Greenhouse microclimate control

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Abstract. Extensive data have been accumulated indicating that for the regions of the Far North, the most effective are opaque greenhouses with enclosing structures of sufficiently high resistance to heat transfer, providing for the cultivation of plants under artificial or joint (semi-opaque greenhouses) lighting. From 1 m of such structures, you can get 140 ... 300 kg of vegetables per year. To maintain a certain air temperature in greenhouses, mainly two heating systems are used: water and air. Extensive data have been accumulated indicating that for the regions of the Far North, the most effective are opaque greenhouses with enclosing structures of sufficiently high resistance to heat transfer, providing for the cultivation of plants under artificial or joint (semi-opaque greenhouses) lighting. From 1 m of such facilities, you can get 140 ... 300 kg of vegetables per year. When growing plants in cultivation rooms in winter and spring, it is necessary to artificially maintain climatic factors affecting the growth and development of plants. In this regard, the automatic regulation of these factors in accordance with the requirements of agricultural technology is of great importance. To automatically maintain the temperature in greenhouses, a two-position control system is used. Large-scale greenhouse production is currently developing along the path of introducing technologies for intensive cultivation of vegetable crops and the use of automated control systems for technological processes based on micro- and mini-computers. One of the important technological processes is watering and feeding plants with mineral fertilizers. The need to automate this process is associated with the laboriousness of the process of preparing solutions, accurately maintaining a given concentration of substances in them, timely supply and uniform dosing over the entire area of the greenhouse under various disturbances of the external environment.

1. Introduction
Greenhouses are divided into stationary and mobile. The former are intended to supply the population with vegetable products year-round or seasonally. They are divided into variation series, the most characteristic of which are vegetation and climatic chambers and cabinets, growth rooms, growing rooms, actually greenhouses, satellite greenhouses of the main production, combined with administrative buildings, children's and medical institutions, catering establishments, storage facilities, warehouses livestock and poultry farms, greenhouses with external concentrators of natural light, internal cylindrical and flat light guides, tower, with a water-filled roof and walls, equipped in mine workings, basements, in storage of agricultural products, etc. The classification can be used in investigated, construction multifactor models of greenhouse systems, creation of a systemic...
information fund for greenhouses. The structures under consideration can be single-storey and multi-storey. With a single-storey version, the useful area of their chambers is 200 (greenhouse size 24.0 × 24.0 m) ... 1000 m² (138.0 × 64.0 m), with a multi-storey 1000 ... 40,000 m² (three-storey), 1000 ... 60,000 m² (four-storey).

In multi-storey buildings, radiation and temperature conditions are most economically used, the building area is reduced, and foundation costs are reduced. The space-planning solutions of such greenhouses are based on the principles of technological interconnection of premises, a reduction in the length of communications, and ease of use. The chamber type of cultivation facilities allows you to simultaneously grow crops that require different modes, ensures the continuity of the output of products over time and the constant load of the service personnel and equipment. In greenhouse vegetable growing, more than half of the operating costs are associated with the cost of heating the cultivation premises. In addition to biological fuel, heat wastes from industrial enterprises, hot water or steam from boiler houses and electric energy are used to heat wigs. If it is impossible to use thermal waste, the absence of local fuel resources or their high cost, it is economically expedient to use electric energy to heat greenhouses. Contact mercury thermometers, bimetallic or manometric temperature sensors are used as temperature-sensitive elements, and starters or contactors are used as actuators.

To ensure safety when working on electric greenhouses, thermosensitive elements are included in a 6-12 V low voltage network. The experience of operating greenhouses shows that growing plants in artificial environments can significantly increase the yield of vegetables while reducing the growing season, reduce labor costs for caring for plants, completely eliminate such laborious operations as processing and replacing soil in greenhouses, and also significantly simplify the process of disinfecting the substrate. ... The use of artificial nutrient media opens up wide opportunities for the effective use of means of automation of production processes, especially with large areas of greenhouse and greenhouse facilities. The main operations to be automated when growing vegetables in artificial environments are the periodic supply of nutrient solution to the working racks and its removal into the storage tank, as well as feeding the solution with water with periodic or constant addition of the corresponding salts. The need for additional feeding of the solution is caused by its partial absorption when passing through the mineral substrate. In conventional greenhouses, due to the large area of translucent surfaces, significant heat losses occur, for which compensation requires a certain fuel consumption in the heating system. Greenhouses can be heated with hot water, steam, heated air, infrared radiation or combustion products. When creating a solar greenhouse, first of all, you need to take care of a significant reduction in heat loss through the use of thermal insulation. In addition, it is necessary to ensure the capture of the maximum possible amount of solar energy and the accumulation of excess heat [1-4,8].

