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Control of operability of Peltier modules in cooling systems based on the analysis of transient operating modes

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Abstract The paper is devoted to the control of operability of Peltier modules based on the analysis of transient modes of their operation. Advantages of using low-power thermoelectric modules for the development of thermoelectric plants with adaptive control systems for the needs of the agricultural complex, which significantly reduce their cost characteristics, are shown. The problem of using the stationary mode of their operation, associated with the low efficiency of the modules, as well as the dynamic mode, associated with the presence of transient processes, is indicated. It is noted that overcoming this problem requires solution of the task of automation of reliability providing the well-known approaches to its solution are shown, for which the key advantages and disadvantages are given. An approach is proposed to complex control of the operability and quality of thermoelectric modules during their expluatation in three components of the physical process of thermoelectric conversion (Peltier thermoelectric effect, electrical and thermal transfer phenomena) by analyzing transients in the system based on identification algorithms. To justify it, the necessary equations and mathematical relations are given. Aprobating of the proposed approach was carried out experimentally by determining the time constants for operable and defective commercially available modules and showed its significant advantages over the standard verification procedure.

Keywords: Thermoelectric systems; Agriculture complex; Transients; Peltier effect; Identification algorithms

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1 Introduction

Currently the development of thermoelectric systems in various fields of technology is based on standard thermoelectric modules. There are a significant number of papers [1–6], which provide information on the characteristics and parameters of thermoelectric modules used. An essential factor determining the possibility of using thermoelectric systems in various production processes of the agro-industrial complex (AIC) is their low cost. However, the cost of thermoelectric plants increases significantly with increasing power associated with a relative decrease in cooling capacity relative to power. That is why today for the needs of the agro-industrial complex, the developments of low-power thermoelectric systems are used, built on low-power thermoelectric modules, the cooling capacity of which does not exceed the level of 100 W [7]. However, in recent years, a trend should be highlighted related to the improvement of the manufacturing technology of both standard thermoelectric modules with adaptive control systems and devices based on them, which can significantly improve the cost parameters of thermoelectric cooling power [8].

In some cases, when the thermostabilized components and equipment at the agro-industrial complex are operating in a stationary mode and the operating conditions (ambient temperature, humidity) are unchanged, the stationary operating mode of a thermoelectric microclimate system can be used. However, it should be noted that the operation of the system in stationary mode is extremely uneconomical due to the impossibility of soft adjustment of the microclimate. It shoulds also take into account the transient processes of turning on and off the modules, which require a power reserve of power supply elements. In this case, the operating current after the system reaches the necessary sector of the stationary mode decreases to a normal level. This effect is especially significant in the mode of creating the maximum temperature difference at the minimum heat load [9]. At present, proportional controllers have been developed and are used with the aid of various algorithms for controlling the output voltage. To control these controllers, resistive semiconductor temperature sensors of various designs are used, located in the microclimate zones in the AIC object and providing feedback from the facility to the controller. Depending on the microclimate environment, the sensors have a linear temperature dependence of resistance in the operating temperature range and can be installed on the object, on a radiator, or directly inside a thermoelectric module [10].

Of particular note is the task of automatically ensuring reliability of operation, which is solved in thermoelectric microclimate systems at AIC objects. The simplest method for thermoelectric module self-diagnosis is the method for control the operability of a thermoelectric module, which consists in measuring the magnitude and changes in the electrical resistance of a thermoelectric module during testing and during operation [11]. The disadvantage of this approach is the implicit informativeness of the criterion, which does not allow high quality reliability to record changes in the quality of the thermoelectric module. In many cases of failure of the thermoelectric module, its resistance does not undergo changes, and therefore additional control methods are required.

Also known is the quality control method of the Harman thermoelectric module [12], in which the quality factor of the thermoelectric module is controlled. In this case, the criterion for the operability and quality of work of the thermoelectric module is the permissible Q-factor deviation within the permissible limits under operating conditions and during diagnostics. In a large number of malfunctioning situations, which especially occur briefly and indicate the onset of destructive processes in the thermoelectric system of automated climate control, the control of quality factor of the thermoelectric module does not allow us to identify many deviations in the quality of thermoelectric module, as well as to identify their causes [13].

