Mathematical model of heat accumulation in the substrate and ground of a heliogreenhouse

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Abstract. This article describes the design and mathematical model for heat accumulation in the substrate and soil of a solar greenhouse. The results of the experimental studies are presented, the thermal processes that occur in the described system are considered, and a mathematical model for heat accumulation in the substrate and soil of the solar greenhouse is compiled. The proposed mathematical model facilitates the calculations for the accumulation and distribution of thermal energy in the different layers. Studied the accumulation of solar energy is carried out both in the greenhouse soil - the substrate, and in the heat storage channel. The article discusses the proposed mathematical model of transport processes in a solar greenhouse allows calculating the changes in the temperature of the soil-substrate and the average volumetric temperature for given initial conditions and external influences, depending on time. The discrepancy between the calculated and experimental data on heat transfer in the IC is ± 2 ÷ 7 for heat transfer in the substrate ± 10 ÷ 15%. The article presents the developed mathematical model of radiation-convective heat exchange of a two-block solar greenhouse with a substrate and heat accumulation is very correct, as evidenced by the comparison of the calculation results using the mathematical model and field experimental data.

1. Introduction
The current stage of agricultural construction is characterized by a tendency to expand the greenhouse economy and mobilize everyone, including a technical means for increasing the productivity of greenhouses. The objective of this trend is to provide the population with fresh vegetables in the required quantities throughout the year, especially during the cold period from October to May [1-2].

Unfortunately, at present, the total annual production of vegetables in the country and during the cold period is significantly less than required. Vegetables are produced mainly in open ground; therefore, the implementation of annual plans for the production of vegetables is critically dependent on weather conditions, and it is almost impossible to obtain the required amount of vegetables in the cold season. To date, the cultivation of crops and plants in greenhouses with technical heating has been recognized, the costs of which amount to 55-60% of the total costs. This cost imposes a special responsibility on the choice of designing a heating system for greenhouses [3-5].

Worldwide experience in the development of greenhouse production indicates an almost widespread transition to methods of growing plants in greenhouses and the use of new structures, materials and energy-saving technologies based on solar energy. For example, more than 263 thousand hectares of...
solar greenhouses are concentrated in Northern China, where 90% of winter vegetables are grown [6-7].

Several active-type greenhouses have been considered by V.V. Adoratsky [8]; their main parameters were determined for the case of the maximum sowing area. A three-bar greenhouse is proposed (figure 1 and 2). It is shown that for certain geometrical sizes of greenhouses, the fencing coefficient and heat loss are minimal. The paper does not consider the shading effect of the greenhouse roof on its heat balance and operating mode.

Figure 1. Mathematical model of heat accumulation in the substrate and soil of the solar greenhouse: 1-tray; 2- substrate; 3- overlap; 4- heat storage channel.

Figure 2. Mathematical model of heat accumulation in the substrate and soil of the solar greenhouse.
An experiment carried out in the state of North Carolina (USA) revealed a positive experience with respect to the technical use of solar energy for the cultivation of vegetable crops (tomatoes, cucumbers) using a hydroponic method. An aqueous nutrient solution served as a solar energy accumulator. The nutrient solution circulated inside the collectors installed at the heating station of the greenhouse, making up 70% of the total surface area of the hydroponic greenhouse trays. Solar collectors accumulated 14-15% of all energy received in the greenhouse [3-4; 7; 9-11].

The studies carried out at Karshi State University regarding the use of substrates revealed that, in addition to fulfilling their agrotechnical purpose, the substrates can be used as an additional source (biomass) of heat in greenhouses. This possibility is due to exothermic chemical reactions occurring in the substrate mass during its biological decay [12-15]. It is obvious that the use of such substrates can reduce energy consumption in the greenhouse. Their use is especially effective in combination with storage systems, particularly those shown in figure 1 and figure 2.

In concrete tray 1, on a special pallet/overlap/3, a layer of substrate 2 is laid. In the space between the overlap and the ground surface, heat-accumulating channel 4 is formed, through which air is driven during the charging and discharging period.

Consider the thermal processes occurring in the described system. Since all modelling is free from assumptions, then the reception model is the main one:

- Internal heat sources caused by exothermic chemical reactions are evenly distributed over the substrate mass and have the same power;
- Conductive heat transfer in each elementary layer along the channel length is one-dimensional;
- Air flow in the channel is hydraulically stable is:
- Surfaces participating in radiation heat transfer are diffuse grey;
- Perfect contact between layers;
- The structure has a finite height and an infinite width;
- Thermophysical properties of materials do not depend on temperature.

Under these assumptions, the design scheme can be represented as an array of sequentially located semi-infinite layers (figure 1 and figure 2) [16-19].

