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Experimental Verification of the Mathematical Model of the Temperature Regime of a Solar-Fuel Trench Greenhouse

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Abstract. At present, thermal management in greenhouses is an important task for the greenhouse industry. This is facilitated by assessing heat loss through the greenhouse enclosing structures, which is an important component of energy management when designing a greenhouse, taking into account local climatic conditions. In this work, for the first time, a mathematical model is proposed for studying the behaviour of the dependence of the air temperature in a solar-fuel trench-type greenhouse in the climatic conditions of Uzbekistan. Since, at present, there is no thermal technical assessment of the microclimate of a solar-fuel trench-type greenhouse for the climatic conditions of the regions of Uzbekistan.

The study aims to develop a mathematical model of the thermal regime and microclimate in a solar-fuel trench greenhouse. To check the reliability of the proposed mathematical model, experimental measurements of the air temperature inside the greenhouse were carried out. The accuracy of the proposed mathematical model of a solar-fuel trench-type greenhouse was estimated using the methods of "standard deviation" and the square of the correlation coefficient. As the results show, the standard deviation is equal to 1.5 °C, the standard deviation in percent is equal to 7.2% and the square of the correlation coefficient is 0.86.

INTRODUCTION

Energy supply and thermal management in greenhouses are important tasks of the greenhouse industry. The cost of heating in greenhouses has risen to 49% of the total cost of production due to the ever-increasing prices of fossil fuels [1]. Moreover, the use of different energy supply methods needs to consider energy conservation measures to reduce the energy consumption of greenhouses and improve the economy of greenhouse crop production. Assessment of heat loss through the greenhouse envelope is an important component of energy management when designing a greenhouse considering local climatic conditions.

Modern greenhouse complexes are divided into two types, depending on their operation: seasonal and year-round. Usually, seasonal greenhouses are used from November to March. Seasonal greenhouses allow harvesting during the cold season and can be either aboveground or underground (trench) [2-4]. It should be noted that aboveground greenhouses are not protected from winds and temperature changes, which leads to a significant loss of energy for heating in the winter season [3]. One of the main advantages of trench greenhouses is their low energy consumption [5-10]. Therefore, the study aims to study the thermal regime and microclimate in a solar-fuel trench greenhouse to improve the energy efficiency of greenhouses in the climatic conditions of Uzbekistan.

Large research has been carried out on the calculation and testing of various cultivation facilities until now. A huge contribution was made by scientific works on heat engineering calculation in works [11–28]. It should be noted that the work [23] presents mathematical models of the thermal technical parameters of the microclimate of a solar trench greenhouse, taking into account the agro-climatic conditions of the regions of Turkmenistan. Based on the model, a climatic zoning map was developed. A nomogram was constructed to predict the temperature regime of a trench-type greenhouse for the country's northern, eastern, central, and southwestern regions. However, at present, there is no thermal assessment of the microclimate of a solar-fuel trench greenhouse, taking into account the climatic conditions of the regions of Uzbekistan.

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RESEARCH METHODOLOGY

To develop a mathematical model of a solar-fuel trench-type greenhouse for each element of the greenhouse, a differential heat balance equation is written (Fig. 1) [29, 34]. The heat balance equations for a plant:

$$\alpha_p(1-\rho)\tau I_T(1-F_n) = M_p C_p \frac{dT_p}{dt} + h_{rp}A_p(T_p - T_R) + h_r A_p(T_p - T_R) \tag{1}$$

where, α_p is plant radiation absorption coefficient (-); ρ is reflectivity of translucent barriers (-); τ is reflectivity of translucent barriers (-); I_T is incident total solar radiation (Bт/м^2); Fn is the ratio of the fraction of solar radiation falling on the northern wall to the total incoming radiation at the same time [30]; Mp is the mass of plants (kg); avg is the specific heat capacity of plants (J / kg • ° C); Tr, TR is temperature of plants and air inside the greenhouse, respectively (K); Apis total surface area of plants (m2); hrp is the general coefficient of heat transfer due to convection and evaporation between the plant and the internal air environment (W / m2 • ° C); hr is the coefficient of heat exchange with radiation between the plant and the internal air (W / m2 • ° C).

$$h_{pr} = h_p + \frac{0.016 \cdot h_p\left[p(T_p) - \gamma_r p(T_R)\right]}{T_p - T_R}$$

$$h_p = 2.8 + 3 \cdot v_w$$

$$h_r = F_{PR}\varepsilon\sigma(T_p^2 + T_R^2)(T_p + T_R)$$

where hp is the coefficient of heat transfer due to the convection between the plant and the air inside the greenhouse (W / m^2 • °C); p is the partial pressure of steam at saturation (at temperatures Tr and TR) (Pa);v is wind speed (м/с); F_{PR} is the form factor between the plant and the greenhouse room; ε is plant emissivity (-); σ is Stefan-Boltzmann constant (W/m^2×C^4).

