Development of environmentally sustainable solutions to provide greenhouse production with alternative energy

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Abstract. The paper presents scientific and technical solutions to improve the efficiency of greenhouse irradiators used in growing plants in the light culture of industrial greenhouses. The author's technology is described, which makes it possible to regulate the energy flows of the irradiation system during the growing process. The results are given that determine the rational temperature range of the air flow 32÷38°C, created by a greenhouse irradiator, for the needs of heating an industrial greenhouse. It has been established that a decrease in the lamp temperature in the voltage range on the greenhouse irradiator of 198÷220 V for every 1°C leads, on average, to an increase in the PAR value by 2.5 mW/cm^2. Dependences of the radiation force distribution as a function of the air flow velocity and PAR as a function of the lamp temperature are obtained. The regularities of influence of network operation modes and lamp temperature on the efficiency of the irradiation system as a whole are determined. Taking into account the experimental data obtained, a technological scheme of irradiation in an industrial greenhouse was developed and the principle of its operation with a greenhouse irradiator with a forced cooling function was described.

1 Introduction

Heating of cultivation facilities during the cold period plays an important role in the year-round cultivation of vegetables, flowers, seedlings. The energy costs of greenhouse facilities for electricity and heat average at least 50% of all costs [1]. Therefore, there is a continuous search for alternative and cheaper energy sources and ways of its transformation for these purposes [2].

There are modern technologies for energy supply of cultivation facilities using alternative energy, based on the use of low-grade heat of the soil and the environment [3, 4], solar radiation [5], geothermal energy sources [6], as well as wind energy, biomass, etc. [7]. Despite the attractiveness of these technologies, they contain environmental risks associated with attracting additional energy resources for their implementation. It is economically more expedient to heat winter greenhouses using thermal energy from third-party production processes or from local heat sources [8]. A more effective environmentally sustainable solution to improve energy efficiency and provide greenhouse production with alternative

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energy is to expand the functions of the irradiation facility with the development of new technological irradiation schemes [9].

The main receiver in terms of electricity consumption and the amount of installed power in an industrial greenhouse are lighting irradiation installations [10]. Currently, there are two technologies for irradiation in light culture, one of which is based on the use of greenhouse irradiators with high-pressure discharge lamps, which is mainly used in industrial greenhouses, where the share of natural solar radiation is high. Another technology with the use of phyto-irradiators based on LED technologies has found application, for the most part, in phytofactories, where the growing process is carried out without natural light [11]. In both cases, only a small part of the electrical energy in such installations is converted into photosynthetically active radiation (PAR) necessary for plants, and most of it is lost as heat. According to most scientific publications, the radiation energy in the optical wavelength range is 25–30%, and 70–75% of the power is due to heat losses [12].

The thermal operating conditions of the lamp have a significant effect on the radiation efficiency [13]. Changing the temperature of the lamp leads to changes in the thermal, energy and lighting characteristics of the irradiation installation as a whole [14]. Moreover, it is known that plant productivity is related to the PAR value and increases with its growth up to a certain value [15]. However, most of the known ways to increase PAR are associated with additional energy costs. Thus, by applying special operating modes of the greenhouse irradiator and coordinating them with the growing technology, it becomes possible to increase the efficiency of the irradiation system.

The author believes that the existing irradiation technologies have certain disadvantages. Firstly, the thermal operating modes of greenhouse irradiators are not taken into account, which have a significant impact on the radiation efficiency, as a result, the result of growing plants. Secondly, the patterns that establish the relationship between the temperature regimes of the greenhouse irradiator and its lighting and energy characteristics have not been determined, which makes it difficult to control growth processes and leads to an increase in energy costs for irradiation and heating.

The author has developed a technological scheme for irradiation for industrial greenhouses, in which these shortcomings are eliminated. The main differences are of a constructive nature and are implemented through a technical solution that makes it possible to separate the energy flow from the irradiator into components: PAR and the flow of thermal energy. For this, the greenhouse irradiator is additionally equipped with elements for removing thermal energy, as well as elements for controlling energy flows, with the possibility of their distribution in the technological space of the greenhouse with plants. The aim of the study is to determine the dependence of the thermal, lighting and energy characteristics of a greenhouse irradiator on the network operation modes and lamp temperature, as well as the application of the resulting beneficial effects in industrial greenhouses.