2. Research methodology

In some cases, automatic regulation of soil temperature in greenhouses can be carried out by means of a thermostat installed in the air space of the greenhouse. One thermostat controls the simultaneous activation and deactivation of air and soil heating devices. Such regulation is possible when using heating elements with low heat capacity. When the lag time in the nutrient layer of the soil is less than the period of fluctuations in the temperature of the air space in the greenhouse [1,2,10]. In accordance with the considered methods of switching on thermostats, the calculation of the process of two-position temperature control in greenhouses was carried out, the consumption of electric energy for heating and the cost of costs for automation were determined [5-12]. The dependences of the heat loss coefficient of greenhouses on the wind speed and the degree of warming of frames with mats (Figure 1), the value of the delay time and the dead zone of the object-regulator system have been established.
Figure 1. Dependence of the coefficient of heat loss of greenhouses on the wind speed: 1 - greenhouses are not covered with mats; 2 - greenhouses are covered with straw mats in one layer; 3 - greenhouses are covered with straw mats in two layers

The calculation of the temperature control process in greenhouses is made by the fit method. The equations of the control object (greenhouse) are an exponential function with a lagging argument. Relay thermostat inequalities include temperature setpoint and object-controller system deadband.

Table 1 shows the indicators that affect the microclimate of the greenhouse.

| No | Criterion                                                                                                                                               |
|----|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1  | the indoor temperature will usually be higher than the outdoor temperature (even too high with insolation)                                           |
| 2  | the soil temperature rises sufficiently, often even to too high values, at which the germination of seeds of some plants stops. The soil in the greenhouse does not freeze |
| 3  | the amount of lighting entering the greenhouse is almost half that of the outdoors                                                                           |
| 4  | the effect of wind is almost completely eliminated, which significantly increases comfort for humans and only partially for plants                          |
| 5  | different smells may appear                                                                                                                           |
| 6  | air exchange decreases, plants may lack carbon dioxide (CO2)                                                                                           |
| 7  | in the greenhouse, the humidity is higher than is necessary for the plants, because with prolonged humidity, mold formation and fungal growth are observed |
| 8  | the penetration of pests into the greenhouse is also difficult, but if they do get into the room, they begin to multiply in favorable conditions of the greenhouse, which makes a very depressing impression on some people |
| 9  | it is difficult for beneficial insects to access plants, since they can enter the greenhouse only through doors, ventilation hatches or vents              |
| 10 | the greenhouse protects from natural rains, and the receipt of moisture by plants depends entirely on the person who cares for them                          |
| 11 | in an unheated greenhouse, excess humidity, as a rule, does not create additional difficulties for people                                                    |
| 12 | with insolation, as a rule, favorable conditions are created for people to stay in the greenhouse                                                           |
| 13 | due to the presence of plants, the air in the greenhouse contains more oxygen than in the apartment                                                      |

Figure 2 shows a flow diagram of a heated greenhouse of the simplest design. The model obtained for such a scheme on the basis of the proposed methodology can be transformed for more complex schemes [6; nine].
Three main forms of the state-space model:

Continuous

$$X = AX + BU(t) + CF(t), \quad X(t_0) = X_0;$$  \hspace{1cm} (1)

Discrete

$$X[k + 1] = \Phi X[k] + BU[k] + CF[k], \quad X[0] = X_0;$$  \hspace{1cm} (2)

Operator

$$X(p) = W_D(p)U(p) + W_P(p)F(p),$$  \hspace{1cm} (3)

where $A = [n \times n]$– dimensional dynamic matrix; $n$– dynamic model order; $X = [n \times 1]$– dimensional state vector; $B = [n \times m]$– dimensional control matrix; $m$– number of independent controls; $U = [m \times 1]$ – control vector; $t$– time; $C = [n \times r]$– dimensional perturbation matrix; $r$– number of independent disturbances; $F = [r \times 1]$– dimensional disturbance vector; $k$– step numbers; $\Phi = [n \times n]$– dimensional matrix of one step transition; $W_D(p) = \Phi(p)B, W_P(p) = \Phi(p)C$– transfer matrices for control and perturbation defined through the operator image of the transition matrix.

