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Equation of dynamics of greenhouse microclimate parameters

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Abstract. When developing and researching management tasks, a climate model is needed. There are different ways to mathematically describe or predict parameters for controlling a greenhouse complex. Most authors represent the ambient air temperature by a Fourier series or its segment, as well as by trigonometric expressions. This approach makes it possible to use the obtained representation for solving specific thermal and physical problems, as well as for calculating heat and moisture resistance. A mathematical model of greenhouse microclimate dynamics has been developed. The mathematical model describes parameters such as air temperature, relative humidity and soil humidity. The developed model in the form of a differential equation is calculated numerically using the Maple 17.

1 Introduction

The transition to an intensive method of growing and maintaining plants in order to obtain a high yield has caused the need to create management systems that regulate the influence of environmental conditions in greenhouses. There are installations and systems of electrical equipment that allow, to a certain extent, to solve the problem of providing a microclimate and maintain it automatically. Some systems partially use contactless control devices Greenhouse climate is a time-varying nonlinear system with distributed parameters. Therefore, there are many problems in modeling and managing it due to the interaction between the inputs and outputs of the system, the nonlinear relationship between heat carriers, and humidity inside the greenhouse and soil, as well as air releases.

Thus, a random process, which can be considered a change in temperature and humidity over time, is replaced by a mathematical expression. In addition, in some specific cases, it is necessary to take into account the probabilistic structures of the process under study. There are models of outdoor climate: probabilistic-deterministic, probabilistic or “all year round". When solving optimal control problems based on mathematical modeling of the microclimate regime, there are requirements for the description of disturbing influences based on external and mechanical factors. This is due to the fact that the control system or model must work in real time, that is, the time for the control action should be small compared to the time separating two consecutive control actions. To do this, it is advisable to use the approximation of disturbing influences.

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The greenhouse microclimate mode can be controlled at different levels, depending on the equipment with control devices. The first level of control is automatic start and stop, as well as emergency protection. The second level is the control and stabilization of microclimate parameters at a given level by automatically regulating the operation of elements of the microclimate system. The third level is relevant: optimal control of the operation of the microclimate system according to the criteria of the minimum consumption of heat and electric energy [1, 2, 3].

2 Materials and methods

The studies reflected in the works [4,5] substantiate the expediency and validity of the following assumptions in the representation of the physical properties of the greenhouse:

- the greenhouse space, limited by the soil surface and a thin light-permeable perforated shell, is filled with well-mixed air, plant matter and working organs of the heating, ventilation and humidification system;
- the heat capacity of the enclosing shell is insignificant and can be equated to zero in calculations;
- the heating and humidification system ensures an even distribution of heat and moisture throughout the entire volume of the greenhouse's air space;
- the plant mass is homogeneous, distributed evenly over the entire area of the greenhouse;
- the air environment of greenhouses does not have the absorption capacity of light radiation;
- the parameters of the external environment are temporal functions that do not depend on spatial coordinates.

This idea of the physical properties of greenhouses allows us to obtain an equation of the dynamics of heat and mass transfer processes based on the equations of thermal and mass balances for individual elements of cultivation facilities. The equations of thermal balances for the time interval dt have the following form [6,7,8]:

$$\begin{cases} dQ_{В} = dQ_{об} + dQ_{ЛВ} - dQ_{ВП} - dQ_{Вент} - dQ_{ИС} \\ dQ_{Л} = dR_{p} - dQ_{ЛВ} - dQ_{ТР} \\ dQ_{П} = dR_{П} - dQ_{ВП} - dQ_{ИСП} - dQ_{П3} + dQ_{об.п} \end{cases} \tag{1}$$

