Mech. Adv. Technol., Vol. 8, No. 2, 2024, pp. 164–171

DOI: 10.20535/2521-1943.2024.8.2(101).298506

UDK 62–53

Mechatronic greenhouse microclimate temperature control system

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Received: 14 February 2024 / Revised: 19 April 2024 / Accepted: 3 June 2024

Abstract. *The composition, functions, and characteristics of microclimate systems in small greenhouses are analyzed. The features that ensure the creation of favorable conditions for growing plants are identified. It is proposed to choose temperature and humidity as the parameters of priority provision. It is taken into account that modern methods and systems of microclimate of greenhouse facilities are focused on the regulation of air mass flows and heat exchange flows. The aim of the study is to create a mechatronic system for controlling air mass flows and heating elements to ensure heat balance in a greenhouse, taking into account the thermal radiation of the greenhouse object and heat exchange processes in a closed volume. A feature of the approach is a biased algorithm for controlling heat and mass transfer processes based on a daily weather forecast. A computer model of a greenhouse facility has been substantiated and developed, which takes into account heat exchange processes in the greenhouse, heat exchange with the external environment, added heat output by heaters, convection and forced air movement in the greenhouse. The study does not take into account the effect of water vapor on thermal radiation and the mixed convection mechanism inside the greenhouse. To generalize the model, the greenhouse was modeled without plants. Based on the results of the research, a mathematical model of changes in the heat flow of the greenhouse during the day was developed in SOLIDWORKS software. A one-day simulation of changes in air parameters in a greenhouse was performed to forecast the weather in the Kherson region (May 23, 2023). The simulation was based on the design parameters of the greenhouse, an initial temperature of 20 °C in the greenhouse, and an ambient temperature ranging from 14 °C to 20 °C according to the weather forecast. The modeling results were used to determine changes in the heat flux density on the greenhouse surfaces and the total heat output of heat exchange processes. It was found that the obtained characteristics provide an estimate of the total heat transfer coefficient and heat flux of the greenhouse, which served as the basis for determining the required power of heaters and developing a control cyclogram for the greenhouse temperature stabilization system. Based on the results of the model experiment, an operating mode for the heaters was developed. The results of the study and the developed algorithm for controlling heaters are suitable for use in mechatronic microclimate control systems, taking into account daily changes in environmental parameters.*

Keywords: *mechatronic control system, microclimate, temperature, heat output, greenhouse.*

Introduction

Changing weather conditions cause deviations in the microclimate parameters of a greenhouse facility, both during the entire operating period and during the day.

The air temperature inside the greenhouse can be regulated by using a fan with a heater. During the warm season, the greenhouse is ventilated by periodically opening the ventilation windows. Heat flow is transferred through the greenhouse covering in the form of heat loss or heat gain whenever the air temperature in the greenhouse exceeds the temperature of the outside air or vice versa. The rate at which heat flow is transferred through the greenhouse depends on various parameters such as thermal conductivity, outside and inside temperatures, cover material, and air movement (airflow rate) inside and outside the greenhouse. The microclimate control system should respond to changes in the internal environment, maintaining a stable temperature regime in the closed volume of the greenhouse [1]. Greenhouse microclimate control is based on the main four parameters involved in thermodynamic exchanges: the structure of the greenhouse, the air inside the greenhouse, the plants, and the soil. The role of each component of the system is as follows: the greenhouse

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structure retains heat (made of polycarbonate); the air inside the greenhouse regulates temperature and humidity through heat and mass transfer; the soil absorbs heat radiation and moisture; plants promote evaporation and distortion of air flows [2].

In this paper, a microclimate control system is proposed based on the design of the greenhouse facility and its heat exchange with the environment, as well as the temperature inside the greenhouse.

Literature review and problem statement

The coefficient of heat transfer between the greenhouse cover and the outside atmospheric air under the influence of wind on the outer surface of the greenhouse cover has been considered in many works [3]–[7]. No general relationship has been found that can be used for any greenhouse geometry under all environmental conditions. Papadakis et al. [4] developed a relation that can be used for daytime conditions when T_c (cover) > T_{am} (ambient). However, the coefficients in their relation include the effect of the temperature difference between the coating and ambient air ($T_c > T_{am}$). This relationship, which is suitable for use in this study, is given in [4].

$$h_{c-am} = 0.95 + 6.76 V_w^{0.49}, T_c > T_{am}, V_w \leq 6.3 m \times s^{-1}, \quad (1)$$

where h_{c-am} is the coefficient of heat transfer between the greenhouse cover and the ambient air; T_c is the temperature of the cover; T_{am} is the ambient temperature; V_w is the wind velocity outside the greenhouse.

Studies indicate the instability of thermodynamic processes in a greenhouse facility and the lack of parameters for changing heat losses.