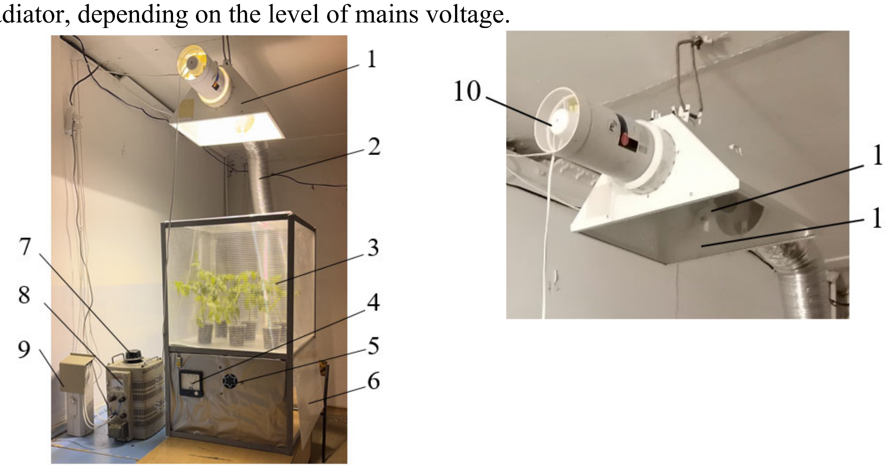
2 Research methods

A mandatory element in the design of greenhouse irradiators is the heat removal system [16]. There are designs with water (Figure 1a) and forced air (Figure 1b) cooling, but currently only greenhouse irradiators with natural convection cooling (Figure 1c) have found more use. To improve heat dissipation, heat pipes or other known methods of removing heat stress can be used in the design of the radiator. It is known from special literature [17] that the range of operating temperatures for greenhouse irradiators with high-pressure gas-discharge lamps cooled by natural convection lies within the following limits: lamp temperature 450°C, structural elements temperature 240°C.

a) water cooled b) with forced air cooling c) cooled by natural convection

Fig. 1. Designs of greenhouse irradiators.

The studies were carried out with a greenhouse irradiator FitoTech CoolMaster 125 (Figure 2b), with a SON-T 1000 W E40 lamp located above the growth chamber with a dashboard shown in Figure 2a. The purpose of the experiment was to establish patterns of change in the heat engineering, energy and lighting characteristics of the greenhouse irradiator, depending on the level of mains voltage.



a) growing chamber with dashboard b) greenhouse irradiator

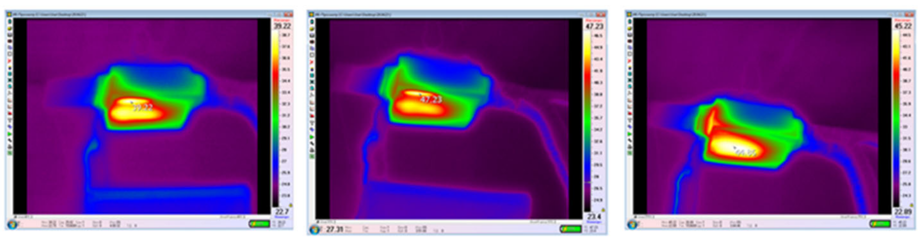
c) instruments and equipment

Fig. 2. Device for researching greenhouse irradiators: 1 - irradiator body; 2 - corrugated heat sink; 3 - chamber with plants; 4 - voltmeter for the cooling fan; 5 - laboratory autotransformer for the cooling fan; 6 - technological compartment; 7 - laboratory autotransformer for greenhouse irradiator; 8 - voltmeter for greenhouse irradiator; 9 - throttle; 10 - cooling fan; 11 - lamp; 12 - heat-resistant glass; 13 - spectrophotometer; 14 - anemometer; 15 - netbook; 16 - portable computer thermograph IRTIS-2000.