where $dQ_{В}$, $dQ_{Л}$, $dQ_{П}$ the change in the heat content of air, respectively, the green mass of plants and the surface layer of soil (J) during dt, filling the space of the greenhouse; $dQ_{об}$ *and* $dQ_{об.п}$ thermal energy (J) released by air and soil heating devices during dt; $dQ_{ЛВ}$ $dQ_{ВП}$ $dQ_{П3}$ heat transfer of heat (J) during dt, respectively, from the leaves to the air, from the air to the surface layer of the soil and from the surface layer of the soil to the ground; $dQ_{ВН}$ heat transfer of heat (J) during dt from the indoor to outdoor air through the enclosing surface; $dQ_{Вент}$ the cost of heat (J) during the time dt due to the air exchange of the greenhouse with the environment; $dQ_{ТР}$ the cost of heat (J) during the time dt due to the transpiration of plants; $dQ_{ИСП}$ the cost of heat (J) during the time dt for the evaporation of soil moisture; dR_{P}, $dR_{П}$ respectively the amount of heat of solar radiation (J) absorbed at the level of the vegetation cover and on the soil surface of the greenhouse during the time *dt*.

The change in the heat content of the air during *dt* is equal to:

$$dQ_{ЛВ} = C_{B} j_{B} \cdot \zeta \cdot F \cdot d\theta_{B}(t) \tag{2}$$

where C_{B}, j_{B}, θ_{B} – accordingly, the specific heat capacity, density and air temperature (J /kg, ° C, kg/m3 s); ζ - the volume coefficient (m), determined by the ratio of the volume of the greenhouse space to its area $\zeta = V / F$.

The values $dQ_{Л}$, $dQ_{П}$, $dQ_{ЛВ}$, $dQ_{ВП}$, $dQ_{ПЗ}$, $dQ_{ВН}$, $dQ_{Вент}$ are expressed by the following formulas:

$$\begin{aligned} dQ_{Л} &= C_{Л} M_{Л} d\theta_{Л}(t) \\ dQ_{n} &= C_{n}\gamma_{n} \cdot h_{n} \cdot F \cdot d\theta_{n}(t) \\ dQ_{ЛВ} &= K_{ЛВ}\eta_{Л} \cdot \zeta \cdot F \cdot (\theta_{Л} - \theta_{В})dt \\ dQ_{ВП} &= K_{ВП} \cdot F \cdot (\theta_{В} - \theta_{n})dt \\ dQ_{П3} &= K_{n3} \cdot F \cdot (\theta_{n} - \theta_{3})dt \\ dQ_{ВН} &= K_{ВН} \cdot \eta_{егг} \cdot F(\theta_{В} - \theta_{Н})dt \\ dQ_{Вент} &= C_{В} \cdot \gamma_{В}\zeta \cdot F \cdot Z(\theta_{В} - \theta_{Н})dt \end{aligned} \quad (3)$$

where $C_л$ is the average specific heat capacity of leaves (J/kg •°C); $M_л$ is the total mass of plant leaves (kg); C_n up are, respectively, the specific heat capacity and soil density (J/kg • °C; kg/m^3); h_n is the height of the surface soil layer (m); $K_{лв}$, $K_{вн}$, $K_{лз}$ respectively the coefficients of heat transfer from leaves to air, from air through the enclosing surface and outside air, from the surface layer of soil to the ground (W/m^2 • C);); $\eta_{огр}= F_{огр}/F$ is the coefficient of fencing; $\eta_л= F_л/F$ is the coefficient of the sheet surface; F, $F_л$ и $F_{огр}$ are, respectively, the area of the greenhouse, the total surface area of the leaves and the total surface area of the fence (m^2); Z is the multiplicity of air exchange (1/s), which depends on the size of the cracks and the design of the greenhouse, the degree of opening of the vents and wind speed.

The value of Z is represented as follows:

$$Z = (K_1 + K_2\alpha)(1 + K_3\upsilon) \quad (4)$$

where is the degree of opening of the vents (%); υ is the wind speed (m/s); *K1 , K2, K3* are the coupling coefficients.

