International Journal of Agriculture and Biosciences 2023 12(4): 228-233.
https://doi.org/10.47278/journal.ijab/2023.069

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Control and Stabilization of the Spatiotemporal Distribution of Climatic Parameters at Agricultural Facilities using Thermoelectric Systems

Gleb S Vasilyev*, Oleg R Kuzichkin, Dimitry I Surzhik and Aleksandr V Koskin

Belgorod State Research University, Belgorod, 85 Pobedy Street, Russia
*Corresponding author: vasilievgleb@yandex.ru

ABSTRACT

Nowadays, thermoelectric modules represent important components of energy-saving systems. Controlling and stabilizing the spatiotemporal distribution of climatic parameters at agricultural facilities using thermoelectric systems is based on models and algorithms for optimal control. In this context, technical indicators and energy-saving criteria act as minimization factors. The foundation for addressing the challenge of developing and analytical support for an energy-saving thermoelectric microclimate control system in agricultural facilities is based on the principles of building an adaptive microclimate control system, taking into account both the current climatic state of the control object, as well as the ability to adapt automatically in automatic mode to changes in the technological operating conditions of the object and climatic environmental conditions. All these tasks are complicated by the nonlinear dependencies of the control branches of thermoelectric equipment and the parameters of climatic conditions in the controlled object. To address climate control challenges using thermoelectric systems, we propose spatiotemporal algorithms for processing and controlling thermoelectric cooling and regenerative systems. We also introduce a criterion for optimizing transient control in thermoelectric systems. In conclusion, we have conducted modeling and analysis of a transient mode TEM-based climate management system with the aid of new algorithms and computer-assisted systems. The simulation results demonstrate potential improvements in the system's transient characteristics.

Keywords: Agricultural climate systems, Biometeorology, Modeling, TEM-based climate management system, Thermoelectrics.

Article History
Article # 23-513
Received: 01-Sep-2023
Revised: 05-Oct-2023
Accepted: 10-Oct-2023

INTRODUCTION

Thermoelectric modules have become an essential component in many applications today. These modules operate on the principle of the Seebeck effect, which involves the generation of a thermal electromotive force when two dissimilar metals or semiconductors (thermocouples) are subjected to heat. To enhance electrical power output, a common approach involves cascading multiple thermocouples (thermoelements). A cascading thermoelectric battery refers to a sequential arrangement of thermocouples, where the heated junction of one cascade is connected (and subsequently cooled) to the cold junction of the next cascade. This configuration forms a thermoelectric module that operates as either an electric generator or a cold source (Patil and Patil, 2013; Shatar et al., 2018).

Weather and climate changes have hazardous effect on livestock production (Godde, et al., 2021; Osuji et al., 2023). Various processes on livestock farms produce waste thermal energy, which can be harnessed and converted into electrical energy using thermoelectric modules (Shatar et al., 2018). The use of thermogenerators is economically feasible, taking into account the amount of heat lost in the production of agricultural products at agricultural enterprises (Vodyannikov et al., 2021).

In particular, applications of TEM in agriculture are in greenhouse technologies, aquaponics, hydroponics and water condensation (Ahamed, et al. 2023). The study of technologies and applications of thermoelectric modules is carefully considered in Ramachandra and Kumar (2020). From a review of the relevant literature, it can be concluded that considerable attention is paid to thermoelectric technology using various modules used for both cooling and heating. However, using these technologies in agriculture and industry needs thorough research and a theoretical basis to combine different thermoelectric solutions into one cooling and regenerative system (Surzhik et al., 2020). This device requires addressing several challenges, including the development of effective localized cooling systems that integrate with energy-efficient distributed thermoelectric systems. Additionally, it entails research, the creation of hardware and methodological support for energy-saving adaptive power management in agricultural facility air conditioning (Sumalan et al., 2020).