Obviously, the principle of operation of thermoelectric modules is based on three components of the physical process of thermoelectric conversion, namely: the Peltier thermoelectric effect, as well as electrical and thermal transport phenomena. Therefore, the control of the operability and quality indicators of thermoelectric modules must be determined comprehensively during the operation of the modules. One of the possible approaches to solving this problem is to control all three components characterizing the mechanism of thermoelectric phenomena based on the analysis of transients in the system based on identification algorithms.

2 Management and control of operation of thermoelectric elements

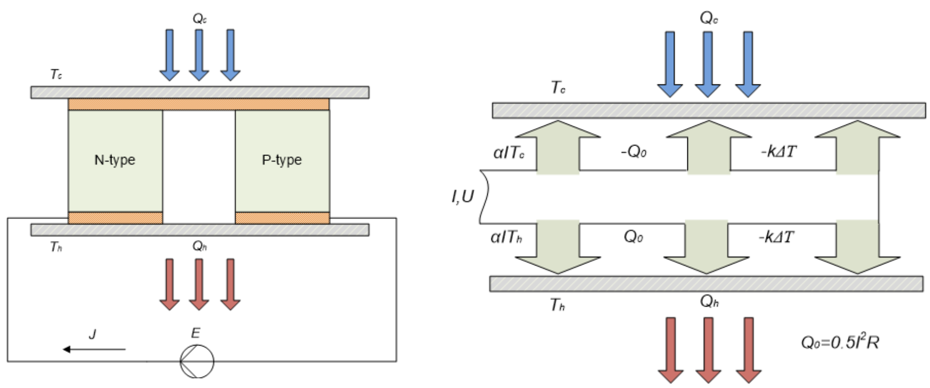
The simplest Peltier thermoelectric device is a thermocouple consisting of connected semiconductor wires of n-type and p-type conductivity. The model of a thermoelectric battery can be represented in the form of thermoelements connected thermally in parallel and electrically in series (Fig. 1a).

In this case, the equations describing the thermoelectric conversion based on the Peltier effect relate the thermal conversion of the current through the element [14, 15]:

$$J = \sigma E - \sigma\alpha\nabla T, \tag{1}$$

$$Q = \pi J - k\nabla T, \tag{2}$$

where J is the electric current density, σ is the electrical conductivity, E is the electric field, α is the Seebeck coefficient, ∇T is the temperature gradient, Q is the amount of heat, π is the Peltier coefficient, and k is the thermal conductivity.



(a) (b)

Figure 1: Model of an element of a thermoelectric battery based on the Peltier effect.

In accordance with (1)–(2), the model of energy transformations in a element of a thermoelectric battery based on the Peltier effect can be represented in the form of a simplified schematic thermoelectric model (Fig. 1b). In accordance with it, the energy balance equations on the cold and hot sides in the static mode are written in the following form [16–18]:

$$Q_c = \alpha I T_c - \frac{1}{2} I^2 R - k\Delta T\,, \tag{3}$$

$$Q_h = \alpha I T_h - \frac{1}{2} I^2 R - k\Delta T\,, \tag{4}$$

where I is the electric current, $\Delta T = T_h - T_c$, T_h is the temperature of the hot side of the thermoelectric battery, T_c is the temperature of the cold side of the thermoelectric battery, R is the electrical resistance of the Peltier element.

Power consumption is determined in accordance with the following relation:

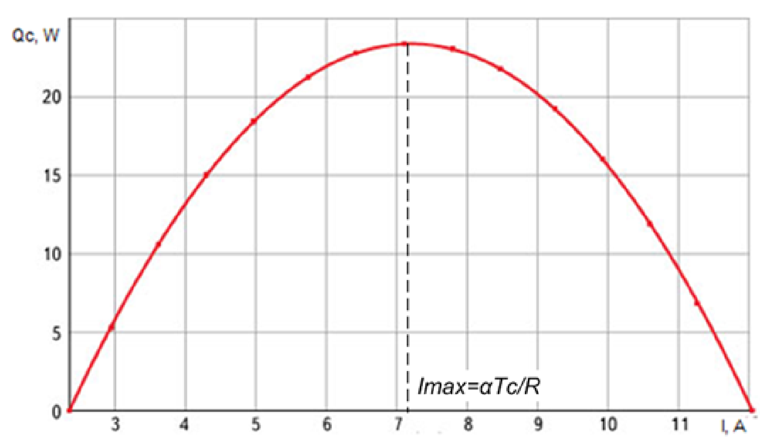
$$W = \alpha I \left(T_h - T_c\right) + I^2 R. \tag{5}$$

