Evaluation of the effectiveness of a helio-greenhouse with soil heating

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Abstract. In most cases, various industrial greenhouses are used to grow vegetables in large volumes. Smallholder farms and horticultural individual plots have recently begun to use small polycarbonate greenhouses. However, it is not always possible to fully use the capabilities of such greenhouses due to the influence of weather, especially in early spring and late autumn. According to the authors, one of the methods to increase crop production in greenhouses is the collection and accumulation of solar energy, its further use for heating the lower layers of air in the greenhouse, and heating the soil. To solve this problem, an experimental helio-greenhouse with a height of 4.2 m has been made. The design of the helio-greenhouse provides for a system of underground pipes 110 mm in diameter buried to a depth of about 1 m into which air heated by the sun is fed from the upper part by an axial fan. The article presents the results of experimental studies of the microclimate (temperature and relative humidity) in an experimental Helio-greenhouse in comparison with a standard greenhouse and the environment. The results prove the effectiveness of the experimental Helio-greenhouse, namely, the temperature in it is 3 - 35 °C higher than the ambient temperature; there is a possibility of accumulation of warm air and its further use for heating the soil; it is possible to sow (plant) plants earlier than in a standard greenhouse.

1. Introduction

Decree of the Government of the Russian Federation from 14 July, 2012 No. 717 “On the State Program for the Development of Agriculture and Regulation of Agricultural, Commodity and Food Markets” set the task of technological and technical leap in agricultural production. In this Decree, a special place is occupied by the production of vegetable products which provide a person with all the essential vitamins for the body. They are in demand by the population all year round.

It is known that the production of vegetable products over the past decade has increased compared to the eighties-nineties of the XX century. At the same time, the volume of vegetable production in households according to the official statistical publication of the Federal State Statistics Service of the Russian Federation according to which 7.5-8.5 million tons of vegetables are produced annually (table 1).
Table 1. Vegetable production in households of the population of the Russian Federation [1].

| Years | 1992 | 2000 | 2005 | 2010 | 2014 | 2015 | 2016 | 2017 | 2018 |
|-------|------|------|------|------|------|------|------|------|------|
| Vegetables production, million tons | 5.5  | 8.1  | 8.4  | 7.5  | 8.2  | 7.9  | 7.7  | 7.5  | 7.5  |

However, it can be noted that today the market for vegetable products represented in the Russian Federation has a large portion of imported products. That is, there is a shortage of own competitive vegetable products. We believe that one of the ways to solve the above problem is the wider growing of vegetables in the protected soil - the use of various greenhouses, including in small farms, garden plots, etc. Nowadays greenhouses made of metal frames and coated with polycarbonate have become the most popular for these purposes. These greenhouses can be made in almost any size and shape and have a relatively low price. That is why such seasonal greenhouses at the current stage of agricultural development are becoming very significant for agricultural producers [2, 3].

In world practice, solar greenhouses are widely used. The work published by [4] describes the design of energy-efficient heating technology and the model of a greenhouse in northern China. The other is to employ energy-efficient heating technologies, such as heat storage with phase change materials and heat pumps. In this paper, the recently developed greenhouse energy-saving technologies and their optimal design based on models were reviewed and discussed. Many studies have demonstrated that the performance and design of heating systems can be improved by such models as computational fluid dynamics.

In the USA the authors’ team designed, built, and instrumented a 1000 square foot research greenhouse in Boulder, Colorado that uses only sunlight for heat and illumination. The building employs high R-value foundation perimeter, wall, and roof insulation; high solar heat gain coefficient windows; light shelves; automated insulating shutters that lower night-time losses through fenestration six-fold; large quantities of thermal mass; and efficient air handling systems that ventilate the structure and collect, store, and distribute thermal energy and moisture [5].

Theoretical research in the field of modeling of the heat and moisture balance of the helio-greenhouse is described in the scientific article [6]. The authors proposed the physico-mathematical model of the heat and moisture balance of a solar heater with a pyrolysis heating installation under steady-state conditions is developed in the article.

When designing and building greenhouses, it is necessary to take into account all environmental factors (heat, humidity, lighting, etc.). Scientists have also determined the dependence of absorption and assimilation of energy by plants on the wavelength of light radiation which is called the energy spectrum of photosynthetic active radiation (PAR). Photosynthetic active radiation is a stream of energy of a certain spectrum used by plants. Light with different radiation frequencies (and different colors in the visible range) affects growth, plant development, and photosynthesis in different ways. Based on the foregoing, according to the influx of natural PAR, Russian scientists have divided the territory of Russia into 7 light zones. Thus, the territory of the Chuvash Republic falls into the II light zone where the total PAR makes up 400-580 cal/cm² [7].