When setting up operational supervision for thermoelectric cooling and regenerative systems, it's essential to identify potential faults and their underlying

Cite this Article as: Vasilyev GS, Kuzichkin OR, Surzhik DI and Koskin AV, 2023. Control and stabilization of the spatiotemporal distribution of climatic parameters at agricultural facilities using thermoelectric systems. International Journal of Agriculture and Biosciences 2023 12(4): 228-233. https://doi.org/10.47278/journal.ijab/2023.069

A Publication of Unique Scientific Publishers

causes by analyzing climatic and control data measurements. In this case, the assessment of the state of the thermoelectric control object can be based on the analysis of the transient system response. Space-time spectral analysis can be attributed to promising methods that make it possible to build appropriate algorithms (García and Rezapouraghdam, 2023).

Algorithms for self-diagnosis of thermoelectric cooling and regenerative systems in agricultural facilities involve adaptive processing of recorded climatic parameters. These algorithms analyze spatially registered data from climate control to detect unusual components and signaling issues in the control system. Such unusual components can result from malfunctions or technological errors. The identified unusual signals are marked by deviations from the expected changes in the climate control system, which stem from discrepancies between the recorded climatic parameters and their calculated values.

When monitoring the climate control system at the agro-industrial complex facility, the most informative conditions are non-stationary steady-state regimes, specifically transient ones, because of their inherent nature and the potential to isolate the system's inertial properties (Kuzichkin Oleg et al., 2016). At the same time, various deterministic models can be used, which represent the distribution of climatic parameters within the control object, characterizing various failure situations in the thermoelectric microclimate control system. In this scenario, a typical strategy involves examining how malfunctions described in these models, particularly the technological aspects of management, affect the spatio-temporal distribution of climatic parameters. This allows for a more refined approximation of the intricate climate control processes and establishes a foundation for both qualitative and quantitative interpretations of the system. Attributing fault data to the specific system components responsible for those faults within the total set of control data typically requires complex diagnostic procedures. These diagnostics involve extended test periods to verify fault origins and operations. While this fault localization approach can pinpoint issues with relatively high precision, implementing it requires substantial complexity and human effort.

The use of spectral methods for monitoring transients using the fault model selection algorithm, using the spectral method, makes it possible to simplify the processing of measurement data and identify the operation of the climate control system.

The goal of regulating and stabilizing spatial and temporal climate conditions in agricultural facilities using thermoelectric systems relies on optimal control models and algorithms (Vasilyev et al., 2020). These optimization approaches minimize not only technical parameters but also energy consumption as a key priority. The optimization challenges around spatial and temporal placement and control of thermoelectric system sensor networks can be addressed through adaptive monitoring methods. This entails adaptively reconfiguring the network of software and hardware sensors in an order that minimizes resource intensity. The sensors collect critical climate data on the dynamics at the controlled site and in the telecom environment. The reconfiguration order is determined by formed functional requirements and the goal of minimizing resource use. The non-linearity of the relationships between the control actions for the reconfiguration of thermoelectric climate systems, including the information and communication environment, and the change in their functional and technological purpose allows them to be classified as complex organizational and technical systems, which requires the development of algorithms for predicting the suitability and resource intensity of the reconfiguration of a thermoelectric system based on the fuzzy forecasting method and a system of analogues.

MATERIALS & METHODS

Developing software and analytical support for energy-efficient thermoelectric microclimate control in agricultural facilities relies on principles for constructing adaptive systems. These principles involve accounting for both the current climate state and automatically adapting in real-time to changes in technological conditions and environmental dynamics. An effective system must monitor the existing microclimate while remaining responsive to evolving operating and climatic conditions (Loginov et al., 2021). Additionally, energy consumption must be minimized to achieve the specified climatic conditions that support required health, comfort and technological standards. The climate control system needs to dynamically adapt to the specific technological characteristics of the agricultural facilities. Additionally, the climate control approach must account for both the room parameters and heat exchange dynamics across heating, ventilation, and other modes. This includes considering the specifics of technical systems for thermal energy supply and withdrawal within the agricultural facility. When developing algorithms for thermoelectric control systems, they must adapt to external climate conditions and daily cycles. Adding complexity, the control components of thermoelectric equipment and the climate parameters within the agricultural facility exhibit nonlinear interdependencies.