The mechatronic system includes heaters as a source of thermal energy (Fig. 1). The operation of the heaters is controlled by a general algorithm in accordance with the current changes in parameters and predicted changes in ambient temperature (daily and seasonal temperature changes). The general algorithm should use the input data to calculate the expected change in heat output in the greenhouse during the day. The calculated changes in heat output are used to generate control signals that adjust the operation mode of the heaters.

The aim of the study

The aim of this work is to create a mechatronic control system for air mass flows and heating elements. In order to test the control system, the operation of the system was simulated for one day, on weekends [12]. The effect of water vapor on thermal radiation and the mixed convection mechanism inside the greenhouse were not taken into account in the study.

The analysis and research results will enable estimation of the total heat transfer coefficient and heat flow of the greenhouse, which will serve as the basis for the creation and testing of a simplified mechatronic greenhouse microclimate control system.

A control object and the processes that determine its state

The control program for ventilation and curtain window drives, damper drives, a fan, and heaters should maintain a stable temperature inside the greenhouse regardless of the influence of external factors.

To develop a control algorithm, it is necessary to have the dependence of changes in the heat exchange between the greenhouse and the surrounding environment over time and taking into account the predicted changes in the parameters of the surrounding environment. This will make it possible to determine the additional thermal power and the direction of the stabilization heat flow to preserve the microclimate in the greenhouse. Obtaining the indicated dependencies was carried out by modelling the operation of the greenhouse during the day. At the first stage, the processes taking place in the control facility, their mathematical descriptions and limits of application, parameters and coefficients necessary for thermal power calculations were considered.

The heat transfer coefficient between the cover and the internal air of the greenhouse. The average air velocity, *u*, inside the greenhouse used in this study (Fig. 1 *a*, *b*) was estimated to be approximately 0.1 m/s. Consider Monteith's criterion, as stated in [4], [7], which assumes that pure free convection occurs if $Gr/Re^2 > 16$ (where Gr is the Grashof number), pure forced convection occurs if $Gr/Re^2 < 0.1$ and mixed convection occurs if $0.1 < Gr/Re^2 < 16$. Applying these criteria to the greenhouse (Fig. 1), using different values of the ($T_c - T_a$) difference, results in the mixed convection mechanism occurring at ($T_c - T_a$) < 7 °C. This is consistent with the conclusion made in [4], [7]. The corresponding relation given in [4] for estimating the heat transfer coefficient (based on the mixed convection mechanism) in the daytime is as follows:

$$h_{c-am} = 1.95 \times \left(T_c - T_{am}\right)^{0.3}, \quad \left(T_c - T_{am}\right) \leq 11.1\ ^{\circ}\mathrm{C} \quad (2)$$

where h_{c-am} is the heat transfer coefficient between the greenhouse cover and the greenhouse interior air.

Equation (2) is valid for ($T_c - T_a$), but no equation was found to express this coefficient during the daytime for temperature differences greater than 11.1 °C.

The heat transfer coefficient between the floor and the greenhouse interior air. Various ratios have been used to estimate the heat transfer coefficient, for example, [5]–[10]. All of these ratios are based on a free or forced convection mechanism of heat transfer between the greenhouse floor and the internal air. The dependence given in [11], which is used in this study, considers a mixed convection heat transfer mechanism to estimate the coefficient as follows:

$$h_{s-a} = 1.52 \times \left(T_s - T_a\right)^{0.33} + 5.2\left(\frac{u}{L}\right)^{0.5}, \quad (3)$$

where h_{s-a} is the coefficient of heat transfer between the soil and the internal air of the greenhouse; T_s is the temperature of the soil surface; T_a is the temperature of the internal air of the greenhouse; $\bar{u}$ is the average air velocity inside the greenhouse; L is the characteristic length of the greenhouse floor ($L = 4$ m).

The convective heat transfer between the greenhouse cover and the ambient environment ($Q_c - Q_{am}$), and between the floor surface and the internal air ($Q_s - Q_a$) are calculated based on the temperature difference, surface areas, and corresponding heat transfer coefficients calculated using equations 1–3, respectively.

The heat transfer due to infiltrated air leakage $Q_{\inf}$ is calculated by the following formula:

$$Q_{\inf} = 2V_g \times N_{\inf} \frac{\left(\rho C_p\right)_a}{3600}\left(T_a - T_{am}\right), \quad (4)$$

where V_g is the volume of the greenhouse; $N_{\inf}$ is the number of changes of infiltrated air per hour; ρ is the density; C_p is the correction factor.

The coefficient 2 is included because the infiltrated air leaves the greenhouse at an average temperature of $\left(T_a - T_{am}\right)/2$). Thus, the heat transfer coefficient associated with infiltration air, $h_{\inf}$, is calculated by the following formula:

$$h_{\inf} = \frac{V_g \times \left(\rho C_p\right)_a}{600 A_c}, \quad (5)$$

where $h_{\inf}$ is the heat transfer coefficient; A_c is the surface area of the greenhouse cover.

