MODELING OF SUBSTRATE AND AIR TEMPERATURE DYNAMICS IN THE MUSHROOM GREENHOUSE
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МОДЕЛЮВАННЯ ДИНАМІКИ ТЕМПЕРАТУРИ СУБСТРАТУ ТА ПОВІТРЯ У ГРИБНИЦІ

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ABSTRACT

Economic efficiency of greenhouse vegetable growing depends quite significantly on the cost of energy carriers, which is why the introduction of energy-saving technologies in greenhouse vegetable growing is an urgent issue. One of the ways to save energy resources can be the use of a closed ventilation system of the "plant greenhouse - mushroom greenhouse" type, which is based on the opposite type of respiration of plants and mushrooms. A closed ventilation system includes air exchange between the greenhouse with growing plants and the cultivation room for growing mushrooms. The closed ventilation system allows you to save energy by reducing the heating of the incoming air, as well as increasing the yield of vegetable products due to the increased concentrations of carbon dioxide in the air that flows from the cultivation room for mushrooms to the greenhouse and mushrooms due to the increased concentrations of oxygen in the air that flows into the cultivation room for mushrooms from the greenhouse. Mathematical modeling of the process of heat transfer between greenhouses makes it possible to simulate transitional processes between rooms in order to assess the quality and accuracy of regulation, as well as to evaluate the parameters of the object in transitional modes. Mathematical modeling of dynamic processes is the basis for the formulation of transfer functions for the automatic control system. As a result of the study, mathematical models of the temperature dynamics of the substrate of mushrooms and greenhouse vegetables were obtained due to the analytical solution of the system of differential equations. The adequacy of the solution was verified by the Runge-Kutta method and compared with experimental data. The difference between the theoretical and experimental values is not significant and amounted to -3 % for the substrate temperature and -3.2 % for the air temperature.

АНОТАЦІЯ

Економічна ефективність тепличного овочівництва досить суттєво залежить від вартості енергоносіїв, у зв'язку з чим впровадження енергозберігаючих технологій у тепличному овочівництві є питанням актуальним. Одним із способів економії енергоресурсів може бути використання замкнутої системи вентиляції типу «рослинна теплиця - грибниця» яка основана на протилежному типі диханні рослин та грибів. Замкнута система вентиляції включає в себе повітрообмін між теплицею з вирощуванням рослин та культиваційним приміщенням для вирощування грибів. Замкнута система вентиляції дозволяє економити енергоносії за рахунок зменшення нагріву припливного повітря, а також збільшити вихід овочевої продукції завдяки підвищеним концентраціям вуглекислоти у повітрі, яке поступає із культиваційного приміщення для грибів в теплицю та грибів завдяки підвищеним концентраціям кисню у повітрі, яке поступає в культиваційне приміщення для грибів із теплиці. Математичне моделювання процесу переносу тепла між теплицями дає можливість моделювати перехідні процеси між приміщеннями з метою оцінки якості та точності регулювання, а також для оцінки параметрів об'єкту у перехідних режимах. Математичне моделювання динамічних процесів є підставою для формулювання передаточних функцій для системи автоматичного управління. У результаті дослідження були отримані математичні моделі динаміки температури субстрату грибів та тепличних овочів за рахунок аналітичного вирішення системи диференційних рівнянь. Перевірка адекватності рішення була перевірена методом Рунге-Кутти та порівняна із експериментальними даними. Розходження між теоретичними та експериментальними значеннями не суттєва і склала по температурі субстрату – 3 % і по температурі повітря – 3,2 %.

INTRODUCTION

The energy efficiency of a closed ventilation system and the dynamics of temperature changes in the buildings of this system were studied, which made it possible to use the ventilation system to carry out gaseous inter-fertilization of plants and mushrooms, since it is well known that plants absorb CO_2 and release O_2 during photosynthesis, and mushrooms, on the contrary, during respiration absorb O_2 and emit CO_2. CO_2-enriched air from the mushroom greenhouse and O_2-enriched air from the greenhouse circulates in a closed circuit using the ventilation system, and supply air is supplied to the system only when the concentration of CO_2 in the mushroom greenhouse exceeds the set norm. At the same time, the air that moves between the greenhouses has some thermal potential. That is, there is not only gas exchange, but also heat transfer (*Girchenko, et al., 2003)*. These studies are a continuation of the studies presented in *(Golub & Kepko, 2017*).

In addition to technological advantages, such a ventilation system provides significant savings in thermal energy for heating supply air. To ensure automatic control of the temperature regime in the "plant greenhouse - mushroom greenhouse" system, it is necessary to know its dynamic characteristics as an object of automatic control of temperatures of the substrate and circulating air.

