Accumulation of solar energy to heat greenhouses

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Abstract. The primary task of a greenhouse is to create optimal microclimate, which doesn’t depend on external climatic conditions, to grow plants. We can observe significant air temperature and humidity difference in a traditional greenhouse during 24 hours. The stable microclimate in greenhouses is provided by different engineering systems such as heating, ventilation, lighting, etc. These systems require a lot of energy. Saving energy and reducing the mode of temperature amplitude inside the operating greenhouse during exploitation period can be achieved by using solar energy in the greenhouse heating system, namely, by using heat accumulators. However, the test method of optimal heat accumulator to equalize the temperature amplitude inside the greenhouse wasn’t described in any research. The purpose of this research is to determine the optimal heat accumulator for equalizing temperature amplitude inside the greenhouse under atmospheric effects in spring. The experimental research of the heat-humid regime was carried out for the greenhouse without any heat accumulation. Relationship between the volume and the surface area of the accumulator and its efficiency was identified.

1. Introduction

The primary purpose of a greenhouse is to create optimal microclimate, which doesn’t depend on external climatic conditions to grow plants. Greenhouses are usually used to grow plants in areas where geographical factors or seasonal climatic variations don’t allow growing plants on the field. However, the structure of the greenhouse itself doesn’t provide optimal microclimate for growing plants.

In a traditional greenhouse, significant air temperature and humidity difference is observed over 24 hours. The difference between day and night temperatures can achieve 40°C and more.

A stable microclimate in greenhouses can be provided by different engineering systems such as heating, ventilation, lighting, etc. These systems require a lot of energy, especially when the greenhouse is used around the year.

The large areas of transparent surface in greenhouses also contribute to heat losses. During any warm season the air temperature in greenhouse increases quickly to the level significantly higher than required. Sometimes natural ventilation isn’t enough to escape excess heat. During the cold season heat losses in a greenhouse are very high through transparent surfaces. The microclimate stability in greenhouses is constantly supported by the heating systems during this period, and as a result, everything leads to
significant energy losses. Thus, greenhouse agriculture production is the most energy-intensive and expensive kind of agricultural industry.

Therefore, more and more attention is focused on the search of design solutions to create sustainable and energy efficient greenhouses. Such greenhouses can be highly productive with minimal energy consumption but have a high productivity.

One of the ways to increase energy efficiency and reduce energy costs is to accumulate and to use the excess solar energy in greenhouses. The heat accumulator can be used to level the temperature fluctuation in greenhouse.

2. Statement of the problem

Heat accumulators can be classified according to their properties of heat-accumulation materials. There are accumulators of capacitive type, which use the heat capacity of the accumulating material. The material of this accumulator is heated (cooled) without any change to its aggregate state [1 - 3]. There are also accumulators with phase transition of substance. Such accumulators use melting heat (solidification) of a substance [1, 4].

The accumulators that based on a phase transition are more efficient than accumulators of capacitive type because they have a much higher the enthalpy value of the phase transitional than the heat content. However, these accumulators also are expensive. Additional research on the economic feasibility of their use in the greenhouse have to carry out for each case [4, 5].

The accumulators of capacitive type are mostly employed in greenhouses. Concrete, stone, water, brick, other materials and their combination can be used as heat accumulation materials [3, 6]. As heat accumulators in a greenhouse element of its structures (floor, walls, soil and other structural elements) can be used. The separate objects (for example, tanks with water, stones and other subject, which can accumulate heat) can be also used [2, 6, 7].

The heat accumulation capacity of materials depends on their thermal storage properties and temperature difference. The materials with higher density have got generally the highest heat storage properties, but at the same time these materials have got a higher thermal conductivity. The properties of some materials and substances to create heat accumulators are presented in the Table 1 [8].