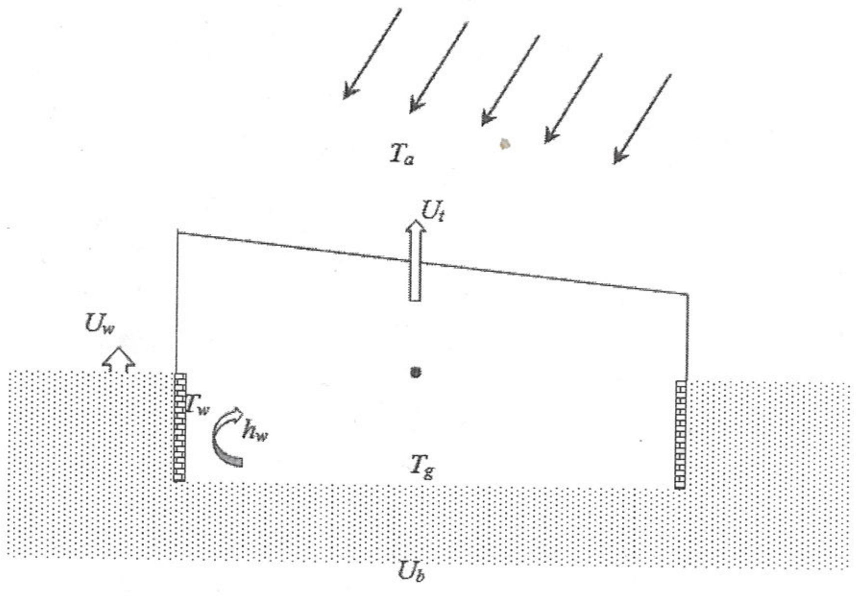


FIGURE 1. Schematic diagram of heat transfer in a greenhouse, heat balance equations for a greenhouse floor:

$$\alpha_g(1-\alpha_p)(1-\rho)\tau I_T(1-F_n) = -k_g A_g \frac{\partial T_g}{\partial x}_{x=0} + h_a A_g\left(T_{g_{x=0}} - T_R\right) \tag{2}$$

where, α_g is the coefficient of absorption of sunlight by the earth (-); A_g is surface area of the earth (m^2); k_g is coefficient of thermal conductivity of the earth (m^2); T_g issurface temperature (m^2); h_a is heat transfer coefficient with convection between the ground (Vt/m^2·°C) and internal air.

$$-k_g A_g \frac{\partial T}{\partial x}_{x=0} = U_b A_g\left(T_{g_{x=0}} - T_\infty\right),$$

where, U_b is the heat transfer coefficient between the earth's surface (W / $m^2 \cdot {}^\circ$ C) and from one meter of the depth of the earth.

Heat balance equations for the bottom (blank wall) part of the wall [31]:

$$\alpha_w(1-\alpha_p)(1-\rho)\tau I_T(1-F_n) = -kA_w \frac{\partial T_w}{\partial x}_{y=0} + h_w A_w \left(T_{w_{y=0}} - T_R\right) \qquad (3)$$

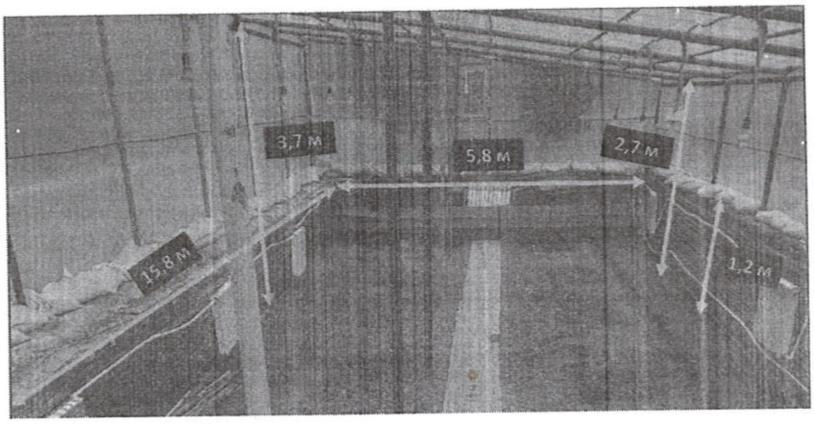
where, α_w iswall absorption coefficient (-); T_w istemperature of the surface of the lower part of the wall (°C); h_w isheat transfer coefficient with convection between the bottom of the wall and the indoor air ($W/m^2 \cdot {}^\circ C$); A_w iswall surface area (m^2).

