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ТЕХНОЛОГИИ И СРЕДСТВА МЕХАНИЗАЦИИ СЕЛЬСКОГО ХОЗЯЙСТВА / TECHNOLOGIES AND MEANS OF AGRICULTURAL MECHANIZATION

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Original article

Light and Temperature Control for Greenhouse Plant Growth

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Introduction. The article deals with the conditions for growing greenhouse plants. Supplementary lighting supports the process of plant photosynthesis and the microclimate in the greenhouse. The authors suggest the ways to reduce energy consumption in greenhouses by controlling the microclimate and process of supplementary lighting in greenhouses.
Materials and Methods. Special lighting and temperature are required for growing greenhouse plants. A method of efficient plant growing is light and temperature control. The development of a control algorithm requires the mathematical models that relate the process of photosynthesis to the microclimate parameters. There are given the mathematical models based on the experimental data.
Results. The control system and algorithm to control plant-growing conditions have been developed to maintain the greenhouse microclimate. LED lamps are used to control the lighting process. The authors present the developed block diagram of the control system, which contains four channels responsible for the main energy-intensive microclimate factors. The description of the algorithm of the greenhouse light-temperature control is given.
Discussion and Conclusion. In conclusion, the need to maintain the greenhouse microclimate and supplementary lighting with the different radiation spectrum for the efficient cultivation of greenhouse plants is shown. The developed structure and control algorithm for the supplementary plant lighting process and greenhouse illumination through using LED lamps help reduce energy consumption.

Keywords: greenhouse plants, supplementary lighting, illumination, temperature, greenhouse microclimate, radiation spectrum, control system, control algorithm, LED lamps

Conflict of interest: The authors declare no conflict of interest.

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Оригинальная статья

Принцип управления свето-температурным режимом для роста тепличных растений

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Введение. В статье рассматриваются условия выращивания тепличных растений, среди которых важным фактором является поддержание процесса фотосинтеза путем досвечивания растений и необходимого микроклимата в теплице. Выращивание тепличных растений с помощью снижения потребляемой электроэнергии за счет управления микроклиматом в теплице и процессом досвечивания растений является актуальной задачей.
Материалы и методы. Показано, что для выращивания тепличных растений требуются особые условия, поддержание освещенности теплицы и необходимой температуры. Методом эффективного выращивания растения является управление процессом контроля микроклимата и досвечивания. Показано, что для разработки алгоритма управления требуются математические модели, связывающие процесс фотосинтеза с параметрами микроклимата. Приведены математические модели, полученные на основе экспериментальных данных.
Результаты исследования. Для поддержания микроклимата в теплице разработана система и алгоритм управления режимами выращивания растений. Для контроля процесса досвечивания и освещенности используются LED-светильники. Приведена разработанная структурная схема системы управления, которая содержит четыре канала, отвечающие за основные энергоемкие факторы микроклимата. В статье содержится описание алгоритма управления свето-температурным режимом теплицы.
Обсуждение и заключение. Показана необходимость поддержания микроклимата теплицы и досвечивания растений различным спектром излучения для интенсивного роста светокультурных растений и эффективного выращивания их в условиях теплицы. Разработанные структура и алгоритм управления процессом досвечивания растений и освещенности теплицы на базе LED-светильников позволяют снизить потребление электроэнергии.

Ключевые слова: тепличные растения, досвечивание, освещенность, температура, микроклимат теплицы, спектр излучения, система управления, алгоритм управления, LED-светильники

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Introduction

In modern conditions, the production of greenhouse vegetables and greens should be included in the number of important tasks planned by the state program for the development of agriculture and markets for agricultural products, raw materials and food. The program aims to increase the area of greenhouses in Russia to 5,000 ha by 2020. At the same time, the forecast increase in vegetable production should be about 1.4 million tons, and an increase in gross vegetable production over the off-season period is expected to reach 768.6 thousand tons.

Effective cultivation of greenhouse plants requires maintaining the microclimate and light-cultivated plants lighting.

In fact, maintaining the light-temperature regime for the greenhouse plants growing.

The greenhouse microclimate includes the combination of factors, but the most important of them are temperature and light. Maintaining the given microclimate is energy intensive, and it requires reduction. For this purpose, we consider the process of controlling the consumption mode of electricity depending on the specified microclimate parameters and plant lighting. At the same time, it is important that the technical means and the proposed solutions make it possible to control these processes taking into account their relationship with each other.

Nowadays, sodium lamps are used for lighting, which contain the emission spectrum closest to natural solar radiation. Recommended lighting time is about 20 hours a day. At the same time, their control is not provided due to technical difficulties and leads to a wastage of electricity.