Table 1. The heat accumulation capacity and thermal conductivity of some materials and substances.

| Material / substance              | Density, $\rho_0$, kg/m$^3$ | Specific heat, $C_0$, kJ / kg · K | Thermal conductivity, $\lambda$, W / (m · K) |
|----------------------------------|-----------------------------|-----------------------------------|---------------------------------------------|
| Water                            | 1000                        | 4.2                               | 0.55                                        |
| Ground                           | 1600                        | 0.8                               | 1.02                                        |
| Natural stone (granite, rubble)  | 2800                        | 0.88                              | 3.49                                        |
| Concrete                         | 2400                        | 0.84                              | 1.86                                        |
| Brick                            | 1800                        | 0.88                              | 0.81                                        |
| Gravel                           | 800                         | 0.84                              | 0.23                                        |
| Sand                             | 1600                        | 0.84                              | 0.58                                        |
| Timber                           | 500                         | 2.3                               | 0.18                                        |

Water is characterized by the highest heat capacity among all heat accumulation materials. Different water tanks can be used for heat accumulation. The key distinctive feature of the water heat accumulator is that a big accumulator tank saves the heat longer, but the deeper water layers are heated slowly. The small tanks quickly respond to temperature change that makes possible to avoid overheat inside a
greenhouse. However, they give the accumulated heat back very quickly. Water-filled passive solar hoses were used to heat Canary greenhouses as an additional heat source [3].

One of the cheapest and accessible ways to accumulate thermal energy is to use the soil. However, the soil has a lower heat storage capacity than water. Therefore, systems of ventilators and underground air tubes are used to increase the efficiency of the soil accumulator [4, 9].

Natural and artificial stones are of high heat storage capacity and such accumulators, along with additional equipment (ventilators and air tubes) can be used as seasonal heat accumulators.

The existing studies don’t provide any methodology to choose the optimal heat accumulator in order to reduce the internal temperature fluctuations in a greenhouse.

3 Materials and methods
The purpose of this research is to determine the optimal heat accumulator to level the temperature fluctuation in a greenhouse with atmospheric effects during an early spring.

The experimental investigations of temperature and humidity were carried out in the greenhouse without any heat accumulator. The investigations were conducted in climatic conditions of Dnipro.

This experimental greenhouse is located in Dnipro (Ukraine) and it has a transparent gable roof and the following dimensions – 7.9 x 7.3 m. The height of the greenhouse is 3.1 m. The greenhouse frame is made of metal pipe profile 40 x 40 mm. Transparent material of the envelope is 8.0 mm thick polycarbonate. The general view of the experimental greenhouse is presented in Figure 1.

![Figure 1. General view of the experimental greenhouse.](image)

The continuous measurements of the temperature and humidity were carried out at a height of 0.3 m and 2.2 m above the ground inside and outside the greenhouse. The measurements were taken in the period from 23.03.2019 to 06.04.2019. The period for the study was chosen and based on the weather forecast. According to it, significant changes in the weather were expected during the measurement period – from cloudy weather with precipitation to a significant increase in temperature to +20°C.

The temperature and relative humidity measurements were performed by the digital sensors Tinytag Ultra 2 TGU-4500 (Figure 2). These sensors control temperature from −25°C to +85°C and relative humidity from 0 to 95%. Tinytag Ultra 2 sensors is usually used for internal monitoring. However, the sensor can be used for outside monitoring and is equipped with a special security screen – Stevenson screen. Software and a USB cable (CAB-0007-USB) should be used for Tinytag Explorer monitor. The full technical specification of the sensors employed is available at [https://www.geminidataloggers.com/data-loggers/tinytag-ultra-2/tgu-4500](https://www.geminidataloggers.com/data-loggers/tinytag-ultra-2/tgu-4500).
Figure 2. Tinytag Ultra 2 data logger.

The measurements were made during the established period around the clock at 1-hour interval. Changes in weather conditions (cloudiness, precipitation, wind speed and direction) were also recorded throughout the study to determine their effect on the microclimate in the greenhouse. The experimental measurements are presented in Figure 3.

Figure 3. The experimental measurements of the temperature and humidity inside and outside the greenhouse during the period from 31.03.2019 to 05.04.2019 (without a heat accumulator).