In accordance with (3) and (4), the relationship between the temperature on the cold side and the energy of the cooling capacity of the Peltier element is as follows [19]:

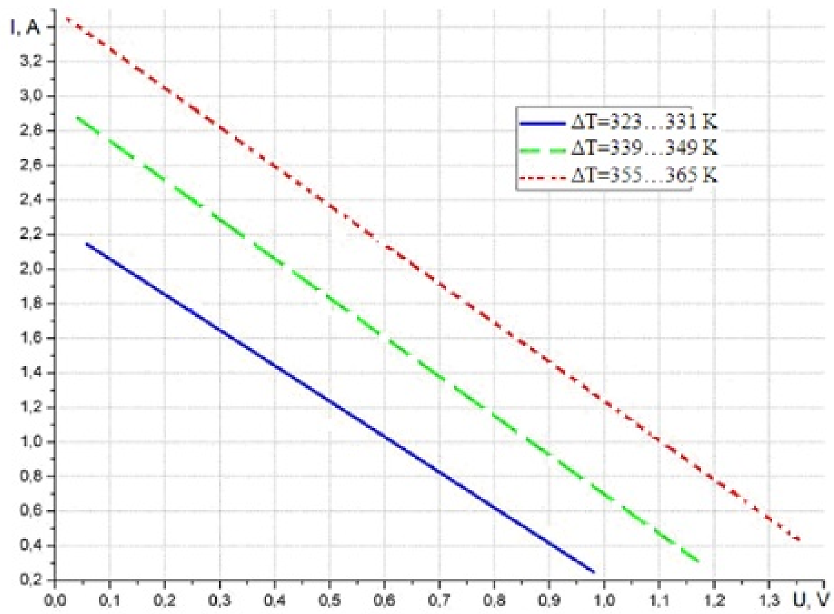
$$\frac{\partial Q}{\partial I} = \alpha T_c - IR\,. \tag{6}$$

Based on (6), it is possible to determine theoretically the maximum possible cooling capacity and the condition for its achievement at a given temperature (Fig. 2a). Figure 2b shows the operational current-voltage $(I - U)$ characteristics at various operating temperatures for the Peltier element TEC-12709 [18].

However, when using dynamic control of the cooling mode when using Peltier modules in microclimate maintenance systems at AIC objects, in addition to the static mode, it is necessary to take into account the transient characteristics of their operating mode, which largely determine the quality indicators of the system as a whole. In this case, based on the analysis of the transfer characteristics, it is possible to control the operability of thermoelectric modules and their wear.



(a)



(b)

Figure 2: Static characteristics of Peltier thermoelectric converters.

3 Thermodynamic transients and their control based on identification algorithms

Transients in Peltier modules are determined by the effect of heat and mass transfer, which determines the diffusion nature of the temperature distribution in the branches of the module. In general form, they are described by the differential diffusion equation of heat distribution. For the simplest one-dimensional case [20] the transient reads:

$$\frac{\partial T}{\partial t} = a^2 \frac{\partial^2 T}{\partial x^2} + q(x,t), \tag{7}$$

where q is the heat flow, t is time, and the space coordinate x is set up along the direction of electrical current as shown in Fig. 1a. Obviously, in accordance with (7) in Eqs. (1)–(2), the temperature gradient has a time dependence that determines the transitional nature of the process of thermoelectric transformations in the Peltier module. In accordance with these assumptions, the inertia of the thermoelectric module can be described after the corresponding transformations of Eqs. (1)–(2) in the form:

$$\varepsilon \frac{\partial E}{\partial t} = J - \sigma E + \sigma\alpha \frac{\partial T}{\partial x}\,, \tag{8}$$

$$\rho C_\nu \frac{\partial T}{\partial t} = \sigma E\left(E - \alpha\frac{\partial E}{\partial x}\right) + \frac{\partial}{\partial x}\left[\left(k + \sigma\alpha^2 T\right) - \sigma\alpha T E\right], \tag{9}$$

where ε is the dielectric constant, ρ is the density of the module and C_ν is the specific heat.