The most promising are LED technology, which is now at the peak of development, in terms of energy conservation. The use of LED elements reduces the energy consumption for lighting various buildings. LED lamps are also successfully integrated into the lighting control system because of the possibility to control the operational level and radiation spectrum without any problems and costs.

To control the process of greenhouse plants growing, it is necessary to simulate the process itself. The development of the control algorithm according to a model characterizing the physiological needs of plants is possible but it is very difficult to produce it because it is necessary to carry out appropriate experimental studies for each light-cultivated plants or species of greenhouse plants.

All existing experimental researches study the individual tasks, for example, the effects on the plants development viewed only in the light levels measured in kiloluxes. Moreover, it has been experimentally shown that individual emission spectra activate various growth properties of plants. It is essential to study the effect of individual emission spectra on the growth of the greenhouse plants.

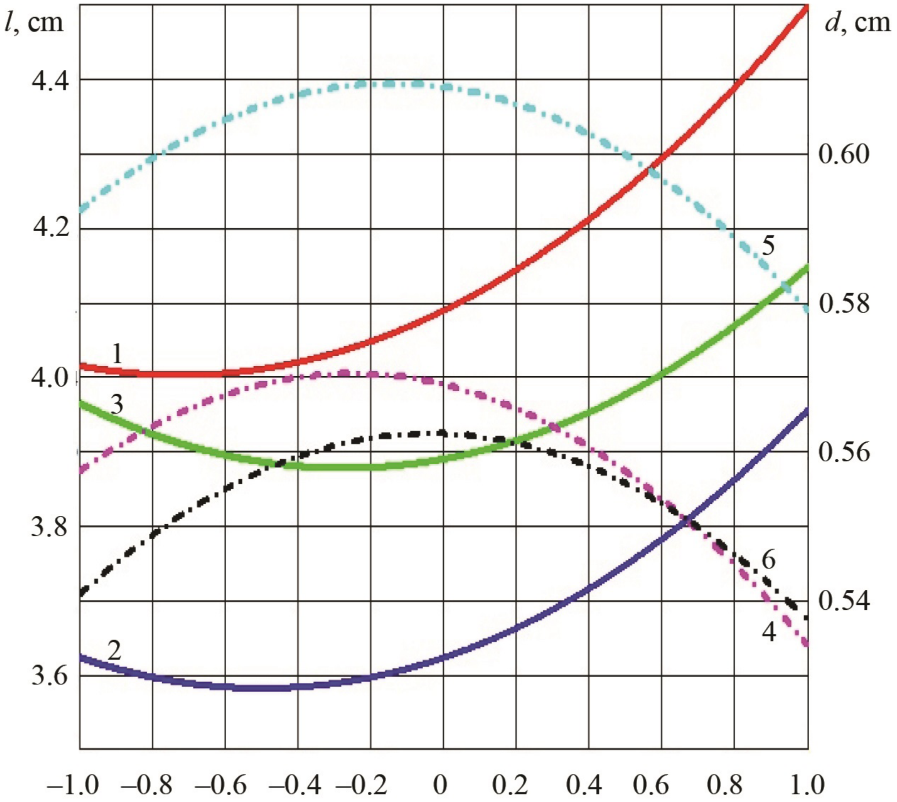
Insufficient researches in the field of growing greenhouse plants, in particular the influence of light-temperature modes on plant growth conditions, inhibits the development of this branch. Under the circumstances, there is a need to combine research results and to determine the best conditions for growing greenhouse plants as well as to find new engineering solutions acceptable for the entire amount of received scientific information. The development of the necessary energy-saving mode control system is required.

Thus, researches have established the influence of not only light-temperature regimes on plant growing, but also radiation spectra, which are successfully assimilated by plants. Then the development of a control system to maintain the necessary regimes for the greenhouse plants growing is an urgent task. Meanwhile, the popularity of LED irradiators for greenhouse plants lighting has become obvious.

Literature Review

Certain emission spectra of LED elements are recognized useful for the plant [1–4]. So, the researches show the effect of the blue-red spectrum on the geometry of the plant stem [5–8]. The experimental data prove that the irradiation in the red spectrum influences on the length of the plant’s stem and the blue spectrum affects the diameter of the stem [9–11].

The graphs shown in Figure 1 prove that their combined influence on the development of the stem is not unambiguous [12]. These dependences are presented in the form of coded values of the red $X1$ and blue $X2$ irradiation spectra of LED lamps. These dependences were obtained from the experimental data on the genetically homogeneous material of potatoes grown from meristem cells.



