Modeling and optimization of the parameters of the heat accumulator of the combined livestock-heliogreenhouse complex

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Abstract: In the article, the heat exchange process in the water tank battery, which acts as a wall between the livestock building and the solar greenhouse, is studied. The division consists of parallelepiped-shaped tanks, between which the coefficients of heat transfer in charge and discharge mode are determined, taking into account the different temperatures and speeds of the air in the livestock building through the air-moving corridors. A mathematical model of the temperature regime was developed based on the balance equation of the water tank accumulator. The geometric dimensions of the water tank accumulators are optimized based on the criterion equations. A computer model was created using the COMSOL Multiphysics software tool and thermal efficiencies were determined. Based on the results of the conducted research and numerical calculations, it is based on the high heat exchange and energy efficiency when the size of the water tank accumulator is 40x60x25 cm.

1 Introduction

The analysis of combined systems in world practice shows that M.Parmar received a patent for an invention called a livestock-greenhouse complex (device and method) for the northern regions of the country [1]. Livestock-heliogreenhouse complex has complex technical-technological mechanisms and disadvantages such as the fact that it is not intended to be used in hot climate conditions, and the possibility of heat accumulation is not available.

The analysis of the biological characteristics of livestock shows that depending on their total weight and age, heat, moisture, and carbon dioxide gases are released. In normal livestock buildings, in order to reduce the concentration of carbon dioxide gas in the building air, it is continuously circulated with the outside air. As a result, a large amount of heat and carbon dioxide gas is released into the atmosphere, which has a negative impact on the ecological situation. If the process of transferring the wastes of this livestock building to the helio-greenhouse through ventilation is carried out in the winter, the temperature of the heliogreenhouse will be moderated and the need for CO2 food source for plant photosynthesis will be satisfied [2-9].
By building a livestock building and a solar greenhouse side by side, the heat load of the solar greenhouse is compensated by three sources, namely, ventilation between them, solar radiation passing through the transparent surface of the greenhouse, and burning biogas obtained from livestock waste in the boiler unit and heating water. On sunny days, excess heat is transferred to the greenhouse through a water tank installed on the wall between the livestock building and the solar greenhouse, and a certain part of the heat is accumulated in the water [10-16].

2 Materials and methods

It is known that the effective use of heat accumulators plays an important role in creating a microclimate regime in the “livestock-helio-greenhouse complex”. For this purpose, the coefficient of heat transfer for different temperatures during the process of heat accumulation in the water tank accumulator was calculated and the accumulator design was developed (figure 1). The efficiency of the heat accumulator was determined according to the results of analytical and experimental research, and the process of heat accumulation was studied on this basis. Determining the optimal size characterizing the efficient operation mode of the heat accumulator requires the use of equations that represent its high-efficiency process. When calculating the volume distribution of heat in a water tank heat accumulator, the level of efficiency of heat accumulation is determined during the placement of water tanks along a flat wall and the flow of hot air through their gaps to the heliogreenhouse.

Fig.1. Cross section of the wall with the water tank accumulator

Equal half of the water tanks are placed on the side of the wall of the greenhouse and the other half on the side of the livestock building. When viewed from the vertical axis of the wall, the arrangement of the water tanks looks like a checkerboard. When the wall thickness is 450 mm and the width of the water tanks is placed with the side \( w.t. = 250 \) mm, 200 mm square section corridors for air movement are formed between the water tanks.

3 Equations and mathematics

The equivalent diameter \( (d_{w.t.,eq.}) \) of the water tank accumulator (parallelepiped) in length \( (b_{w.t.}) \) and height \( (h_{w.t.}) \) is determined using the following expression [13]:

\[
\]
The equivalent diameter of the air space \( d_{eq} \) is determined using the following expression:

\[
d_{eq} = \frac{4b_{w,t}h_{w,t}}{2(b_{w,t} + h_{w,t})} = \frac{2b_{w,t}h_{w,t}}{(b_{w,t} + h_{w,t})}
\]  

(1)

A cross-section of the water tank battery packs placed on the wall between the livestock building and the solar greenhouse (relative to the interior of the solar greenhouse) is shown in Figure 1, with their arrangement in a strip shape. A higher Reynolds number (at the same value as the air velocity) for the air that washes the water tank accumulators is estimated by a higher equivalent diameter \( d_{eq} \) of the space between the water tank stacks. According to expressions (1) and (2), we calculate the equivalent diameter \( d_{w,t,eq} \) of the water tank accumulator of different sizes and the equivalent diameter of the space between them \( d_{eq} \) and express it in table 1.