Interest in the automation of greenhouses has now reached a significant level. The introduction of digital technologies into agricultural production has made it possible to introduce new technologies, technical information and ease of management, making crop production manageable on the basis of such technologies *(Achour, et al., 2021), (Tokmakov & Hrudynyn, 2008), (Rodrıǵuez, et al., 2001)*.

Transient processes in closed heating and ventilation systems can be quite complex, therefore, to assess the quality and accuracy of regulation, as well as to evaluate the object at any part of the transient process, it is desirable to have simulated mathematical models of these processes *(Dudnyk, et al., 2020*), (*Johansson, 1993*), which will make it possible to reduce the use of fuzzy conclusions in the microclimate management system in greenhouses, which leads to the need to use fuzzy neural networks in management *(Lysenko, et al., 2022*).

In many cases, when studying complex dynamic processes in greenhouses, systems of differential equations are solved using numerical methods (*Lendyel, 2016*).

The nature and duration of transient processes in greenhouses with large volumes of production *(Sethi, et al., 2013), (Costantino, et al., 2021)* requires modeling of these processes to evaluate the object at any part of the transient process *(Gorobec & Yatsenko, 2014), (Dudnyk, 2014)*. This issue is especially relevant for closed ventilation systems, due to their complexity.

Formulation of mathematical models for temperature dynamics in cultivation rooms with their subsequent analytical solution for plant greenhouses *(Koshkin & Babenko, 2011), (Voynova, 2007), (Berzan, et al., 2012), (Semenov & Krushel', 2009), (Takakura & Son, 2004)* and mushroom greenhouses *(Koshkin, 2015), (Peshko, 2011)*, did not consider models of temperature dynamics for the "plant greenhouse - mushroom greenhouse" system.

The task of the study was to investigate the transition processes in the system "plant greenhouse - mushroom greenhouse" and to obtain an analytical solution of the mathematical model of the dynamics of the substrate temperature and air in the system and to compare them with the results of investigational studies.

MATERIALS AND METHODS

During the investigation, differential equations characterizing the dynamic properties of objects in the "plant greenhouse - mushroom greenhouse" system were formulated and analytically solved by creating a mathematical model of air and substrate temperature dynamics.

In order to check and confirm the analytical dependences, studies of changes in air and substrate temperature were carried out in experimental greenhouses, which were connected to the "plant greenhouse - mushroom greenhouse " system (Fig. 1), where green onion was grown in the plant greenhouse, and in the mushroom greenhouse – oyster fungus. The choice of research methodology and processing of experimental data was based on the recommendations outlined in *(Hashchuk, 2002), (Trehub, 2017), (Pushkar & Protsenko, 2013)*.

The research on temperature dynamics was carried out with the aim of obtaining dynamic (accelerating) characteristics and comparing them with dynamic characteristics obtained from experimental dependencies. The method of active experiment was used to study the dynamic characteristics *(Pushkar & Protsenko, 2013), (Ryss & Hurvych, 1986)*.

During the investigation, differential equations characterizing the dynamic properties of control objects, existing schemes of ventilation systems of greenhouses and cultivation rooms for growing mushrooms were used.

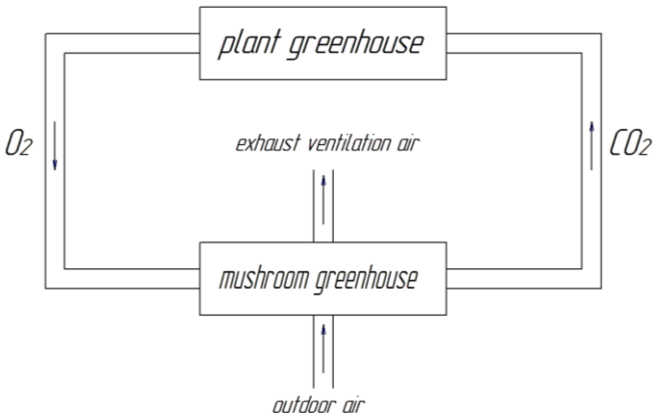

Fig. 1 - Schematic diagram of the closed system of heating and ventilation "plant greenhouse – mushroom greenhouse"

To determine the impact of the studied parameters on the processes that take place in the "plant greenhouse – mushroom greenhouse" system, a pairwise comparison of two factors was carried out, with other factors constant.