F i g. 1. The dependence of the growth of the stem length l and the diameter of the greenhouse plants under the irradiation of LED lamps red $X1$ and blue $X2$ spectra: for l: 1 – $X2$ = –1; 2 – $X2$ = 0; 3 – $X2$ = +1; for d: 4 – $X2$ = –1; 5 – $X2$ = 0; 6 – $X2$ = +1

The analysis of the presented data shows that the growth length of the plant stem has a minimum, and the diameter of this section has a maximum at the same values of the red spectrum irradiation level (Fig. 1, $X1$). Depending on the combination of levels of blue and red spectra, the curves are shifted in the coordinate axes, but do not have an acceptable general solution, which requires the task of finding the optimal solution.

The task solution requires the development of a mathematical model that describes the growth of the stem geometry to control the regimes of lighting in the greenhouse complexes. Therefore, the length l and the diameter d were taken as a response in the study of the efficiency of the blue-red spectrum on the growth of seed potato plants [12]. The result of the study is the mathematical model of the growth of the length and the diameter of the plant stem:

$$l_{\text{stem}} = 3.622 + 0.167X1 - 0.1X2 + \\ + 0.167X1^2 - 0.075X1X2 + \\ + 0.366X2^2; \quad (1)$$

$$d_{\text{stem}} = 0.609 - 0.007X1 - 0.003X2 - \\ - 0.023X1^2 + 0.005X1X2 - 0.043X2^2. \quad (2)$$

The plants were grown from genetically identical material, which is valuable because the plants reacted equally to environmental conditions and obtained from the research materials, the mathematical models were definitely adequate. However, potatoes do not belong to the standard greenhouse crops; they grow primarily cucumbers, peppers, tomatoes and leafy greens. Nevertheless, the result shows the effect of the individual irradiation spectra on the growth of the greenhouse plants, and for the other plants, the mathematical models of their growth can be obtained.

The development of the mathematical model is also required, linking the conditions for growing plants with the parameters affecting their growth to control the process of maintaining the greenhouse microclimate. The main parameters of the greenhouse microclimate are the light and the temperature.

Thus, growing greenhouse plants is a complex and energy-intensive process. The study of the greenhouse plants growing and the modeling their growth to control this process is an urgent task for reducing energy consumption.

Materials and Methods

It is possible to control the process of growing greenhouse plants based on special algorithms. Although, it is necessary to maintain the specified microclimate and light parameters related to the photosynthesis indices and plant growth.

The greenhouse plants such as cucumbers and tomatoes belong to the light cultivated plants when a 20-hour lighting is necessary and the duration of their vegetation reaches 10–12 months. During this time, the stems of plants are stretched to 10–12 meters and according to the technology of the growing they are turned into peculiar bays. Here, of course, the geometry of the stem is important, but it is difficult to take into account the amount of radiation received by the plant in a particular spectrum. The result of the lighting is the unsteady lighting especially along the height of the plant and the light weakly penetrates into the lower level.

Different sources of radiation can be used for plants lighting. Thus, lighting can be received naturally by solar radiation and artificially by lamps, lighting plants in height, upper and lower light for inter-row irradiation, if any.

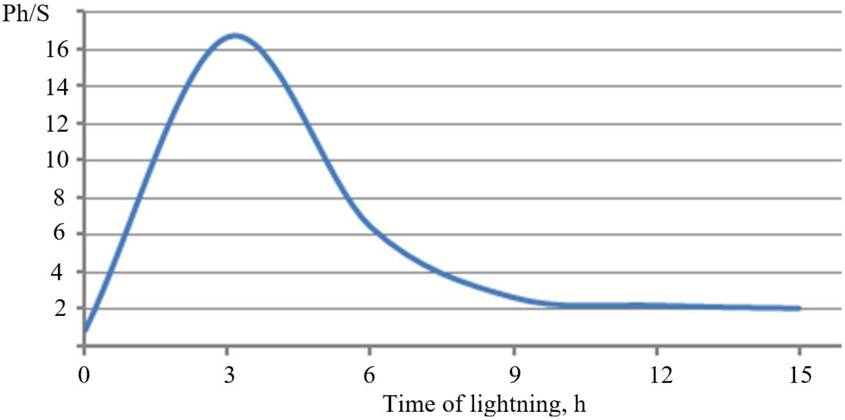
The lighting in height is required for the plants growth. It will be necessary to control the modes of artificial lighting by various lamps located at both the upper and middle levels in such circumstances.