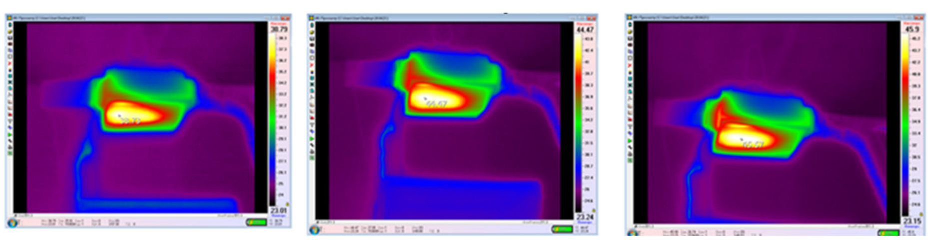
Voltage regulation was carried out using two laboratory autotransformers, which make it possible to independently control the operation of the cooling fan and greenhouse irradiator. The voltage ranges from 198 V to 242 V, established in [18], was investigated. The experiment took place in the following sequence. Initially, using a laboratory autotransformer for a greenhouse irradiator, the nominal mains voltage U_n=220 V was set. After that, using a laboratory autotransformer for a cooling fan, three voltage levels were set in series from 198 V to 242 V with $\Delta U=\pm 10\% U_n$ and a time interval of 5 minutes to control the airflow rate. At the same time, to determine the temperature of the elements of the greenhouse irradiator, thermograms were taken using a portable computer thermograph IRTIS-2000 with a netbook, the speed and temperature of the air flow were determined with an anemometer, and the PAR value and the radiation strength were determined using a spectrophotometer (Figure 2c). Further, the experiment was carried out at a voltage level on the greenhouse irradiator of 198 V and 242 V.

3 Results

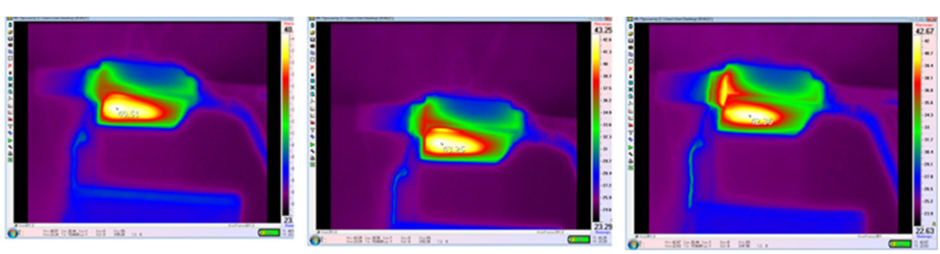
Figure 3 shows thermograms for the investigated operating modes of the greenhouse irradiator and cooling fan. It is possible to observe a characteristic shift of the peak values of the lamp temperature from the minimum value T_{lmin}=38°C at the minimum value of the mains voltage on the greenhouse irradiator U_{gimin}=198 V and the maximum air flow velocity of 3.4 m/s, to the maximum value T_{lmax}=47°C at two values of the mains voltage on the greenhouse irradiator U_n=220 V and U_{gimax}=250 V, and the minimum value of the air flow velocity is 2.7 m/s.



Air flow velocity 2,7 m/c



Air flow velocity 3,0 m/c



Air flow velocity 3,4 m/c

a) U_{gi}=198 V b) U_{gi}=220 V c) U_{gi}=242 V

Fig. 3. Thermograms of greenhouse irradiator.

The convective flow required for heating the greenhouse, W, generated by the greenhouse irradiator in the studied operating modes and assimilated by the ventilation air, was determined by the formula [14]:

$$Q_{va} = 860P_e(0,8 \div 0,9)n, \quad (1)$$

where P_e – power of one emitter, kW.

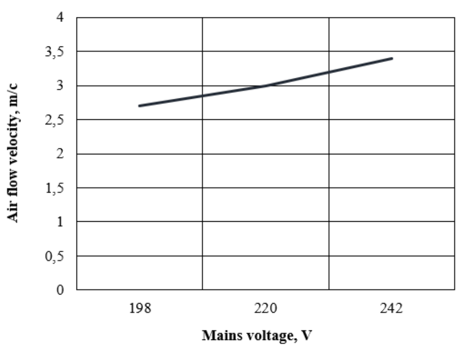
To define P_e when changing the voltage, we used the formula [19]:

$$P_e = P_n(K_U)^{4,6}, \quad (2)$$

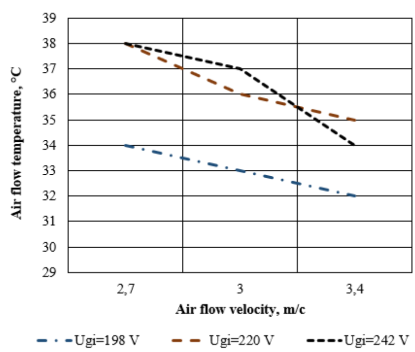
where P_n – rated power of the emitter, W;

$K_U = U \cdot U_n^{-1}$ – relative stress.

