USE OF ACCUMULATED SOLAR THERMAL ENERGY IN GREENHOUSE FOR EXTENDING VEGETATION PERIOD OF CROP PLANTS

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Abstract. The consumption of thermal energy for growing vegetables in greenhouses depending on the type of energy resource can make up to 40-60% of the production cost structure, so solutions to reduce it are pressing. Research on possibilities to accumulate thermal energy and extend the growing period was conducted in an experimental greenhouse with created gravel thermal mass for thermal energy accumulation in the hot periods and its recovery in the cool periods. The air delivery to the thermal mass and the recovery of thermal energy from it are provided by a fan, regulated by an automated control unit. A sensor system records the outdoor temperature, the temperature in the greenhouse and the thermal mass. The purpose of the research is to find out how much solar energy can be accumulated in the created thermal mass, as well as to study the possibilities of extending the vegetation period of the plants using the accumulated solar thermal energy. Experiments in the greenhouse were carried out on 01.06. to 05.12.2022. At the beginning of the period the average temperature in the thermal mass was 15 ºC, in the middle of June it rose to 20 ºC, and from then, until 29.08.2022, it kept fluctuating within the range of 20-22 ºC. Despite the very high outdoor and greenhouse air temperatures, the thermal mass showed a positive effect by stabilizing the greenhouse and soil temperatures, thus improving the growing conditions. After 01.09.2022 the temperature in the thermal mass gradually decreased, and on 14.10. it reached the initial 15 ºC. In the period of 136 days 4175 kWh of energy was accumulated in the thermal mass. From then until 13.11. the temperature in the thermal mass remained stable at 12 ºC, which is the minimum, allowed for the plant growth in greenhouses, then a sharp drop followed, and vegetation ended. Under these meteorological conditions the use of the thermal mass allowed extending the vegetation period in the greenhouse by approximately 20 days.

Keywords: solar energy accumulation; vegetation period, control system, passive greenhouse.

Introduction

The costs for heating or cooling in greenhouses make up 40-60% of the total production costs [1], similar data are also indicated by the Latvian Rural Consulting and Education Centre, so research on the use of solar energy to ensure an optimal temperature regime in greenhouses is relevant. Various options for the use of solar energy in greenhouses are being researched in the world, some studies using a solar collector and a heat pump have also been carried out in Latvia [2], but the developed technique is relatively expensive and complicated. The analysis of the previous research showed that a simple and economical technique is to accumulate the solar heat in the accumulating layer (hereinafter referred to as thermal mass) created under the greenhouse [3; 4]. During the warm periods, the air heated by the sun is blown out of the greenhouse with a fan into the pipe system created in the accumulation layer, heating the accumulation layer and recovering the heat from it during the cold periods, thus creating a solar energy accumulation system. Another terminology can also be found in the literature in the descriptions of systems of similar operation: a greenhouse heating system by using heat accumulators [5], a solar heating cooling system (SHCS) [6], an active solar soil heating system [7], thermal energy storage (TES) [8]. Several authors [9; 10] also indicate the efficiency of a technique – by recovering heat in the cold periods it is possible to increase the temperature in the greenhouse by 2-5 ºC. Some authors [11; 12] indicate also the extension of the plant vegetation period.

However, most investigations have been conducted in the countries with much more intense solar radiation. In Latvia, the total solar energy received is about 1100 kWh m^2 per year. The highest solar intensity is on the Kurzeme coast (western Latvia), the coast of the Gulf of Riga and part of Zemgale (southern Latvia) [13]. To test the effectiveness of the method, an experimental greenhouse of 50 m^2 (125 m^3) was built on the organic farm “Skudriņas” (coordinates 57.013352, 21.583264). A thermal mass was created under the greenhouse and a pipe system was installed. The pipe system was used to transfer warm air from the greenhouse to the thermal mass for storage and, when necessary, to transfer the stored heat from the thermal mass back to the greenhouse. The PostgreSQL system used in the previous study [14] was applied to monitor the thermal energy storage parameters and to record and store the data. The aim of the work is to find the possibilities and usefulness of thermal energy storage and recovery in a greenhouse with a thermal mass, as well as the possibilities of extending the vegetation period of the plants in such greenhouse.

