a(\bar{X}_E, \Delta\bar{E}, \bar{\Delta}_L, t). \quad (2)$$

Based on the principles of operation of thermoelectric batteries on Peltier modules and taking into account the parametric dependencies for the modules used in the battery in the operator form, equations (2) will take the following form [22]:

$$T(p, x) = \frac{E(J - \bar{\varepsilon}p)}{a_0(x,\vartheta) + \sum_{i=1}^{n} a_i(x,\vartheta)T^i + (b_0(x,\vartheta) + \sum_{j=1}^{m} b_j(x,\vartheta)T^j)p} F_a(\bar{X}_E, \Delta\bar{E}, \bar{\Delta}_L, p)\ , \quad (3)$$

where p is the Laplace operator. Equation (30) takes into account the thermoelectric inertia of Peltier elements operating in both forward and inverse modes of the trigeneration system. Finally, the temperature regime can be described by the following operator model in the form of a differential equation

$$\sum_{i=0}^{n} a_i(x, \vartheta)\, T^{i+1}(x) + \sum_{j=0}^{m} b_j(x, \vartheta)\, T^{j+1}(x)p = E(J - \bar{\varepsilon}p) F_a(\bar{X}_E, \Delta\bar{E}, \bar{\Delta}_L, p). \quad (4)$$

Control algorithm based on the identification method for multidimensional objects

The control algorithm of the TRS can be built based on the identification method for multidimensional objects. In this case, we assume that the points control the operating mode of TRS on agroindustrial object's temperature can be determined on the basis of these models (2-4):

$$T^*(t, x) = \tilde{S}_E^* E(t) \text{ и } T(t, x) = \tilde{S}_E E(t), \quad (5)$$

where $\tilde{S}_E$ is the true operator of the TRS operation, $\tilde{S}_E^*$ is the optimal operator approximating the true one. The optimal operator can be determined on the basis of regression relations based on observations of transients in the TRS by the minimum standard error approximation criterion [23]:

$$\frac{1}{n} \sum_{i=1}^{n} [T_i\,(t, x) - \tilde{S}_E^* E_i(t)]^2 \to min \quad (6)$$

In accordance with (2-4), the TRS model can be represented in the form of a linear differential equation of the form

$$T^{[n]} + \sum_{i=0}^{n-1} D_{Ti}(t, x)\, T^{[i]} = \sum_{i=1}^{m} D_{Ei}(t, x) E^{[i]} \quad (7)$$

or $\tilde{L}_T T = \tilde{L}_E E$. Where $\tilde{L}$ is the linear parametric differential operator defining the transfer function of the TRS, which can be defined in accordance with the operator model:

$$\tilde{L}_T = \sum_{i=0}^{n} a_i(x,\vartheta)\,T^i(x) + \sum_{j=0}^{m} b_j(x,\vartheta)\,T^j(x)p\tilde{L}_E\ ,\ \tilde{L}_E = E(J - \bar{\varepsilon}p)F_a(\bar{X}_E, \Delta\bar{E}, \bar{\Delta}_L, p) \quad (8)$$

Switching to the spectral form of the description of thermoelectric processes in the TRS, equations (7,8) can be presented in the following form

$$\tilde{L}_T(j\omega)S_T = \tilde{L}_E(j\omega)S_E.$$

From it follows

$$S_T = [\tilde{L}_T(j\omega)]^{-1}\tilde{L}_E(j\omega)S_E = \tilde{L}(j\omega)S_E\ ,$$

where $\tilde{L}(j\omega)$ is the spectral characteristic of the TRS object.

This ratio is the basis for constructing algorithms for identifying the TRS and its individual components.

Let's assume that the trigeneration system is generally affected by a non-stationary influence that determines the qualitative changes in the process of establishing climate regimes in the control zones of the AIC object $\bar{X}_E(t) \Rightarrow S_E$. The reaction of the TRS control and monitoring system can be represented as a spectral decomposition over the selected orthonormal basis.

$$T(t,x) = \widetilde{\Psi}^T(x,t)\tilde{L}(j\omega)S_E \quad (9)$$

In this case, for the mathematical expectation of the cross-correlation function of the input action and the reaction of the system

$$\mathrm{M}\{T(t_1,x)E(t_2)\} = \mathrm{M}\{\widetilde{\Psi}^T(x,t_1)\tilde{L}(j\omega)S_E S_E^T\widetilde{\Psi}(x,t_2)\} \quad (10)$$