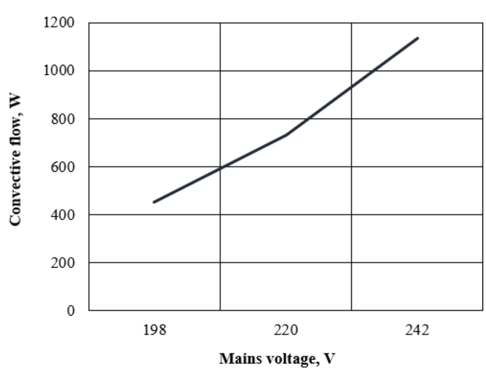
Figure 4 shows the thermal characteristics of the greenhouse irradiator. Figure 4a shows the linear dependence of the change in airflow rate as a function of the magnitude of the mains voltage. The range of change is from -10% to +13%. An analysis of the graphical dependences of the air flow temperature on its speed (Figure 4 b) allows us to conclude that a change in the mains voltage within the limits specified in [18] $\Delta U = \pm 10\% U_n$ leads to a slight change in the air flow temperature, in the Taf range =32÷38 °C, which lies within the temperature range recommended for most greenhouse crops [20] and makes it suitable to use thermal energy from a greenhouse irradiator without additional transformations for the needs of heating an industrial greenhouse.



a) air flow velocity



b) air flow temperature



c) convective flow

Fig. 4. Thermal characteristics of the greenhouse irradiator.

The value of the convective flow required for heating the greenhouse, generated by the greenhouse irradiator in the studied operating modes (Figure 4 c), ranges from 450 W to 1150 W, which makes it possible to heat with one greenhouse irradiator, approximately from 1.5 m^3 to 4 m^3 of an industrial greenhouse [21].

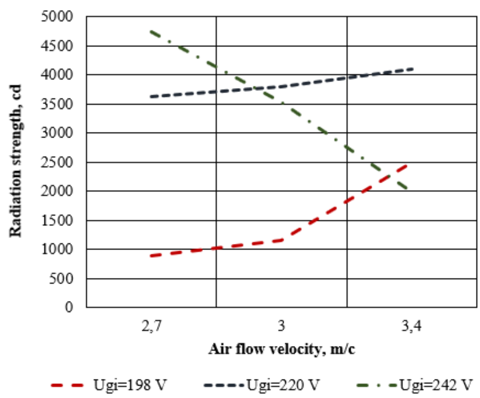
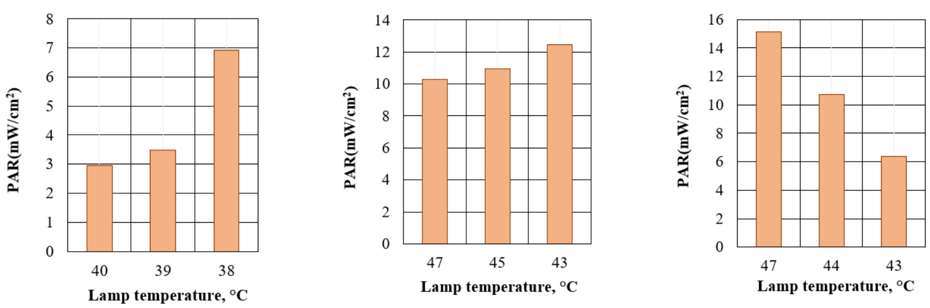


Fig. 5. Graphs of changes in radiation strength.

A characteristic feature of the change in the radiation strength is a linear increase in its value in the modes U_{gi1}=198 V from 887 cd to 2500 cd, and U_{gi2}=220 V from 3600 cd to 4100 cd (Figure 5). Moreover, in the U_{gi3}=242 V mode, there is a sharp decrease in the radiation strength from 4700 cd to 1500 cd. This circumstance makes the operation mode at U_{gi3} =250 V and the regulation of the air flow rate impractical for practical use.

According to the graphs in Figure 6, we can observe the change in the distribution of PAR as a whole over the surface, depending on the magnitude of the mains voltage and the temperature of the lamp.



a) U_{gi}=198 V b) U_{gi}=220 V c) U_{gi}=242 V

Fig. 6. Change in PAR distribution depending on the magnitude of the mains voltage and lamp temperature.