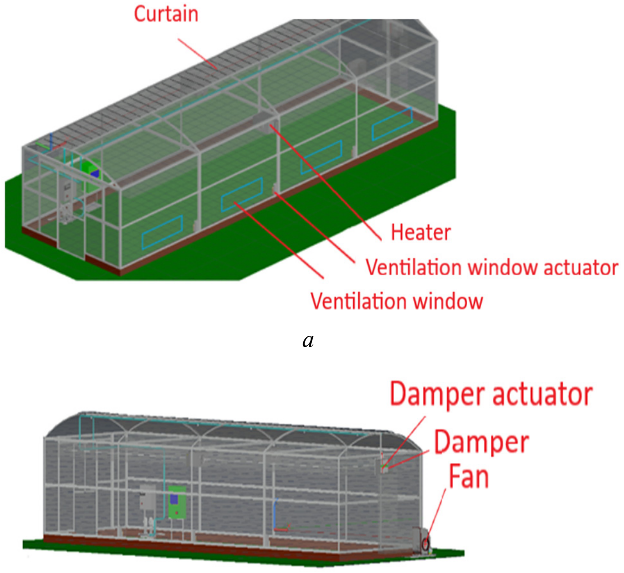
The properties of greenhouse air are considered equivalent to those of dry air and water vapor. The net exchange of thermal radiation between a greenhouse covering with emissivity T_{am} and temperature T_c can be calculated as follows:

$$q_{c-sky} = \varepsilon_c - A_c F_{c-sky} \sigma\left(T_c^4 - T_{sky}^4\right) = A_c h_r\left(T_c - T_{am}\right), \quad (6)$$

where $q_{c\text{-}sky}$ is the coefficient of visibility between the coating and the ambient environment (assuming $q_{c-sky} = 1$ for a single-span greenhouse); ε_c is surface radiation; F_{c-sky} is the coefficient of visibility between the cover and the sky; σ is the Stefan-Boltzmann constant; h_r is the radiation heat transfer coefficient.

In the case when T_{am} is equal to T_{sky}, the radiation heat transfer coefficient h_r is calculated by the following formula:

$$h_r = \varepsilon_c \sigma\left(T_c^2 - T_{sky}^2\right)\left(T_c + T_{sky}\right). \quad (7)$$



a

b

Fig. 1. Exterior of the greenhouse model

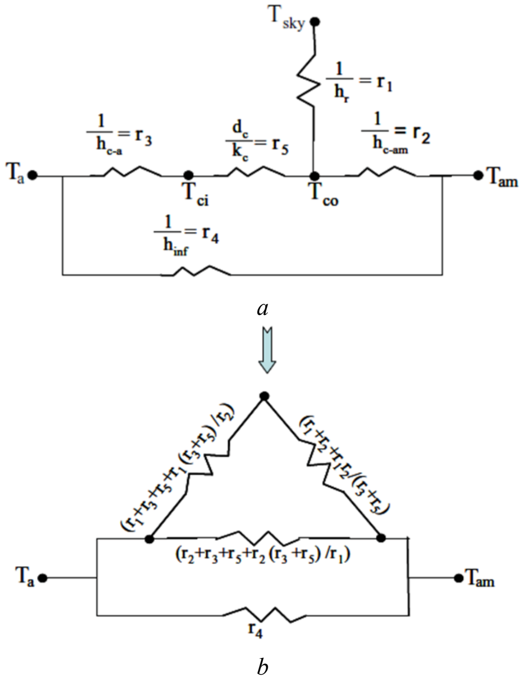
Total heat transfer coefficient. The heat transfer resistance between the inside and outside of the greenhouse (Fig. 2 *a*) includes five components: (1) thermal radiation resistanceю r_1 (= $1/h$) between the outer surface of the cover and the sky, (2) convective resistance r_2 (= $1/h_{c-am}$) between the outer surface of the cover and the ambient air, (3) convective resistance r_3 (= $1/h_{c-a}$) between the inner surface of the cover and the greenhouse air, (4) the infiltrated air resistance r_4 (= $1/h_{\inf}$) between the inside and outside air, and (5) the conductive resistance r_5 (=d_c/k_c) due to the cover thickness. The temperatures of the inner and outer surface of the cover (T_{ci} i T_{co}) are nearly the same, and the equivalent cover temperature T_c was taken into account. Thus, the resistance d_c/k_c (r_5) can be neglected (i.e., the temperature gradient across the coating thickness can be neglected) without any significant error in calculating U.

The star-shaped connection of thermal resistances shown in Fig. 2 *a*, was transformed into a triangle connection with equivalent three resistances connected in parallel between the internal and external temperature potentials (T_a and T_{am}), as shown in Fig. 2 *b*.