**Table 1.** Table of geometric parameters of water tank accumulator.

<table>
<thead>
<tr>
<th>No.</th>
<th>Water tank accumulator cross-sectional dimensions, mm</th>
<th>Water tank accumulator cross section equivalent diameter ( d_{w,t,eq} ), mm</th>
<th>The equivalent diameter of the space through which the air moves ( d_{eq} ), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( h_{w,t} = 300 ) mm, ( b_{w,t} = 300 ) mm</td>
<td>300</td>
<td>761</td>
</tr>
<tr>
<td>2</td>
<td>( h_{w,t} = 400 ) mm, ( b_{w,t} = 400 ) mm</td>
<td>400</td>
<td>746</td>
</tr>
<tr>
<td>3</td>
<td>( h_{w,t} = 500 ) mm, ( b_{w,t} = 500 ) mm</td>
<td>500</td>
<td>748</td>
</tr>
<tr>
<td>4</td>
<td>( h_{w,t} = 400 ) mm, ( b_{w,t} = 600 ) mm</td>
<td>480</td>
<td>794</td>
</tr>
<tr>
<td>5</td>
<td>( h_{w,t} = 500 ) mm, ( b_{w,t} = 600 ) mm</td>
<td>545</td>
<td>764</td>
</tr>
<tr>
<td>6</td>
<td>( h_{w,t} = 600 ) mm, ( b_{w,t} = 600 ) mm</td>
<td>600</td>
<td>759</td>
</tr>
</tbody>
</table>

From the graphs based on table 1 (figure 2), it can be seen that for size \( b_{w,t} = 600 \) mm, \( h_{w,t} = 400 \) mm the equivalent diameter of the air moving space \( d_{eq} = 794 \) mm is high (figure 2, a) and the Reynolds number is high in this size, and is almost the same in all other sizes (figure 2, b-picture) can be seen.
The change in physical properties during heat transfer to air-water tank accumulators can be expressed as follows by taking temperature factors into account [14]:

\[ \Theta = \frac{T_w}{T_{air}} = \frac{273 + t_w}{273 + t_{air}} \]  

(3)

In air cooling (charge) \( 0.5 \leq \Theta \leq 1 \):

\[ Nu = Nu_{air} (1.27 - 0.27\Theta) \]  

(4)

In the heating of the air (discharge) \( 1 \leq \Theta \leq 3.5 \)

\[ Nu = Nu_{air} \Theta^{-0.55} \]  

(5)

Where, \( t_w \) – temperature of water in water tank accumulators, °C; \( t_{air} \) – the temperature of the air moving through the space between the batteries, °C; \( Nu_{air} \) – is the Nusselt number in the turbulent regime for a cross-sectional set of air flow washing water tank accumulators and can be found using the following expression:

\[ Nu_{air} = 0.021 \text{Re}_{air}^{0.8} \text{Pr}_{air}^{0.43} \varepsilon_a \]  

(6)

where, \( \text{Re}_{air} = \frac{w_{air}d_{eq}}{V_{air}} \), \( \text{Pr}_{air} \) – are the Reynolds and Prandtel numbers for the air moving in the space between the accumulators, calculated by the average value of the air temperatures at the inlet and outlet of the stack; \( \varepsilon_a \) – depending on the wall thickness of the water tank accumulator size (a\_w\_t=250 mm) to the ratio of the diameter of the space
through which the air moves \( (t_{w.t}/d_{eq}) \) and the Reynolds number for the air flow, it is selected according to [13]. \( a_{w.t} / d_{eq} = 250 / 791 \approx 0,32 \) under study.