RESULTS AND DISCUSSION

Space-time Algorithms for Processing and Control of Thermoelectric Cooling and Regenerative Systems

Fig. 1 shows a generalized scheme of cooling and regenerative systems at agricultural facilities. Here the operating mode is defined by the input vector $\bar{X}$ and the conditions $\bar{E}^*$ and $\bar{E}$. Dynamic management of the thermoelectric regenerative system (TRS) is provided by a feedback loop containing a processing unit, a control unit and a measurement subsystem.

The control vector $\bar{U}$ is a function of input parameters, taking into account the energy saving $\bar{X}_E$

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

Where $\bar{\Delta}_L$ – is the control error.

The measurement information has a spatial discrete character:

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

where $\bar{T}_c, \bar{T}_h, \bar{E}_T$ are trigenerative parameters, $\bar{\Delta}_m$ is the error of measurement. Also, anthropogenic factors $\bar{\xi}_T$ and natural factors $\bar{\xi}_p$ need to be taken into account.

The identification model assessment is based on regression for the registered parameters $\bar{\mathrm{Y}}^*$ and the model parameters of the system $\bar{\mathrm{Y}}$ with the correction $\bar{\Delta}_{\mathrm{Y}}$.

The optimization problem can be formulated as follows:

$$\dot{X}(T, W) = f(X, U), \quad (1)$$

Where $X = f(X, U)$ is vector of climatic parameters at the facility, $f(X, U)$ is the function of thermoelectric climate control.

The problem of optimal control is reduced to the formation of such a control action, in which the object from the climatic state $X_0(T(t), W(t))|_{t=0}$ to state $X_T(T(t), W(t))|_{t=T}$ will move in time *T*, taking into account the minimization functional

$$\psi = \int_{t=0}^{t=T} f(X, U)\partial t \quad (2)$$

At the same time, the following conditions must be met:

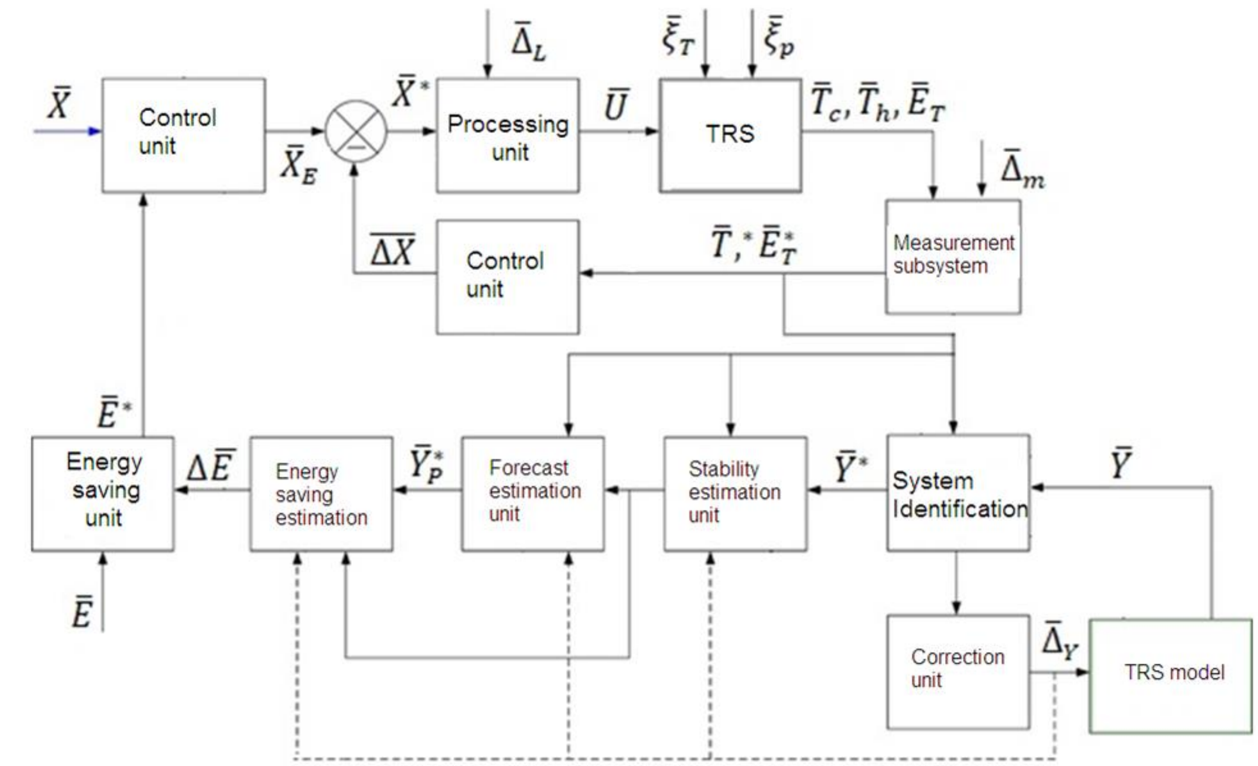

Fig. 1: A generalized scheme of cooling and regenerative thermoelectric systems at agricultural facilities.

- the object is controllable, i.e. for any climatic conditions of the object $X_0(x_1(t=0),\dots,x_n(t=0))$ and $X_T(x_1(t=T),\dots,x_n(t=T))$ there is a control action $U(t)$ at the time interval $=[0,T]$ that transfers the object from the state X_0 to the state X_T;
- the state $\{x_i, i=\overline{1,N}\}$ is uniquely determined by measurement data $\{S_j, j=\overline{1,M}\}$. This condition means that the climate control data S obtained during the interval $[t_k-\theta, t_k]$ completely and unambiguously determine the states of the object $X_K(x_1(t=t_k),\dots,x_n(t=t_k))$.

In this case, almost always the measurement points S_j do not coincide with the model points of climate control at agricultural facilities. This is due to the peculiarities of technological processes at these enterprises. Therefore, as a rule, they resort to estimated regression algorithms for establishing a connection and a one-to-one correspondence between the measured data and the state of the control object based on the accepted model of the control object and the thermoelectric system for maintaining climatic parameters.

Therefore, at the initial stage, a model is determined that can be defined by the functional dependence between the recorded climate control data S_j and the climatic parameters of the object X_i:

$$x_i = F_i(S_1, S_2, \dots, S_k)|i=1,\dots,N; j=1,\dots,k. \quad (3)$$

For regression estimation of the parameters of the functional dependence between the recorded climate control data S_j and the climatic parameters of the object X_i it is necessary to present these dependencies as a linear continuous piecewise function of the form:

$$x_i = a_{i1}S_1 + a_{i2}S_2 + \dots + a_{ik}S_k)|i=1,\dots,N; j=1,\dots,k \quad (4)$$

as a sum of piecewise continuous functions approximating the functional dependence $F_i(S_1, S_2, \dots, S_k)$.

If it is impossible to take into account all the disturbances in equations (3), which are usually stochastic in nature, they can be taken into account in the ratios for the recorded climate control data in accordance with the model:

$$S_j = S_j^* + \xi_{sj}, \quad (5)$$

Where ξ_{sj} are noise factors.

From equations (4), which forms an indefinite redundant system. In this case, based on regression processing algorithms, it is possible to determine the approximation type of functional dependencies F_i. The correspondence of the results of processing the time series of climate control with the accepted technological model of the climate control object can be represented as:

$$\tilde{Q}_i = q_i(X_1^*, \dots, X_n^*, S_1^*, \dots, S_m^*, \vec{\xi}_{xi}, \vec{\xi}_{sj})|i=1,\dots,n; j=1,\dots,k. (6)$$

The estimation of the vector of geotechnical variations of the monitoring object can be reduced to one of the regression processing algorithms discussed in the previous paragraph. At the same time, we need to specify:

– models approximating the results of indirect registration of climatic parameters X_i^* and S_i^*, models of observation errors ξ_{xi} and ξ_{si}, as well as models of the influence of external interference factors;

– a quality indicator that characterizes the degree of approximation of the estimate of the function $\tilde{Q}_i$ to the true value of Q_i at each interval of piecewise approximation.