Materials and methods

Within the framework of this investigation there was built, as shown in Figure 1, an experimental greenhouse (1) to study the possibilities of solar energy accumulation. Its area is 50 m^2 and volume 125 m^3, a thermal mass (7) is created under the entire area in which the accumulated energy is used for heating or cooling the greenhouse. Most authors believe that the optimal thickness of the thermal mass is 800-1200 mm, a 1000 mm thick thermal mass being most often chosen [15]. Materials such as sand, gravel, pebbles and stones are commonly used to form the thermal mass layer [3; 15]. For the experimental greenhouse, gravel was chosen as it is the most cost effective and accessible material.

The constructive design of such greenhouse is shown schematically in Figure 1.

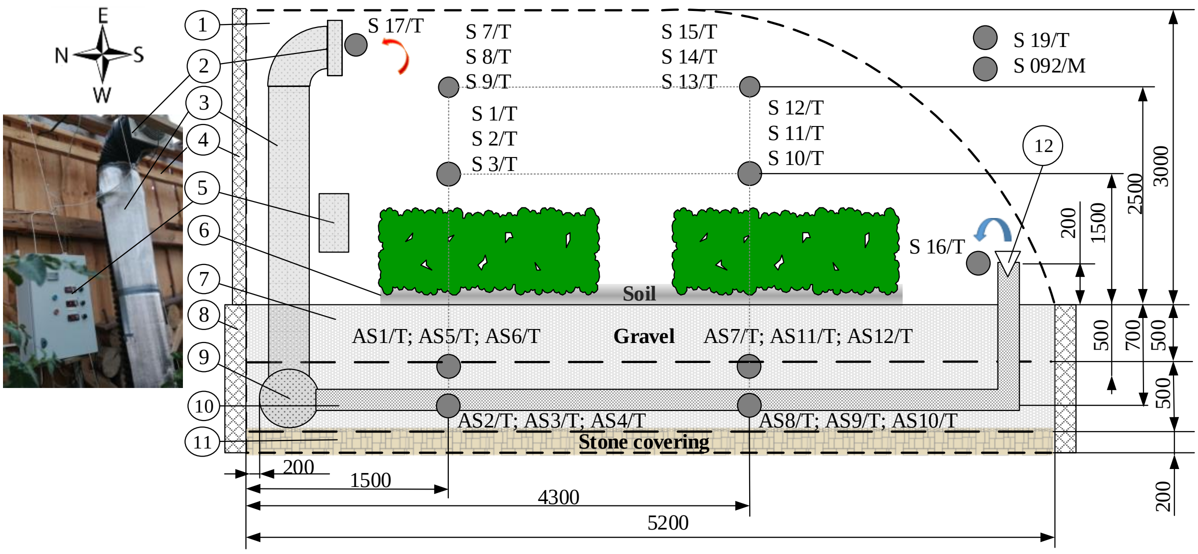

Fig. 1. **Arrangement diagram of the components and sensors of the solar energy storage experimental greenhouse**

One end of the heat exchange pipes (10) is led out 200 mm above the thermal mass layer (7) at a 90 ° angle, the other is connected to the distribution pipe (9), 300 mm in diameter, in the centre of which there is a 300 mm vertical inlet pipe (3) connected with a fan (2). The capacity of the fan is 40 W, the flow rate 4 m s^{-1}, the output 800 m^3 h^{-1}, it ensures six – fold air exchange per hour. The operation of the fan is regulated by the control unit (5), which contains the sensors for the indoor air temperature, outdoor air temperature and humidity S1/T - S15/T; AS1/T - AS12/T S16/T; S17/T; S092/T. The air discharged from the thermal mass is adjusted by means of deflectors (12) mounted on the outlets of the heat exchange pipes (10). The greenhouse is intended for growing tomatoes.