The assessment of the accuracy and reliability of the results of experiments, which contain systematic and random errors, is carried out using the methods of probability theory and mathematical statistics *(Vedenyapyn, 1973), (Drahanov, et al., 1993).*

To assess the state of the "plant greenhouse – mushroom greenhouse" system, the heat balance equation will be used (*Stroy, 1983*):

$$Q_{T.I} - Q_{H.ios} = Q_{exc} \tag{1}$$

where: $Q_{T.I}$ – total heat input to the room, [W]; $Q_{H.ios}$ – total heat loss from the room, [W]; Q_{exc} – excess ("–" deficit) of heat in the room, [W].

A positive value of Q_{exc} determines the power of the heating system, a negative value – the power of the air conditioning system.

Representing equation (1) through its components, the heat balance equation for rooms operating in the "plant greenhouse - mushroom greenhouse" system is obtained:
for the greenhouse:

$$-Q_{T.I.1} - Q_{H.1} + Q_{HL.1} - c_a \cdot \left[G_{M.1.1}\left(t_{in.2} - t_{in.1}\right) + G_{M.1.2}\left(t_{out} - t_{in.2}\right)\right] = 0 \tag{2}$$

for mushroom greenhouse:

$$-Q_{T.I.1} - Q_{H.1} + Q_{HL.1} - c_a G_{M.1.1}\left(t_{in.1} - t_{in.2}\right) = 0 \tag{3}$$

where: $1,2$ – respectively, a mushroom greenhouse and a plant greenhouse; $Q_H = Q_{exc}$, [W]; Q_{HL} – heat losses due to enclosing structures, [W]; c_a – heat capacity of air, [J/(kg·K)]; $G_{M.1.1}$ – air exchange between rooms, [kg/s]; $G_{M.1.2}$ – air exchange with the outside environment [kg/s]; t_{out} – outside air temperature, [°C]; $t_{in.1}$ – air temperature in the mushroom greenhouse, [°C]; $t_{in.2}$ – air temperature in the vegetable greenhouse, [°C].

Air and substrate temperature are the main factors affecting the process of mushroom cultivation in a mushroom greenhouse, and air temperature is the main factor in growing vegetable crops in a vegetable greenhouse. To determine the dependence between the temperature of the substrate and the air in time, we will use the theoretical prerequisites outlined in (*Golub, 2003)*, where it is proposed to determine this dependence by a system of differential equations. Assuming that the air temperature in the plant greenhouse is maintained by a separate control system, then in this case the temperature of the air entering the greenhouse from the greenhouse is assumed to be constant, which makes it possible to compile the following system from two differential equations:

$$\begin{cases} \dfrac{dt_S}{d\tau} = \dfrac{q_S m_S - r m_{EV}}{m_S c_S} - \dfrac{a_S S_S}{m_S c_S}\left(t_S - t_{in.1}\right) \\ \dfrac{dt_{in.1}}{d\tau} = -\dfrac{k_{EN} S_{EN}}{m_a c_a}\left(t_{in.1} - t_{out}\right) + \dfrac{a_S S_S}{m_a c_a}\left(t_S - t_{in.1}\right) + \dfrac{k_{HD} S_{HD}}{m_a c_a}\left(t_{HD} - t_{in.1}\right) + \ldots \\ \qquad \ldots + k_{E1}\left(t_{in.2} - t_{in.1}\right) + k_{E2}\left(t_{out} - t_{in.1}\right) + k_{A.INF}\left(t_{out} - t_{in.1}\right) \end{cases} \tag{4}$$

where: t_S – substrate temperature, [°C]; m_S – mass of the substrate in the mushroom greenhouse, [kg]; c_S – specific heat capacity of the substrate, [J/(kg°C)]; q_S – heat release of the substrate, [W/kg]; α_S – coefficient of heat transfer from the substrate, [W/(m²·°C)]; S_S – the surface area of the substrate that is blown by air, [m²]; r – specific heat of vaporization of water, [J/kg]; m_{EV} – intensity of water evaporation, [kg/s];

τ – time, [s]; m_a – air mass in the mushroom greenhouse, [kg]; k_{E1} – the multiplicity of air exchange in the "plant greenhouse – mushroom greenhouse" system, which is organized between the premises of the system, [s^{-1}]; k_{E2} – the multiplicity of air exchange in the "plant greenhouse – mushroom greenhouse" system, which is organized between the mushroom greenhouse and the external environment, [s^{-1}]; k_{EN} – coefficient of heat transfer through enclosing structures, [W/(m²·°C)]; S_{EN} – surface area of fences, [m²]; S_{HD} – surface area of heating devices, [m²]; k_{HD} – coefficient of heat transfer from heating devices, [W/m² °C]; t_{HD} – water temperature in heating devices, [°C]; $k_{A.INF}$ – air exchange rate of infiltration, [s^{-1}].