Currently, sodium lamps that contain the necessary radiation spectrum carry out the upper lighting. In this case, the duration and the control of the lighting process are important, since under general favorable microclimate conditions, photosynthesis quickly decays, as can be seen from the diagram (Fig. 2) obtained experimentally [13–15].

Night lighting of plants with powerful sodium lamps leads to environmental pollution, which, in turn, affects the health of people and animals, flora and insects in the vicinity of the greenhouse complexes [16; 17]. As a result, it becomes important to use LED light sources instead of sodium lamps. The use of new light sources will make it possible to reduce the time of lighting reasonably in the nighttime and the lower location among plants at an average productive level will reduce the environmental impact of light sources.

It is LED sources that can form the optimum effective luminous flux of the necessary spectrum. In combination with the solar, blue-red spectrum of LED lamps will provide the required conditions for the development of the necessary geometry of the light cultivated plants.

The mathematical models like (1) and (2) and already obtained for other plants will allow us to determine the necessary values of red and blue radiation, which should be included as the sources of ligh-



F i g. 2. The dynamics of changes in the intensity of the photosynthesis if E = 30 klx and T_1 = 35 °C

ting, if the natural source of radiation does not provide the necessary plant growth. Moreover, if the lamps for lighting are divided into the upper and middle levels, then the upper light should be turned off after a 12-hour photoperiod to protect the environment. The average level of lighting with LED elements, can be turned on at night without any harm for the environment and the nearest residential areas [18].

The intensity of daytime photosynthesis is the other parameter responsible for the plants response to the changes in environmental factors and most often used by researchers [19; 20]. The intensity of photosynthesis can be fixed using gas analyzers of various designs. These devices are complex and are rarely used as sensors. However, having obtained a mathematical model of the intensity of photosynthesis of a particular culture according to the main factors such as light and temperature, we can use it to develop the algorithm to control light lamps.

Figures 3 and 4 show the dependences of the photosynthesis intensity on the energy-intensive parameters of the environment, the temperature and the light [19].

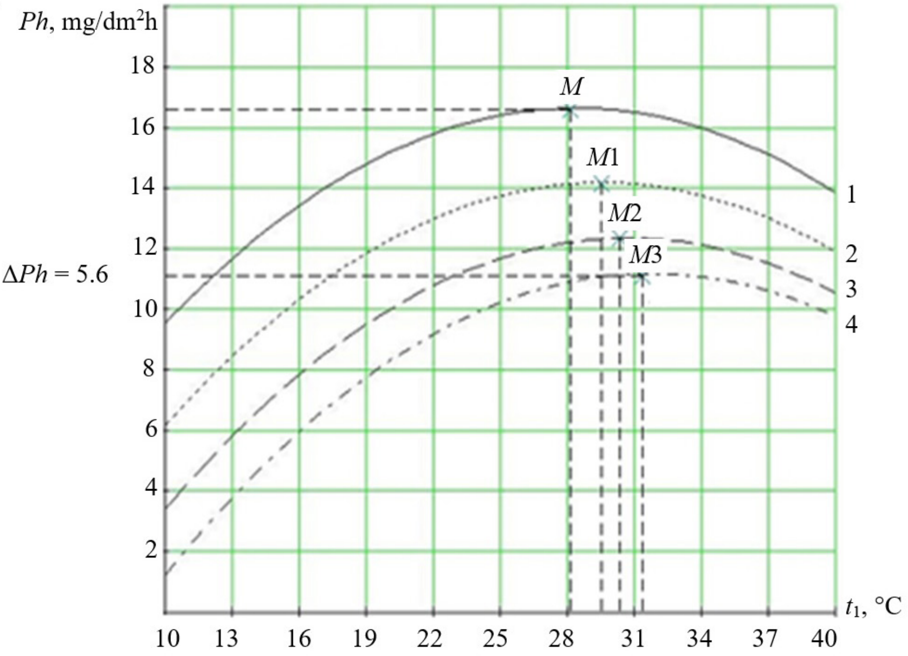
The Figures 3 and 4 show data at fixed humidity values for the curve: *1* – φ_1 = = 50 %; *2* – φ_1 = 60 %; *3* – φ_1 = 70 %; *4* – φ_1 = 80 %. In this case, the night temperature was taken equal to T_2 = 23 °C and the duration of the photoperiod τ_1 = 8 h at the plants age τ_2 = 24 days. Figure 3 shows the curves under different lighting conditions.