To solve differential equations (1) - (3), an operational method was used, i.e.,the Laplace transform method.

RESULTS AND DISCUSSION

Experimental procedure

In order to test the developed mathematical model of a solar-fuel trench greenhouse, experimental measurements of the air temperature inside the greenhouse were carried out. For this, an experimental trench-type greenhouse was built on the experimental site of the Tashkent State Technical University.



.**FIGURE 2**. A prototype solar-fuel greenhouse.

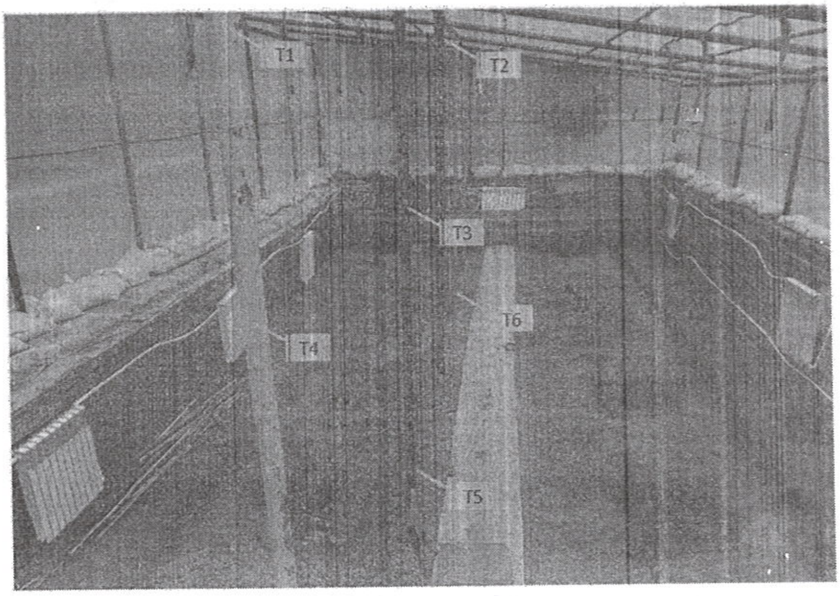


FIGURE 3. Installation of thermometers inside the solar-fuel greenhouse.

Temperatures at different points of the air inside the greenhouse are shown in Figure 3 and Table 1. Such a measurement allows you to find the average temperature of the non-uniformly heated air environment inside the greenhouse (Figure 4). HTC-1 liquid crystal temperature and humidity meter weather station alarm clock is used to measure temperature and humidity: temperature measurement range: -10 ° C ~ + 70 ° C, humidity measurement range: 10% ~ 90% RH. Temperature measurement accuracy ± 1 ° C and humidity ± 5% with resolution: temperature 0.1 ° C and 1%.

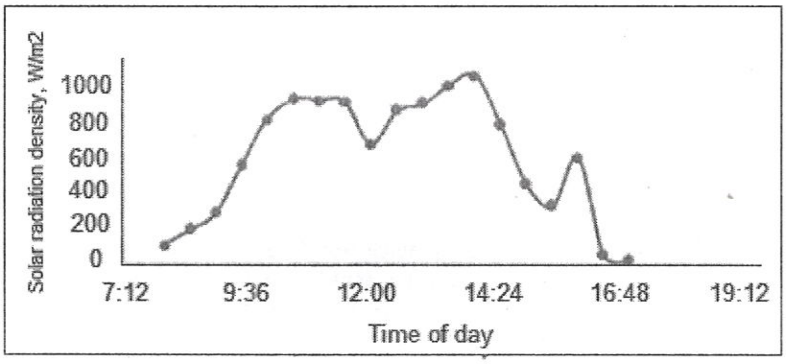


FIGURE 4. Dynamics of changes in ambient temperature during the day (05.02.2021).

TABLE 1. Air temperatures inside the greenhouse (02.05.2021).

Time	T1	T2	T3	T4	T5	T6
8:00	3	2	5	4	5	4
8:30	4	4	5.5	6	6	5.5
9:00	7	6	9	8	10	8
9:30	10	11.4	11	10	16	16
10:00	17	16.2	20	18	20	18
10:30	20	20.4	20.5	20	20.5	20.3
11:00	26	26	28	27	24	25
11:30	26	26	29	30	26	28
12:00	24	26	29	27	26	26
12:30	29	28	30	30	26	28
13:00	29	29	29	31	27	29
13:30	30	29	30	30	28	30
14:00	31	29	29	30	28	31
14:30	30	27	28	31	27	32
15:00	26	25	27	26	24	26
15:30	21	21	24	21	22	23
16:00	21	21	23	22	23	23
16:30	17	16	19	16	18	19
17:00	16	15	18	17	16	18

The Di-logSolarPowerMeter solar flux meter was used to measure the solar flux density (Fig. 5). The measuring range of the solar radiation flux density sensor is 1999 W / m². The measuring accuracy of the device is within ± 10 W / m².