The general solution of the system of differential equations will be as follows:

$$t_S = C_1 \exp(k_1\tau) + C_2 \exp(k_2\tau) + t_S^c \tag{5}$$

$$t_{in.1} = \left(\frac{k_1}{c}+1\right)C_1 \exp(k_1\tau) + \left(\frac{k_2}{c}+1\right)C_2 \exp(k_2\tau) + t_{in.1}^c \tag{6}$$

where: k_1, k_2 – roots of the characteristic equation; C_1, C_2 – permanent solutions of the differential equation; t_S^c – constant value of the temperature of the substrate, [°C]; $t_{in.1}^c$ – constant value of the air temperature in the mushroom greenhouse, [°C]; $C = a_S S_S / m_S c_S$.

Permanent solutions of differential equations are determined from the condition that at the initial moment of time the temperature of the substrate and air are equal to their initial constant values. In the presence of incoming exciting influences (changes in the temperature of the outside air, the amount of heat released by the substrate, which depends on the intensity of the passage of biological processes in the substrate or the temperature of the supply air), new constant values of the temperature of the substrate and air are established. Therefore, this can be written as:

$$C_1 = -\frac{(k_2 + C)(t_S^{CB} - t_S^{CE}) - C(t_{in.1}^{CB} - t_{in.1}^{CE})}{k_1 - k_2} \tag{7}$$

$$C_2 = -\frac{(k_1 + C)(t_S^{CB} - t_S^{CE}) - C(t_{in.1}^{CB} - t_{in.1}^{CE})}{k_1 - k_2} \tag{8}$$

where: t_S^{CB}, t_S^{CE} – initial and final constant value of substrate temperature, [°C]; $t_{in.1}^{CB}, t_{in.1}^{CE}$ – initial and final constant value of the air temperature in the mushroom greenhouse, [°C].

The inhomogeneous differential equation of the second order that can be obtained by solving the system of equations (4), which describes the dynamic properties of the cultivation room – greenhouse system, can be represented through the Laplace transform in the form of a transfer function, which is important for the performance of functions of automatic control of the temperature of the substrate:

$$W(p) = \frac{k}{(T_1+1)(T_2+1)} \tag{9}$$

where: T_1 – response time for the substrate, [s]; T_2 – response time for the air, [s].

Checking the analytical solution of the system of differential equation (4) by solving the second-order differential equation by the Runge-Kutta method using MathCad software showed the coincidence of the results.

The experimental greenhouse of the Horticulture Department of Uman National University of Horticulture was used to check analytical dependences on temperature dynamics. The premises were equipped with a heating and ventilation system and a temperature control and regulation system.

A production inspection was carried out, the task of which was to determine the energy indicators of a closed heating and ventilation system and to compare them with the indicators obtained as a result of analytical and experimental studies.

RESULTS

Modeling of the power of the heating installation of the mushroom greenhouse and the plant greenhouse in the range of internal temperatures from 10 to 22°C according to (2) and (3) is shown in Figures 2 and 3, respectively.