Therefore the territory of the Chuvash Republic is considered a dysfunctional zone for obtaining high yields from land husbandry. That is, the yield strongly depends on weather conditions in this zone, i.e. much depends on weather conditions. The change of PAR to 31% is significant and leads to great risks of agricultural production in the Chuvash Republic [3]. That is why the effective use of the total PAR is an urgent task.

One of the most recent studies in this area is presented in [8]. The authors studied the effect of external roof shading on the spatial distribution of air temperature and relative humidity in a greenhouse was evaluated under the arid climatic conditions of Riyadh City, Saudi Arabia. Two identical, evaporatively-cooled, single-span greenhouses were used in the experiment. One greenhouse was externally shaded using a movable black plastic net (30% transmissivity), and the other greenhouse was
kept without shading. Strawberry plants were cultivated in both greenhouses. The external shading improved the spatial distribution of the air temperature and relative humidity and improved the cooling efficiency of the evaporative cooling system by 12%, since the transmitted solar radiation and accumulated thermal energy in the greenhouse were significantly reduced.

The paper [9] presents a systematic review of methods for managing strategies to improve the energy efficiency of agricultural greenhouses, in particular for low-energy greenhouses. This review could provide a guidance to probe into the advanced control strategies to reduce the energy consumption for the greenhouse and maintain suitable growing environment simultaneously. This work has also demonstrated several control perspectives on the future low energy greenhouse trends.

Given the above, the main goal of these studies is to determine the effectiveness of an experimental solar greenhouse, to determine how much higher the temperature in a helio-greenhouse is compared to a standard greenhouse, and the possibility of sowing or planting earlier.

2. Materials and methods

To maximize the use of the total PAR in growing plants in dysfunctional areas, it is necessary to get the best of solar radiation to heat the soil in summer and to extend the life of plants in late autumn with the possibility of obtaining vegetable products in different categories of management. For this, we have built an experimental rectangular solar greenhouse with dimensions of 4 × 6 meters, covered on all sides with transparent polycarbonate 8 mm thick. The height of the greenhouse is 4.2 m, while the roof of the greenhouse is pitched, the angle of inclination is chosen so that in the daytime the sun's rays penetrate the roof surface at an angle of 90°С, thus the angle of inclination of the roof is about 30°С to the horizon. The experimental helio-greenhouse is intentionally built high - more than 4 m so that the heated air inside could accumulate in the upper part under the roof where a water tank can be installed. In the underground part of the solar greenhouse, at a depth of 1 m, plastic pipes with a diameter of 110 mm are laid to supply thermal air taken from the upper air zone of the greenhouse. They are located along the entire width and length of the greenhouse: a total of 6 pipes 2.5 m long with a pitch of 0.4 m. One end of the pipes is connected to the intake manifold, the other to the outlet. An axial fan is located in the upper part of the greenhouse at a height of 4 m; it blows heated air from the upper part of the greenhouse through a vertical air duct (pipe with a diameter of 110 mm) and feeds it into the intake manifold. The heated air passing through underground pipes gives off its heat to the soil and, when cooled, exits through the exhaust manifold at a height of 0.5 m. Such heating of the soil will allow sowing or planting as early as possible which will extend the growing season. For experimental studies, 2 different greenhouse constructions were used: 1) an experimental solar greenhouse; 2) an arched greenhouse 3 m wide with standard parameters, covered with transparent polycarbonate with a thickness of 8 mm, which is widely used by amateur gardeners. Both greenhouses are located on a regular garden plot close to each other. The results of experimental studies were processed using standard methods, classical methods of statistical processing of data sets in the MS Excel application program.

The results of the study in the experimental greenhouse were compared with the results of studies obtained in the standard greenhouse for amateur gardeners which is shown in figure 1. Besides, the perimeter of the underground part of the experimental helio-greenhouse was lined with an environmentally friendly heat-insulating material, with a low coefficient of thermal conductivity and an impregnated substance for repelling rodents. Automatic temperature and relative humidity recorders were installed in both greenhouses at a height of 0.5 m to analyze the microclimate.

UNI-T UT330B and UT330C devices (Uni-Trend Technology Co. Ltd., China) with a USB connector were used as recorders which make it possible to measure and record temperature, humidity, and atmospheric pressure. UT330-USB series data loggers use high-precision temperature, humidity, and atmospheric pressure sensors for long period monitor and record. The recorders’ memory had a size for storing up to 60,000 data (records). Data from the recorders were transferred to any computer via a USB port. For data processing, there was special software – UT330ABC.
3. Discussion of results

In figure 2 shows graphs of changes in temperature and relative humidity of the air inside the greenhouse and outside air for the period: from April 1 to April 6, 2019.