2. Materials and methods
The most effective way to improve the construction of solar greenhouses is to combine mathematical modeling with field tests. The use of mathematical modeling of heat transfer processes makes it possible to analyze the effectiveness of the proposed design solutions under various external conditions much faster than in field studies. Therefore, the development of sufficiently flexible mathematical models of solar greenhouses is relevant, allowing one to take into account the geometric and physical features of structures.

The mathematical models of solar greenhouses described in the literature are characterized by insufficient flexibility due to the fact that they are designed for a certain geometry of the structure, or only part of the processes are taken into account in them. In addition, a typical feature of these models is the use of empirical coefficients, which can only be measured (or calculated from measurements) using field tests.

This paper proposes an approach to the construction of mathematical models of solar greenhouses based on the modern theory of heat and mass transfer.

The totality of empirical information accumulated in this branch of science and the developed theoretical methods makes it possible to simulate heat transfer processes in a greenhouse without involving data from field tests.

For the accepted design scheme in the elementary section $dz$ for the first $x \in (1_1, 0)$ and third $x \in (1_2, 1_3)$ layers, the heat conduction equations are written in the form:
\[
C_i \rho_i \frac{\partial \tau_i(x, t)}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda_i \frac{\partial \tau_i(x, t)}{\partial x} \right]
\]  
(1)

where \( \tau \) is the temperature (K), \( C_i \) is the heat capacity (J/kgK), \( \rho_i \) is the density (kg/m\(^3\)), \( \lambda_i \) is the thermal conductivity coefficient (W/m\(^°\)C); \( t \) is time, and \( c, x, \) and \( z \) are spatial coordinates (m).

In the substrate layer \( x \in (1_3, 1_4) \), taking into account internal heat release, the heat conduction equation is written in the form:

\[
C_4 \rho_4 \frac{\partial \tau_4(x, t)}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda_4 \frac{\partial \tau_4(x, t)}{\partial x} \right] + q_{\nu H}
\]  
(2)

where \( q_{\nu H} \) is the power of the volumetric heat source, W/m\(^3\).

For the elementary section \( dz \), the heat balance of air in the heat-collecting channel is determined from the equation:

\[
1_2 \rho_b (T_{cp}, S, t) C_b (T_{av}, S, t) V(t) \frac{\partial T_2(z, t)}{\partial z} + q_{T_b}(0, z, t) + q_{T_3}(1_2, z, t) = 0
\]  
(3)

where \( T_{av2} \) is the average air temperature in the duct, determined from the ratio:

\[
T_{cp2} = \frac{1}{l} \int_0^l T_2(z, t) dz
\]  
(4)

Convective heat fluxes at the channel boundaries due to a small temperature difference between its walls can be taken equal and calculated by the formula [7; 10-12]:

\[
q_{T_3}(1_2, z, t) = \alpha_{T_3}(T_{av}, t) [T_2(z, t) - \tau_3(1_2 z t)]
\]  
(5)

where \( \alpha_{T_3} \) is the convective heat transfer coefficient calculated by the formula:

\[
\alpha_{T_3}(T_{av}, t) = \frac{\lambda_b \cdot (T_{av2}, t) \cdot Nu(T_{av2}, t, U)}{212}
\]  
(6)

where \( Nu \) (Nusselt's number) is calculated according to the well-known formula:

\[
Nu = 0,23 R e^{0,8} \cdot P r^{0,5}
\]  
(7)

The solution of the differential equations of heat transfer in the layers of the structure is carried out taking into account the balance of heat fluxes at its boundaries [6-7; 9].

The size of layer 1 is selected from the depth of penetration of the heat wave of daily fluctuations. Thus, at \( x=1_1 \), the condition \( \tau_1(1_1, t) = \tau_0 \) (where \( \tau_0 \) is the temperature of the isothermal layer at the boundary) is satisfied.

At the boundary \( x = 0 \), the balance of heat fluxes is written in the form:

\[
q_{T_3}(0, z, t) + q_r(0, t) - \lambda_1 \frac{\partial \tau_1(x, z, t)}{\partial x} \bigg|_{x=0} = 0,
\]  
(8)

where \( q_r(0, t) \) is the radiative heat flux, determined by the formula:

\[
q_r(0, t) = \sigma \varepsilon_{re} [\tau_{av}^4(1_2, t) - \tau_{av}^4(0, t)]
\]  
(9)

where \( \sigma \) is the Stefan-Boltzmann constant, W/(K\(^{4}\)m\(^4\)); \( \varepsilon_{re} \) is the reduced emissivity and \( \tau_{av} \) is the average surface temperature calculated in a similar manner to (4).