The values $dQ_{тр}$, $dQ_{исп}$, $dQ_{ис}$ according to [9] are presented in the following form:

$$\begin{aligned} dQ_{ТР} &= 1/2 \cdot L \cdot F_{Л} \cdot G_{ТР} dt \\ dQ_{ИСП} &= L \cdot F \cdot G_{П} dt \\ dQ_{ИС} &= K_{u} L \cdot F \cdot G_{u} dt \end{aligned} \quad (5)$$

where G_{TP} is the transpiration intensity (kg/s • m^2); G_u is the performance of moisture sprayers reduced to 1 m^2 (kg/s • m^2); G_n is the evaporation rate of moisture from the soil surface (kg/s • m^2); L is the latent heat of evaporation (J/kg).

In expression (5), half of the leaf area is taken into account, since moisture evaporates only from the side "where the stomata are located.

The values of the dR_p in the dR_n are expressed by the following formulas:

$$\begin{aligned} dR_{p} &= \eta_{p} F \cdot E_{p} dt \\ dR_{n} &= (1 - \eta_{p}) \cdot F \cdot E_{n} dt \end{aligned} \quad (6)$$

where $\eta_p = F_p/F$ is the coefficient of vegetation cover; Fr is the area occupied by plants (m2); Ep is the specific radiation balance on the surface of vegetation cover (W/m2); specific radiation balance on the soil surface (W/m^2).

Substituting expressions (1) - (6) into the system of equations (2) and after small transformations we obtain the following system of equations:

$$\begin{cases} C_{В}\gamma_{В}\zeta \dfrac{d\theta_{В}}{dt} = N_{В} + K_{ЛВ}\eta_{Л} \cdot (\theta_{Л} - \theta_{В}) - K_{ВП}(\theta_{В} - \theta_{n}) - (K_{ВН}\eta_{огр} + C_{В}\gamma_{В}\zeta \cdot Z)(\theta_{В} - \theta_{n}) - K_{u} \cdot L \cdot G_{u} \\ \dfrac{C_{Л}M_{Л}}{F} \cdot \dfrac{d\theta_{Л}}{dt} = \eta_{p}E_{p} - K_{ЛВ} \cdot \eta_{Л} \cdot (\theta_{Л} - \theta_{В}) - \dfrac{1}{2} L \cdot \eta_{Л} \cdot G_{ТР} \\ C_{n}\gamma_{n}h_{n}p \cdot \dfrac{d\theta_{n}}{dt} = (1 - \eta_{p})E_{n} + K_{ВП}(\theta_{В} - \theta_{n}) - K_{П3}(\theta_{n} - \theta_{3}) + N_{об.п} - L \cdot G_{П} \end{cases} \quad (7)$$

where $N_в$ is the output power of the heating system reduced to 1 m2 (W/m2).

The leaves, due to their small mass compared to their own area, practically do not retain the absorbed thermal energy. For practical purposes, the expression $\frac{C_Л M_Л}{F}\cdot\frac{d\theta_Л}{dt}$ can be equated to zero and we get the following system of equations:

$$\begin{cases} C_B\gamma_B\zeta\dfrac{d\theta_B}{dt}=N_B+\eta_П E_П-K_{BП}(\theta_B-\theta_n)-(K_{BH}\eta_{огр}+C_B\gamma_B\zeta\cdot Z)(\theta_B-\theta_n)-K_u\cdot L\cdot G_u+q_1 \\ C_n\gamma_n h_n\dfrac{d\theta_n}{dt}=(1-\eta_p)E_N+K_{BП}(\theta_B-\theta_n)-K_{П3}(\theta_n-\theta_3)+N_{об.n}+q_6 \end{cases} \tag{8}$$