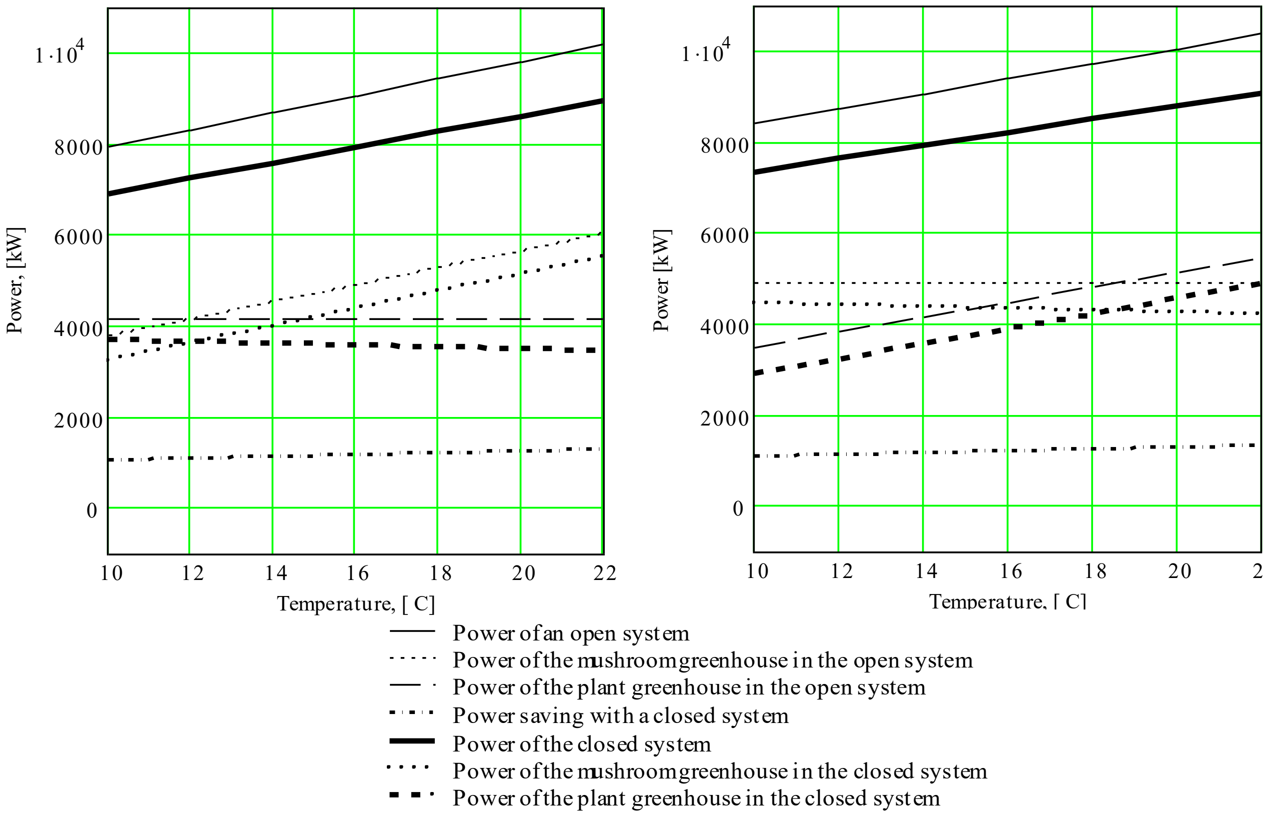

Fig. 2 - Dependence of the power of the heating system on the temperature of the internal air in the mushroom greenhouse (night)

Fig. 3 - Dependence of the power of the heating system on the temperature of the internal air in the plant greenhouse (night)

Heat and heat air balances for experimental mushroom greenhouse and plant greenhouse are given in Tables 1-4.

Table 1

Heat balance of the cultivation room for mushrooms

Indicator	Winter	Transition period	Summer
Outdoor air temperature, t_{out}, ºC	–21	5	24
Air temperature in the room, t_{in}, ºC	16	16	16
Heat input: from solar radiation, $Q_{s.r}$, kW	1.444	2.403	3.105
Other, Q_{OTH}, kW	0.599	0.599	0.5985
Total, $Q_{T.I}$, kW	2.042	3.002	3.703
Heat losses: due to enclosing structures, Q_{HL}, kW	3.857	1.131	–0.86
on infiltration, Q_{INF}, kW	0.249	0.055	–0.03
on evaporation, Q_{EVA}, kW	0.408	0.408	0.408
on heating the supply air, $Q_{I.AIR}$, kW	1.995	0.593	–0.431
Total, $Q_{H.ios}$, kW	6.508	2.188	–0.914
Excess ("-"deficit) of the heat flow, Q_{exc}, kW	–4.466	0.814	4.617

Table 2

Heat-air balance of the cultivation room for mushrooms

Indicator	Winter	Transition period	Summer
Excess ("-"deficit) of the heat flow, Q_{exc}, kW	–4.466	0.814	4.617
Inflow of air into the room, GM, kg/s	0.054	0.054	–0.523
Outdoor air temperature, t_{out}, ºC	–21	5	24
Heat flow with supply air, Q_{IA}, kW	–1.132	0.27	–12.6
Heat flow for room heating, Q_H, kW	4.466	–0.814	–
Heat flow for heating supply air, $Q_{I.AIR}$, kW	1.995	0.593	–
Extraction (removal) of the air from the room, G_M, kg/s	0.054	0.054	–0.523
Air temperature in the room, t_{in}, ºC	16	16	16
Heat flow with exhaust air, Q_{OA}, kW	0.863	0.863	–8.4
Balance: in the air, G_M, kg/s	0	0	0
in the heat flow, $Q_{баланс}$, kW	0	0	0