The temperature curve shows that the temperature fluctuations inside the greenhouse are from $-1^\circ C$ to $52^\circ C$ in the experimental period. The indoor air temperature in the greenhouse was reduced to a level of the outside air temperature or a few degrees below at night. The analysis of similar studies shows that the same problems often occur in ordinary greenhouses. This fact can be explained by technological space between the frame and the glazing material of the greenhouse enclosure structures. Therefore, the cold outside air gets into a greenhouse very easily and stays inside, especially when it is windy [10]. In
the daytime, the inside air temperature of a greenhouse rises to 50°C, that is far to exceed the comfortable temperature for a plant. The excess heat is usually removed from the greenhouse by ventilation, but in general, it is simply lost.

This indicates that the indoor temperature in the greenhouse does not meet the established temperature to grow plants, which is from 15...18°C (at night) to 26...30°C (in the afternoon), even in spring [11].

A thermal physical model was proposed to investigate the efficiency of the heat accumulator use in the greenhouse. The model takes into account the heat input from solar radiation $Q_3$, the heat losses through to enclosing structures $Q_2$, and the heat that was accumulated in a heat accumulator $Q_1$ (Figure 4).

![Figure 4. Thermal model of the greenhouse with a heat accumulator.](image)

The heat balance equation for the greenhouse with the accumulator reads:

$$\Delta Q_{gr} = Q_1 - Q_3 - Q_2,$$

where $\Delta Q_{gr}$ is the heat increment into the greenhouse, W.

The heat accumulated by the heat accumulator is:

$$Q_1 = \alpha_A \left( T_{inside} - T_A \right) \cdot F_A,$$

where $\alpha_A$ is the heat transfer coefficient on the accumulator surface, $W / (m^2 \cdot K)$; $T_{inside}$ is the indoor temperature in the greenhouse, °C; $T_A$ is the accumulator temperature, °C; $F_A$ is the surface area of the accumulator, $m^2$.

The heat losses through the enclosing structures are:

$$Q_2 = \frac{1}{R} \left( T_{inside} - T_{outside} \right) \cdot F_{gr},$$

where $R$ is the heat transfer resistance of the greenhouse enclosing structures, $m^2 \cdot K / W$; $T_{outside}$ is the outdoor air temperature, °C; $F_{gr}$ is the area of the greenhouse envelope constructions, $m^2$.

The heat input from solar radiation depends on the time and surface orientation:

$$Q_3 = Q_3(\tau).$$

For this model of the greenhouse, the accumulator temperature $T_A$, the indoor $T_{inside}$ and the outdoor $T_{outside}$ temperatures are considered as time-dependent functions:
\[
T_A = T_A(\tau),
\]
(5)
\[
T_{\text{inside}} = T_{\text{inside}}(\tau),
\]
(6)
\[
T_{\text{outside}} = T_{\text{outside}}(\tau).
\]
(7)

The dependence (7) of the outdoor air temperature on time is numerically determined according to the experimental data. Hence, there are two unknown functions: the indoor air temperature \(T_{\text{inside}}\) and the accumulator temperature \(T_A\).

The heat balance equation for the indoor air can be written as follows:
\[
c_p V_g T_{\text{inside}} = \Delta Q_g d\tau,
\]
(8)
and the heat balance equation of the accumulator is:
\[
c_A m_A dT_A = \alpha_A F_A (T_{\text{inside}} - T_A) d\tau,
\]
(9)
where \(c\) is the heat capacity of the air, \(J/(kg \cdot K)\); \(\rho\) is the air density, \(kg/m^3\); \(V_g\) is the internal volume of the greenhouse, \(m^3\); \(c_A\) is the heat of the heat accumulator, \(J/(kg \cdot K)\); \(m_A\) is the mass of the heat accumulator, \(kg\).

