Some Aspects of the Analysis during Heating Plastic Tunnel by the Use of Heat from Stone Accumulator

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Abstract: The paper presents the results of research which showed the energy effects when used in foil tunnel heat accumulator. The study was conducted in two tunnels (with and without heat accumulator) and two cycles of growing cucumbers, i.e., in the cultivation of spring and autumn. The heat accumulator is divided into three segments of varying capacity coal deposits (porphyry-type stones). During the test crops (cucumbers) measured parameters associated with the surrounding climate, microclimate parameters inside the building and parameters of the injected and flowing out air from the accumulator have been monitored and archived by a computer system. The intensity of solar radiation, the technology of cultivation and cultivated species of plants were the same in both the tunnel with heat accumulator as well as the control object. On the basis of the balance of behavior, the heat and mass are described occurring processes related to the exchange of air during ventilation facility. The resulting effects were converted into differences in heat demand between the tunnel and the tunnel with an accumulator of heat. It was found that despite the increase ventilation in adopted arbitrary surface of the foil tunnel, the scope of changes in the amount of heat saved in one of the cultivation is in the range from 0.0015 GJ to over 1.4 GJ of heat.

Key words: Stone accumulator, storage, heat, foil tunnel.

1. Introduction

Greenhouses productions (greenhouses, foil tunnels) are sought as a variety of technical solutions that will reduce production costs and create the parameters of the microclimate inside the building acceptable for plants. Maintaining optimal values of microclimate parameters (including the reduction of air humidity) lead to the improvement of the health of crops and consequently reducing the use of chemicals for reducing fungal diseases and are accomplished through intensive ventilation and forced air flow around the plants. The issue of ventilation intensity depends on the configuration ventilators and analysis of its impact on indoor air humidity thus the life processes of plants grown in the greenhouse and energy consumption have been studied among others [1-3]. The authors concluded that the change of humidity (water VPD (vapor pressure deficit)) influences of ventilators distribution and the control algorithm of their position. Too low VPD can reduce the growth of plants, while too high of the value (above the dew point) results in condensation of water vapor on the leaves which can lead to the appearance of disease. In addition to the environmental effects associated with controlled humidity, another important factor limiting the cost of production is thermal management at the facility. As a result of use of the greenhouse cover material transparent to solar radiation, there are periods inside the object, where there is the air temperature significantly exceeding the requirements of the plants. At this time, there is therefore a potential opportunities of heat development among others through storage. Problems of heat storage were also analyzed in different research centers. For example, Berruga et al. [4], on
Some Aspects of the Analysis during Heating Plastic Tunnel by the Use of Heat from Stone Accumulator

one of the walls of the greenhouse, put material PCM (phase change material), which was used for the heat storage in a passive system. The considered system formulated the mathematical model of heat storage process and has tagged effects of heat and humidity change in the air inside the building. Attar et al. [5] conducted experimental and simulation experiments to assess the effects of heat using solar energy for greenhouse heating using ground heat exchanger fed with hot water from solar collectors. Xu and Wang [6] presented construction solutions for long-term storage of heat energy in the accumulators at the same time presenting the physic-chemical characteristics of the materials used in accumulators (both using chemical reactions and sensible heat) and the recommended system configuration. Broad overview of the construction solutions with the received effects obtained in heating greenhouses with heat storage systems presented Sethi et al. [7]. Kurpaska and Latala [8] analyzed the storage of surplus heat from the interior of laboratory foil tunnel in two accumulators (soil and water). Specified daily amount of stored heat, and set out the conditions for which the heat stored in the accumulator soil sufficient to cover the daily demand of heat through the test object. Ghosal and Tiwari [9] developed a mathematical model describing the changes in air temperature and solar radiation inside the greenhouse to greenhouse in which installed the heat screens and heating cables supplied with geothermal water.