The thickness of the thermal mass layer (7), made of gravel, is 1000 mm; under it there is a 200 mm thick layer of stones for draining the condensation moisture from the perforated heat exchange pipes. Characteristics of the gravel: density 1800 kg·m^{-3}, specific heat 0.84 kJ·(kg·K)$^{-1}$ [5]. Along the perimeter around the greenhouse, there is created thermal insulation of the foundations, 50 mm thick; the cover of the greenhouse from 6 mm polypropylene slabs (8), with a slope towards the southern side. A corrugated perforated heat exchange pipe (10), 100 mm in diameter, was chosen for placement into the thermal mass layer with a distance between the pipes of 800 mm (Fig. 2). An approximate diameter and distance of such pipes are obtained, using the selection and placement criteria of pipes, given in study [16]. The total number of the heat exchange pipes is 12; they are placed on a pile of stones, 200 mm thick, located at a depth of 1000 mm, which corresponds to the recommendations of other authors [15; 18].

In order to record and store the temperature and humidity measurement data, a system (Postgre SQL) has been arranged for monitoring and control of the modes, as well as for evaluation of the efficiency of thermal energy accumulation [14]. The measurement system (Fig. 1) includes 17 temperature sensors, installed in the greenhouse (S1/T – S17/T) and two sensors for determining the outdoor air temperature and humidity (S19/T and S092/T), as well as 12 pcs. of temperature sensors (AS01/T – AS12/T) are installed in the thermal mass layer (Fig. 2) at the level of 500 mm and 700 mm. The sensors for the study were designed in order to reduce thermal inertia by clearly exposing the chips to the air flow and reducing the connected mass [2].

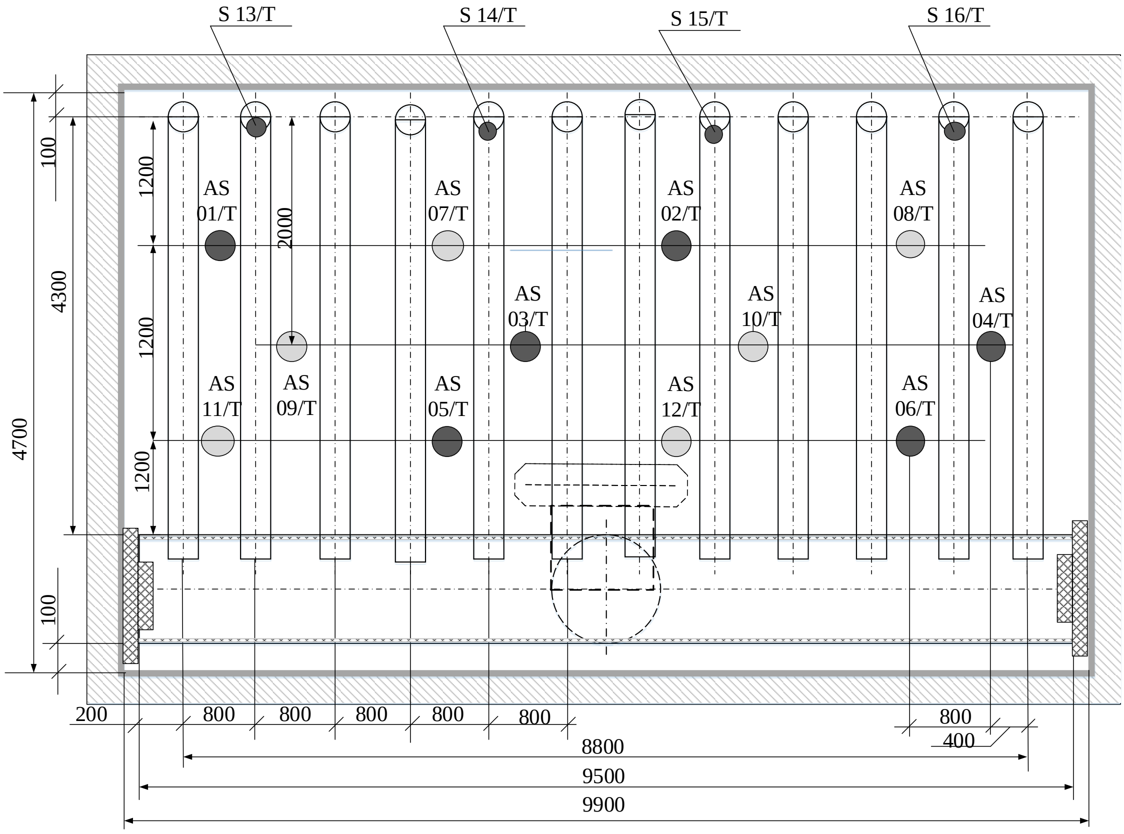

Fig. 2. **Scheme of placement of sensors in the thermal mass layer:**
○ – placed between the pipes at a depth of 700 mm; ● – placed above the pipes at a depth of 500 mm