Figure 4 shows the curves under different day temperature conditions

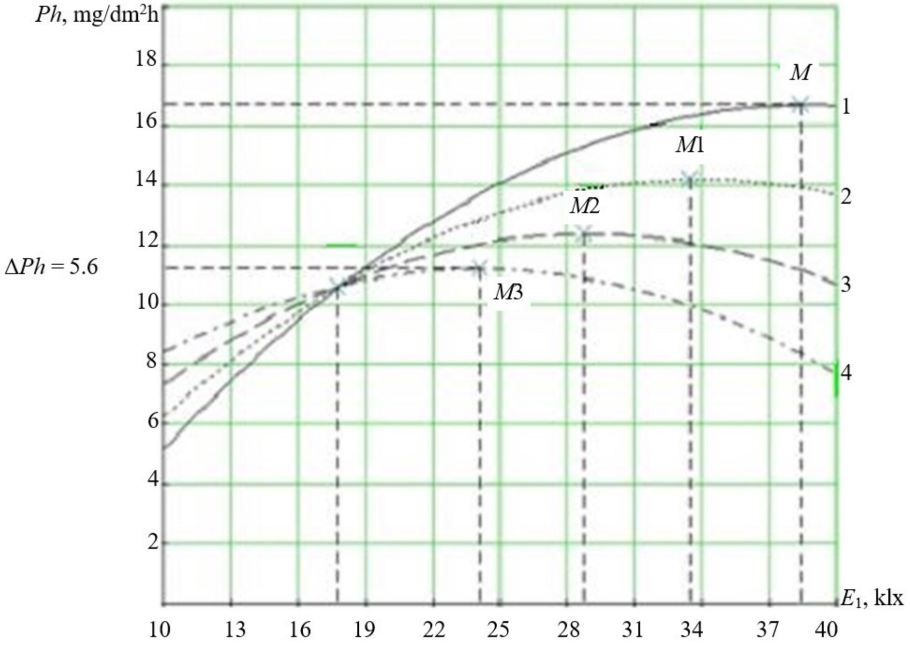
The mathematical model of the following form presents the obtained dependence of cucumber photosynthesis:

$$\begin{gathered}Ph = a_0 + a_1E_1 + a_2t_1 + a_3T_2 + a_4\tau_1 + a_5\tau_2 + \\ + a_6\varphi_1 + a_{11}E_1^2 + a_{12}E_1 + a_{13}E_1T_2 + a_{14}E_1\tau_1 + \\ + a_{15}E_1\tau_2 + a_{16}E_1\varphi_1 + a_{22}t_1^2 + a_{23}t_1T_2 + \\ + a_{24}t_1\tau_1 + a_{25}t_1\tau_2 + a_{26}t_1\varphi_1 + a_{33}T_2^2 + \\ + a_{34}T_2\tau_1 + a_{35}T_2\tau_2 + a_{36}T_2\varphi_1 + a_{44}\tau_1^2 + \\ + a_{45}\tau_1\tau_2 + a_{46}\tau_1\varphi_1 + a_{55}\tau_2^2 a_{56}\tau_2\varphi_1 + a_{66}\varphi_1^2, \quad (3)\end{gathered}$$

where t_1 – the current value of the daily temperature in the greenhouse, °C; E_1 – the current value of light, klx; T_2 – the average temperature of the previous night, °C; τ_2 – the plants age, days; φ_1 – the current value of humidity in the greenhouse, %; τ_1 – the duration of the photoperiod (the duration of the light factor), h; a_0, a_1, a_2 and so on – the coefficients of the mathematical model of photosynthesis intensity.



F i g. 3. The dependence of the photosynthesis intensity from the temperature at optimal values of light: 1 – E_{opt} = 38.6 klx; 2 – E_{opt} = 33.8 klx; 3 – E_{opt} = 38.6 klx; 4 – E_{opt} = 38.6 klx



F i g. 4. The dependence of the photosynthesis intensity from the light at the optimal values of temperature: 1 – t_{opt} = 28,4 °C; 2 – t_{opt} = 29,5 °C; 3 – t_{opt} = 30,6 °C; 4 – t_{opt} = 31,7 °C

The analysis of the given dependences shows that the photosynthesis process has an optimum at a certain temperature and light of the plant environment. It is necessary to find derivatives according to these parameters based on solving the system of equations to optimize the temperature and the light:

$$\begin{cases} \dfrac{dPh}{dE} = 0 \\ \dfrac{dPh}{dt} = 0 \end{cases}. \quad (4)$$