The subject analyzed in the study is surplus heat storage system in a bed of accumulator stone. The reasons to apply for financial means for this project resulted directly from the physical basis of such a system work. It is generally known that as a result of the forced air flow inside the greenhouse, it is possible to reduce the intensity of such a ventilation object. In turn, reduced ventilation in the object leads directly to savings in the consumption of heat in the greenhouse facility. The idea of such a system work is based on injecting during the period of excess, heat into the bed of accumulator warm air (battery charging cycle), and providing hot air from the accumulator to the interior of the object during the periods of accumulator energy needs. Storage of heat (as a result of conversion of solar energy) can be implemented in various systems, including in an accumulators filled a bed stones. Summary of the work of this system is forcing the humid air (obtained from the inside of the object) through the porous structure of the bed, which in turn leads to occurrence two extensive processes: a heat exchange and mass exchange. The analysis of this system will be the main objective of the present work.

2. Material and Method

The study was carried out in two foil tunnels (cultivation surface area of 270 m² and 135 m²), in which, one was the control object, in the second there is installed an accumulator stone. In both tunnels on the ballots filled with coconut fiber were grown cucumbers in greenhouses with an average cast of 1.54 piece·m⁻². Fig. 1 shows a schematic of the tunnel with the installed accumulator stone. In the tunnel with the accumulator, was used 3-segment accumulator heat of dimensions: one segment 11 m to 3.5 m and two segments 11 m to 1.7 m. The accumulator filled with a bed of stones (porphyry) has a height of 0.7 m. The idea of the work of such a system lies in the suction of warm air from the inside of the object using a perforated cable and then pumping in it to the battery through the perforated cables arranged at the bottom of the bed. The warm air after passing through the porous structure of the bed reduces the enthalpy in favor of its temperature rise of the bed. The air with modified enthalpy flow through the structure of the bed and then through conduits receiving air (Fig. 1) through the common rail is supplied to the inside of an object. Air flow direction control is performed by varying the position of the electrovalve (EZ₁). Installed in the collector supply electrovalves (EZ₂, EZ₃ and EZ₄) would control the flow of air into the individual segments of the bed. Location dampers in
Some Aspects of the Analysis during Heating Plastic Tunnel by the Use of Heat from Stone Accumulator

Fig. 1  Schematic foil tunnel with battery stone. \( t_{in}, t_{out} \)—inside/outside temperature; \( RH_{in}, RH_{out} \)—inside/outside relative humidity; \( V_{wind} \)—wind speed; \( R_{out} \)—solar radiation; \( q_{in}, q_{out} \)—stream of heat; \( t_{ent} \)—temperature of the air forced into the accumulator; \( RH_{ent} \)—relative humidity of air forced into the accumulator; \( V_{air} \)—speed of air injected into the accumulator.

electrovalves were automatically controlled by a proprietary algorithm that was implemented on a PC (personal computer). To ensure a uniform air flow through the bed, the system uses a centrifugal fan (marked with the W symbol in Fig. 1).

While performing experiments, both tunnels were equipped with computers climatic parameters that regulate the parameters of microclimate inside the object (temperature and RH (relative humidity)).

In the course of the experiments, monitored parameters were associated with the:

- ambient climate parameters (solar radiation, air temperature and humidity and wind speed);
- speed and air temperature pumped and discharged from the bed accumulator;
- the temperature and humidity inside the tunnel;

The measurement of the measured parameters used is as the following devices: the intensity of solar radiation—pyranometer LP PYRA 02; air temperature—resistance sensors PT1000; relative humidity—sensor with capacitive sensor HD49; wind speed—anemometer MAX40; air flow rate—the meter Mini Air64.

The study was measured by leaf area and the daily media consumption by grown tomatoes.