Taking into account the expressions (3), (4), (5), (6), calculate the coefficient of heat transfer by heated (cooling) air to the water tank accumulator set (in charging mode) and the coefficient of heat transfer to the air accumulated in the water tank accumulator (in discharge mode) we can write as follows [15]:

In charging mode:

\[
\alpha_{w.t.} = 0,021 \text{Re}^{0.8} \text{Pr}^{0.43} \varepsilon_a \left( 1,27 - 0,27 \frac{273 + t_w}{273 + t_{air}} \right) \frac{\lambda_{air}}{d_{eq}} \tag{7}
\]

In discharge mode:

\[
\alpha_{w.t.} = 0,021 \text{Re}^{0.8} \text{Pr}^{0.43} \varepsilon_a \left( \frac{273 + t_w}{273 + t_{air}} \right)^{-0.55} \frac{\lambda_{air}}{d_{eq}} \tag{8}
\]

When creating a moderate climate regime in the combined livestock-heliogreenhouse complex on sunny days, the hot air in the livestock building, heated due to the free flow of heat released from the livestock, is circulated to the greenhouse through the water tank accumulator placed between the walls, a certain part of the heat is accumulated (charged) in the water accumulator, in the evenings, the air in this water tank when it circulates through the space between the batteries, it serves to heat (discharge) the air. Using expressions (7) and (8), we calculate the coefficients of heat transfer from air to water and from water to air during the charge and discharge processes, respectively, and express them in figure 3.

![Figure 3](image)

**Fig. 3.** Temperature dependence of heat transfer coefficients from the air to the water tank battery (a – charge) and from the water tank battery to the air (b – discharge).

Based on the graph above, taking into account the values of the heat transfer coefficients at different speeds, we create a mathematical model of the temperature of the air at the outlet of the water tank accumulator and the temperature of the water in the water tank accumulator over time. In it, we accept the following conditions: thermal-physical properties of water and air are unchanged; since the thermal resistance of the tank battery wall is very small, the internal and external temperatures are the same; the temperature gradient of the heat accumulator does not differ much in terms of height and length, so the
temperature of the tank accumulator is the same everywhere, that is, the temperature is evenly distributed throughout the volume.

We assume that the temperature of the air entering the water tank accumulator is equal to the internal temperature of the livestock building \( t_{\text{air}(0)} = t_{\text{liv}} \). When the temperature of the greenhouse rises above 20ºC, a fan located on the wall between the livestock building and the greenhouse drives the air from the livestock building to the water tank battery pack, and from there the temperature drops to the greenhouse. The equation in the process of heat accumulation from hot air to a water tank can be expressed as follows [13]:

\[
V_{\text{air}} c_{\text{air}} \rho_{\text{air}} \frac{dt'_{\text{liv}}(\tau)}{d\tau} = c_{\text{air}} \rho_{\text{air}} L_{\text{air}} (t_{\text{liv}} - t'_{\text{liv}}(\tau)) - \alpha_{\text{w.t.}} F_{\text{w.t.}} (t_{\text{liv}} - t_{\text{w}}(\tau)) \tag{9}
\]

The equation for the process of heat transfer from the water tank accumulator to the air can be written as follows:

\[
V_{\text{air}} c_{\text{air}} \rho_{\text{air}} \frac{dt'_{\text{liv}}(\tau)}{d\tau} = -c_{\text{air}} \rho_{\text{air}} L_{\text{air}} (t_{\text{liv}} - t'_{\text{liv}}(\tau)) + \alpha_{\text{w.t.}} F_{\text{w.t.}} (t_{\text{w}}(\tau) - t_{\text{liv}}) \tag{10}
\]

The time variation of the temperature of a mass element with a water tank accumulator can be written as:

\[
(m_w c_w + m_m c_m) \frac{dt_{\text{w}}(\tau)}{d\tau} = K_{\text{w.t.}} F_{\text{w.t.}} (t_{\text{liv}} - t_{\text{w}}(\tau)) \tag{11}
\]

