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Technology for managing thermal energy flows in industrial greenhouses

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Abstract. The paper presents technical solutions to improve the energy efficiency of growing greenhouse vegetables using artificial irradiation. The authors describe the technology of controlling the flow of thermal energy during irradiating of plants. A comparison of the developed technology with the fifth generation Ultra Clima greenhouse technology has been carried out. Key technical solutions have been identified, the introduction of which increases the efficiency of using thermal energy by 6%, increases the area irradiated by a single irradiator by 2.5% while maintaining photosynthetically active irradiation reaching the biocenoses, and provides an increase in the yield of vegetable crops by 2-5%. It has been established that with equal economic conditions of greenhouse growing of vegetables, the savings in energy costs compared to Ultra Clima technology is 5-6%, depending on the climatic conditions of the environment.

1. Introduction

In the climatic conditions of Siberia and the Far East, year-round vegetable production is possible only in greenhouses. The developed energy infrastructure and the availability of reserves of energy capacities allow forming the production potential of greenhouse vegetable farming for the long term. The current state of the industry is characterized by underproduction and the presence of unsold demand. Rational physiological norms of consumption of vegetables per person per year are 140 kg [1]. In accordance with the current population of the Russian Federation, the estimated total consumption should be at the level of 20,551 thousand tons. But the estimated actual domestic production of vegetables is 15,427 thousand tons (75% of the rational demand), and personal consumption of households is 1,5185 thousand tons (73% of the norm). One of the significant reasons for the reduced demand for vegetables is their high price in the winter-spring period. Another deterrent to the development of greenhouses in Russia is high tariffs for heat and electricity. To reduce the negative effect of the cost of electricity, as well as price incentives for demand for vegetables, it is necessary to introduce energy-saving technologies in greenhouse vegetables.

In modern greenhouses, growing vegetables using artificial irradiation is most cost-effective, where irradiating installations are widely used to control the production process of plants [2, 3]. Such installations account for approximately 15% of the electricity consumed by the greenhouse complex. The feasibility of using thermal energy from irradiating systems to improve the energy efficiency of greenhouses also has a scientific and practical justification [4, 5]. It should be noted that in the energy balance of such installations, the share of thermal energy reaches 90%, part of which is utilization [6]. The fifth generation greenhouses use the Ultra Clima technology, which allows to obtain significant

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savings in heating costs due to the secondary use of thermal energy [7]. The authors believe that the technology has some drawbacks. First, thermal energy from the irradiators circulates freely in the upper part of the greenhouse, which can cause overheating of the tops of the plants. Secondly, it is difficult to predict how much heat energy will be generated by the irradiator of a certain type at a particular point in time. And finally, there is no opportunity to influence the flow of thermal energy rationally for the implementation of controlled growth of vegetable crops.

The authors have developed and patented energy-saving technology for controlling the flow of thermal energy for plant growth using light culture, in which these disadvantages have been eliminated [8]. The main differences are constructive in nature and are realized through the unification of irradiators into a single system with the technical ability to more efficiently manage the flow of thermal energy. The purpose of this work is the technical and economic substantiation of the proposed technology, as well as the evaluation of the beneficial effects obtained with controlled plant growth.

2. Research methodology

Initially, an analysis was made of the implementation schemes for the Ultra Clima technology and the proposed technology for describing design differences. The results of the experiment described in [9] were used. Based on these data and comparison of the schemes, comparative effects were determined by the following indicators:

1. Thermal energy efficiency when lighting greenhouse plants (KBU_E), %:

$$KBU_E = \frac{Q_{total} - Q_U}{Q_{total}} \times 100 \qquad (1)$$

Q_{total} – total amount of heat energy released by the lighting system, kcal; Q_U – amount of unused (utilization) heat energy, kcal.

2. The irradiated area of a single feed while ensuring the density of the photosynthetic photon flux in the amount of 150 μmol/s·m^2.

To ensure the effective growth of greenhouse plants, it is required to maintain with irradiating the rate of photosynthetically active light reaching biocenoses in the amount of 150 μmol/s·m^2. One irradiator allows maintaining this rate within a certain area without loss of useful heat. The larger the size of such an area, the fewer irradiators are required in general for the entire useful area of the greenhouse.