Analyzing the obtained experimental data (figure 2), it can be noted that, the average temperature inside the greenhouse was always higher than the outside temperature by 1.5…5.0 °C. The minimum temperature in the greenhouse during this period reached minus 2.2 °С (04 April, 2019), and at the meteorological station the lowest temperature was recorded at minus 3.8 °С. The maximum outdoor temperature for the entire period was 6.7 °C. In the daytime, the temperature in the greenhouse increased to 12…20 °С, and the maximum temperature of 20.2 °С was recorded on 04 April, 2019 from 14:30 to 14:50. At the same time, cloudiness prevailed on all observation days.

As shown in the figure 2, it can be concluded that at night, the temperature inside the helio-greenhouse was the closest to the outside, while during the daytime it was 3…5°С higher, and the maximum temperature difference was in the range between 5 and 20°С. This is because during the day, solar radiation is quite high and it is excessive for plants. Therefore, it is necessary to remove this excess
heat from the plants. As mentioned above, we recommend sending this heat to the subsoil pipes to heat the soil, thereby cooling the air at the output we create the most favorable temperature near the plants. And the accumulated heat in the soil will give its heat in the cold period of growing.

It can also be noted, as the analysis of figure 2, the air humidity in the greenhouse changes in antiphase with the temperature, which confirms the classical laws of nature and the reliability of the recorded parameters by the recorder.

Studies of microclimate parameters in a standard greenhouse showed that the inside temperature was 10…20°C higher than the outside temperature on sunny days; and 5…10°C in cloudy weather. However, the standard greenhouse did not allow sufficient heat storage to further maintain the temperature, for example, at night when outside temperatures were below zero.

Our results are consistent with the research presented in the following papers: in [10], the effect of a solar greenhouse heating system using black plastic hoses filled with water was studied. The results show that the use of this heating system improves the night temperature inside the greenhouse by 3.1°C and reduces the relative humidity by 10% compared to the control greenhouse, which has a positive effect on tomato production.

In [11], the influence of using a vacuum tube solar collector as a solar water heater using an electric heat pump for heating greenhouses was studied. The results showed that the internal air temperature in the heated greenhouse exceeds the temperature inside the unheated (control) greenhouse by 2-3°C, while the relative humidity in the heated greenhouse decreased by 10%. In [12], the possibility of heat accumulation for use in greenhouses in circumpolar territories, where the main problem is: too large a temperature difference between day and night, which hinders the development of agricultural crops. Heat storage reduced this difference and kept the minimum temperature above 10 °C for most of the growing season.

Another way to store heat in a solar greenhouse is to install a water tank in the upper area of the greenhouse. Preliminary studies of the use of this method have shown that water on a sunny day is capable of warming up to a temperature of 50…60°C. For this, we installed a standard metal barrel with a capacity of 200 liters at a height of about 3 m. This heated water can also be supplied through the pipe system to underground pipes.

4. Conclusion
Taking into account the results obtained, the experimental Helio-greenhouse can be considered effective in comparison with standard greenhouses. The effectiveness is as follows: The proposed design of the helio-greenhouse allows the most efficient use of the total PAR which will increase the growing season. Due to internal heat transfer, all the energy coming from the sun is not lost anywhere but is accumulated and, in the future, it will help maintain the optimum temperature in the helio-greenhouse for growing plants until late autumn. Moreover, the cooled air after leaving the underground creates the optimum temperature at the plant level and superheated air will go up.

The technical effect of the proposed solutions is to reduce energy costs for the production of a unit of plants grown in the greenhouse, to increase their crop yield, to get products at the earliest possible period in comparison with the production of a conventional greenhouse and on the open ground as well as to protect the environment from industrial pollution.

Experimental studies have shown that the temperature inside the helio-greenhouse is always 2…5°C higher than in a standard greenhouse. The heat accumulated in the soil allows maintaining the air temperature for a longer time; it changes more smoothly with sudden changes in outdoor temperature than in a standard greenhouse. During hot sunny periods in the experimental helio-greenhouse, excess heat goes to the top - this creates a more optimal temperature below the plants. At the same time, in a standard greenhouse, the air temperature in the lower and upper zones differed slightly (1…2°C).

The results of experimental studies have confirmed our hypothesis about the possibility of heat accumulation in the soil as well as the possibility of earlier sowing (planting) of vegetable crops in comparison with standard greenhouses for amateur gardeners as well as the extension of the life of plants in late autumn. Based on the data obtained in 2019, for the first time in a greenhouse without artificial
heating, it was possible to sow radish and onion sets on 1 April, 2019, into the soil, which made it possible to obtain an onion crop for greens with a feather length of 55 … 60 cm already on 19-20 April, 2019, and a full the radish harvest was received on 21-23 April, 2019. When placing the soil in a special container, the sowing can be placed in the upper zone, and thus the sowing time can be advanced even earlier.

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