Mathematical modeling of greenhouse-livestock complex heated by solar and bioenergy sources

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Abstract. The article develops a mathematical model of the heat supply system of the greenhouse complex, taking into account the free heat flow in the animals, solar energy, heat energy stored in heat accumulators and developed through the program MATLAB / Simulink.

In the development of a mathematical model of the heat supply system of the greenhouse complex, a block diagram of the equation in the program MATLAB / Simulink was developed, without taking into account the change in air density and specific heat capacity with temperature. According to the graphic results obtained for the daily value of solar radiation 500 W/m², outside air temperature, -6 °C in Karshi, the air temperature inside the greenhouse rises to 22 °C, water tank battery temperature to 13 °C, underground heat accumulator temperature to 17 °C. can be seen. while the amount of total solar radiation was 300 W/m², this figure was found to be 14 °C, 9 °C, and 12 °C.

1. Introduction

The strategic directions of energy development in the Republic of Uzbekistan provide for the widespread use of non-traditional energy sources, including the energy of organic animal biomass. Calculations show that when processing organic biomass into biological gas, 4.2 times more energy can be produced annually than is produced at power plants in the Republic of Uzbekistan. Closely related to the problem of waste management is another - increasingly exacerbating - environmental protection, which also requires intensive and rational processing of organic biomass.

The use of renewable energy in the world is becoming increasingly important because traditional sources of energy (coal, oil, natural gas) are limited, and their use for the production of heat and electricity causes great harm to the environment. In this regard, solar energy is becoming increasingly important, which can be used to produce environmentally friendly heat and electric energy [1-4].

The sun is a giant source of "clean" energy, not polluting the environment. Efficient use of solar energy can significantly reduce the consumption of natural resources. Climatic and weather conditions in the south of Uzbekistan create wide opportunities for the efficient use of solar energy in the Kashkakdarya region [2-5].

To achieve maximum efficiency of biogas formation, anaerobic processing requires certain temperature conditions and technological processes, preferably close to achieving the optimum process [6-7].
The current stage of agricultural construction is characterized by a tendency to expand the greenhouse economy and mobilize everyone, including technical means to increase the productivity of greenhouses. This trend is aimed at solving the problem of providing the population with fresh vegetables in the required quantities throughout the year and, which is especially important in the cold period from October to May [7-8].

Until now, the cultivation of crops and plants in greenhouses with technical heating has been recognized, the costs of which amount to 55-60% of the total costs. This imposes a special responsibility on the choice of design of the heating system for greenhouses [1;3-5].

Construction of a heating system for the airspace and the root layer of the soil of greenhouses, high costs of materials and funds for construction and installation work, annual fuel use, limiting the thickness of the root layer by placing heating structures in it, the presence of zones of local overheating of the soil, the cost of maintaining the system significantly affect for the cost of products grown in the greenhouse [1-2].

2. Materials and methods

Lowering temperatures in greenhouses against the required ones entails a decrease in yield and death of plants and vegetables. A decrease in humidity leads to a sharp decrease in the yield of vegetables and a loss of their marketability. Excessive moisture leads to the production of watery high-quality vegetables and, as a rule, leads to the development of their diseases [6-7].

The most effective way to improve the construction of solar greenhouses is to combine mathematical modeling with field tests. The use of mathematical modeling of heat transfer processes makes it possible to analyze the effectiveness of the proposed design solutions under various external conditions much faster than in field studies. Therefore, the development of sufficiently flexible mathematical models of solar greenhouses is relevant, allowing one to take into account the geometric and physical features of structures.

The mathematical models of solar greenhouses described in the literature are characterized by insufficient flexibility due to the fact that they are designed for a certain geometry of the structure, or only part of the processes are taken into account in them. In addition, a typical feature of these models is the use of empirical coefficients, which can only be measured (or calculated from measurements) using field tests [1].

This paper proposes an approach to the construction of mathematical models of solar greenhouses based on the modern theory of heat and mass transfer.