The unit of the control system (Fig. 3) regulates the operation of the fan; for this purpose two thermoregulators are installed in it. The fan turns on when the temperature in the greenhouse drops below 12 ºC or rises above 25 ºC. If the greenhouse has a temperature mode of 12-25 ºC, suitable for growing tomatoes, then the fan does not work. Depending on the growth phases of tomatoes, it is possible to reprogram the operation of the fan.

When programming the fan control system unit, the basic requirements of tomato cultivation must be observed. After planting the tomato seedlings in the greenhouse, a temperature of 10-12 ºC is provided for their cultivation. After 45-50 days of cultivation, they formed 6-7 leaves, but no flower buds had yet developed. 10-14 days before the formation of flowers, the temperature should not exceed 16-17 ºC, but during flowering it should be 17-18 ºC. When the fruits in the first bunch have dropped and begin to ripen, the temperature should be gradually increased.

Fig. 3. **Greenhouse heating and cooling control unit**

The optimum temperature for the growth of tomato plants is 20-25 ºC during the day and 16-18.5 ºC at night. In the months when there is intense lighting, the temperature should be higher: during the day in sunny weather 22-25 ºC, in cloudy days – around 18-20 ºC, at night 15-17 °C. To exceed the limit of 26 ºC even in bright, sunny weather is not desirable. At a temperature above 30 °C, tomatoes no longer pollinate, but above 35 °C, the flowers, and gradually, the whole plant die. The optimal air humidity in the greenhouse is 60-75% at night, and 80-90% during the day.

In order to control the operation of the control unit during the operation of the fan, measurements of the temperature, humidity and the air flow rate, entering and leaving the thermal mass layer were periodically performed with hand tools (see Fig. 4).

a) b)

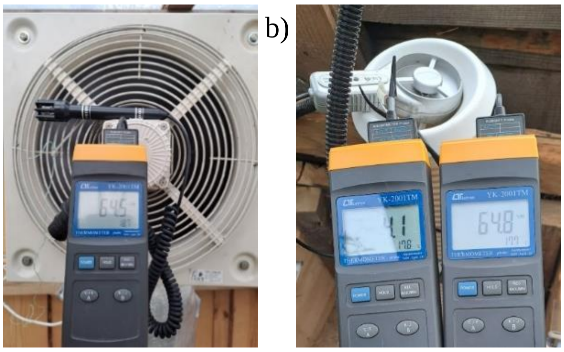

Fig. 4. **Air temperature, humidity and flow rate control measurements:** a – the air flow rate for the incoming air; b – the flow rate and humidity for the air leaving the thermal mass layer

The measurement system records the fixed temperature and humidity data of 31 sensors every 5 minutes, accumulating them in the Post GIS spatial extension of the DB storage. The total volume of registered data is very large – approximately 1.5 million. The registered data were analysed by day, month and over the whole period.

Results and discussion

The registration of the air temperature entering and leaving the thermal mass layer, the greenhouse and the outdoor air temperatures, as well as humidity was started on 01.06.2022, and continued until 05.12.2022; so, monitoring of these parameters was carried out for 6 months. A temperature of 16-17°C is particularly important for tomatoes at the beginning of the growing season. We achieved this, with slight variations at the beginning and end of the month. As an example, Figure 5 shows the temperature variations on 10.06.2022.

As it is evident, the temperature in the greenhouse does not exceed 22 ºC; the temperature in the thermal mass layer is 18.1-18.6 ºC, and its impact upon the temperature in the greenhouse is minimal. As the tomatoes develop, the optimal temperature in the greenhouse is up to 25 ºC, but in the months of July and August, the temperature often exceeded the critical 30 ºC for several hours a day, which negatively affected the growth of tomatoes.