Differential equations characterizing changes in the moisture content of the air in the greenhouse, the carbon dioxide content in the greenhouse air and the specific soil moisture in the greenhouse as follows [9]:

$$\begin{aligned} &\gamma_B\zeta\frac{d\chi_B}{dt}=\gamma_B\zeta Z(\chi_H-\chi_B)+K_u Gu_u+q_3 \\ &\gamma_B\zeta\frac{dv_B}{dt}=\gamma_B\zeta Z(v_H-v_B)+\sigma-K_ф E_ф+q_4 \\ &\frac{1}{h}\frac{dW_p}{dt}=G_p+(1-K_u)G_u+q_5 \end{aligned} \tag{9}$$

where χ_H, χ_B is the moisture content of the indoor and outdoor air, respectively (kg/kg); v_B and v_H are the carbon dioxide content, respectively, in the greenhouse air, in the outdoor air and in the greenhouse soil (g/kg); σ is the performance of the CO_2 fertilizing device reduced to 1 m^2 (kg/s • m^2); $K_ф$ is the coefficient the relationship between the intensity of photosynthesis and the intensity of the sun; Wn- specific soil moisture in the greenhouse (kg/ m3); h_n - the height of the soil layer in the greenhouse (m); $G_л$ - the productivity of the soil irrigation device reduced to 1 m^2 (kg/s • m2) q1, q2, q3, q4, q5 - the total values of unaccounted impacts on changes in air temperature, air moisture content, air carbon dioxide content, specific humidity and soil temperature in the greenhouse, respectively.

3 Results

By adopting the symbol:

$$\begin{cases} a_{11}=\dfrac{K_{BП}+K_{BM}\cdot\eta_{огр}}{C_B\cdot\gamma_B\cdot\zeta};a_{15}=\dfrac{1}{C_B\cdot\gamma_B\cdot\zeta};a_{16}=\dfrac{K_{BП}}{C_B\cdot\gamma_B\cdot\zeta};b_{12}=\dfrac{K_H\cdot L}{C_B\gamma_B\zeta}; \\ d_{11}=\dfrac{K_{BM}\eta_{огр}}{C_B\gamma_B\zeta};l_{11}=\dfrac{\eta_P}{C_B\gamma_B\zeta};b_{22}=\dfrac{K_U}{\gamma_B\zeta};b_{33}=(1-K_u)h_B;b_{44}=h_n. \end{cases} \tag{10}$$

Combining equations (8) and (9) taking into account (4), we obtain a system of equations for the dynamics of microclimate processes in a greenhouse:

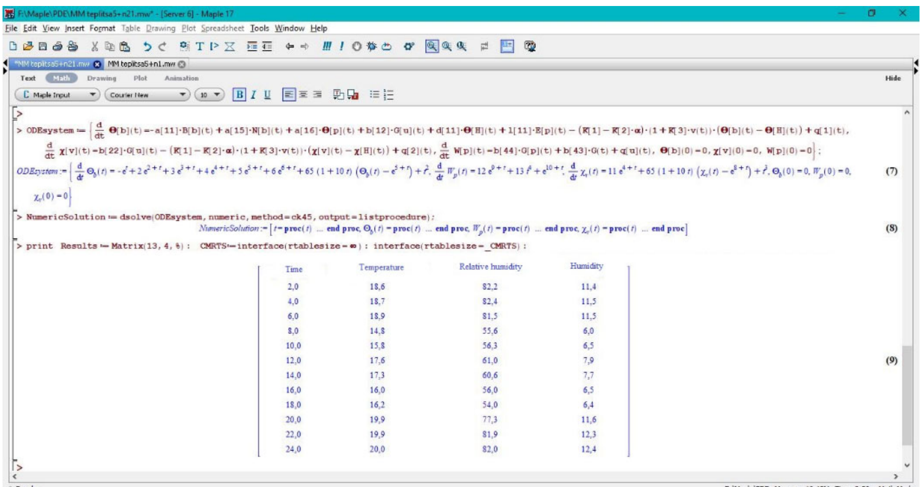
$$\begin{cases} \dfrac{d\theta_B}{dt}=-a_{11}B_B(t)+a_{15}N_B(t)+a_{16}\theta_П(t)+b_{12}G_u(t)+d_{11}\theta_H(t)+l_{11}E_P(t)-(K_1+K_2\alpha)\left[1+K_3v(t)\right]\left[\theta_B(t)-\theta_H(t)\right]+q_1(t); \\ \dfrac{dW_p}{dt}=b_{44}G_p(t)+b_{43}G(t)+q_u(t); \\ \dfrac{d\chi_B}{dt}=b_{22}G_u(t)-(K_1+K_2\alpha)\left[1+K_3v(t)\right]\left[\chi_B(t)-\chi_H(t)\right]+q_2(t). \end{cases} \tag{11}$$