Providing the required temperature and humidity conditions for soil and air in greenhouses is a serious task, which is complicated by the need to save heat energy and minimize water consumption for irrigation.

The research methodology was based on the methods of mathematical modeling and computational studies using a computer, instrumental studies of the physical characteristics of the greenhouse-livestock complex, the theory of similarity, and static processing of experimental data [8].

For an effective solution to the problem of soil and air moistening in solar greenhouses, it is advisable to fundamentally focus on an intra-soil irrigation system with preheating of water.

At present, in the development of farms and businesses in the country, special attention is paid to the modernization of livestock buildings based on modern systems, the introduction of energy-efficient, high-efficiency equipment, technologies, and modern equipment, in particular the use of renewable energy sources. is focused. For this purpose, an experimental version of the device consisting of a flat-walled water tank and an underground heat accumulator greenhouse-livestock complex designed to create a temperate climate regime using solar and bioenergy for family entrepreneurs was developed (figure 1).

The livestock building is designed for 40 head of livestock, and the amount of harmful gases in the air of the livestock building is normalized, along with the partial heating of the greenhouse air by utilizing the free heat flow separated from the livestock. On sunny days, the solar energy that enters the greenhouse is stored underground and in a water tank located between the livestock building and
the greenhouse. On chronic cloudy days, a microclimate is created in the greenhouse at the expense of gas from the biogas plant [9-13]. The mathematical model of the combined thermal greenhouse-livestock complex with the design of the thermal regime of constructive, technical, technological, and meteorological systems can be written as follows:

\[
\begin{align*}
\rho \cdot V_{\text{liv},h} \cdot c \cdot \frac{d}{dt} (t_{\text{liv},h}(\tau)) &= Q_{\text{Liv}} - (Q_{\text{rad}} + Q_{\text{Liv}} + Q_{\text{out}} + Q_{\text{inf}} + Q_{\text{all}}) , \\
\rho \cdot V_{\text{g,h}} \cdot c \cdot \frac{d}{dt} (t_{\text{g,h}}(\tau)) &= Q_{\text{rad}} + Q_{\text{Liv}} + Q_{\text{g,h,bar}} - Q_{\text{Liv}} - Q_{\text{out}} - Q_{\text{inf}} - Q_{\text{all}} , \\
\rho \cdot V_{\text{ang,ac}} \cdot c \cdot \frac{d}{dt} (t_{\text{ang,ac,ext}}(\tau)) &= L_{\text{ang,ac}} \cdot \rho \cdot c(t_{\text{g,h}}(\tau) - t_{\text{ang,ac,ext}}(\tau)) - \alpha_{\text{ang,ac}} \cdot F_{\text{ang,ac}} (0.5(t_{\text{g,h}}(\tau) + t_{\text{ang,ac,ext}}(\tau)) - t_{\text{ang,ac}}(\tau)) , \\
\rho \cdot V_{\text{bak,ac}} \cdot c \cdot \frac{d}{dt} (t_{\text{bak,ac}}(\tau)) &= L_{\text{bak,ac}} \cdot \rho \cdot c(t_{\text{g,h}}(\tau) - t_{\text{bak,ac}}(\tau)) - \alpha_{\text{bak,ac}} \cdot F_{\text{bak,ac}} (0.5(t_{\text{g,h}}(\tau) + t_{\text{bak,ac,ext}}(\tau)) - t_{\text{bak,ac}}(\tau)) , \\
(m_{\text{w}} \cdot c_{\text{w}} + m_{\text{h}} \cdot c_{\text{h}}) \cdot \frac{d}{dt} (t_{\text{b,g}}(\tau)) &= K_{\text{b,g}} \cdot F_{\text{b,g}} (0.5(t_{\text{g,h}}(\tau) + t_{\text{b,g,ext}}(\tau)) - t_{\text{b,g}}(\tau)) .
\end{align*}
\]