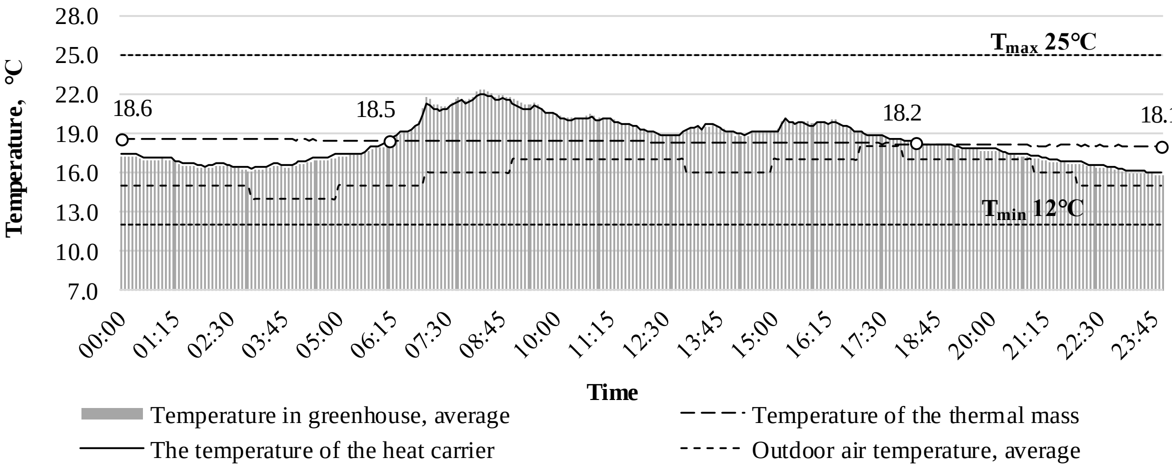

Fig. 5. **Temperature variations in the greenhouse 10.06.2022**

As evident in Figure 6, for example, on 10.07.2022, the temperature in the greenhouse temporarily reached up to 37 ºC, the temperature in the thermal mass layer increased to 19.6-19.9 ºC, but its effect upon the temperature in the greenhouse was insufficient; it was not possible to ensure the required temperature in the greenhouse in the middle of the day without additional ventilation. The temperature in the greenhouse, similar to the outside air temperature, varies widely, falling close to the critical 12 ºC at night, but it is relatively constant in the thermal mass layer, stabilizing the temperature in the greenhouse.