Using the commutativity property of the TRS spectral characteristic operator and the expression (10), we obtain an expression for the mutual spectral function [24]:

$$R_{TE}(t_1,t_2) = \widetilde{\Psi}^T(x,t_1)\tilde{L}(j\omega)M\{S_E S_E^T\}\widetilde{\Psi}(x,t_2)\ , \quad (11)$$

where

$$M\{S_E S_E^T\} = \left\|\begin{matrix} c_1^E c_1^E & \dots & c_1^E c_L^E \\ \dots & \dots & \dots \\ c_L^E c_1^E & \dots & c_L^E c_L^E \end{matrix}\right\|,\ M\{c_i^E c_j^E\} = \iint_0^t R_{EE}(t_1,t_2)\psi_i(t_1)\psi_j(t_2)dt_1dt_2 = c_{ij}^{EE} \quad (12)$$

In spectral form, this expression is represented as follows:

$$R_{TE}(t_1,t_2) \Rightarrow R_{TE}^{\psi}(t_1,t_2)\sum_{i=1}^{L}\sum_{j=1}^{L} c_{ij}^{EE}\,\psi_i(t_1)\psi_j(t_2) = \widetilde{\Psi}^T(x,t_1)M\{S_T S_E^T\}\widetilde{\Psi}(x,t_2) \quad (13)$$

In accordance with (11) and (13), we can write

$$M\{S_T S_E^T\} = \tilde{L}(j\omega)M\{S_E S_E^T\},$$

$$\text{or} \quad \sum_{\nu=1}^{L} c_{\nu j}^{EE} l_{i\nu} = c_{\nu j}^{TE} \quad (14)$$

The control algorithm of the TRS implies sequential evaluation of the spectral characteristics of the control actions and the recorded values of temperature conditions at the control points, as well as the corresponding correlation functions. On the basis of the obtained data, the coefficients of the differential equation set by the control model of the TRS are determined based on the regression analysis [25].

In order to test the proposed algorithm, a full-scale simulation of the control of a separate Peltier element (as a simplified TRS module) operating in the active cooling mode, was carried out.

Experimental studies

To verify the transient's identification method on the Peltier module, an experiment with a commercially available module was conducted. The type of module under test is 1MS06-030-05 manufactured by RMT thermoelectric, which is a single-stage thermoelectric module with a cross section of thermoelectric branches of 0.6 × 0.6 mm, 30 pairs of branches; the height of the branch is 0.5 mm. Its main parameters: maximum current 3.4 A, resistance 0.86 ± 0.04 Ω, quality factor 2.52 ± 0.1. The scheme of experimental setup is depicted in Figure 3.

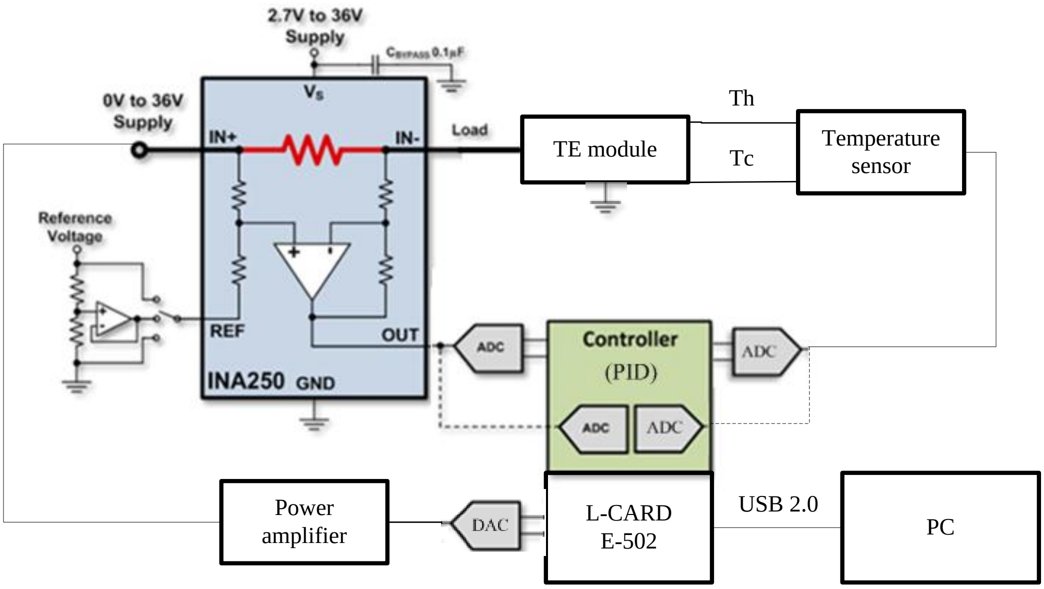

Figure 3 – The scheme of experimental setup

TE module under test was connected to the current supply based on the INA250 microchip, which is shown on the left side of the Fig. 3. A PID controller and four analog-to-digital converters (ADC) were used for adjustment of its working mode.