Table 3

Heat balance of a plant greenhouse

Indicator	Winter	Transition period	Summer
Outdoor air temperature, t_{out}, °C	– 21	5	24
Air temperature in the room, t_{in}, °C	14	14	14
Heat input: from solar radiation, $Q_{s.r}$, kW	1.197	2.462	3.387
other, Q_{OTH}, kW	0	0	0
Total, $Q_{T.I}$, kW	1.197	2.462	3.387
Heat losses: due to enclosing structures, Q_{HL}, kW	3.983	0.992	–1.194
on infiltration, Q_{INF}, kW	0.231	0.044	–0.037
on evaporation, Q_{EVA}, kW	0.116	0.116	0.116
on heating the supply air, $Q_{I.AIR}$, kW	0.681	0.175	–0.194
Total, $Q_{H.ios}$, kW	5.011	1.327	–1.309
Excess ("-"deficit) of the heat flow, Q_{exc}, kW	– 3.814	1.135	4.696

Table 4

Air and heat balance of a plant greenhouse

Indicator	Winter	Transition period	Summer
Excess ("-"deficit) of the heat flow, Q_{exc}, kW	–3.81	1.135	4.696
Inflow of air into the room, G_M, kg/s	0.0194	0.0194	–0.448
Outdoor air temperature, t_{out}, °C	–21	5	24
Inflow of air into the room, G_M, kg/s	–0.408	0.097	–10.8
Heat flow for room heating, Q_H, kW	3.814	–1.135	–
Heat flow for heating supply air, $Q_{I.AIR}$, kW	0.681	0.175	–
Extraction (removal) of the air from the room, G_M, kg/s	0.0194	0.0194	–0.448
Air temperature in the room, t_{in}, °C	14	14	14
Heat flow with exhaust air, Q_{OA}, kW	0.272	0.272	–6.3
Balance: in the air, G_{bal}, kg/s	0	0	0
in the heat flow, Q_{bal}, kW	0	0	0

Production inspection was carried out at LLC "Slavuta" of Bila Tserkva district, Kyiv region, in order to check the efficiency of the "plant greenhouse – mushroom greenhouse" system, where oyster fungus culture (strain NK 35) was cultivated in the mushroom growing workshop (Fig. 4). The production inspection was carried out for 30 days.

Fig. 2 – Production premises (general view)

The energy efficiency of the close system of ventilation in the mushroom room was carried out as follows: one day the heating and ventilation system worked in a closed mode, and the next – in an open mode, on the third day again – in a closed mode, etc. During the inspection, the following parameters were recorded: the temperature of the external and internal air in the cultivation room and the temperature of the water in the heating system at the entrance and exit from the room, the temperature of the water at the entrance and exit from the heater, the temperature of the air at the entrance and exit from the heater, and the temperature of the substrate. Two arrays of data, i.e. data on a closed and an open system, were statistically processed and grouped by outdoor air temperatures. Graphs constructed based on these data are shown in Figures 5, 6 and 7.

According to the obtained data, thermal energy savings during the inspection period (30 days) at “Slavuta” LLC amounted to 1,980 kW/h of heat energy, which made it possible to reduce heating and ventilation costs by 10.7%. When using "plant greenhouse – mushroom greenhouse" system during the entire cycle of mushroom fruiting, the saving of heat energy will be 4032 kW/h with a payback period of 0.64 per year.