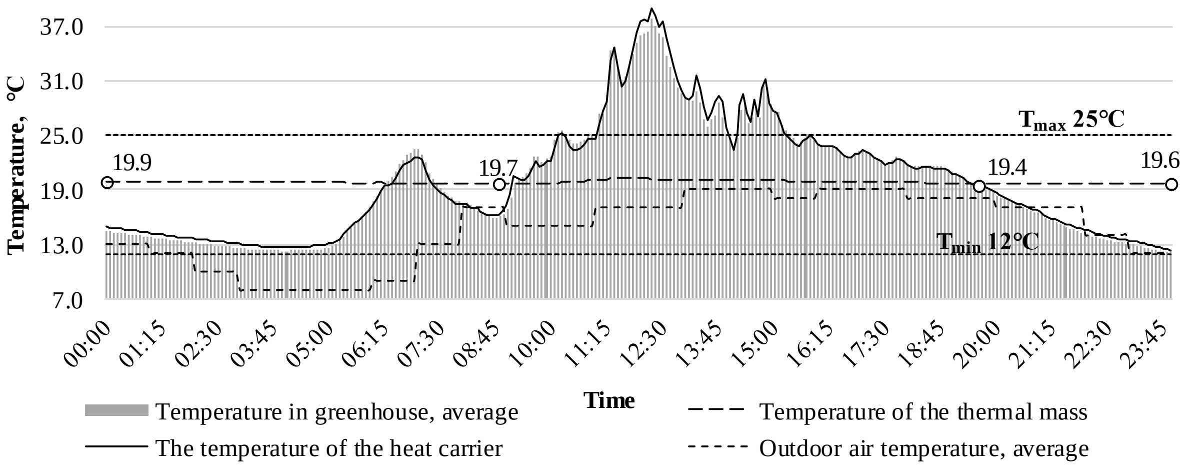

Fig. 6. **Temperature variations in the greenhouse 10.07.2022**

In the months of July and August, despite the high air temperature in the greenhouse, the temperature in the thermal mass layer remained within the range of 20-22 ºC, which had a very favourable effect on the tomato root system, as it is important that the temperature in this area is equalized [7]. The temperature stabilization in the root zone during the day is also noted by other authors as an important advantage [9; 19]. During the day the thermal mass layer changes the temperature in the root zone within 2-3 ºC, but, when the outdoor air temperature approaches 30 ºC, it is unable to stabilize the temperature in the greenhouse, and additional ventilation is necessary. Compared to another study [19], the temperature fluctuations of the thermal mass layer during the day within the limits of 2-3 ºC are considered minimal, which can be explained by its relatively large mass.

The changes in the average values of the four recorded temperature variations by months are shown in Figure 7. It can be seen that during the summer months, the temperature in the thermal mass layer is lower than in the greenhouse. But from September onwards, the temperature in the thermal mass layer is higher than in the greenhouse, thus stabilising the temperature in the greenhouse and ensuring an adequate temperature in the root zone.

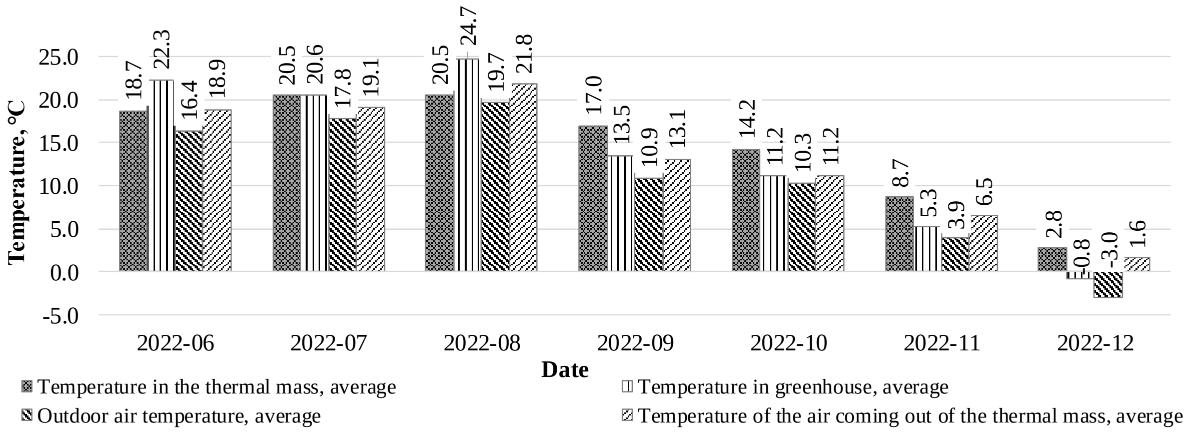

Fig. 7. **Changes in temperature variations in the greenhouse by months**

Still in October the temperature in the greenhouse was 14.2 ºC, which allows the late tomatoes to ripen normally, thus extending the vegetation period. With the gradual cooling of the thermal mass layer in the autumn, the difference between its temperature and the temperature of the outgoing air decreases, which is the lowest in December – 1.2 ºC. The greatest positive impact upon the thermal mass layer is exactly in the autumn because, starting from September, the temperature in the thermal mass layer is by 3-3.5 ºC higher than in the greenhouse.

The temperature conditions in the thermal mass layers and the energy balance in the greenhouse throughout the period are shown in Figure 8.