During the experiment, it was found that when the mains voltage on the greenhouse irradiator U_{gi1}=198 V and the lamp temperature decreases from 40°C to 38°C, a sharp increase in the PAR value from 3 mW/cm^2 to 7 mW/cm^2 is observed, and at U_{gi2}=220 V and lowering the lamp temperature from 47°C to 43°C, the FAR value increases from 10 mW/cm^2 to 12.5 mW/cm^2. Moreover, in the U_{gi3}=242 V mode, a sharp decrease in the PAR value from 15 mW/cm^2 to 6.5 mW/cm^2 is observed when the lamp temperature decreases from 47°C to

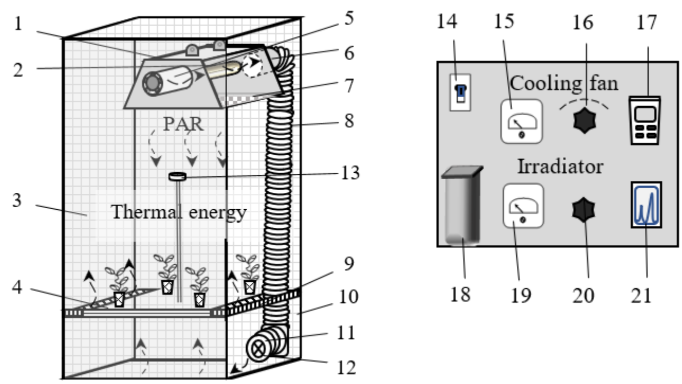
 https://doi.org/10.1051/e3sconf/202339006004

43°C. This circumstance also makes the operation mode at U_{gi3} =250 V and lamp temperature control inapplicable for practical purposes.

Thus, it can be preliminarily concluded that a decrease in the lamp temperature in the voltage range on the greenhouse irradiator of 198–220 V for every 1°C leads, on average, to an increase in the PAR value by 2.5 mW/cm^2. The results obtained during the experiment are the basis for the modernization of existing technological schemes of irradiation in industrial greenhouses to obtain additional effects.

Figure 7 shows a technical solution for the technological scheme of irradiation in an industrial greenhouse, which makes it possible to provide greenhouse production with alternative energy, the required parameters, by dividing the energy flow of the greenhouse irradiator into a PAR flow and a thermal energy flow and managing these flows. This technological scheme provides for the implementation of the laws and algorithms obtained as a result of the experiment due to the following technical solutions:

- The inclusion of a greenhouse irradiator in the technological space of the greenhouse.
- Separation of the technological space of the greenhouse using a plant table with ventilation ducts from the technical room.
- Equipping the control cabinet with instruments and equipment for the regulation and control of technological parameters of cultivation.



a) fragment of an industrial greenhouse b) control cabinet

Fig. 7. Technological scheme of irradiation in an industrial greenhouse:1 - greenhouse irradiator; 2 - lamp; 3 - technological space of the greenhouse; 4 - table for plants; 5 - branch pipe with an axial fan; 6 - outlet flange; 7 - tempered glass; 8 - corrugated heat sink; 9 - ventilation ducts; 10 - technical room; 11 - outlet of the corrugated pipe; 12 - anemometer sensor; 13 - spectrophotometer sensor; 14 - automatic switch; 15 - voltmeter for the cooling fan; 16 - autotransformer for the cooling fan; 17 - anemometer; 18 - throttle; 19 - voltmeter for greenhouse irradiator; 20 - autotransformer for greenhouse irradiator; 21 – spectrophotometer.

The technical and technological solutions proposed have the following fundamental differences from existing systems:

- The efficiency of using the greenhouse irradiator is increased by dividing the energy flow into components, by additionally supplying elements for removing thermal energy, as well as elements for controlling energy flows, with the possibility of their distribution in the technological space of the greenhouse with plants.

- The functionality is expanded due to the placement of a greenhouse irradiator with a lower temperature of its elements closer to the plants, which makes it possible to rationally distribute the energy flow in space.
- Energy costs for irradiation are reduced due to the operation of the greenhouse irradiator according to the algorithms and patterns found in the work.

4 Conclusion

Thus, it becomes obvious that the development and application of rational modes and schemes of operation of greenhouse irradiators can be the basis for providing greenhouse production with additional alternative energy. Taking into account the operating modes of the network with simultaneous regulation of the lamp temperature is another way to control the flow of PAR, and with it the growth processes of plants. Reducing the temperature of the elements of the greenhouse irradiator will make it possible to more rationally distribute the energy flow in space, as well as create an additional flow of thermal energy necessary for heating industrial greenhouses.

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