Where: 
- \( Q_{\text{Liv}} = n \cdot q_{\text{Liv}} \) - heat flux freely separated from livestock; in this, \( n \) - number of livestock, \( q_{\text{Liv}} \) - heat flux from a single livestock, W; 
- \( Q_{\text{bar}} = Q_{\text{out}} + Q_{\text{sun}} + Q_{\text{floor}} \) - heat flux lost through the barrier (outer wall, ceiling and floor), W; 
- \( Q_{\text{out}} \) - heat flux lost through the outer wall, W; 
- \( Q_{\text{sun}} \) - heat flux lost through infiltration, W; 
- \( Q_{\text{sun}} = \frac{F_{\text{out,wall}}}{R_{\text{out,wall}}} (t_{\text{liv,bar}}(\tau) - t_{\text{ext}}) \) - heat flux lost through the outer wall, W; 
- \( Q_{\text{floor}} = \frac{F_{\text{floor}}}{R_{\text{floor}}} (t_{\text{liv,bar}}(\tau) - t_{\text{ext}}) \) - heat flux lost through the floor, W; 
- \( Q_{\text{steam}} = 0.278 \cdot 2.49 \cdot W_{\text{steam}} \) - Heat used to evaporate moisture (from floors, irrigation, nutrition, etc.) that evaporates from the damp surface of a building, W; 
- \( Q_{\text{inf}} = 0.1 \cdot Q_{\text{out,wall}} \) - heat flux lost through infiltration, W; 
- \( Q_{\text{ven}} = L_{\text{w}} \cdot \rho \cdot c \cdot (t_{\text{liv,bar}}(\tau) - t_{\text{g,h}}(\tau)) \) - heat exchange in the air exchange between the livestock building and the solar house, W; 
- \( Q_{\text{b,g}} = G_{\text{w}} \cdot c_{\text{w}} \cdot (t_{\text{int}} - t_{\text{exit}}) \) - heat transferred from a biogas boiler unit, W; 
- \( Q_{\text{g,h,bar}} = \kappa_{\text{inf}} \cdot K \cdot t_{\text{g,h}}(\tau) - t_{\text{exit}} \) - heat flux lost through greenhouse barriers, W; 
- \( Q_{\text{ang,ac}} = L_{\text{ang,ac}} \cdot \rho \cdot c \cdot (t_{\text{g,h}}(\tau) - t_{\text{ang,ac,ext}}(\tau)) \) - heat transferred to the underground heat accumulator, W; 
- \( Q_{\text{g,h,wall}} = \frac{F_{\text{g,h,wall}}}{R_{\text{g,h,wall}}} (t_{\text{liv,bar}}(\tau) - t_{\text{g,h}}(\tau)) \) - heat loss through the wall between the livestock building and the greenhouse, W; 
- \( Q_{\text{b,g,ac}} = L_{\text{b,g,ac}} \cdot \rho \cdot c(t_{\text{g,h}}(\tau) - t_{\text{ang,ac,ext}}(\tau)) \) - the water used to heat the water tank heat accumulator mounted on the wall between the livestock building and the greenhouse, W.

All the components of the equation can be expressed as follows:
Greenhouse-livestock complex includes the following technological processes. The 1 wall 2 and the roof 3 of the livestock building are made of heat-insulating materials. The building is equipped with energy-saving lighting fixtures 4. When the indoor air temperature of the livestock building rises, ventilation pipe 5 is activated and normalizes the indoor air temperature. Sunlight 6 a solar air heater 7 installed on the roof of a livestock building heats the air, the heat of the air being driven by the fan 8 is accumulated in a flat-walled heat accumulator 9. As the indoor air temperature rises above 24 °C, fan 10 sucks the air through a flat-walled heat accumulator and pumps it into the livestock building. As a result of the respiration of livestock inside the livestock building, carbon dioxide-saturated air is
introduced into the greenhouse 12 through a fan 11, which improves the indoor microclimate and accelerates plant growth. In the daytime mode, the sunlight passing through the transparent coating 13 has its effect on the heating of the air in the greenhouse 12 and causes the temperature to rise to 24 °C. At night, when the internal temperature of the building drops below 15 °C, fan 10 stops working, and the air driven by fan 8 pushes the heat from the flat-walled heat accumulator into the solar panel. On cloudy days and in the evenings when the air temperature is low, the greenhouse is heated by hot water heating coils 14 supplied from the water heating boiler 17 using a pump 16 through a hot water supply pipe 15. In the water heating boiler, the biogas generated in the bioreactor 21 is burned to pass through valve 18, collected in the gas holder 19, and processed in the refrigerator 20 chilled manure. In the bioreactor, the manure mass is stirred during the fermentation process through a mixer 22, and after using the biomass, the residual fertilizer is removed through the discharge point 23 in the reactor.