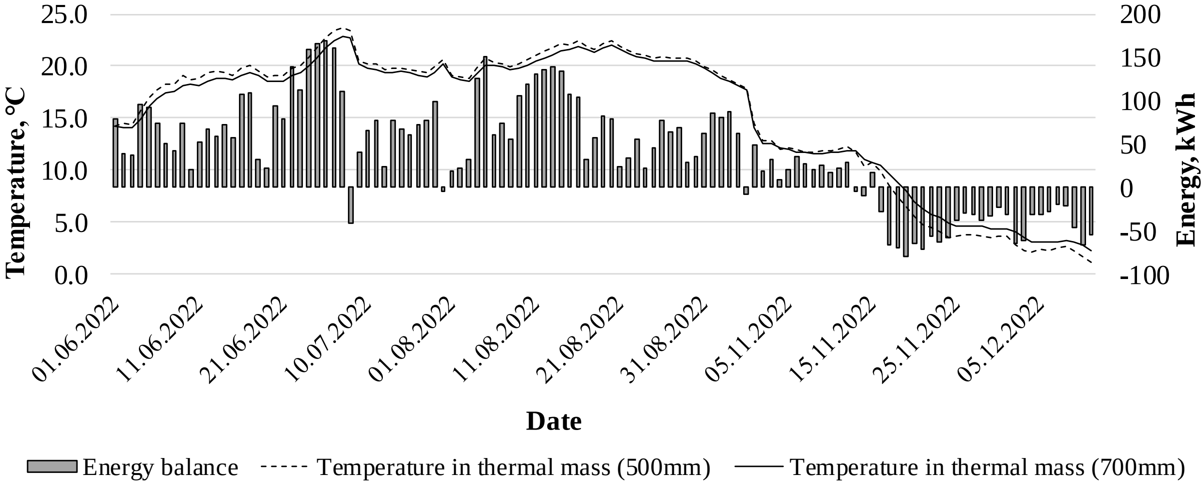

Fig. 8. **Temperature conditions in thermal mass layers and the energy balance in the greenhouse throughout the period**

It is obvious that in the summer months the temperature in the thermal mass layer at a depth of 500 mm is higher than at 700 mm, but from September to mid – November it is practically the same. On the other hand, starting from November 20, the upper thermal mass layer cools faster than the deeper one, and accumulation of the thermal energy ends. However, the temperature in the thermal mass layer and in the greenhouse is positive, which gives a good opportunity to successfully collect various cold – resistant green crops for consumption in such a greenhouse, thus extending the time of use of the greenhouse by approximately 20 days. The possibilities to extend the vegetation period in a greenhouse with a thermal mass layer are also found by other authors [11; 12].

The energy balance is the difference between the amount of the heat energy, stored and consumed in the thermal mass layer during the day. The energy balance for the entire experimental period is calculated by summing the amount of the heat energy, accumulated or consumed per day throughout the entire period. The daily amount of energy Q can be calculated according to formula [20]:

$$Q = \frac{cm(t_2 - t_1)}{3600}, \text{ kWh} \tag{1}$$

where: c – specific heat capacity of the thermal mass layer, J·(kg·K)$^{-1}$ (c = 840);
m – mass of the thermal mass layer, kg (m = 90 000);
t_2 – temperature at the end of the day, K
t_1 – temperature at the beginning of the day, K.

The calculated thermal energy balance during the experimental period was 4697 kWh. The accumulated heat balance shows the feasibility of this technology, where the heat energy can be stored in the thermal mass layer and then gradually released back into the greenhouse during the cooler autumn months. The electric energy, consumed by the fan during the period, was 72 kWh.

The control measurements of the air temperature and air flow rate in and out of the thermal mass layer, periodically carried out with hand tools, coincided with those, shown by the measurement system within the limits of the allowed error.

Conclusions

1. The energy, stored in the thermal layer, stabilizes the temperature in the root zone of the plants, partially neutralizing the negative impact of drastic temperature fluctuations in the greenhouse during the development of tomatoes in the summer months.
2. In the summer months, when the outdoor air temperature exceeds 25 °C, it is necessary to provide additional ventilation to maintain the allowed temperature in the greenhouse.
3. Under the specific conditions of 2022, the energy, stored in the thermal mass layer, made it possible to extend the vegetation period in the autumn by approximately 20 days.
4. During the experimental period 01.06. to 05.12.2022, the balance of the heat energy, stored/consumed in the thermal mass layer, was 4697 kWh; the fan consumed 72 kWh of electricity during this time.

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Author contributions

Conceptualization A.R. and A.A., methodology A.R. and M.N; investigation A.R. and M.N., writing – review and editing D.V, S.I. and A.R. All authors have read and agreed to the published version of the manuscript.

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