3. Yields of vegetable crops per 1 square meter of the usable area of the greenhouse obtained using the compared technologies.

Comparative economic effect from the use of technology was determined through the reduction of the cost of growing the main vegetable crops (cucumbers and tomatoes in greenhouses). Determination of the total heat output per 1 square meter of the greenhouse to maintain the temperature in accordance with the adopted cultivation technology was carried out according to the formula:

$$Q = k_1 \times k_2 \times (t_1 - t_2) \qquad (2)$$

Q – thermal power of the heat source, kcal/hour;

k_1 – the heat transfer coefficient of the greenhouse material (for polycarbonate with a thickness of 10 millimeters k_1=3.1 W/m^2·K);

k_2 –infiltration coefficient (for greenhouses with good thermal insulation k_2=1.2);

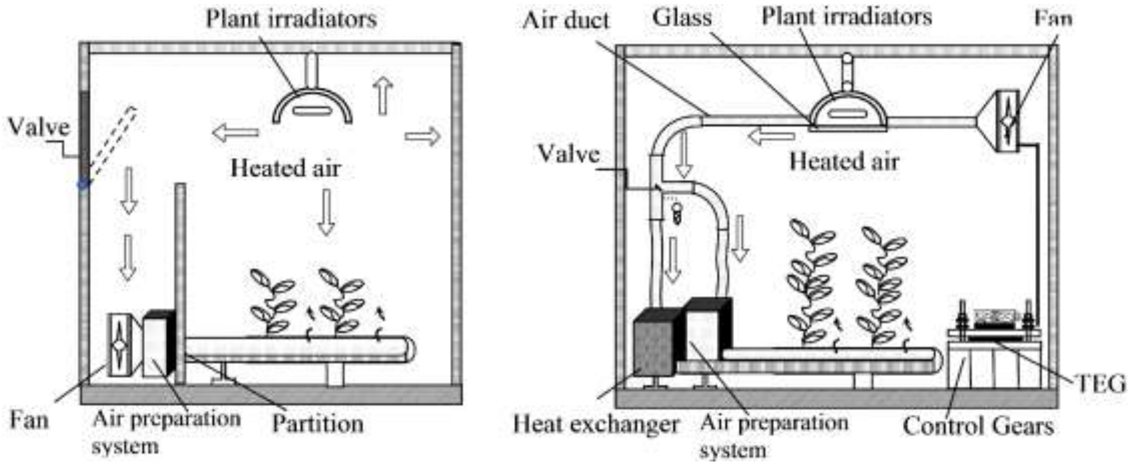
t_1 – air temperature inside the greenhouse, ºC;

t_2 – air temperature outside the greenhouse, ºC. The temperature was determined on the basis of average and limiting temperature norms in the autumn-winter and winter-spring seasons in Siberia and the Far East.

Estimation of energy cost savings and changes in the cost of 1 kg of vegetable crops was calculated based on the cost structure of the industry. Also, the actual yield per 1 m2 will affect the cost of 1 kg of vegetables. Data on the yield of greenhouse vegetables were taken from industry reports, official statistical compilations.

3. Results

Figure 1 shows the implementation schemes for the Ultra Clima technology and the technology for controlling the heat energy flow of the author [8].



a) Ultra Clima Technology b) Proposed technology

Figure 1. Technologies of using thermal energy from irradiators in greenhouses.

Figure 2 shows the flowchart of the fifth generation greenhouse with Ultra Clima technology equipment. In figure 3, the flow chart of the greenhouse is based on the author's technology for controlling the flow of thermal energy from plant irradiators using thermoelectric generator modules and heat exchangers.