For the given greenhouse scheme, the return heat carrier temperature $x_1 = \theta_2$; average temperature of heaters $x_2 = \theta_h$; average air temperature in the greenhouse $x_3 = \theta_i$; average temperature of the fence $x_4 = \theta_f$; coolant temperature at the heat exchanger outlet $u = \theta_f$; outdoor temperature $f = \theta_o$.

Obviously, for the considered model $n = 4, \ m = 1, \ r = 1$.

As a result of identification, the parameters of the discrete form of the model were obtained

$$\Phi = \begin{pmatrix}
0.0996 & 0.0943 & 0 & 0 \\
0.3585 & 0.2573 & -0.017 & 0.2705 \\
0 & 0.0103 & 0.0255 & -0.1715 \\
0 & 0.0058 & 0.2122 & 0.0661
\end{pmatrix}.
Using the equation of connection of matrices of discrete and continuous forms of state space models (1), (2)

\[ \Phi = e^{At}, \quad B = A^{-1}(e^{At} - I)B, \quad C = A^{-1}(e^{At} - I)C, \]

where \( \tau \) – sampling interval; \( I = [n \times n] \) – dimensional unit matrix, we will have the parameters of model (1) for the time scale \( K_M = 1200: \)

\[
A = \begin{pmatrix}
-3.007 & 0.315 & 0 & 0 \\
1.197 & -2.481 & 0.057 & 0.903 \\
0 & 0.0344 & -3.255 & -0.573 \\
0 & 0.019 & 0.709 & -3.119
\end{pmatrix};
\]

\[
B = \begin{pmatrix}
0.4579 \\
0 \\
0
\end{pmatrix}; \quad C = \begin{pmatrix}
0 \\
0 \\
0.13 \\
0.0147
\end{pmatrix}.
\]

Using expressions for transfer matrices \( W_U(p)W_F(p) \) and transition matrices \( \Phi(p) \), we obtain the transfer functions for the internal air temperature, the components \( X_4 \) of the state vector (for convenience of subsequent calculations, the components \( \tilde{X}_4 \) are swapped)

\[
W_U^{X_4}(p) = \frac{1218p + 1}{3.79p^4 + 5.79p^3 + 7.753p^2 + 4.574p + 1};
\]

\[
W_F^{X_4}(p) = \frac{2.535p^3 + 6.693p^2 + 5.782p + 1}{3.79p^4 + 5.79p^3 + 7.753p^2 + 4.574p + 1}.
\]

Thus, we considered the methodology for constructing balanced models of heated greenhouses. But before proceeding to examples of their use, let us show the sequence in calculating the accuracy using these models [11-15].

The simulation results are comparable to the actual state of the greenhouse. Based on the results of this comparison, one can calculate the accuracy matrix \( \Omega = \{M[X[k] - X_m[k]](X[k] - X_m[k])^T\} \).

Assuming that the simulation error vector obeys the Gaussian law, we write an expression for the joint error probability distribution density based on the parameters \( \Phi, B, C \) of the model and the accuracy matrix \( \Omega: \)

\[
\pi(\varepsilon|\Phi, B, C, \Omega) = (2\pi)^{-\frac{1}{2}}|\Omega|^{\frac{1}{2}} \times \exp \left\{ -\frac{1}{2} (X[k + 1] - \Phi X[k] - BU[k] - CF[k])^T \times \Omega (X[k + 1] - \Phi X[k] - BU[k] - CF[k]) \right\}. \]

Expressions (9) and (10) allow, given the admissible vector of modeling errors \( \varepsilon_A = [\varepsilon_{A1}, \varepsilon_{A2}, \varepsilon_{A3}, \varepsilon_{A4}] \), calculate the confidence level for the obtained identification result

\[
\Pi(\varepsilon) = 2\Phi(\varepsilon^T\Omega\varepsilon),
\]

where \( \Phi(\cdot) \) – Laplace function for which special tables have been compiled [10, c.18].
For our case, with the vector of admissible errors $\varepsilon^T = [2, 2, 4, 1]^T$ confidence level $\Pi(\varepsilon) = 0.96$.

Let us show several examples of the use of models of heated greenhouses for the synthesis of temperature controllers on a computer.