The temperature in the bioreactor is regulated using water flowing through an inner tube 24. 27 manure is delivered from the manure collector using a transmission line 25 to the bioreactor. The hot water flowing out of the water heating boiler passes through the soil layer of the solar panel and the flow of hot water to the heating coils 14 is adjusted employing valves 18 depending on the climatic conditions. 26 water in the return pipe is directed to the heating boiler. In turn, on sunny days, as the internal temperature of the solar panel rises above 24 °C, hot air is pumped through the fan 29 to the underground heat accumulator 30 and excess heat is accumulated, helping to improve the microclimate conditions of the solar panel at night.

3. Results and Discussion
In the development of the mathematical model, we construct a block diagram (figure 2) in the MATLAB/Simulink program, expressing all the magnitudes of the equation in table 1, without taking into account the change in air density and specific heat capacity over temperature [14].

| No. | Parameters                                           | Assignment | Unit of measurement | Value |
|-----|------------------------------------------------------|------------|---------------------|-------|
| 1   | Density of air                                        | ρ          | kg/m³               | 1.293 |
| 2   | The size of the livestock building                   | V_{liv.b}  | m³                   | 720 m³|
| 3   | The size of the greenhouse                           | V_{g.h.}   | m³                   | 540 m³|
| 4   | Specific heat capacity of air                        | c          | J/(kg·°C)           | 1005  |
| 5   | Number of livestock                                  | n          | -                   | 40    |
| 6   | Free heat released from a single animal               | q_{liv.}   | W                   | 593   |
| 7   | Thermal resistance of the outer wall                 | R_{out.wall} | (m²·°C)/W       | 1.34  |
| 8   | Exterior wall surface                                | F_{out.wall} | m²           | 126   |
| 9   | Outdoor air temperature                              | t_{ext.}   | °C                  | -6°C  |
| 10  | Thermal resistance of the exterior (door and window) window | R_{win}  | (m²·°C)/W       | 0.345 |
| 11  | The surface of the windows                           | F_{win}   | m²                  | 12    |
| 12  | Thermal resistance of roofing                         | R_{ceiling} | (m²·°C)/W      | 2.79  |
| 13  | Roof and floor surface                               | F_{ceiling} = F_{floor} | m²     | 240   |
| 14  | Thermal resistance of the floor layer                | R_{floor}  | (m²·°C)/W       | 4.46  |
| 15  | Air exchange consumption in the livestock building   | L_{w}      | m³/s                | 2.772 |
| No. | Parameters                                                                 | Assignment | Unit of measurement | Value   |
|-----|---------------------------------------------------------------------------|------------|---------------------|---------|
| 16  | Moisture that evaporates from the damp surface of the building (floors, from watering, feeding, etc.). | $W_{\text{steam}}$ | g/hour              | 2550    |
| 17  | Solar radiation falling on 1 m$^2$ of surface                              | $q_{\text{fall}}$ | W/m$^2$             | 200-500 |
| 18  | Coefficient                                                               | $\kappa_{\text{trans}}$ | -                  | 0.8     |
| 19  | Coefficient                                                               | $\alpha_{\text{trans}}$ | -                  | 0.8     |
| 20  | Greenhouse surface                                                        | $F_{\text{g.h.}}$ | m$^2$               | 180     |
| 21  | Infiltration coefficient                                                   | $\kappa_{\text{inf.}}$ | -                  | 1.1-1.2 |
| 22  | Heat transfer coefficient of two-layer polyethylene film                   | $K$        | $W/(m^2 \cdot ^0C)$ | 5.8     |