Temperature on the module's hot side Th and its cold side Tc were measured by the temperature sensor YEW3655A. The controller was implemented based on the L-CARD E-502 board, which was connected to a personal computer (PC) via USB 2.0 interface.

Then the results were used to determine the time constant based on the given identification algorithm. After the end of the transient mode (in stationary mode), the thermoelectric element operated at 10% of the maximum load at a current of 0.35 Amperes. This allowed the use of a thermoelectric module without thermal load at steady temperatures.

In this case, to control the transient thermoelectric process, the supply current of the module is incrementally increased by another 10% to a value of 0.7 Amperes. The experiment was repeated 20 times with an interval of 5 minutes to establish a stationary mode. After 5 seconds, the current was reduced again to 0.35 amperes. The graph shows the transient average temperature of the cold side. A current pulse lasting 5 seconds caused the temperature to drop by about 3 K and the module to reach a new stationary operating point.

Table 1 shows transient time constant on a correct and defective thermoelectric module 1MS06-030-05, obtained in the experiment**.**

Table 1 – The obtained transient time constant on a correct and defective thermoelectric module 1MS06-030-05

Experiment number	Time constant for a correct module, s	Time constant for the defective module, s
1	0.567	0.519
2	0.627	0.233
3	0.734	0.437
4	0.727	0.397
5	0.662	0.458
6	0.655	0.491
7	0.71	0.403
8	0.534	0.494
9	0.715	0.298
10	0.642	0.566
11	0.588	0.519

Experiment number	Time constant for a correct module, s	Time constant for the defective module, s
12	0.748	0.425
13	0.586	0.427
14	0.596	0.319
15	0.843	0.339
16	0.711	0.411
17	0.779	0.396
18	0.718	0.49
19	0.755	0.295
20	0.662	0.464

For the correct module, the following distribution parameter values were obtained based on the Table 1 data: the average value of 0.7 s; the standard deviation of 0.065 s; the confidence interval for the significance level of 0.05 – 0.03 s. Values correspond to the passport data of the module 1MS06-030-05.

The next experiment was a series of repeated measurements of transients with an initial current of 0.35 A and then an abrupt increase in current to a value of 0.7 A, but with a defective module. About 5% of the branches were mechanically removed in it. During the experiment, such a defect was well manifested in measurements by the considered identification algorithm. Moreover, the standard check of the thermoelectric module based on the measurement of resistance and Q-factor did not identify the module’s defect: the obtained values of resistance 0.89 Ohm and Q-factor 2.51 are within the tolerances specified by the manufacturer (resistance 0.86±0.04 Ohm, Q-factor 2.52±0.1).

For the defective module, based on the Table 2 data, the following distribution parameters were obtained: the average value of 0.42 s; the standard deviation of 0.063 s; the confidence interval for the significance level of 0.05 – 0.028 s. Thus, as a result of the experiment, the time constant turned out to be 0.42 s, which is almost two times less than the standard value for a correct module. Therefore, the measurement of the time constant unambiguously identifies a defective module (t-value=13.622 for sample size 20, i.e., the correct and defective module differ at a significance level <0.001). The results show a good prospect of the developed method for monitoring the performance and efficiency of Peltier modules based on the analysis of transients in order to insure the reliability of refrigeration equipment.

Conclusion

To reduce energy consumption at the objects of the agro-industrial complex, a generalized structure of thermoelectric regenerative systems for providing microclimate has been developed. An operator model of TRS identification based on parametric approximation is proposed, as well as an TRS monitoring algorithm based on this model. The experiment has shown a significant difference between the transient duration of a correct (0.7 s) and defective (0.42 s) module RMT thermoelectric 1MS06-030-05 with a standard error of 0.068 s and a significance level <0.001 (*t*-value=13.622 for sample size 20). At the same time, the measurement of static parameters (resistance and Q-factor) did not reveal a significant difference between a correct and defective module. The results show a good prospect of the developed method for monitoring the performance and efficiency of Peltier modules based on the analysis of transients. This makes it possible to build automated systems for maintaining the microclimate at agricultural facilities with a built-in diagnostics subsystem, which is an extremely important problem to ensure the reliability of refrigeration equipment. In further research, it is planned to validate the proposed method by testing a wide variety of Peltier thermoelectric modules.

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