According to the electrical analogy of a heat network, Fig. 2 *b*, the total heat transfer coefficient is calculated by the following formula:

$$U = \frac{1}{(2r_1 + r_2 + r_3 + r_5 + \dfrac{r_1(r_3 + r_5)}{r_2} + \dfrac{r_1 r_2}{(r_3 + r_5)}} + \frac{1}{(r_2 + r_3 + r_5 + \dfrac{r_2(r_3 + r_5)}{r_1}} + \frac{1}{r_4}, \quad (8)$$

where U is the total heat transfer coefficient; r – is the thermal resistance.



a

b

Fig. 2. Electrical analogy with the resistances of the heating network for heat transfer between the internal air of the greenhouse and the external environment: (*a*) – actual network resistances, (*b*) – equivalent transformed resistances [7]

The steady-state energy balance was applied to the greenhouse cover and the surface of the mulched soil, respectively, as follows:

$$S_a + R_{CE} + R_{SE} + R_{skyE} + q_{v-c} - \varepsilon_c \sigma T_c^4 - Q_{c-a} = 0.0,$$
$$S_n + q_n - Q_{s-a} - D = 0.0, \qquad (9)$$

where S_a – is the solar radiation absorbed by the cover; R is the reflection of thermal radiation; $q_{v\text{-}c}$ is the net exchange of thermal radiation between water vapor and the cover; $Q_{c\text{-}a}$ is the convective heat flow from the cover to the internal air; S_n is the net solar radiation flux on the soil surface; q_n is the net thermal radiation flux on the soil surface; $Q_{s\text{-}a}$ is the convective heat flux from the soil surface to the internal air; D – is the conductive flux into the soil depth, calculated by the following formula:

$$D = \lambda_s A_s \frac{T_s - T_\infty}{H}, \qquad (10)$$

where λ_s is the thermal conductivity of the soil, and T is the temperature of the soil at a certain depth H (m), which is not affected by changes in the greenhouse conditions.

Study of the functioning of the greenhouse

A mathematical model was built in the SOLIDWORKS environment to determine the functions of heat and mass exchange with the surrounding environment during the operation of the greenhouse.

Initial conditions. It is assumed that the study is conducted for 24 hours. The greenhouse environment has an initial temperature of 20 °C. Based on the results of the analysis, a mathematical model of the change in the heat flow of the greenhouse during the day was built. For the model study, it was decided to accept the temperature of the external environment as an input variable. The process of studying the microclimate of a greenhouse object occurs in a continuous time throughout the day. The reference model of the greenhouse object provides regulation of the difference in thermal power with the help of a heater during constant cooling of the greenhouse during the day (Fig. 3).

To test the model, a data set was created in accordance with the task and the main parameters of the research object. The following initial data were entered:

1 – the initial value of the air temperature inside the closed volume of the greenhouse is 20 °C;

2 – the initial value of the ambient temperature: – 15 °C; – 10 °C; – 5 °C; 0 °C; 5 °C; 10 °C; 15 °C;

3 – the waiting period for stabilization of heat exchange processes is from 20 minutes to 3 hours.

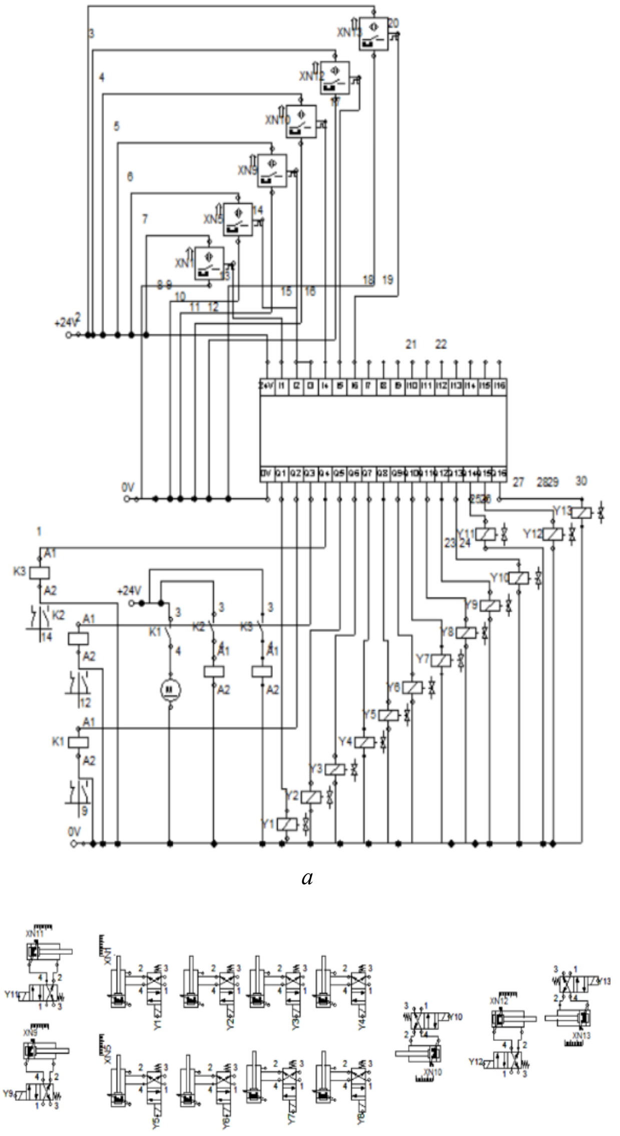
In the SOLIDWORKS environment, a model of changes in microclimate parameters (changes in the thermal power of the greenhouse, the distribution of the density of thermal power over the surface of the greenhouse).