For the corresponding dependencies in the interval of the approximation window ΔU, the functional dependencies can be reduced to a linear form:

$$X_i = Q_\alpha(S_1, \dots, S_k, \Delta U) = \sum_{j=1}^{n} a_{ij}(\Delta U)\phi_{xi}(S_j). \quad (7)$$

In this case, the regression minimization condition takes the following form:

$$min\{Q, \Delta U\} = \sum_{j=1}^{m}\left[S_j - \sum_{j=1}^{n} a_{ij}(\Delta U)\phi_{xi}(S_j)\right]^2 \quad (8)$$

$$\frac{\partial(min\{Q,\Delta U\})}{\partial a_i} = -2\sum_{j=1}^{m}\left[S_j - \sum_{i=1}^{n} a_{ij}(\Delta U)\phi_{xi}(S_j)\right]\phi_{xi}(S_j) = 0. (9)$$

From the system (4), a linear system is obtained with respect to the model parameters a_{ij}:

$$\sum_{i=1}^{n} a_{ij}(\Delta U)b_{ij} = c_j|j=1,\dots,n, \quad (10)$$

Where $b_{ij} = \sum_{i=1}^{n}\phi_{xi}(S)\,\phi_{xj}(S)$; $c_i = \sum_{i=1}^{n} Y_i\,\phi_{xj}(S)$.

Based on the obtained ratios, the parameters of the climate model $a_{ij}(\Delta U)$ can be determined in the zone of piecewise approximation of the control of the thermoelectric system $u = (\Delta U)$.

Optimal Control Criteria for Thermoelectric System Dynamics

Algorithms for optimal control of the thermoelectric microclimate formation system at agricultural facilities can be constructed using the control quality criterion (2)

$$\psi = \int_{t=0}^{t=T} f(X_1, X_2, \dots, X_n, U_1, U_2, \dots, U_m)\partial t \quad (11)$$

In each zone of linear approximation of the system mode, the control object might be represented as a linear feedback control system

$$\frac{\partial \boldsymbol{X}}{\partial \boldsymbol{t}} = \boldsymbol{f_u}(\boldsymbol{t}, \boldsymbol{X}, \boldsymbol{U}) \quad (12)$$

At the same time, as a result of linearization, it is possible to proceed to the equations of state of a linear system

$$\frac{\partial \boldsymbol{X}}{\partial \boldsymbol{t}} = \boldsymbol{A}(\boldsymbol{t})\boldsymbol{X}(\boldsymbol{t}) + \boldsymbol{B}(\boldsymbol{t})\boldsymbol{U}(\boldsymbol{t}) \quad (13)$$

and thermoelectric parameter control equations

$$\boldsymbol{S}(\boldsymbol{t}) = \boldsymbol{C}(\boldsymbol{t})\boldsymbol{X}(\boldsymbol{t}) \quad (14)$$

Accordingly, the object of climate control can be described using the vector-matrix Cauchy equation

$$\begin{bmatrix} x_1(t) \\ \dots \\ x_n(t) \end{bmatrix} = \begin{bmatrix} r_{11}(t,\tau) & \dots & r_{1m}(t,\tau) \\ \dots & \dots & \dots \\ r_{n1}(t,\tau) & \dots & r_{nm}(t,\tau) \end{bmatrix} \begin{bmatrix} u_1(\tau) \\ \dots \\ u_n(\tau) \end{bmatrix} \quad (15)$$

or

$$\boldsymbol{X}(\boldsymbol{t}) = \int_{\boldsymbol{t}=\boldsymbol{0}}^{\boldsymbol{t}=\boldsymbol{T}} \boldsymbol{K}(\boldsymbol{t}, \boldsymbol{\tau})\boldsymbol{U}(\boldsymbol{\tau})\boldsymbol{\partial t}$$

When approximating the functional dependencies of a thermoelectric control system with piecewise continuous functions $u_i(t) \in L^2[0,T]$, representing the control vector as unitary functionals with unknown coefficients provides a viable parametrization method. In accordance with the spectral theory of control systems analysis, the components of the control vector of a thermoelectric system are represented as the spectral form of an entry in the orthonormal basis $\boldsymbol{\phi}(\boldsymbol{t})$

$$\boldsymbol{u}(U,t) = \sum_{\nu=1}^{l} u_\nu^U \phi_\nu(t) = \boldsymbol{U^T}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})\boldsymbol{\phi}(\boldsymbol{t}) \quad (16)$$