The above relations can be used to control the operability and quality of operation of thermoelectric modules based on the identification algorithm. In this case, suppose that at the control points of the transient operating mode of the thermoelectric module and the formation of temperature can be determined the model

$$T^*(t,x) = \widetilde{S}_E^* E(t) \qquad \text{and} \qquad T(t,x) = \widetilde{S}_E E(t), \tag{10}$$

where $\widetilde{S}_E$ is the true operator of the thermoelectric module, and $\widetilde{S}_E^*$ is the optimal operator approximating the true operator of the thermoelectric module.

The optimal operator can be determined on the basis of regression relations according to the observation of transients by the criterion of the minimum mean-square approximation [21]

$$\frac{1}{n}\sum_{i=1}^{n}\left[T_i(t,x) - \widetilde{S}_E^* E_i(t)\right]^2 \to \min\,, \tag{11}$$

where n is the number of sample points. The model of the control object (thermoelectric module) will be found in the form of a linear differential equation of the form

$$T^{[n]} + \sum_{i=0}^{n-1} a_i(t,x) T^{[i]} = \sum_{i=0}^{m} b_i(t,x) E^{[i]} \tag{12}$$

or

$$\widetilde{L}_T T = \widetilde{L}_E E\,,$$

where $\widetilde{L}$ is a linear parametric differential operator that defines the transfer function of the thermoelectric module, m is the size of temperature vector T, the symbols $[n]$ and $[i]$ denote the last and current element of the vectors T and E whereas subscripts T and E denote vectors of temperature and electric strength values, respectively.

Accordingly, when simplifying and assuming the uniformity of the branches of the thermoelectric converter and, accordingly, the homogeneity of the electric field in its branches, the model of the thermoelectric module in accordance with the above relations can be presented in the operator form

$$K(p) = \frac{\widetilde{L}_E}{\widetilde{L}_T} = \frac{E(J - \varepsilon p)}{\dfrac{\sigma(\alpha E - \alpha)^2 \partial T}{\partial x} + \rho C_\nu p}\,, \tag{13}$$

where p is the density and ρ is specific electric resistivity.

4 Experimental studies

To assess the applicability of the identification method for control transient thermoelectric processes on the Peltier module, an experiment was conducted using a commercially available module. The type of module according to the manufacturer's classification RMT thermoelectric-1MC06-030-05 [22], which is a single-stage thermoelectric module with a cross section of thermoelectric branches of 0.6 mm $\times$ 0.6 mm, for which the number of pairs of branches is 30, the height of the branch is 0.5 mm. Its main parameters: maximum current – 3.4 A, resistance – $0.86 \pm 0.04\ \Omega$, quality factor – 2.52 ± 0.1.

Figure 3 shows the results of an experiment to determine the time constant characterizing the thermoelectric transient of a modules based on the presented identification algorithm. The number 1 in the figure indicates the transient curve for a working module, and the number 2 for a defective module. In this case, the thermoelectric element in stationary mode worked at 10% of the maximum load at a current of 0.35 A, which made it possible to use a thermoelectric module without thermal load at steady temperatures. The lower diagram shows electrical current applied to the module during the experiment.

At the same time, to control the transient thermoelectric process of the supply module, the current jump increased by another 10% to a value of 0.7 A. The experiment was repeated 20 times with an interval of 5 min to establish a stationary regime. After 5 s, the current decreased again to 0.35 A. The graph below shows the transitional averaged temperature of the cold side. A current pulse lasting 5 s caused a temperature drop of about 3 degrees and the module to reach a new stationary operating point.