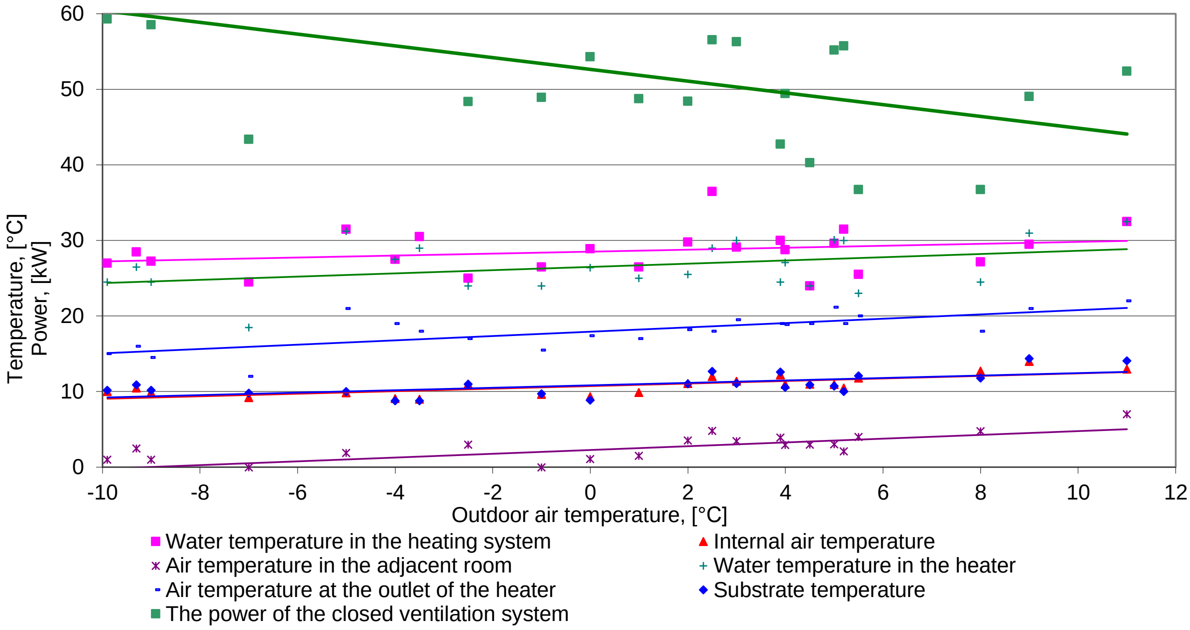

Fig. 5 – Mushroom greenhouse parameters in a closed ventilation system

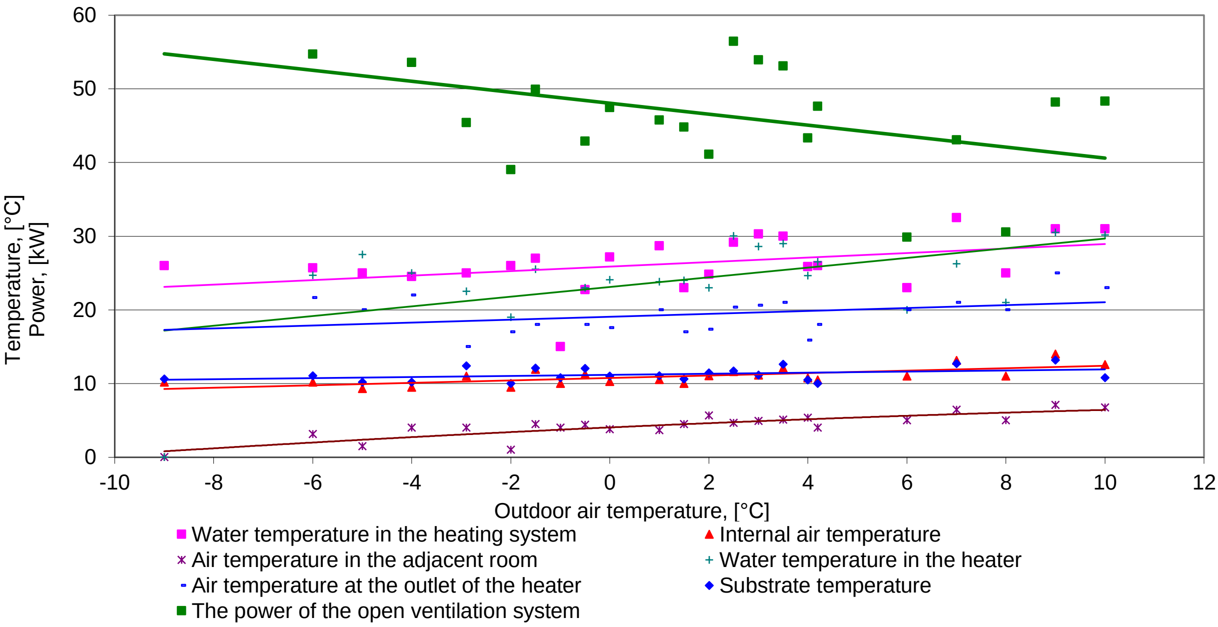

Fig. 6 – Mushroom greenhouse parameters in an open ventilation system

Experimental studies were carried out at a constant air temperature in the plant greenhouse of 14°C and at an initial temperature of the substrate of 15.2°C and air in the mushroom greenhouse of 12.9°C. An increase in the temperature of the water in the heating system of the mushroom greenhouse from 50°C to 60°C led to a transition process (Fig. 8), and new constant values of substrate and air temperatures were set at 18.8°C and 16.4°C.

Approximation of experimental data was carried out using exponential regression:

$$f(x) = a \cdot e^{bx} + c \tag{10}$$

where: a, b, c – are exponential regression coefficients.