where, \( V_{\text{air}} = \delta_{\text{wall}} h_{\text{wall}} - V_{\text{com.w.t.}} = 0.45 \cdot 12 \cdot 2.6 - 2.88 = 11.16 \text{m}^3 \) – the size of the space through which the air moves, \( m^3 \); \( c_{\text{air}} \) – specific heat capacity of air, \( J/(\text{kg} \cdot ^\circ\text{C}) \); \( \rho_{\text{air}} \) – air density, \( \text{kg}/\text{m}^3 \); \( t_{\text{liv}}, t'_{\text{liv}}(\tau) \) – the temperature of the air entering (the temperature of the air in the livestock building) and the air leaving the water tank accumulator, \(^\circ\text{C} \); \( L_{\text{air}} \) – volumetric consumption of air supplied to the water tank accumulator, \( \text{m}^3/\text{s} \); \( \alpha_{\text{w.t.}} \) – coefficient of heat transfer from the air to the water tank battery (charge) or from the water tank battery to the air (discharge), \( W/(\text{m}^2 \cdot ^\circ\text{C}) \); \( F_{\text{w.t.}} \) – common surface through which air washes water tank accumulators, \( m^2 \); \( t_{\text{w}}(\tau) \) – temperature of water tank accumulators, \(^\circ\text{C} \); \( m_w, m_m \) – mass of water and tank accumulator material, respectively, \( \text{kg} \); \( c_w, c_m \) – the specific heat capacity of water and tank accumulator material, respectively, \( J/(\text{kg} \cdot ^\circ\text{C}) \); \( K_{\text{w.t.}} \) – air-to-water or water-to-air heat transfer coefficient, \( W/(\text{m}^2 \cdot ^\circ\text{C}) \).

We convert the differential equations (9), (10), (11) into the canonical form and use Euler’s “first-order linear differential equations” method to solve them [15]:

In heat accumulation mode:
In the mode of heat transfer to the air:

\[
\frac{dt'_\text{liv}}{d\tau} = -\frac{L_{\text{air}}}{V_{\text{air}}} t'_\text{sup}(\tau) + \frac{\alpha_{\text{w,t}} F_{\text{w,t}}}{V_{\text{air}} c_{\text{air}} \rho_{\text{air}}} t_w(\tau) + \frac{c_{\text{air}} \rho_{\text{air}} L_{\text{air}} - \alpha_{\text{w,t}} F_{\text{w,t}} t_{\text{liv}}}{V_{\text{air}} c_{\text{air}} \rho_{\text{air}}} t_{\text{liv}}.
\] (12)

For tank battery:

\[
\frac{dt_w}{d\tau} = -\frac{K_{\text{w,t}} F_{\text{w,t}}}{(m_w c_w + m_m c_m)} t_w(\tau) + \frac{K_{\text{w,t}} F_{\text{w,t}} t_{\text{liv}}}{(m_w c_w + m_m c_m)}
\] (14)

We find the solution of the differential equation (14) and put it in expressions (12), (13). In this case, we consider the temperature of the air supplied from the livestock building to the solar greenhouse as constant. But in the following paragraphs, this change is taken into account when studying the general temperature regime of the “livestock heliogreenhouse complex”. The solution of equation (14) can be expressed as follows:

\[
t_w(\tau) = C \times e^{-\frac{K_{\text{w,t}} F_{\text{w,t}} \tau}{(m_w c_w + m_m c_m)}} + t_{\text{liv}}.
\] (15)

Where: \(C\) is a fixed number, and since \(\tau = 0\), \(t_w(0) = t_{w(0)}\) is \(C = t_{w(0)} - t_{\text{liv}}\). Based on the condition, we express the expression (15) as follows:

\[
t_w(\tau) = \frac{t_{w(0)} - t_{\text{liv}}}{\exp(-\frac{K_{\text{w,t}} F_{\text{w,t}} \tau}{(m_w c_w + m_m c_m)})} + t_{\text{liv}}
\] (16)

Substituting the expression (16) into the differential equation (12), we find the temperature change of the air coming out of the water tank accumulator in the charging mode:

\[
t'_\text{liv}(\tau) = C \times \exp(-\frac{L_{\text{air}}}{V_{\text{air}}} \tau) + \frac{\alpha_{\text{w,t}} F_{\text{w,t}} (t_{w(0)} - t_{\text{liv}})}{c_{\text{air}} \rho_{\text{air}} L_{\text{air}}} \exp(-\frac{K_{\text{w,t}} F_{\text{w,t}} \tau}{(m_w c_w + m_m c_m)}) + t_{\text{liv}}.
\] (17)