Based on a series of experiments, the time constant determined on the basis of the identification algorithm using the regression analysis turned

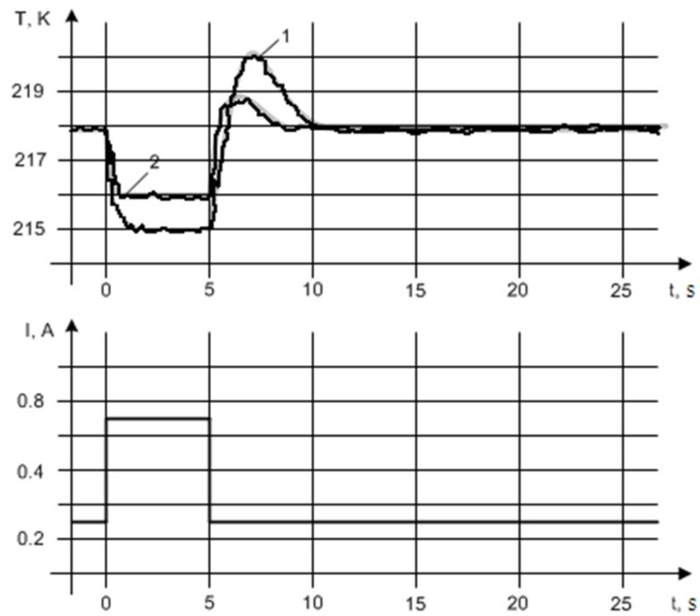


Figure 3: The results of a study of transients on a thermoelectric module 1MC06-030-05.

out to be 0.7 s with a confidence interval of 0.03 s and a probability of 0.95, which corresponds to the passport data of the module under test.

The next experiment was a series of repeated measurements of parameters of transients in the same mode with an initial current of 0.35 A with 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 model identification algorithm. Figure 4 also shows the improvement in the performance when the optimized control are installed and using the optimized thermoelectric module and heat sinks. One of the reasons for the significant disparity in the cold air temperature difference between the optimum values and the predicted results is because of the different heat sinks fin spacing. Moreover, the standard check of the thermoelectric module based on the measurement of resistance with the quality Q-factor did not allow to identify the module defect. At the same time, the measurement of the time constant unambiguously identifies the defective module. 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 working module.

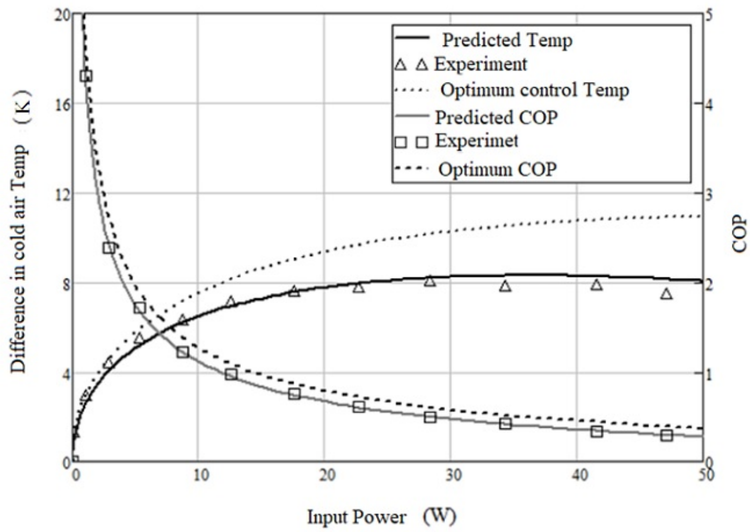


Figure 4: Variation of experiment and predicted coefficient of performance (COP) and cold air temperature difference against input power.

5 Conclusion

The studies showed a good prospect of using the developed method for the control of the operability and efficiency of thermoelectric modules based on the Peltier effect using the analysis of transient characteristics. In general, the application of the presented thermoelectric cooling system enabled to decrease the air temperature in the experimental room by 5.3 K up to 15.1 K, depending on the research stage, while better cooling performance was connected with the use of heat recovery for water heating. According to the previous studies, there is a possibility to obtain higher coefficient of performance (COP) values by keeping the temperature difference between the cold and hot side of thermoelectric module as low as possible. Therefore, it is possible to develop a preliminary water heating system on the basis of the presented prototype, and the trials on the coefficient of performance optimization while keeping the functionality of thermoelectric cooling and heating system will be authors' future research direction. This allows to build automated systems for maintaining the microclimate at AIC objects with a built-in diagnostic subsystem, which is an extremely important problem of ensuring the reliability of refrigeration equipment.

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