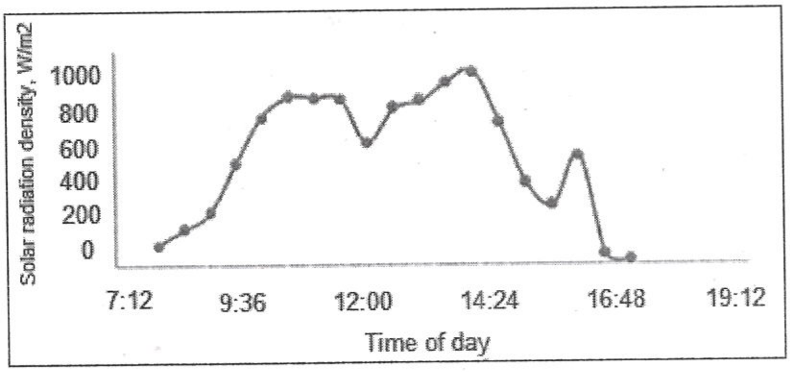


FIGURE 5. Dynamics of changes in the solar radiation flux density during the day (05.02.2021).

As the results of the experiment show, the highest value of the flux density falling on the horizontal surface of solar radiation is 994 W / m^2 and corresponds to 14:00 in the afternoon (Fig. 5). At the same time, there is a peak value of the air temperature inside the greenhouse (Fig. 4).

Experimental verification of the mathematical model

The statistical analysis of the proposed mathematical model of a solar-fuel trench-type greenhouse was carried out by comparing the experimental results carried out on February 5-9, 2021. in the laboratory area of the Tashkent State Technical University with calculated results. For this, the following initial data were used:

TABLE 3. Initial data for checking the mathematical model of a solar-fuel trench greenhouse.
Experimental verification of the mathematical model

Value	Designation	Numerical value	Unit of measurement
Plantradiationabsorptioncoefficient	α_p	0,4	
Reflection coefficient of a translucent fence	ρ	0,1	
Reflection coefficient of a translucent fence	τ	0,75	
The ratio of the fraction of solar radiation falling on the northern wall to the total incoming radiation at the same time	F_n	0,2	
Plantmass	M_p	0,1	kg
Specificheatofplants	C_p	4190	J/kg·°C
Totalplantsurfacearea	A_p	70	m^2
Form factor between plant and greenhouse room	F_{PR}	0,05	
Sun absorption coefficient of the earth	α_g	0,2	
Surface area of the earth (floor)	A_g	91,64	m^2
Solar absorption coefficient of the wall	α_w	0,1	
Wallsurfacearea	A_w	51,84	m^2
Surface area of translucent barriers	A_c	167,847	m^2
Doorsurfacearea	A_d	1,8	m^2
Psychrometricconstant	γ_o	0,55	
Air flow between the inside of the greenhouse and the environment	$\dot{m}$	0,143	kg/s
Densityofair	ρ_a	1,2	kg/m^3
Coefficient affecting the air velocity inside the greenhouse	f_w	0,22	m/s
Coefficient affecting the air velocity inside the greenhouse	f_T	0,16	m/s
Coefficient affecting the air speed inside the greenhouse	f_f	$5\cdot10^{-4}$	
Fanarea	A_v	0,64	m^2
Openingangle	ξ	20	°C

Comparisons of the calculated and experimental results of the air temperature in the greenhouse are shown in Fig. 6-7. Due to the establishment of thermodynamic equilibrium, i.e., thermal inertia and averaging the air temperature inside the greenhouse, there is some discrepancy at the beginning of the experiment and calculations (see Fig. 6).