The Theoretical Analysis

In both objects for the differential time \( dq_{c,acc} \) elementary unitary heat fluxes describes the relationship:

\[
dq_{c,acc} = dq_{str} + dq_{vent} + dq_{TR} \tag{1}
\]

while the differential mass balance as the:

(a) tunnel control:

\[
V \cdot dC_{in-c} = \frac{d\Phi (C_{in} - C_{out}) + dq_{m-TR}}{F} \tag{2}
\]

(b) tunnel with accumulator:

\[
V \cdot dC_{in-acc} = \frac{d\Phi (C_{in} - C_{out}) + dq_{m-TR} \pm dq_{m,acc}}{F} \tag{4}
\]

where, the various symbols mean: \( q_{str} \)—stream of heat loss, W·m\(^{-2}\); \( v_{ent} \)—stream of ventilation, W·m\(^{-2}\); \( q_{TR} \)—heat flux used in the process of transpiration,
Some Aspects of the Analysis during Heating Plastic Tunnel by the Use of Heat from Stone Accumulator

157

W·m^{-2}; \Phi—stream of air exchanged between the interior of the object and the environment in the process of ventilation, m^{3}\cdot s^{-1}; \rho_a—air density, kg·m^{-3}; C_{in}, C_{out}—concentration of water vapor in the air inside (C_{in}) and outside (C_{out}) of the object, kg·m^{-3}; q_{m.TR}—stream of plant transpiration, kg·s^{-1}; q_{m.acc}—mass flow in the process of replacing the air flow through the accumulator, kg·s^{-1}; F—surface of the tunnel, m^{2}.

The resulting energy effects (Q) in each cycle was calculated from Eq. (5):

\[ Q_{c.acc} = F \cdot \int_{0}^{\tau} (q_{e} - q_{e}) d\tau \]  

(5)

where, \( \tau \) means the duration of the cycle, s.

All the necessary calculation related to the change of air thermodynamic state (pumped and discharged) from the bed was performed using standard psychometric dependence. The experiments measured the geometric parameters and the number of leaves, and the surface was calculated using the formula developed by Medrano, et al. [10] were monitored daily consumption of the medium, and the intensity of transpiration was calculated from the formula published in Blanco and Folegatti [11].

3. Results and Discussion

The study was conducted in objects in two cycles of growing cucumbers, namely: the cultivation of spring (from April 15, 2013 to August 6, 2013) and in the cultivation of autumn (from August 15, 2013 to October 15, 2013). All parameters were measured every 120 s, and a detailed analysis of the average values was performed for a further 5-IU measurements. The authors analyzed a total of 6,750 cycles of charge and nearly 9,880 cycles of discharge of the accumulator. Tables 1-4 show the extent of changes in the factors of experience (depending on the time of cultivation and cycle of the accumulator).

It can be seen that in object with the accumulator, there is the higher air humidity, which results in lower values of the water vapor deficit (VPD). The average value of VPD was: 1.33 for the control tunnel, and the tunnel with accumulator 1.27 kPa. In turn, the mean value of air temperature in the control tunnel reached 29.6, while in the tunnel with accumulator 25.9 °C. Statistical analysis (using the Student’s t test) showed that in both objects, these differences are statistically significant. Average charge time in the cultivation of spring was 7.9, while in the autumn cultivation 4.9 h.

### Table 1  Factors experience (spring cultivation) in accumulator charge.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min/max</th>
<th>( t_{\text{out}} ) (°C)</th>
<th>( RH_{\text{out}} ) (%)</th>
<th>( R_{\text{out}} ) (W·m^{-2})</th>
<th>( t_{\text{in}} ) (°C)</th>
<th>( RH_{\text{in}} ) (%)</th>
<th>LAI (m²·m⁻²)</th>
<th>TR (g·s⁻¹·tunnel⁻¹)</th>
<th>Cycle time (h)</th>
<th>VPD (kPa)</th>
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</thead>
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<tr>
<td>Control</td>
<td>6.3</td>
<td>39.5</td>
<td>0</td>
<td>15.7</td>
<td>14.3</td>
<td>0.09</td>
<td>0.73</td>
<td>-</td>
<td>0.05</td>
<td></td>
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<tr>
<td>Storage</td>
<td>39.5</td>
<td>99.0</td>
<td>895</td>
<td>17.1</td>
<td>20.1</td>
<td>0.07</td>
<td>0.04</td>
<td>0.5</td>
<td>0.13</td>
<td></td>
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<tr>
<td>Control</td>
<td>4.15</td>
<td>20.2</td>
<td>77.1</td>
<td>12.1</td>
<td>35.1</td>
<td>0.05</td>
<td>0.11</td>
<td>0.2</td>
<td>0.05</td>
<td>0.04</td>
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<tr>
<td>Storage</td>
<td>29.1</td>
<td>97.1</td>
<td>773</td>
<td>28.1</td>
<td>97.9</td>
<td>1.39</td>
<td>9.60</td>
<td>12.4</td>
<td>1.90</td>
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</tbody>
</table>