Since the automated microclimate system must ensure a constant temperature throughout the greenhouse, it is necessary to predict expected temperature changes and maintain the temperature at the required level with the help of a heating element. (Fig. 1). That is, the task of determining the necessary duration and power of turning on electric heaters falls on the research function. For this purpose, by modeling, the heat radiation density field of the greenhouse during the day was determined. By integrating the heat radiation density area over the surface of the greenhouse, the function of heat loss during the day was calculated.

The purpose of the model study is to determine the amount of heat lost by the greenhouse during cooling, as well as the control algorithm for the heaters, fan and window drives to maintain a constant temperature inside the greenhouse.

The research was carried out in SOLIDWORKS Simulation.

The task of using the software is to determine the mode of operation of the heaters to compensate for the external influence: based on taking into account the change in the thermal power of the greenhouse during its cooling. The control algorithm, based on the dependence of changes in the temperature of the internal environment of the greenhouse, should determine the compensating added or negative thermal power provided by heaters or ventilation. The value of the compensating power and the time of its arrival determine the operating modes of the heaters. For this purpose, simulation of the change of the temperature field in the volume of the greenhouse was performed and the dependence of the loss of thermal power over time was obtained.



a

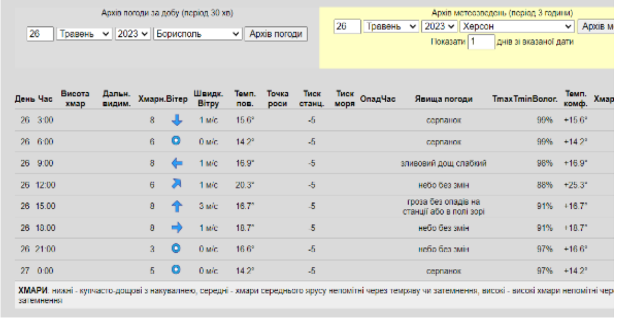
b

Fig. 3. *a*, *b* – Schemes of actuators (FluidSIM): Y1–Y8 – control of the lower ventilation window actuators; Y9, Y10 – control of the upper ventilation window actuators; Y11 – control of the curtain actuator; Y12, Y13 – control of the damper actuator; K2 and K3 – control of heaters; K1 – control of the fan

Results of the experiment

The air exchange rate of the greenhouse facility is 1400 m^3/h; the initial air temperature inside the greenhouse is 20 °C; the temperature of the air flow around the greenhouse ranges from 14.2 °C to 20.3 °C, based on the weather forecast (Fig. 4).

According to the results of the experiment, the distribution of the heat power density of the greenhouse during cooling under the influence of constant values of the external temperature from “– 15 °C” to “+ 15 °C” was obtained. (Fig. 5). The initial consumption of thermal power in the facility is assumed to be 0 kW, the initial temperature in the middle of the greenhouse is + 20 °C. It is assumed that a temperature regime of “+ 20 °C” was created in the greenhouse object by preliminary heating, after which the heater was turned off. Next, the change in the air temperature of an unheated greenhouse with different values of the outside air temperature was simulated. Since the heat exchange with the environment is unstable, the simulation time ranged from 20 minutes to 3 hours to determine the average value of the thermal power. According to previous experiments, the stabilization time of the velocity profiles in the greenhouse does not exceed 2...5 minutes, that is, the simulation time should ensure the stabilization of heat exchange processes during the experiment [13]. The first experiment with a temperature difference of 35 °C showed almost the same heat flow density on the surface of the greenhouse (Fig. 5 *a*). The maximum thermal radiation is observed along the perimeter of the greenhouse and the average heat flow density is 138 V/m^2. The density of thermal radiation gradually decreases as the temperature of the environment increases (Figs. 5*b*–5*e*). This is evidenced both by zones of lower heat flow density and by a general decrease in the calculated power. Thus, with a temperature difference of 10 °C, the highest power falls on the lower part of the surface and the density is 103 V/m^2. For all experiments, the highest heat flux power density (light layer) occurs at the lower edge of the wall surface, which is caused by convective flows of external air (Fig. 5). That is, the maximum temperature difference on both sides of the greenhouse occurs only near the soil. Further, along the height of the walls, the air that has been affected by the thermal radiation of the greenhouse rises. The temperature difference on both sides of the surface decreases vertically along the walls. Internal convective flows lead to local zones of reduced temperature difference, reflecting dark zones of heat flux density distribution.