| 23  | The mass of water in the tank accumulator                                 | $m_w$      | kg                  | 2880    |
| 24  | Specific heat capacity of water                                            | $c_w$      | J/(kg $\cdot ^0C$)  | 4180    |
| 25  | The mass of the tank battery material (metal)                              | $m_m$      | kg                  | 834     |
| 26  | Specific heat capacity of metal                                            | $c_m$      | J/(kg $\cdot ^0C$)  | 460     |
| 27  | Volumetric consumption of air pumped to the underground heat accumulator  | $L_{\text{ung.ac}}$ | m$^3$/s             | 0.1413  |
| 28  | Volumetric consumption of air pumped to the water tank accumulator         | $L_{\text{bak.ac}}$ | m$^3$/s             | 0.35325 |
| 29  | The of the underground heat accumulator                                   | $V_{\text{ung.ac}}$ | m$^3$               | 6.1544  |
| 30  | The size of air between the water tank battery wall                        | $V_{\text{bak.ac}}$ | m$^3$               | 9.6     |
| 31  | Heat exchange surface of underground heat accumulator pipes                | $F_{\text{ung.ac}}$ | m$^2$               | 123     |
| 32  | The heat exchange surface of the water tank accumulator                    | $F_{\text{bak.ac}}$ | m$^2$               | 52.8    |
| 33  | Coefficient of heat transfer of air to the underground heat accumulator    | $\alpha_{\text{ung.ac}}$ | $W/(m^2 \cdot ^0C)$ | 0.75   |
| 34  | The coefficient of heat transfer by air to the water tank accumulator      | $\alpha_{\text{bak.ac}}$ | $W/(m^2 \cdot ^0C)$ | 25     |
| 35  | The heat transfer coefficient between the water tank accumulator and the air | $K_{\text{bak.ac}}$ | $W/(m^2 \cdot ^0C)$ | 24.5   |
| 36  | Mass consumption of hot water supplied from the biogas boiler to the heating batteries in the greenhouse | $G_w$ | kg/s | 0.5 |
Given that the daily value of solar radiation in the conditions of the city of Karshi is $q_{solar} = 200 - 500 \text{W} / \text{m}^2$, the following results can be obtained from the block diagram in figure 2 for the case of outdoor air temperature -6°C:

![Figure 2. Block diagram of the mathematical model of the heat supply system of the greenhouse-livestock complex in the program MATLAB/Simulink.](image-url)
Figure 3. The graph shows the changes in the temperature of the livestock building, greenhouse, underground heat accumulator, and water tank accumulator.

As can be seen from the graphs of figure 3, even though the outside air temperature is 6 °C, when the total solar radiation is 500 W/m², the indoor air temperature rises to 22 °C, the water tank battery temperature to 13 °C, and the underground heat accumulator temperature to 17 °C can be seen. While the amount of total solar radiation is 300 W/m², it can be seen that this figure will be 14 °C, 9 °C, and 12 °C.

4. Conclusion
In summary, if the working area of the building where 40 head cattle are stored is 240 m², if we place a greenhouse through a wall with the south side of this building, then by circulating the free heat and CO₂ gases separated from the cattle, we can fully give the greenhouse with a useful area of 180 m², taking into account that.

The developed mathematical models of radiation-convective heat exchange of a two-block solar greenhouse with a underground heat accumulator, and water tank accumulator, as evidenced by a comparison of the calculation results using a mathematical model and field experimental data. The implemented modeling method and the obtained mathematical dependencies can be effectively used in new scientific research and for practical calculations.

On the basis of computational (theoretical) and experimental studies, methods of heat engineering and hydraulic calculations of tray heat storage systems greenhouse-livestock complex have been developed, which can be used in the calculations and design of solar greenhouses, in other areas of heat power engineering.

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