Using the spectral approach, it is possible to represent the components of the climatic state of the control object in the form of a parametric equation using Chebyshev polynomials and a control vector

$$\widetilde{\boldsymbol{x_k}}(U,t) = \sum_{\nu=1}^{l} [\sum_{i=0}^{m} \sum_{r=0}^{g} d_{ir}^{k\nu} c_r^{ui} + \sum_{p=1}^{n} x_p(0) P_p^{k\nu} \ ]\phi_\nu(t) \quad (17)$$

At the same time, we need to take into account the restrictions imposed on the climatic parameters of the thermoelectric control object

$$| \sum_{\nu=1}^{l} [\sum_{i=0}^{m} \sum_{r=0}^{g} d_{ir}^{k\nu} c_r^{ui} + \sum_{p=1}^{n} x_p(0) P_p^{k\nu} \ ]\phi_\nu(t) \ | \le \boldsymbol{x_k^{max}} (18)$$

It determines the permissible scope of climate regulation.

The quadratic criterion of optimal control in general has the following form

$$\psi = \int_{t=0}^{t=T} \{\boldsymbol{U^T}(\boldsymbol{t})\boldsymbol{R}(\boldsymbol{t})\boldsymbol{U}(\boldsymbol{t}) + \boldsymbol{X^T}\boldsymbol{L}(\boldsymbol{t})\boldsymbol{X}(\boldsymbol{t})\} \ \partial t + \boldsymbol{X^T}(\boldsymbol{T})\boldsymbol{Q}\boldsymbol{X}(\boldsymbol{0}) \quad (19)$$

Where the defined matrices $R(t),\ L(t),\ \ Q$ must keep the climatic parameters within the permissible control range $\boldsymbol{G} = \{g_k\}$.

Let us express the parameters of the quality criterion through the corresponding matrix-vector, which determines the optimization of the transients of the formation of the necessary climatic regimes

$$\boldsymbol{C^U} = \{c_r^{ui} \quad \dots \quad c_r^{ui}\} \quad (20)$$

In this case

$$\psi = \int_{t=0}^{t=T} \boldsymbol{U^T}(\boldsymbol{t})\boldsymbol{U}(\boldsymbol{t})\partial t = \int_{t=0}^{t=T} [\sum_{v=1}^{m} u_v^2 (t)]\partial t = \sum_{v=1}^{m} \sum_{r=1}^{g} (c_r^{uv})^2 \quad (21)$$

Consequently, the minimization ratio for the criterion of optimal control in the system of thermoelectric regulation of microclimate at agricultural facilities will take the following form

$$\boldsymbol{min}\ \psi = \sum_{\boldsymbol{k}=\boldsymbol{1}}^{\boldsymbol{n}} \sum_{\nu=1}^{l} g_k (\sum_{i=0}^{m} \sum_{r=0}^{g} d_{ir}^{k\nu} c_r^{ui} + \sum_{p=1}^{n} x_p(0) P_p^{k\nu} \ )^{\boldsymbol{2}} + \quad \sum_{i=0}^{m} \sum_{\nu=1}^{l} r_k (c_r^{ui})^2 \quad (22)$$

Modeling and Analysis of the TEM-based Climate Control System

An example of a functional model of a trigenerative system based on TEM is shown in Fig. 3. Here $\mathbf{T}_{DES}$ – desired temperature, $\mathbf{T}_{noise}$ – noise, $\mathbf{T}_{PS}$ – the local source temperature, $\mathbf{T}_{D}$ – the recorded temperature.

The transfer function of a ventilation system, when omitting its inertiality, takes the following form:

$$T_{VS}(p) = k_v \, . \quad (23)$$

Therefore, the transmission coefficient of the open-loop system is described as follows:

$$H_{open}(p) = k_{p1} + \frac{k_{i1}}{p} + \frac{k_v k_{TEM} \cdot \left(k_{p2} + \frac{k_{i2}}{p}\right)}{1 + k_{TEM}\, p} \ , \quad (24)$$

and the transfer function of the closed-loop system without the 1st climate control channel CCS1 (k_{i1}=k_{p1}=0) is written as

$$H(p) = \frac{k_v k_{TEM} \cdot (1 + T_d\, p)(k_{i2} + k_{p2}\, p)}{k_d k_{i2} k_v k_{TEM} + (1 + k_d k_{p2} k_v k_{TEM})p + (k_{TEM} + T_d)p^2 + k_{TEM} T_d\, p^3} . \quad (25)$$