As a result of transformations of expressions (8), (9), we obtain the following matrix structure:

$$
\Phi = \begin{pmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
-\bar{\phi}_4 - \bar{\phi}_3 - \bar{\phi}_2 - \bar{\phi}_1
\end{pmatrix};
\bar{B} = \begin{pmatrix}
\bar{b}_1 \\
\bar{b}_2 \\
\bar{b}_3 \\
\bar{b}_4
\end{pmatrix};
\bar{C} = \begin{pmatrix}
\bar{c}_1 \\
\bar{c}_2 \\
\bar{c}_3 \\
\bar{c}_4
\end{pmatrix}.
$$

It is easy to determine the coefficients of the stabilizing digital controller in the basis of the transformed system (9):

$$
k_{pi} = d_i^T - \bar{\phi}_i,
$$

where $d_i^T$ – the required values of the characteristic polynomial of the matrix $\Phi$.

Having adopted $d_1^T = 0.08, d_2^T = 0.12, d_3^T = 0.18, d_4^T = 0.24$ will have for the system (22), (23) $k_{p,1} = 0.0796, k_{p,2} = 0.107, k_{p,3} = 0.238, k_{p,4} = -0.206$.

The equation of the combined digital controller is found from the condition that the current control error is zero:

$$
u[k] = \beta^{-1}_1 \left\{ \sum_{i=2}^{4} u[k-i] \beta_i - \sum_{i=1}^{5} (\phi_i y[k-i] - \gamma_i f[k-i]) \right\}.
$$

As a result of calculations using formulas (21), (22), (24, 27), the following parameters of the digital combined controller were obtained:

$$
\beta^T = [-2.058; 1.724; 1.311; -0.093];
\gamma^T = [10.623; -12.113; -31.777; 5.674].
$$

Note that the parameters of digital controllers are synthesized in the transformed basis, i.e., for the state $\bar{X}$. Therefore, to pass to the true state vector, it is necessary to apply the inverse transformation $X = S^{-1}\bar{X}$.

3. Conclusion

The lack of sufficiently substantiated mathematical models of heated greenhouses hinders their development and improvement. When creating such models, it is necessary to take into account the heat and mass transfer processes occurring in the greenhouse, the distribution of their parameters, and the randomness of the external disturbances. Additional difficulties arise due to the fact that the requirements for the models often do not correspond to the set goal of inheritance or do not reflect the conditions for its use. The proposed balanced dynamic models allow the most complete use of computers for studying heat consumption modes of heated greenhouses, as well as for the synthesis of temperature controllers. In this case, vector-matrix algebra is used as a mathematical apparatus, the standard programs for which are widely used on computers for various purposes.

In heated greenhouses, they often strive to increase their energy efficiency both by means of automation and by changing the design. In this case, the greenhouse is considered as an object with lumped parameters of the thermal state, averaged over the volume and area of the fence. In this case, do not use detailed thermophysical models. The multistage heat transfer on the dividing surfaces can be taken into account by choosing the general order of the model. When constructing models that reflect the essential energy features of the greenhouse, the most effective is the functional-identification approach. In greenhouse vegetable growing, more than half of the operating costs are associated with the cost of heating the cultivation premises. In addition to biological fuel, heat wastes from industrial enterprises, hot water or steam from boiler houses and electric energy are used to heat
wigs. If it is impossible to use thermal waste, the absence of local fuel resources or their high cost, it is economically expedient to use electric energy to heat greenhouses. Greenhouses differ from each other both in terms of the time period of operation (while they are divided into spring-summer and year-round), and in appearance. The design of the greenhouse depends not only on the possibilities and imagination, as one might think, but also on what kind of plants you are going to grow. Some greenhouses are optimally suited for specific plant varieties, others have a wider range of uses. The presented model of a greenhouse for controlling microclimate parameters, developed for use in computerized yield control systems for finding optimal operating modes. Due to the ease of setting parameters, it can be easily reproduced for many different designs and systems of greenhouse complexes, as well as for various scenarios of changing environmental conditions. The proposed balanced dynamic models allow the most complete use of computers for studying heat consumption modes of heated greenhouses, as well as for the synthesis of temperature controllers. At the same time, vector-matrix algebra is used as a mathematical apparatus, standard programs for which are widely used on computers for various purposes.

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