Архів погоди за добу (період 30 хв)
26 Травень 2023 Бориспіль Архів погоди

Архів метеозведень (період 3 години)
26 Травень 2023 Херсон Архів м
Показати 1 днів зі вказаної дати

День	Час	Висота хмар	Дальн. видим.	Хмарн.	Вітер	Швидк. Вітру	Темп. пов.	Точка роси	Тиск станц.	Тиск моря	Опад	Час	Явища погоди	Tmax	Tmin	Волог.	Темп. комф.	Хмар
26	3:00			8	↓	1 м/с	15.6°		-5				серпанок			99%	+15.6°	
26	6:00			6	○	0 м/с	14.2°		-5				серпанок			99%	+14.2°	
26	9:00			8	←	1 м/с	16.9°		-5				зливовий дощ слабкий			96%	+16.9°	
26	12:00			6	↗	1 м/с	20.3°		-5				небо без змін			88%	+25.3°	
26	15.00			8	↑	3 м/с	16.7°		-5				гроза без опадів на станції або в полі зорі			91%	+16.7°	
26	18.00			8	→	1 м/с	18.7°		5				небо без змін			91%	+18.7°	
26	21:00			3	○	0 м/с	16.6°		-5				небо без змін			97%	+16.6°	
27	0:00			5	○	0 м/с	14.2°		-5				серпанок			97%	+14.2°	

ХМАРИ: нижні - купчасто-дощові з накувалнею, середні - хмари середнього ярусу непомітні через темряву чи затемнення, високі - високі хмари непомітні чер затемнення

Fig. 4. Weather forecast for May 26, 2023 in the Kherson region [12]

According to the results of model studies carried out for daily changes in the temperature of the surrounding environment (Fig. 4), the average value of the thermal power of the greenhouse during the day was calculated, which is shown in Table 1.

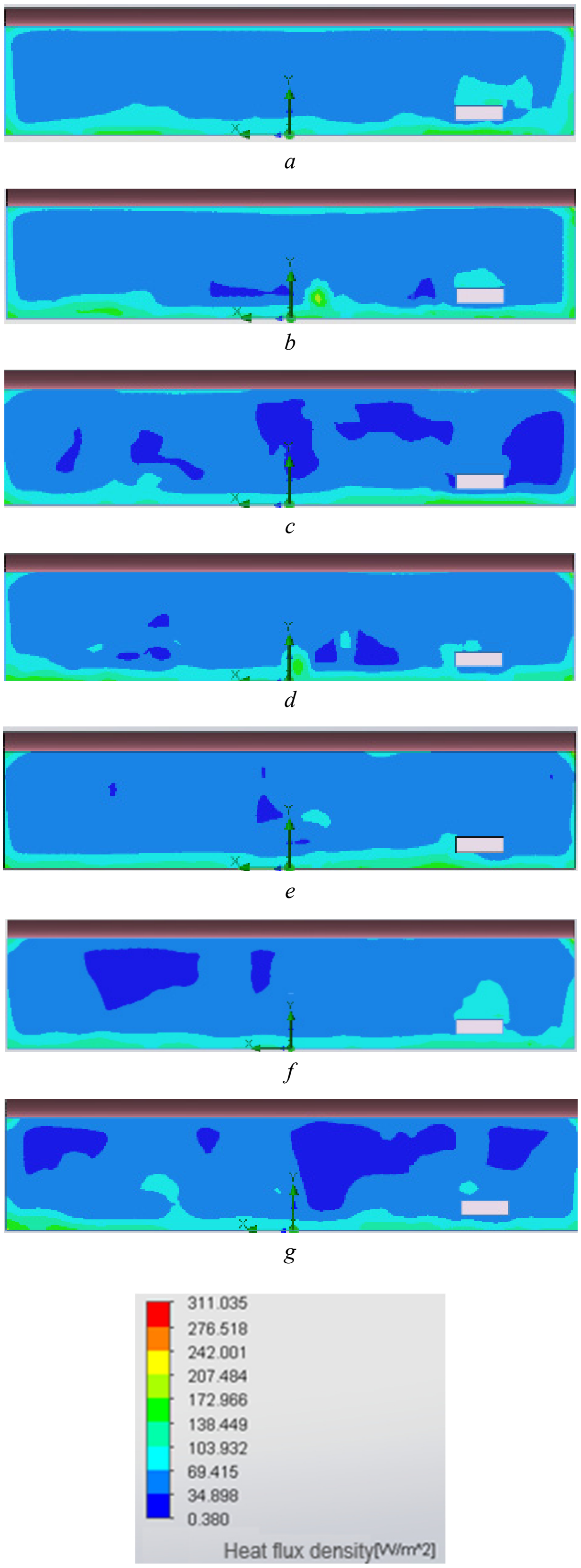


Fig. 5. Results of modeling changes in the consumption of greenhouse heat output during cooling: *a* – at – 15 °C;*b* – at – 10 °C; *c* – at 5 °C; *d* – at 0 °C; *e* – at 5 °C; *f* – at 10 °C; *g* – at 15 °C; *h* – measurements of heat flux density

Table 1. Loss of heat output of the greenhouse during the day

Day hours	Ambient temperature	Heating capacity loss
3	15.6	0.4167
6	14.2	0.4303
9	16.9	0.2896
12	20.3	–0.0134
15	16.7	0.3089
18	18.7	0.1200
21	16.6	0.3187
00	14.2	0.4303

Based on the obtained values of the average loss of thermal power of the greenhouse, a graph of the change in thermal power during the day was constructed (Fig. 6).