The reduced emissivity is calculated from the expression:
\[
\varepsilon_{re} = \frac{1}{\varepsilon_1 + \frac{1}{\varepsilon_2}} - 1
\]

where \(\varepsilon_1\) and \(\varepsilon_2\) represent the degree of blackness of the surfaces of the heat collection channel.

At the boundary \(x=1\), the boundary condition has the form:

\[
\lambda_3 \frac{\partial \tau_3(x, z, t)}{\partial x}|_{x=1_3} = \lambda_4 \frac{\partial \tau_4(x, z, t)}{\partial x}|_{x=1_4}, \tau_3(l_3, z, t) = \tau_4(l_3, z, t)
\]

where \(\lambda_3\) and \(\lambda_4\) are the thermal conductivities of the channel materials, \(l_3\) and \(l_4\) are the lengths of the channels, and \(\tau_3\) and \(\tau_4\) are the temperatures at the boundaries.

3. Results and discussion

The estimated experimental data obtained are characterized by the following:

The average heat flux through the upper surface of the heat storage channel (SCH) is:

\[
q_2 = \alpha_2 \cdot F_2 \cdot \Delta t_{av2}; \quad \Delta t_{av2} = \tau_{a1} - \tau_k
\]

where \(F_2\) and \(F_1\) are the areas of the SCH in the upper and lower walls, respectively; \(\alpha_2\) is the average heat transfer coefficient; \(\tau_{a1}\) and \(\tau_k\) are the air temperatures at the inlet and outlet of the SCH, respectively; \(\Delta t_{av2}\) represents the average heat flux through the lower surface of the SCH:

\[
q_1 = \alpha_2 \cdot F_1 \cdot \Delta t_{av1}; \quad \Delta t_{av1} = \tau_{av1} - \tau_k
\]

where \(\alpha_2\) is the average heat transfer coefficient on the walls of the SCH; \(\tau_{av1}\) and \(\tau_k\) are the air temperatures at the inlet and outlet of the SCH, respectively; \(\Delta t_{av1}\) represents the average heat flux through the lower surface of the SCH:

\[
q = \alpha \cdot F_c \cdot \Delta t_{av}; \quad \Delta t = \frac{\Delta t_{av2} + \Delta t_{av1}}{2}
\]

\[
q = v \cdot \rho_b \cdot c_p \cdot \Delta t_k; \quad \Delta t_k = \tau_{k1} - \tau_{k2}
\]

\(\alpha\) is the average heat transfer coefficient on the walls of the SCH; \(\tau_{k1}\) and \(\tau_{k2}\) are the air temperatures at the inlet and outlet of the SCH, respectively:

\[
F_c = F_2 + F_1 = 14.1 \ m^2; \quad S_c = 0.139 \ m^2
\]
\[ Q(t) = 20.9 \frac{W}{m^2}; \quad \lambda_4 = 0.206 \frac{W}{mK}; \]
\[ a_4 = 0.167 \cdot 10^{-6} \frac{m^2}{c}; \quad b_H = 0.96 m; \quad b_b = 1.152 m \]
\[ \alpha = 15.4 \frac{W}{m^2K}; \quad v = 1.5 \frac{m}{c}; \quad \lambda_1 = 0.57 \frac{W}{mK}; \quad a_1 = 0.35 \cdot 10^{-6} \frac{m^2}{c} \]

(18)

4. Conclusion

Solar greenhouses with a tray system for growing agricultural products with subsurface irrigation and an air-heater system for subsurface heat accumulation were developed, created and investigated. The accumulation of solar energy was carried out both in the greenhouse soil, i.e., the substrate, and in the heat storage channel. The discrepancy between the calculated and experimental data with respect to the heat transfer in the SCH is ± 2 ÷ 7 and for heat transfer in the substrate is ± 10 ÷ 15%.

The developed mathematical models of radiation-convective heat exchange of a two-block solar greenhouse with a substrate and heat accumulation are quite correct, as demonstrated by the comparison of the calculation results using the mathematical model and field experimental data. The implemented modelling method and the obtained mathematical dependencies can be effectively used in new scientific research and for practical calculations.

The change in the average soil temperature of the solar greenhouse, the surface temperature of the greenhouse soil-substrate (h = 0), at a depth of h = 0.15-0.3 m, as well as the accumulation of solar energy in the soil, which indicates the acceptability of the results, have been calculated and experimentally studied. The adequacy of the developed mathematical model of radiation-convective heat exchange of a two-block solar greenhouse (with a glass cover with a tray system for growing vegetables with subsurface irrigation and heat accumulation) was established by an experiment carried out in laboratories (full-scale) and semi-industrial conditions.

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