Substituting expressions (2)–(8) into equation (1) and rewriting equation (9), we obtain the system of two coupled differential equations, which allows us evaluating the unknown functions \(T_{\text{inside}}(\tau), T_A(\tau)\):
\[
\frac{dT_{\text{inside}}}{d\tau} = \frac{1}{c_p V_g} \left[ Q_A(\tau) - \alpha_A F_A \left( T_{\text{inside}}(\tau) - T_A(\tau) \right) \right] - \frac{F_g}{R} \left[ T_{\text{inside}}(\tau) - T_{\text{outside}}(\tau) \right],
\]
(10)
\[
\frac{dT_A}{d\tau} = \frac{\alpha_A F_A}{c_A m_A} \left[ T_{\text{inside}}(\tau) - T_A(\tau) \right].
\]
(11)

Equations (10), (11) describe the dependencies between the parameters of the accumulator (i.e., the volume and the surface area) and the fluctuations of the indoor temperature. These dependencies cannot be expressed explicitly in the analytical form, because the functions \(T_{\text{inside}}(\tau)\) and \(Q_A(\tau)\) are determined by the experimental data and, therefore, are purely non-linear. Meanwhile, these dependencies are revealed by the developed numerical solution. System (10), (11) were integrated numerically by the Euler method. The calculations were performed for the 5 days period with the 1 minute integration step, which provides a good convergence of the procedure. The software implementation was developed in the open-source computer algebra system Maxima.

4. Results

The calculation of the internal temperature change in the greenhouse without taking into account the heat accumulator was performed to verify the greenhouse mathematical model. The comparison of experimental and calculated data are presented in Figure 5.
Having analyzed the graphs, it is possible to conclude that the calculation results are in a good agreement with the experimental data. It confirms the accuracy of the greenhouse mathematical model which was proposed.

The calculations of the temperature change of the heat accumulator and the internal temperature in the greenhouse were worked out to determine the optimal parameters of the heat accumulator for the experimental greenhouse by the mathematical model which was proposed. The water tanks were used as the heat accumulators. Initial heat accumulator temperature for calculation was taken as $T_A = 10^\circ C$.

The calculation results of the heat accumulator temperature changes and the internal temperature in the greenhouse during five days were shown in Figure 6. The calculations were carried out for the heat accumulator with the volume of $V_A = 3\ m^3$ and the accumulator surface area of $F_A = 32.1\ m^2$, which is like fifteen 200-liter water tanks.

The graphs show that the interval of temperature change is decreased. The night temperature was reduced to $8^\circ C$, and the day temperature was increased to almost $35^\circ C$, which isn't suitable for plants. When we increased the volume of the heat accumulator to $V_A = 4\ m^3$ and the accumulator surface area to $F_A = 42.8\ m^2$ (it corresponds to twenty 200-liter water tanks), the interval of temperature change...
didn’t almost change (Figure 7). The temperature dropped to 10°C during the night and rose to 32°C in the daytime. This temperature range is not also friendly and appropriate for plants.

Figure 7. Temperature change of the heat accumulator and the internal temperature in the greenhouse during five days for the heat accumulator with volume of 4 m³ and the accumulator surface area of 42.8 m²: left – internal temperature in greenhouse; right – temperature of the accumulator.

Moreover, it can be concluded that in case of a higher accumulator volume, it is not possible to get necessary results anyway.

The following calculations were conducted for a flat-shaped heat accumulator. The volume of the accumulator adopted was $V_A = 4 \text{ m}^3$, the accumulator surface area was $F_A = 200 \text{ m}^2$. The calculation results were shown in Figure 8.

Figure 8. Temperature change of the heat accumulator and the internal temperature in the greenhouse during five days for the heat accumulator with the volume of 4 m³ and the accumulator surface area of 200 m²: left – internal temperature in greenhouse; right – temperature of the accumulator.

The graph shows that the internal temperature range in the greenhouse was from 14°C to 26°C, which is optimal for the growth of plants.
5. Conclusions
The optimal daily heat accumulator to support the necessary temperature in the greenhouse was determined by the proposed mathematical model for an early spring.

Dependences between the accumulator volume and the accumulator surface and its efficiency were identified. The efficiency of the heat accumulator increases when we extend the accumulator surface area with the same volume accumulator.

The proposed mathematical model of the greenhouse allows determining the optimal volume and dimensions of the daily heat accumulator for any greenhouse. Let us also note that the particular design and the shape of the accumulator may depend on a number of technological factors, e.g., on the internal planning of the greenhouse, types of plants, a space available, etc. The problem of the design of the accumulator may be a topic for a further research.

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