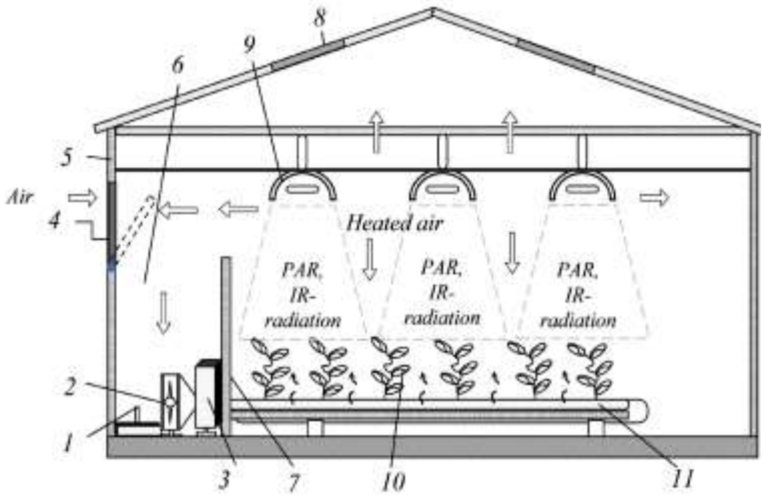


Figure 2. The construction of the fifth generation Ultra Clima greenhouse technology: 1 - nozzle for supplying carbon dioxide; 2 - fans; 3 - heater; 4 - valve; 5 - enclosing structures; 6 - "Ultra Clima" zone; 7 - partition; 8 - transom; 9 - irradiation unit; 10 - plants; 11 - plastic sleeves.

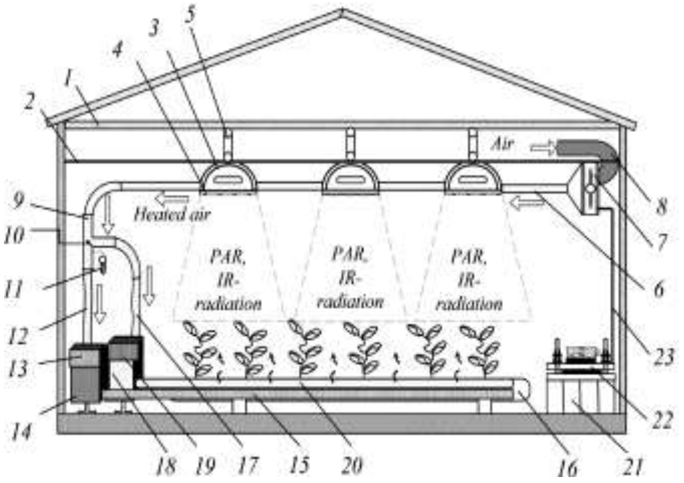


Figure 3. The design of the developed system with the use of thermoelectric generator modules and heat exchangers: 1 - supporting structure; 2 - frame; 3 - irradiators; 4 - protective glass; 5 - movable electric hoists; 6 - exhaust air ducts; 7 - fan; 8 - suction duct; 9 - transition tee; 10 - on-off valve; 11 - temperature sensor; 12 - elastic duct; 13 - heat exchanger; 14 - water tank; 15 - heating radiator; 16 - baths with plants; 17 - flexible duct; 18 - air preparation system; 19 - air heater; 20 - perforated tube; 21 - control gears; 22 - thermoelectric generator modules; 23 - wires.

The proposed technical and technological solutions have the following fundamental structural differences:

1. According to the author's technology, greenhouse irradiators are combined into one system with the help of air ducts. This solution allows to avoid the dissipation of thermal energy and reduce the specific installed capacity in the heating system of greenhouses by 5.5%, for electricity - by 6%.
2. The use of a heat exchanger allows for a more rational regulation of the microclimate of the greenhouse, forming a system for managing energy flows.
3. Installation of control gears, heated during operation up to 200ºC separately from irradiators, allows using their thermal energy, converted into electrical energy using thermoelectric generator modules for driving fans.

The presented technical solutions reduce the requirements for the power of the heat source, which leads to lower energy costs for heating. The infrared component of the irradiators radiation flux, in the form of heat energy of heated air, is not removed from the room, but participates in the formation of the greenhouse microclimate. The irradiation system, with this approach, can be positioned closer to the plants due to the fact that the irradiators are cooled and cannot harm the plants. This increases the area of irradiation with the required rate of photosynthetically active radiation without installing additional feeds by 0.2 square meters per feed. The result is an increase in yield of vegetable crops:

- greenhouse cucumbers - 2-5%, depending on the variety;
- greenhouse tomatoes - 1.5-4%, depending on the variety;
- green cultures (dill, parsley, salad) - 3-5%.

The utilization of heat energy increases by 6%, which leads to a decrease in electricity by an average of 5.3%. The cost structure of cucumbers and tomatoes in greenhouse conditions is shown in figure 4.