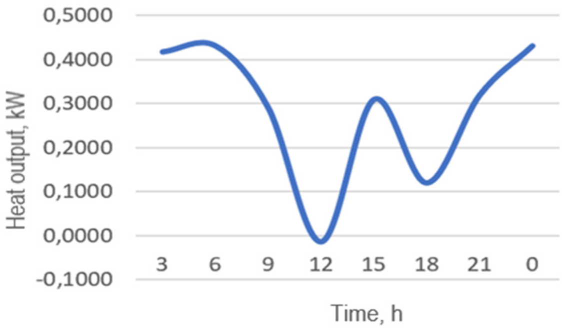


Fig. 6. Changes in the heat output of the greenhouse

To calculate the operating modes of the heaters, air temperature changes according to the forecast for May 26, 2023 in the Kherson region were used as an example. Taking into account the average value of thermal power, it is proposed to use two heaters with a capacity of 3 kW and 1 kW to compensate for heat loss in a closed greenhouse volume. Locations of radiators are shown in Fig. 1.

The determination of the term of switching on the i-th heater is regulated by the accumulated deficit of thermal energy:

$$\int_{t_0}^{t_0+\Delta t} Q_d(t)dt = N_{Fi} \times \Delta t, \qquad (11)$$

where t_0 is the current time, Q_d is the function of daily power losses according to the simulation results (Fig. 6), N_{Fi} is the power of the heater (s), Δt is the duration of the current heating of the heater.

Depending on the initial value of the lost thermal power, we choose to turn on one or two heaters (Fig. 7).

It can be seen from the constructed cyclogram that a 3 kW heater will work from 10 p.m. to 9 a.m., a 1 kW heater will work from 9 a.m. to 11 a.m., from 1 p.m. to

5 p.m. and from 7 p.m. to 10 p.m. From 11 a.m. to 1 p.m. and from 5 p.m. to 7 p.m., no heater will work. In accordance with the obtained mode of operation of the heaters, an algorithm for the control system was developed. The algorithm is implemented in the CoDeSys environment in the ST programming language.

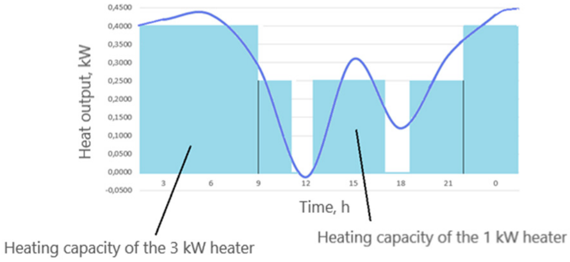


Fig. 7. Predicted change in heat loss with the cyclogram of switching on and off compensating heaters

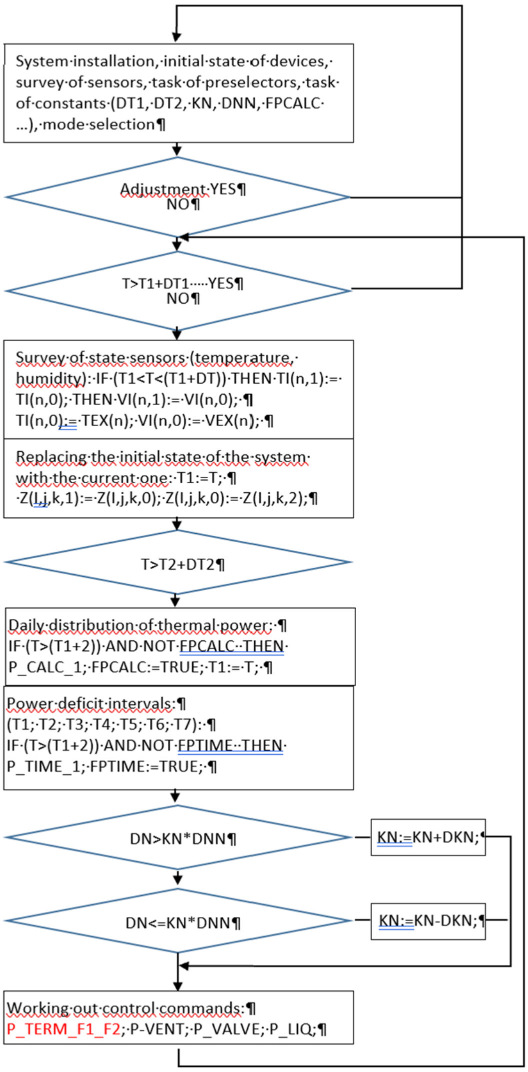


Fig. 8. The general algorithm of the heater control program

A fragment of the program code:

The general algorithm of the heater control program involves turning on the system, updating the values of the control variables, polling the sensors and updating the system status, adjusting constants and general control of the operation of executive devices (Fig. 8). When the control system is turned on, the first priority is the collection of current data from all executive devices and sensors. Next, the program goes to the initial state, the inputs and outputs of the controller are updated (if necessary, automatic or manual control modes can be selected). Also, if necessary, the values of constants are adjusted (time interval, power range, degree of opening or closing of channels). After adjusting the constants, the initial data is recalculated. At the end of the time interval T1, the sensors of the state of the greenhouse object are polled, while the previous current data are stored. Also, when the time T1 expires, the initial data are replaced with the current ones, and when the interval T2 is exceeded, the compensating thermal power is recalculated.

Constant power intervals are calculated according to current temperature changes. If the temperature adjustment is not in the permissible range, the operating time of the heaters decreases or increases.

The execution of heater control commands is given in the code fragment:

```
PROGRAM Main
VAR
  F1_Status : BOOL;  (* Heater status F1 *)
  F2_Status : BOOL;  (* Heater status F2 *)
  T1, T2, T3, T4, T5, T6, T7 : INT;  (* Heater time *)
END_VAR
(* Main algorithm *)
IF T > 0 AND T <= T1 + T2 + T3 + T4 + T5 + T6 + T7 THEN
  IF T <= T1 THEN
    F1_Status := TRUE;
    F2_Status := TRUE;
  ELSIF T <= T1 + T2 THEN
    F1_Status := FALSE;
    F2_Status := TRUE;
  ELSIF T <= T1 + T2 + T3 THEN
    F2_Status := FALSE;
  ELSIF T <= T1 + T2 + T3 + T4 THEN
    F2_Status := TRUE;
  ELSIF T <= T1 + T2 + T3 + T4 + T5 THEN
    F2_Status := FALSE;
  ELSIF T <= T1 + T2 + T3 + T4 + T5 + T6 THEN
    F2_Status := TRUE;
  ELSE
    F1_Status := TRUE;
    F2_Status := TRUE;
  END_IF;
ELSE
  F1_Status := FALSE;
  F2_Status := FALSE;
END_IF;
```

Conclusions

In the work, a mechatronic system for controlling the temperature of the microclimate of a medium-sized greenhouse with the help of heaters is theoretically justified, developed and tested for performance. Tests of the model confirmed its suitability for predicting temperature changes during heat and mass transfer processes under the influence of external factors. It was established that taking into account the processes of heat and mass exchange in the geometric 3D model of the greenhouse, it is possible to simulate changes in the consumption of thermal energy in the greenhouse during the day. The obtained dependences of heat losses made it possible to construct a cyclogram of the operation of compensating heaters during the day. The dependence of the changes in the power of the heaters over time, obtained as a result of the model experiment, shows that two heaters with a power of 3 kW and 1 kW with the corresponding schedule of their connection during the day are enough for the greenhouse. This mode of operation of the heaters allows you to heat the greenhouse at a two-zone tariff for electricity, which is economically beneficial when operating the greenhouse in the cold season. The proposed distribution of the order of operation of the heaters will satisfy the requirements for the temperature regime of the microclimate of the greenhouse. According to the obtained daily cycle diagram of the heater operation, an algorithm for controlling the elements of the mechatronic system (CoDeSys environment, ST programming language) and a diagram of the actuator control system (FluidSIM) were developed.

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Мехатронна система керування температурою мікроклімату теплиці

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Анотація. *Різкі зміни температури та вологості повітря негативно впливають на вирощування сільськогосподарських культур. Сучасні методи регулювання мікроклімату тепличних об'єктів здебільшого зводяться до регулювання потоку та температури повітряних мас. Метою цієї роботи є аналіз теплового випромінювання тепличного об'єкту та створення мехатронної системи керування елементами нагрівання. Виконано моделювання однієї доби в Херсонській області (23 травня 2023 року). Вплив водяної пари на теплове випромінювання і змішаний механізм конвекції всередині теплиці не враховувалися при дослідженні. Для спрощення аналізу, теплиця була змодельована без рослин, оскільки така повна імітаційна модель виходить за рамки цього дослідження. Цей аналіз призводить до точної оцінки загального коефіцієнта теплопередачі і теплового потоку теплиці, що послугувало основою для створення і тестування (перевірка правдоподібності) спрощеної програми керування системою мікроклімату теплиці. Результати дослідження і розроблена програма керування калориферами придатні для використання в алгоритмах керування мехатронною системою теплиці для врахування циклічних добових змін параметрів.*

Ключові слова: *мехатронна система керування, мікроклімат, температура, теплова потужність, теплиця.*