As a result of solving the system, we can derive expressions for the optimal values of lighting E_{opt} and day temperature t_{opt}:

$$t_{\text{opt}} = A_1T_2 + A_2\tau_1 + A_3\tau_2 + A_4\varphi_1 + A_5, \quad (5)$$

$$E_{\text{opt}} = B_1T_2 + B_2\tau_1 + B_3\tau_2 + B_4\varphi_1 + B_5, \quad (6)$$

where A_1, A_2, A_3, A_4, A_5 – multidimensional reduced coefficients of photosynthesis intensity which take the following values after solution the system of equations ($A_1 = -0.127$; $A_2 = -0.302$; $A_3 = -0.738$; $A_4 = -0.492$; $A_5 = 86.25$); B_1, B_2, B_3, B_4, B_5 – multidimensional reduced coefficients of photosynthesis intensity which take the following values after solution the system of equations ($B_1 = -0.003$; $B_2 = -0.299$; $B_3 = -0.215$; $B_4 = 0.116$; $B_5 = 29.63$).

Thus, the recommended mathematical model can realize the control system of the photosynthesis process. Therefore, this model can be applied to develop the light control algorithm.

Results

It is necessary to manage the process of growing greenhouse plants in order to save energy. In this case, it is essential to maintain the greenhouse light and temperature microclimate and to light it up with a certain radiation spectrum for plant growth.

Combined lighting for greenhouse plants is recommended due to natural and artificial light. Artificial lighting serves to light up the plants, and lighting is possible at different plant heights with different light sources.

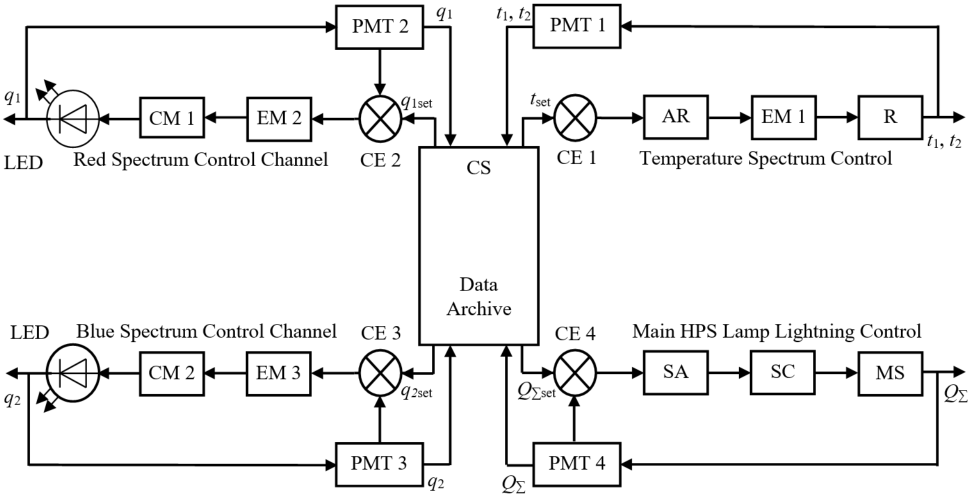
We can use sodium lamps containing the entire natural radiation spectrum to light up the plants at the upper level. It is recommended to light up the plants only with LED sources located at an average level during the daily dark period.

A control system has been developed to control the microclimate and the lighting of plants. Figure 5 shows the structural scheme of the control system.

The given control scheme contains the channels responsible for the four main energy-intensive factors of the microclimate and the plant lighting. Moreover, these factors are interrelated.

The day temperature control channel t_1 allows keeping the optimal temperature due to the change in the task and corresponding to the lighting E that is established due to the natural solar radiation and lighting. The control channel circuit contains a PMT 1 measuring sensor which compares the temperature t_1 measured in the greenhouse with the set temperature at CE 1 and the mismatch signal through the element of the amplifier-regulator AR is transmitted to the executive mechanism EM 1 that controls the regulator R on the greenhouse heating system.

The control channel of the upper lighting lamps, for example, sodium, allows us to turn on the upper light with the lack of natural radiation and turn it off after receiving the total plants phytoactivity for the light period Q_Σ. The task $Q_{\Sigma\text{set}}$ is formed by the computer setter CS according to the recommendations of agronomists and compared on CE 4 with the current measured and calculated as the sum for the past period of PMT 4. The signal through the amplifier SA enters the commutator-switcher, the purpose of which is to turn off the upper light with the end of the photoperiod τ_1 or according to the light sensor signal (not shown in the diagram) if the natural light exceeds the set one.