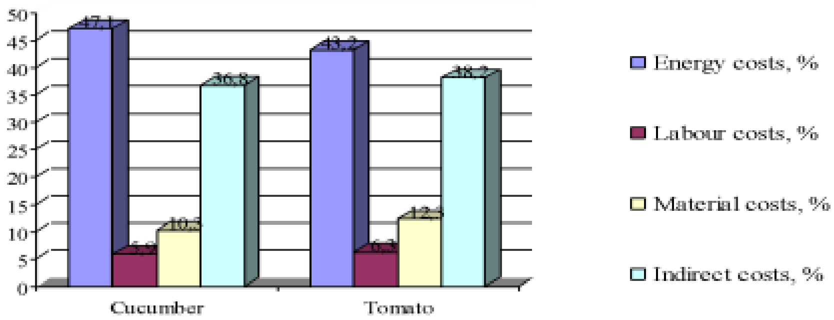


Figure 4. The cost structure of growing cucumbers and tomatoes in greenhouse conditions.

The calculation of the cost of growing vegetables in greenhouse conditions according to compared technologies is given in table 1.

Table 1. Calculation of the comparative economic effect from the use of technology for managing the thermal energy of greenhouses.

Indicator	Value						
Outside temperature, ºC	-40	-30	-20	-10	0	5	10
Q, kW	0.24	0.20	0.17	0.13	0.09	0.07	0.06
W, kW·hour (Ultra Clima)	5.40	4.68	4.19	2.93	2.23	1.82	1.37
W, kW·hour (proposed technology)	5.07	4.39	3.93	2.75	2.10	1.72	1.30
Growing according to Ultra Clima technology							
Cost price of 1 kg of cucumbers, rubles	160.1	138.6	124.0	86.8	66.1	53.9	40.6
Cost price of 1 kg of tomatoes, rubles	105.8	91.6	82.0	57.4	43.8	35.9	27.1
Energy costs for growing 1 kg of cucumbers, rubles	58.0	50.2	44.9	31.4	23.9	19.5	14.7
Energy costs for growing 1 kg of tomatoes, rubles	34.6	30.0	26.9	18.8	14.3	11.8	8.9
Growing according to the technology of managing thermal energy flows							
Cost price of 1 kg of cucumbers, rubles	149.1	129.2	115.6	81.0	61.7	50.7	38.3
Cost price of 1 kg of tomatoes, rubles	98.5	85.4	76.4	53.6	40.8	33.8	25.6
Energy costs for growing 1 kg of cucumbers, rubles	54.4	47.1	42.2	29.5	22.5	18.5	14.0
Energy costs for growing 1 kg of tomatoes, rubles	32.5	28.2	25.2	17.7	13.5	11.1	8.4
Comparative effect							
Cost price of 1 kg of cucumbers, rubles	11.01	9.39	8.37	5.81	4.42	3.22	2.30
Cost price of 1 kg of tomatoes, rubles	7.30	6.23	5.55	3.86	2.93	2.16	1.55

In accordance with the calculated data of table 1, the amount of cost savings will depend on seasonal climatic conditions. At positive air temperatures, the cost of growing using two technologies is approximately comparable. With a decrease in air temperature, the efficiency of using thermal energy by the proposed technology increases. This pattern is expressed in a greater decrease in the cost of growing one kilogram of the vegetable crops in question. When the air temperature in the winter season is -15ºC, the use of technology will reduce the cost of growing vegetables by 6.7%, in the autumn and spring seasons by 5.9%.

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4. Conclusion

Energy saving is a prerequisite for the development of energy-intensive industries. Prospects for the development of greenhouses, the authors see in the implementation of the transition from "power" energy to electric power systems, qualitatively increasing the manageability of energy flows. Calculations confirm that the application of the proposed technology is economically feasible. The main advantages are the reduction in the cost of vegetable crops due to energy savings and an increase in the yield of vegetable crops. The cost of additional structural elements is compensated by reducing the number of irradiators. The implementation of the technology will depend on a number of factors. First, its adaptation to the standards of irradiation devices with LED sources for greenhouses is required. Secondly, work is underway to develop automation equipment and create software for the climate control process in accordance with the adopted technology.

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