From the obtained expressions the transients of the system with TEM have been evaluated. The Heaviside function $T_{DES}(t) = 1(t)$ with operator form $T_{DES}(p) = 1/p$ is assumed as input. The first CCS1 channel is set to be off, so k_{i1}=k_{p1}=0. Other system links have the following coefficients: the 2nd channel CCS2 – k_{i2}=1 and k_{p2}=4, the TEM k_{TEM} =1, the ventilation system k_v=0.9, the climate detector k_d=1, the TEM time constant T_{TEM} =10 s, climate detector time constant T_d =1 c.

The simulation results are shown in Fig. 3-5. Their analysis shows that with T_{TEM} increasing (Fig. 3a) and k_v increasing (Fig. 4b), the control time is lower, but the damping factor rises. With increasing of T_d (Fig. 3b), k_{i2} (Fig. 5a) and k_{p2} (Fig. 5b), transient quality gets worse by both parameters: the end time and damping rise. As the value of *kd* increases (as shown in Fig. 4a), it leads to an increase in the final time, damping, and the final value.

The practical control and stabilization method for managing the spatiotemporal distribution of climatic parameters within agricultural facilities, employing thermoelectric systems, has been previously explored and examined by Kuzmichev et al. (2023) for livestock farms and by Prăvălie et al. (2017) for maize cultivation in field crops. This method is valuable in designing a suitable microclimate for agricultural units.

Conclusions

It has been found that addressing the challenge of developing software and analytical support for an energy-efficient thermoelectric microclimate control system in agricultural facilities relies on establishing an adaptive microclimate control system. This system considers both the existing climatic conditions of the controlled area and the capacity to automatically adjust to alterations in the technological operating conditions of the facility and environmental climatic conditions. We present the configuration of an adaptive regenerative thermoelectric system and derive its transfer functions. To solve the problems of climate control based on thermoelectric systems, patio-temporal algorithms for processing and controlling thermoelectric cooling and regenerative systems is proposed. A criterion for optimal transient control of a thermoelectric system is introduced. The transient response attributes of the system are simulated by varying the gains and time constants of its components. The simulation revealed potential methods to enhance the transient characteristics of the system.

Acknowledgments

The article was prepared as part of the state task "Research and development of complex energy-saving and thermoelectric regenerative systems" application number 2019-1497, subject number FZWG-2020 -0034.

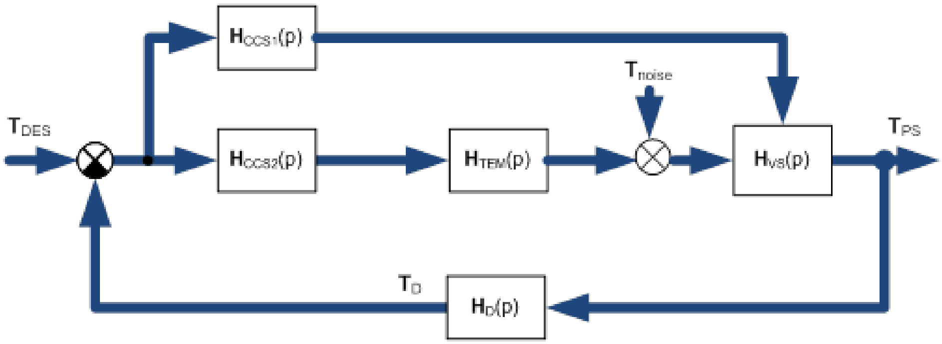

Fig. 2: Functional model of an energy-saving trigenerative climate management system.