### Table 2  Factors experience (autumn cultivation) in accumulator charge.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min/max</th>
<th>( t_{\text{out}} ) (°C)</th>
<th>( RH_{\text{out}} ) (%)</th>
<th>( R_{\text{out}} ) (W·m^{-2})</th>
<th>( t_{\text{in}} ) (°C)</th>
<th>( RH_{\text{in}} ) (%)</th>
<th>LAI (m²·m⁻²)</th>
<th>TR (g·s⁻¹·tunnel⁻¹)</th>
<th>Cycle time (h)</th>
<th>VPD (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7.0</td>
<td>23.1</td>
<td>0</td>
<td>12.2</td>
<td>35.6</td>
<td>0.06</td>
<td>0.20</td>
<td>-</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>29.1</td>
<td>97.1</td>
<td>773</td>
<td>28.1</td>
<td>97.9</td>
<td>1.39</td>
<td>9.60</td>
<td>12.4</td>
<td>1.90</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3  Factors experience (spring cultivation) in a discharging accumulator.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min/max</th>
<th>( t_{\text{out}} ) (°C)</th>
<th>( RH_{\text{out}} ) (%)</th>
<th>( R_{\text{out}} ) (W·m^{-2})</th>
<th>( t_{\text{in}} ) (°C)</th>
<th>( RH_{\text{in}} ) (%)</th>
<th>LAI (m²·m⁻²)</th>
<th>TR (g·s⁻¹·tunnel⁻¹)</th>
<th>Cycle time (h)</th>
<th>VPD (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.15</td>
<td>56.9</td>
<td>0</td>
<td>8.4</td>
<td>77.1</td>
<td>0.05</td>
<td>0.007</td>
<td>-</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>20.25</td>
<td>99.00</td>
<td>230</td>
<td>20.2</td>
<td>96.1</td>
<td>2.17</td>
<td>9.800</td>
<td>20.1</td>
<td>0.520</td>
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Some Aspects of the Analysis during Heating Plastic Tunnel by the Use of Heat from Stone Accumulator

Table 4  Factors experience (autumn cultivation) in a discharging accumulator.

<table>
<thead>
<tr>
<th>Parameters:</th>
<th>Min/max</th>
<th>$t_{\text{out}}$ (°C)</th>
<th>RH$_{\text{out}}$ (%)</th>
<th>$R_{\text{out}}$ (W·m$^{-2}$)</th>
<th>$t_{\text{in}}$ (°C)</th>
<th>RH$_{\text{in}}$ (%)</th>
<th>LAI (m$^{-2}$·m$^{-2}$)</th>
<th>TR (g·s$^{-1}$·tunnel$^{-1}$)</th>
<th>Cycle time (h)</th>
<th>Vpd (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>0.98 70.4 0.0</td>
<td>7.0 84.0 0.06</td>
<td>17.7 99.0 1.78</td>
<td>19.5 97.4 1.39</td>
<td>7.0 84.0 0.06</td>
<td>17.7 99.0 1.78</td>
<td>19.5 97.4 1.39</td>
<td>7.0 84.0 0.06</td>
<td>17.7 99.0 1.78</td>
</tr>
<tr>
<td>Storage</td>
<td>16.60 98.3 62.2</td>
<td>7.7 86.4 0.05</td>
<td>19.5 97.4 1.39</td>
<td>19.5 97.4 1.39</td>
<td>7.0 84.0 0.06</td>
<td>17.7 99.0 1.78</td>
<td>17.7 99.0 1.78</td>
<td>17.7 99.0 1.78</td>
<td>17.7 99.0 1.78</td>
<td>17.7 99.0 1.78</td>
</tr>
</tbody>
</table>