Based on condition \(\tau = 0\), \(t'_\text{liv}(0) = t_{\text{liv}}\), we express the constant number \(C\) as follows:

\[
C = \frac{\alpha_{\text{w,t}} F_{\text{w,t}} (t_{\text{liv}} - t_{w(0)})}{c_{\text{air}} \rho_{\text{air}} L_{\text{air}}}
\] (18)
Substituting the value in expression (18) into expression (17), we create the equation of time variation of the temperature of the cooling air from the tank accumulator:

\[ t'_{\text{liv.}}(\tau) = \frac{\alpha_{w,t} F_{w,t} (t_{\text{liv}} - t_{\text{w}(0)})}{c_{\text{air}} \rho_{\text{air}} L_{\text{air}}} \left( \exp \left( - \frac{K_{w,t} F_{w,t}}{(m_w c_w + m_m c_m)} \tau \right) - \exp \left( - \frac{L_{\text{air}}}{V_{\text{air}}} \right) \right) + t_{\text{liv.}}. \tag{19} \]

Substituting the expression (16) into the differential equation (13), we find the temperature change of the air leaving the water tank accumulator in the discharge mode:

\[ t'_{\text{liv.}}(\tau) = C \times \exp \left( - \frac{L_{\text{air}}}{V_{\text{air}}} \tau \right) + \frac{\alpha_{w,t} F_{w,t} (t_{\text{w}(0)} - t_{\text{liv}})}{c_{\text{air}} \rho_{\text{air}} L_{\text{air}}} \left( \exp \left( - \frac{K_{w,t} F_{w,t}}{(m_w c_w + m_m c_m)} \tau \right) - t_{\text{liv}} \right). \tag{20} \]

Based on condition \( \tau = 0, \ t'_{\text{liv.}}(0) = t_{\text{liv.}} \), we express the constant number \( C \) as follows:

\[ C = 2t_{\text{liv.}} - \frac{\alpha_{w,t} F_{w,t} (t_{\text{w}(0)} - t_{\text{liv}})}{c_{\text{air}} \rho_{\text{air}} L_{\text{air}}}. \tag{21} \]

(21) putting the value in the expression (20) into the expression, we create the equation of time variation of the temperature of the air heated from the tank accumulator:

\[ t'_{\text{liv.}}(\tau) = \frac{\alpha_{w,t} F_{w,t} (t_{\text{w}(0)} - t_{\text{liv}})}{c_{\text{air}} \rho_{\text{air}} L_{\text{air}}} \left( \exp \left( - \frac{K_{w,t} F_{w,t}}{(m_w c_w + m_m c_m)} \tau \right) - \exp \left( - \frac{L_{\text{air}}}{V_{\text{air}}} \right) \right) + t_{\text{liv.}} \left( 2 \exp \left( - \frac{L_{\text{air}}}{V_{\text{air}}} \right) - 1 \right). \tag{22} \]

We make a calculation table for parameters in equations (12), (13), (14) (table 2) and construct a block diagram of these differential equations in the MATLAB/Simulink package (figure 4).

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameters</th>
<th>Designation</th>
<th>Unit of measure</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The size of the air space</td>
<td>( V_{\text{air}} )</td>
<td>m³</td>
<td>11.16</td>
</tr>
<tr>
<td>2</td>
<td>Specific heat capacity of air</td>
<td>( c_{\text{air}} )</td>
<td>J / (kg°C)</td>
<td>1005</td>
</tr>
<tr>
<td>3</td>
<td>Air density</td>
<td>( \rho_{\text{air}} )</td>
<td>kg / m³</td>
<td>1.29</td>
</tr>
<tr>
<td>4</td>
<td>The temperature of the air entering the water tank accumulator from the livestock building</td>
<td>( t_{\text{liv.}} )</td>
<td>°C</td>
<td>Charging: 20 ± 35 Discharge: 5 ± 10</td>
</tr>
<tr>
<td>5</td>
<td>Coefficient of heat transfer by air to the water tank accumulator</td>
<td>( \alpha_{w,t} )</td>
<td>W / (m²°C)</td>
<td>7.5</td>
</tr>
<tr>
<td>6</td>
<td>The common surface of the water tank through which air washes the batteries</td>
<td>( F_{w,t} )</td>
<td>m²</td>
<td>52.8</td>
</tr>
<tr>
<td></td>
<td>Mass of water</td>
<td></td>
<td>Metal mass</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---------------</td>
<td>---</td>
<td>------------</td>
<td>---</td>
</tr>
<tr>
<td>7</td>
<td>$m_w$ kg</td>
<td>8</td>
<td>$m_m$ kg</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>2880</td>
<td>8</td>
<td>625</td>
<td>9</td>
</tr>
</tbody>
</table>