Integrating the system of equations (11) gives the following system of equations:

$$\begin{cases} \theta_b(t) = e^{\int (1+K_3 v(t))(\alpha K_2 - K_1)dt} \left(\int e^{-\left(\int (1+K_3 v(t))(\alpha K_2 - K_1)dt\right)} (-\theta_H(t)v(t)\alpha K_2 K_3 + \theta_H(t)v(t)K_1 K_3 - \right. \\ \left. - \theta_H(t)\alpha K_2 - a_{11}B_b(t) + a_{15}N_b(t) + a_{16}\theta_p(t) + b_{12}G_u(t) + l_{11}E_p(t) + \theta_H(t)K_1 + d_{11}\theta_H(t) + q_1(t))dt + C_l \right); \\ W_p(t) = \int (b_{44}G_p(t) + b_{43}G(t) + q_u(t))dt + C_3; \\ \chi_B(t) = e^{\int (1+K_3 v(t))(\alpha K_2 - K_1)dt} \left(\int (e^{-\left(\int (1+K_3 v(t))(\alpha K_2 - K_1)dt\right)})(\chi_H(t)v(t)\alpha K_2 K_3 - \chi_H(t)v(t)K_1 K_3 + \right. \\ \left. + \chi_H(t)\alpha K_2 - \chi_H(t)K_1 - b_{22}G_u(t) - q_2(t))dt + C_{12} \right). \end{cases} \quad (12)$$

This system cannot be solved analytically, but it can be solved numerically using the Maple 17 package.

Figure 1 shows the calculated values of greenhouse parameters calculated from experimental data.



Time	Temperature	Relative humidity	Humidity
2,0	18,6	82,2	11,4
4,0	18,7	82,4	11,5
6,0	18,9	81,5	11,5
8,0	14,8	55,6	6,0
10,0	15,8	56,3	6,5
12,0	17,6	61,0	7,9
14,0	17,3	60,6	7,7
16,0	16,0	56,0	6,5
18,0	16,2	54,0	6,4
20,0	19,9	77,3	11,6
22,0	19,9	81,9	12,3
24,0	20,0	82,0	12,4

Fig. 1. Solution of the equation system on Maple.

4 Conlusion

The greenhouse microclimate model described in this chapter plays an important role in predicting energy demand and proper design of greenhouse heating and ventilation systems. A dynamic equation of the energy balance has been compiled taking into account the aerodynamics of air movement to solve the problem of the greenhouse air regime, which requires determining the flow of air moved through the gaps in the fence by filtration and through ventilation transoms under the influence of gravitational forces and wind.

The initial and boundary conditions for determining the microclimate parameters were established in the system of equations. Experimentally determined parameters show that not all indicators have a satisfactory agreement of the data. The developed model can only approximate the microclimate of the greenhouse, since it does not take into account the change in the parameters of the microclimate by the volume of the greenhouse. However, using this model, it is possible to calculate tasks for microclimate parameters and predict their mutual influence and predict quality indicators. Dynamic parameters such as air temperature, relative humidity and greenhouse air humidity were modeled, according to which the adequacy of the model was verified by the Fisher method, the maximum deviation was 11%.

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