where, $t_{\text{out}}$—outside temperature, °C; RH$_{\text{out}}$—outside relative humidity of air, %; $R_{\text{out}}$—intensity of sunshine radiation, W·m$^{-2}$; LAI—leaf area index of cultivated plants, [m$^2$·m$^{-2}$]; TR—transpiration of cultivated plants, g·s$^{-1}$·tunnel$^{-1}$; Cycle—time of running system, s; VPD—vapour pressure deficit inside the foil tunnel, kPa.

Average duration of the discharge in the cultivation of spring was 13.2 h, while in the autumn cultivation 9.8 h. Statistical analysis also showed that both the indoor temperature and VPD were statistically different when performing experiments. At the same time, it can be observed that in the object with accumulator there is higher humidity.

Changing the concentration of water vapor in the control object as well as in the heat accumulator was resulted from the air humidification processes (in the process of discharge of the accumulator) and drying (while charging). This is a consequence of processes (evaporation/condensation) occurring at the interface: the flowing air-bed of accumulator.

Figs. 2 and 3 show the average flow of replacement air during the ventilation process (based on unit area of the tunnel) during the battery discharge cycle of the control tunnel (Fig. 2) and heat accumulator (Fig. 3). The calculations were performed for each day performing experiments—both for the cultivation of spring and autumn.

As can be seen in the control object, the range of changes in the amount of air exchanged is in the range from 0.6 m$^3$·m$^{-2}$·h$^{-1}$ to 76 m$^3$·m$^{-2}$·h$^{-1}$, and for the tunnel with heat accumulator from 2.3 m$^3$·m$^{-2}$·h$^{-1}$ to 107 m$^3$·m$^{-2}$·h$^{-1}$.

Much larger values of the stream necessary due to the fact that in the tunnel with the accumulator air humidification process occurs as a consequence forces of ventilators increased opening angle.

Fig. 4 illustrated the change in the reduced amount of heat by the discharge of the accumulator.

The calculations were made for the object of cultivation area equal to 135 m$^2$. It can be seen that despite the increased ventilation in the object with accumulator the amount of saved heat housed from 1.5 MJ to more than 1.4 GJ of heat.

4. Conclusions

(1) In the analyzed tunnels, the differences in air flow exchanged in the process of discharged of the accumulator (control object).
Some Aspects of the Analysis during Heating Plastic Tunnel by the Use of Heat from Stone Accumulator

Fig. 3  The stream of air exchanged in the process of discharge of the accumulator (the object with heat accumulator).

Fig. 4  Changes in the amount of heat saved in the accumulator discharge.

temperature and water vapor pressure deficit both in the charging and discharging a heat accumulator are statistically significant;

(2) The range of changes in the amount of air exchanged during the ventilation is in the range from 0.6 to 76 (control object) and from 2.3 m$^3$·m$^{-2}$·h$^{-1}$ to 107 m$^3$·m$^{-2}$·h$^{-1}$ (tunnel with the heat accumulator);

(3) The calculations performed for an object with cultivation area equal to 135 m$^2$ indicate that, as a result of the heat accumulator in the object, the amount saved in one day heat housed from 0.0015 GJ to more than 1.4 GJ of heat.

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References


Microclimate and Dehumidification Effectiveness under Different Ventilator Configurations.” *Building and Environment* 42 (10): 3774-84.