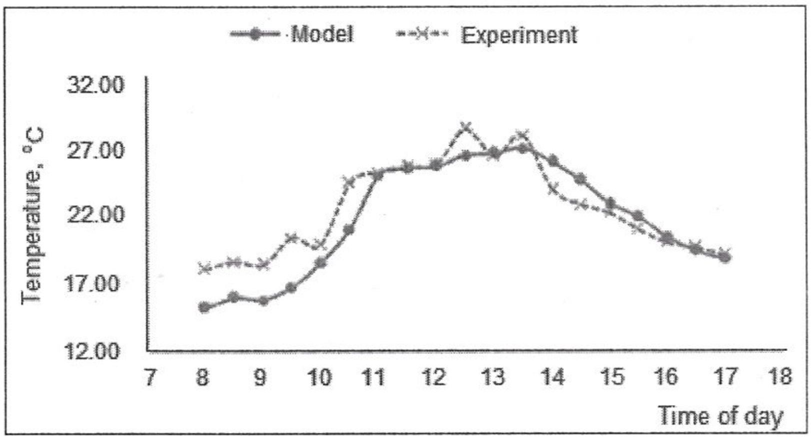


FIGURE 6. Comparison of the calculated and experimental (02/05/2021) results of the air temperature in the greenhouse.

However, comparisons of the calculated and experimental results of the air temperature in the greenhouse, carried out on another day, show an excellent correspondence of the calculated and measured data (see Fig. 7).

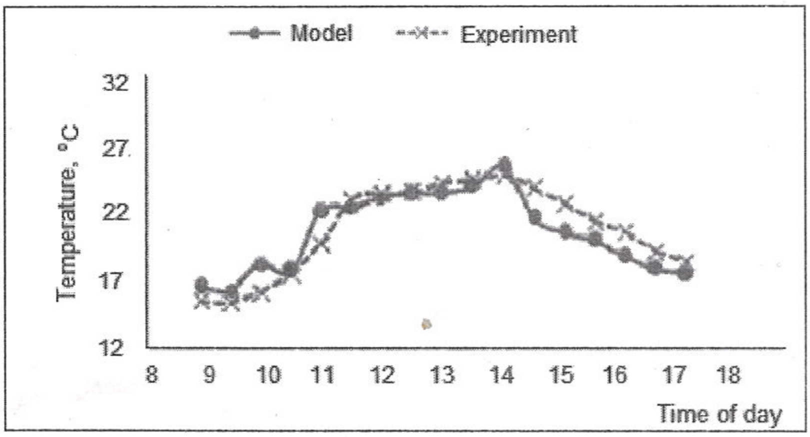


FIGURE 7. Comparison of the calculated and experimental (09.02.2021) results of the air temperature in the greenhouse.

Estimation of the Sufficiency of the Mathematical Model

The accuracy of the proposed model at each level of verification and validation was assessed using the "standard deviation (RMS)" methods. Therefore, we use a general analysis based on the coefficient of determination (R2) and the standard deviation. In general, the coefficient of determination gives an idea of how well a function fits the dataset. The standard deviation is a measure of how concentrated the data is around the line of best fit.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(T_{e_i} - T_{m_i})}{\sum_{i=1}^{n}(T_{e_i} - \bar{T}_{e_i})} \tag{5}$$

$$\text{CKO} = \sqrt{\frac{\sum_{i=1}^{n}\left(T_{e_i} - T_{m_i}\right)^2}{n}}$$

or

$$\text{CKO\%} = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(P_{e_i} - P_{m_i}\right)^2}{n}}}{\frac{\sum_{i=1}^{n} P_e}{n}} \cdot 100\% \tag{6}$$

where n is the number of data points, T is a set of experimental and calculated data, and T¯is the average value of a set of experimental and calculated data. The indices e and m denote the measured and calculated data, respectively. As the results show, the RMS is 1.5 ° C, the RMS in percent is 7.2%, and the square of the correlation coefficient (determination coefficient (R2)) is 0.86 [5, 6].

CONCLUSION

In this work, for the first time, a mathematical model is proposed for studying the behavior of the dependence of the air temperature in a solar-fuel trench type greenhouse in the climatic conditions of Uzbekistan. Currently, greenhouse complexes are divided into two types, depending on their operation: seasonal and year-round. Seasonal greenhouses are used from November to March, allowing harvesting during the cold season and can be either aboveground or underground (trench). The study aimed to develop a reliable mathematical model for studying the thermal regime and microclimate in a solar-fuel trench greenhouse to improve the energy efficiency of greenhouses in the climatic conditions of Uzbekistan. Since, at present, there is no thermal technical assessment of the microclimate of a solar-fuel trench-type greenhouse for the climatic conditions of the regions of Uzbekistan.

To check the reliability of the developed mathematical model of a solar-fuel trench greenhouse, experimental measurements of the air temperature inside the greenhouse were carried out. For this purpose, an experimental trench-type greenhouse was built. The accuracy of the proposed mathematical model of a solar-fuel trench-type greenhouse was assessed at each verification and validation stage using the "standard deviation" methods and the coefficient of determination.

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