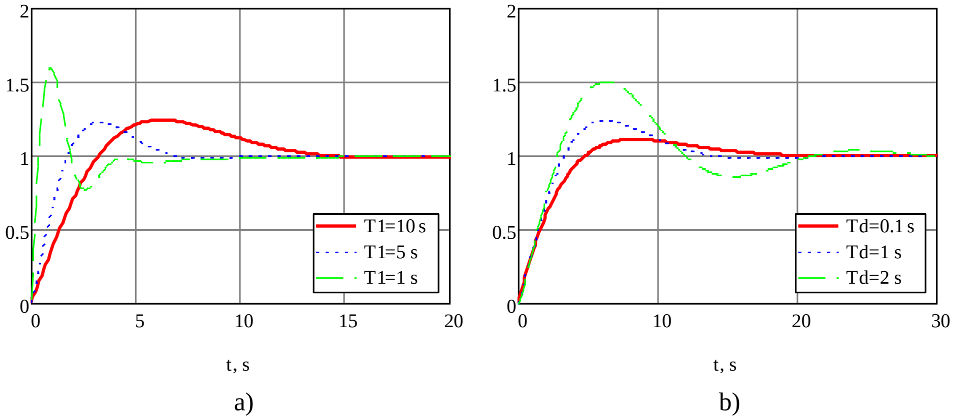

Fig. 3: Dynamic response of the system with various time constants of TEM (a) and climate detector (b).

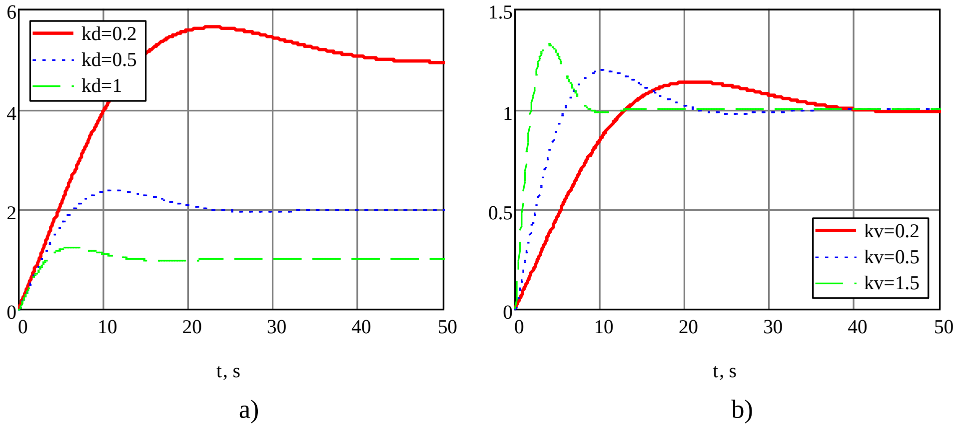

Fig. 4: Dynamic response of the system with various gain of the climate detector (a) and ventilation system (b).

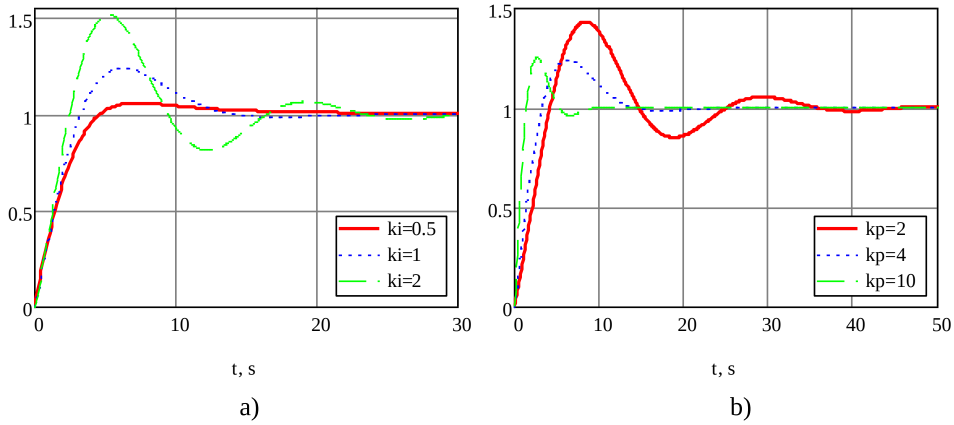

Fig. 5: Dynamic response of the system with various coefficients of inertia (a) and proportionality (b) of CCS2.

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