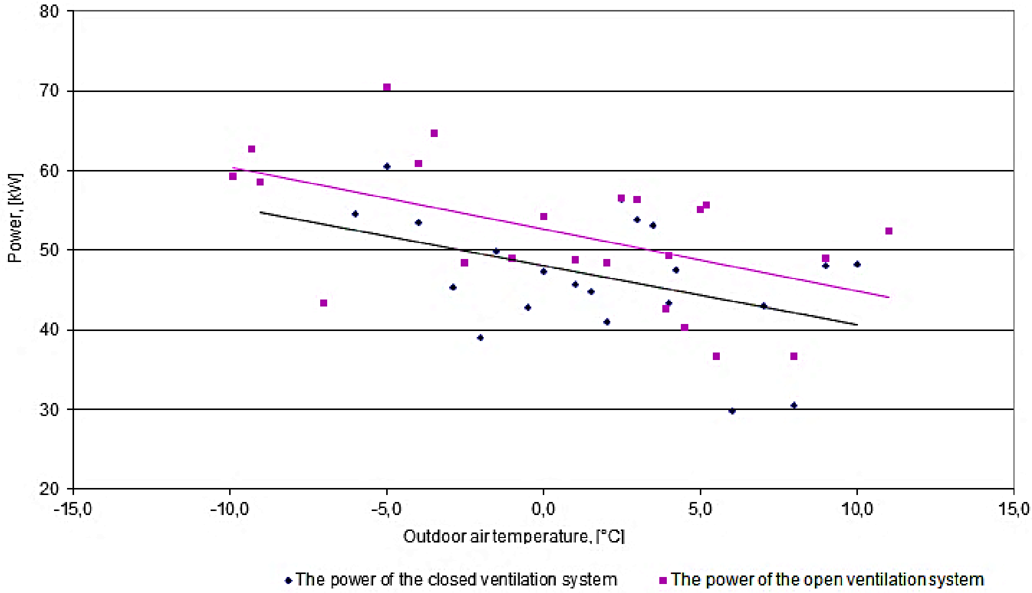

Fig. 7 – Power of mushroom greenhouse in closed and open ventilation systems

Exponential regression coefficients are given in Table 5.

Table 5

Exponential regression coefficients

Parameter	Regression coefficients		
	a	b	c
Internal air temperature	–2.55	–0.089	15.99
Substrate temperature	–3.87	–0.041	18.89

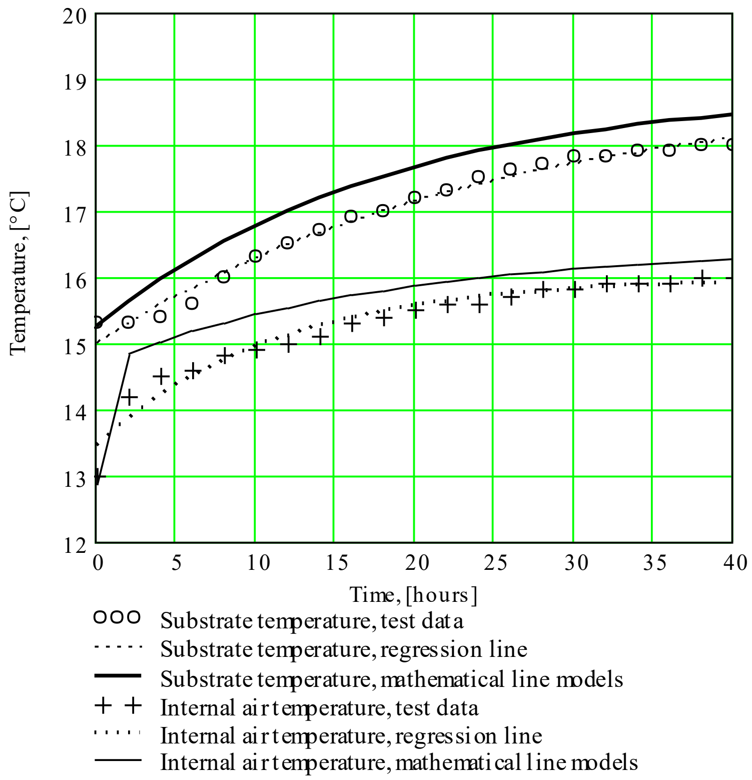

Fig. 8 - Dynamics of changes in the temperature of the substrate and air in the mushroom greenhouse when the temperature of the water in the heating system changes from 50 to 60 °C

CONCLUSIONS

1) The inspection showed that the difference between the theoretical and experimental values is not significant and amounted to 3% for the substrate temperature and 3.2% for the air temperature. Correlation coefficients, respectively, were: 0.99, 0.98.

2) The conducted comparative theoretical and experimental studies make it possible to assert the adequacy of the obtained solution of the differential equation of the temperature change of the substrate and air.

3) Depending on the conditions, the use of the "plant greenhouse – mushroom greenhouse" system makes it possible to reduce heat energy consumption by 12-20%.

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