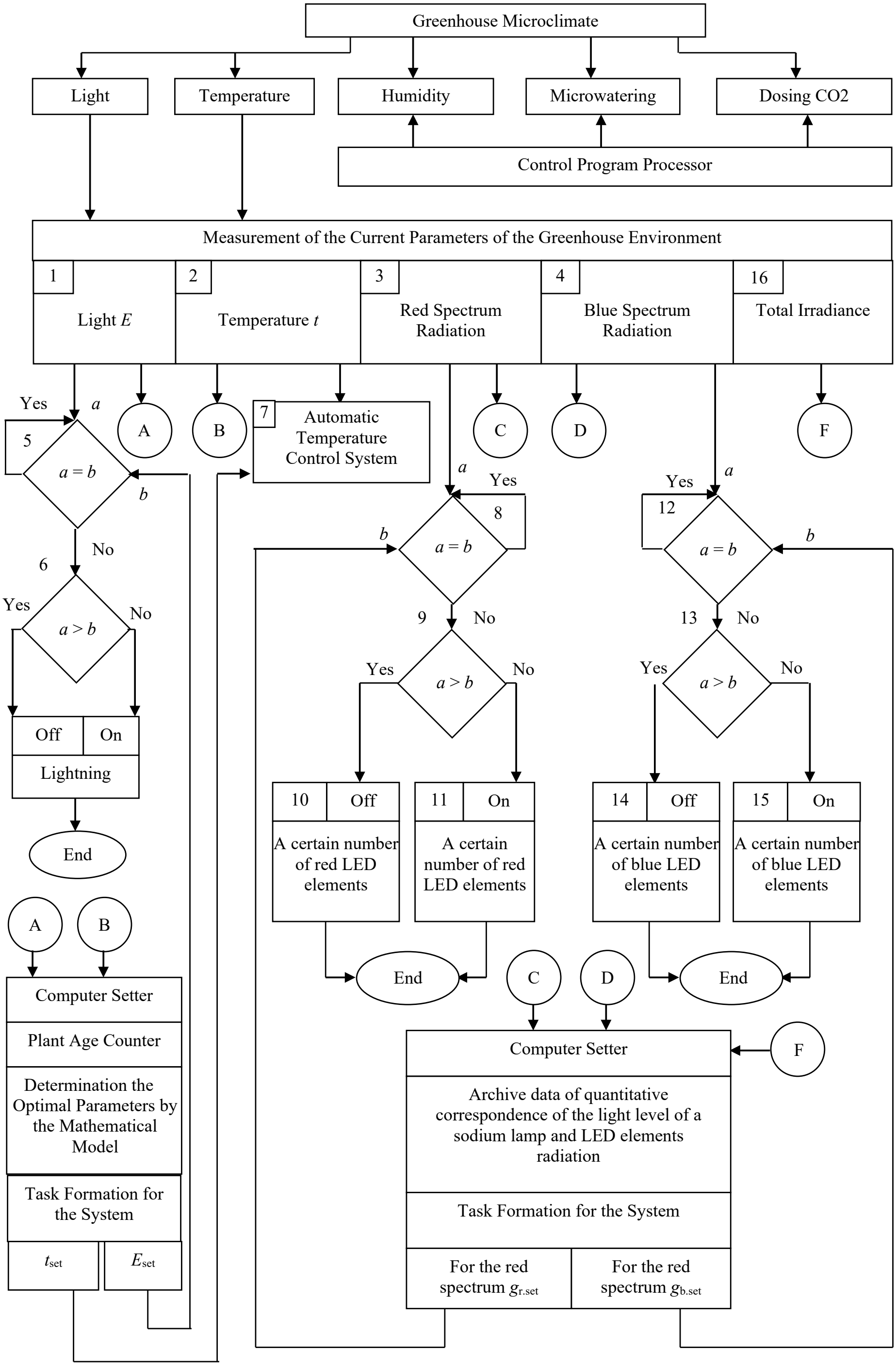
F i g. 5. Structural scheme of Automatic Control System (ACS) with main light-temperature parameters: CS – computer setter; SA – signal amplifier; AR – amplifier regulator; EM 1 … EM 3 – executive mechanisms; R – regulator; MS – magnetic starter for turning on the HPS lamps; SC – switch commutator; PMT 1 …PMT 4 – primary measuring transducers of environmental parameters (sensors); CM 1, CM 2 – control modules for LED equipment; LED 1, LED 2 – light-emitting diode equipment; CE 1 …CE 4 – comparison elements; t_1, t_2 – greenhouse temperature day and night; t_{set} – temperature set by the computer; q_1, q_2 – energy expended on lighting up with red and blue spectrum LEDs; q_{1set}, q_{2set} – energy set by the computer for lighting up with red and blue spectrum LEDs; Q_Σ – total radiation measured in the greenhouse by the sensor during the photoperiod; $Q_{\Sigma set}$ – energy set by the computer necessary for the optimal plant life; τ_1 – photoperiod duration (duration of the light factor)

The channels that control LED elements of a different spectrum should contain a special control module that does not connect all the elements at once but the required number at a given time providing the necessary energy of red q_1 and blue q_2 spectra.