**Fig. 4.** Block diagram of the mathematical model in the MATLAB/Simulink package.

Through this block diagram, we represent the temperature of the air coming out of the water tank accumulator $t'_{liv}$ and the graph of the change of water temperature over time in figure 5.

**Fig.5.** Time variation of air and water temperatures passing from the livestock building to the heliogreenhouse through the water tank accumulator. a) theoretical; b) experience.
When the air temperature in the “livestock-heliogreenhouse complex” is above 25 °C, as a result of air circulation through the water tank accumulators (charge), the air temperature can be reduced to 2-3 °C, and the temperature of the water in the tank accumulator can be increased to 17 °C. 84.47 MJ of heat can be accumulated in water in charging mode.

A computer model was created using the COMSOL Multiphysics software tool to conduct theoretical studies on heat transfer in a water tank accumulator. When the temperature of the air moving through the space between the wall of the water tank accumulator is 25 ºС, a number of studies were carried out on different sizes of the tank accumulator and it was found that the heat exchange is high in the capacity of 40x60x25 cm (figure6).

**Fig. 6.** Temperature field of the water tank battery in charging mode.

The following relative form of the energy efficiency coefficient was used in the comparison of heat exchange devices with a water tank accumulator [14]:

\[
E = \frac{Q}{A} = \frac{\pi d^2 \rho_{air} c_{air} (t_{liv} - t_{liv}^{'}) \tau_{charger}}{4c_{w} m_{w} (t_{w}^{' - t_{w}(0)})}
\]  

(23)

Where: \( \tau_{charger} \) – charging mode time, \( c \); \( t_{liv}^{'}, t_{w}^{'} \) – temperatures of air and heated water at the outlet of the water tank accumulators, °C.

(23) if \( E > 1 \) according to the expression, the water tank accumulator is considered effective, and the rational geometric parameters are determined from \( E = \max \) conditions. Figure 7 shows the parallelepiped-shaped tank accumulator of different sizes and the thermal efficiency according to the speed of the air moving between them.

**Fig. 7.** Thermal efficiencies of water tank accumulators.
As can be seen from figure 7, the rational geometric parameters of the water tank accumulator correspond to the capacity of 40x60x25 cm.

4 Conclusions

As a result of the mathematical calculations and experimental studies carried out on the study of unstable heat exchange processes in the “Livestock-heliogreenhouse complex” and the modeling and optimization of parameters of the heat accumulator of the combined livestock-heliogreenhouse complex, the following conclusion was reached.

Accumulation of heat makes it possible to achieve an effective result when creating a microclimate regime in the “Livestock-heliogreenhouse complex”. For this purpose, the construction of the water tank accumulator was developed and the heat transfer coefficient during the heat accumulation process in different temperature environments was calculated;

Taking into account the values of the heat transfer coefficients at different speeds, a mathematical model of the temperature of the air leaving the water tank-accumulator and the change of the water temperature in the water tank-accumulator over time was created.

When the air temperature in the “Livestock-heliogreenhouse complex” is above 25°C, it was found that 84.47 MJ of heat can be accumulated in water as a result of air circulation through water tank accumulators.

A computer model was developed using the COMSOL Multiphysics software tool to conduct theoretical research on heat exchange in the water tank accumulator when the temperature of the air moving through the space between the battery wall was 25°C, numerous studies were conducted on different sizes of the tank accumulator, and it was determined that the energy efficiency is high in the capacity of 40x60x25 cm.

References

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