Two control channels of LED elements work identically and are used to light up plants with red and blue emission spectra on the midline of planting where the sunrays penetrate weakly. At this level, PMT 2 and PMT 3 sensors are placed by the signal of which they determine the radiation imperfections in any spectrum, comparing the signals from the sensors and the q_{1set} and q_{2set} tasks coming from the CS to the comparison elements CE 2 and CE 3. EM 2 and EM 3 devices include control units CM 1 and CM 2, the purpose of which is to control the work of LED equipment.

The mathematical model of photosynthesis intensity (3) makes it possible to optimize two parameters: lighting up *E* with a dimension of klx and air temperature *t*. For this purpose, we find the partial derivatives in compliance with these two parameters and after solving the resulting system of equations (4), worked out on the basis of equation (3), calculate the optimal parameters E_{opt} and t_{opt} which can then be worked in the system as a task E_{set} and t_{set} for controlling. The algorithm for controlling the greenhouse microclimate is shown in Figure 6.

According to the control algorithm, a signal is set based on the calculated optimal E_{set} that is sent to the comparison element *5*, where it is compared with the measured one, using the light sensor *1*. In the case when two signals are equal, which means that the light entering the green-



F i g. 6. The algorithm for controlling the greenhouse microclimate: $g_{r.set}$, $g_{b.set}$ – energy set by the computer for lighting up with red and blue spectrum LEDs; t_{set} – temperature set by the computer; E_{set} – light set by the computer house is sufficient, the system is waiting for the next commands. If the signals are not equal as reported by element *6*, then, given that the signal measured by the sensor is less than the specified value, the upper level lighting equipment is turned on, and if it is more, the lighting is turned off.

The next important parameter is the temperature, the optimal value of which is set after the calculation according to the equation (5). The task is formed on the basis of it and realized by the temperature control of ACS channel, block *7*.

The structural scheme (Fig. 5) also contains additional control channels for the lighting equipment of the red and blue spectrum LED lamps that are located at the middle level of the plant. Each irradiation spectrum can be controlled by determining what level of lighting E of the red and blue spectrum should be.

The archive data of the setter CS contains the data of the preliminary experiment, the values of the blue and red radiation spectrum, constructed by HPS lamps with different luminosities. For example, with lighting E_{opt} = 40, 35, 30, 20 klx and so on, certain levels of red and blue spectrum correspond.

If necessary, the blue and red spectrum values extract from the archive data as a task. The specified values q_{1set} fall into the comparison block *8*, where the comparison is made with the current level of the same factor from the sensor *3*. If the values are equal, the system is waiting, if not, then the next block *9*, determines what actions the system should take, or turn on additional LED elements (block *11*), or they will turn them off (block *10*).

Similar actions are performed by the blue spectrum elements of the control channel. According to the formed task q_{2set}, the comparison block *12* compares it with the sensor data *4* and either expects the next time period, or if the values are not equal, block *13* turns on (block *15*) or turns off (block *14*) additional light elements of the blue spectrum.

As a result of controlling the greenhouse microclimate and the greenhouse plants lighting up according to the proposed method, two goals are achieved: the energy saving due to switching off the upper level of lighting and turning on LED equipment, which consumes significantly less energy; the reduction of the light influence on the greenhouse areas at night.

Discussion and Conclusion

The important factor for the growth and the development of greenhouse plants is the maintenance of the greenhouse microclimate and the lighting with the different radiation spectrum. This is especially important for light cultivated plants that include cucumbers and tomatoes requiring 20 hour lighting during 10–12 months. It is necessary to support the process of photosynthesis during the lighting, which tends to decrease after 4 hours lighting that subsequently leads to an excessive consumption of electricity.

Under these conditions, it is necessary to control the level and the duration of lighting, to maintain the required lighting and temperature for the greenhouse microclimate. Therefore, the necessity is to use the most perspective LED lamps, the radiation spectrum of which is close to the natural light instead of high-pressure sodium lamps.

Light-temperature automatic control system of the main parameters has been developed to maintain the greenhouse microclimate. In these circumstances, optimal parameters are set for the lighting and the air temperature. It is possible to provide greenhouse plants growing with minimal energy costs by controlling the lighting according to a given value and the spectrum of its radiation on the basis of the experimental data.

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