The effect of PCM with different thermos-physical parameters on indoor temperature of Xi’an Solar Greenhouse

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Abstract. In this paper, the enthalpy method is used to simulate the influence of phase change materials (PCM) with different thermos-physical parameters on the indoor thermal temperature of solar greenhouses in Xi’an, China. The simulation results show that the temperature adjustment effect of PCM on solar greenhouses is significantly greater than common heat storage materials such as rammed soil, gravel and water. The lowest indoor temperature in the solar greenhouse increases first and then decreases with the increase of the phase transition temperature. The influence of PCM with different latent heat values on the average indoor temperature of the solar greenhouse increases first and then stabilizes. Increasing the thermal conductivity of PCM can reduce the temperature range of the solar greenhouse, but the increase in thermal conductivity has little effect on the indoor temperature when the thermal conductivity is greater than 0.4 W/(m·℃). For the Xi'an area, the best thermos-physical parameters of PCM used in solar greenhouses are: phase change temperature of 11 ℃, latent heat value of 140kJ/kg, thermal conductivity greater than 0.4 W/(m·℃). This article provides a reference for the practical application of PCM in solar greenhouses.

Keywords: solar greenhouse; PCM; indoor temperature; thermo-physical parameter.

1. Introduction

The emergence of solar greenhouses effectively solved the problem of vegetable supply in northern China in winter, and contributed to agricultural efficiency, farmers’ income and rural economic development [1, 2]. One of the most important enclosure structures of the solar greenhouse is the north wall, which stores and releases heat by absorbing solar energy to maintain the indoor temperature of the solar greenhouse to meet the growth of vegetable crops.

Scholars have carried out a lot of research on improving the heat storage performance of the north wall of the solar greenhouse in order to increase the winter temperature of the solar greenhouse to enhance the healthy growth and yield of crops. Therefore, with the development of phase-change heat storage technology and materials, PCMs are gradually used in the north wall of the solar greenhouse. Bascetincelik [3] applied phase-change energy storage paraffin to solar greenhouse production and achieved a certain heating effect. F.Berroug [4] analyzed and discussed the temperature change in the solar greenhouse when PCM (PCM) is used as the thermal energy storage medium on the north wall. The results show that under the condition of 32.4 kg PCM per square meter on the ground of the solar
greenhouse, the indoor air temperature at night in winter can be increased by 6-12 °C. Chao Chen [5] developed an active and passive ventilation wall with PCM, and used experiments and numerical methods to prove that its heat storage performance is better than traditional walls. Li Peng [6] sprayed a solid-liquid composite PCM mainly made of paraffin on the inner surface of the trapezoidal north wall of the solar greenhouse. The actual test results show that the phase change coating wall can effectively increase the heat storage and release of the wall and enhance the greenhouse. The temperature is especially the night temperature. Wang Hongli [7] et al. encapsulated the PCM in different ways and placed them in the double or porous hollow blocks on the north wall of the solar greenhouse. The results show that it can effectively reduce the disturbance of the external environment to the indoor temperature through the wall.

At present, the application of PCM in solar greenhouses is mainly focused on the development of phase change heat storage wall materials and the research of construction methods. However, PCM with different thermophysical parameters also have an important influence on the temperature of the solar greenhouse. In order to better realize the effective heat storage of the PCM through the phase change process, it is necessary to conduct a parameter analysis of the phase change temperature, latent heat, thermal conductivity, and thickness of the PCM on the application effect of the solar greenhouse. In this study, Design Builder simulation software was used to simulate the influence of PCM with different thermophysical parameters on the indoor temperature of solar greenhouses in Xi’an, China. This study analyzed the influence of PCM with different thermophysical parameters on the temperature regulation of solar greenhouses, and provided references for practical engineering applications.

2. Overview and simulation of solar greenhouse

2.1. Building model of solar greenhouse

As shown in Figure 1, a model of a solar greenhouse was established based on the passive solar greenhouse located in Xi’an, China. The dimensions of the solar greenhouse are 93 m in length, 12 m in span, and 5.2 m in height, respectively. The height of the north wall and the heat storage wall is 3.6 m. The material structure and parameters of each enclosure structure are shown in Table 1.

![Figure 1. Solar greenhouse model.](image)

Table 1. Material parameters and construction position of envelope.

| Materials              | Thermal conductivity /W·m⁻¹·°C⁻¹ | Specific heat capacity /kJ·kg⁻¹·°C⁻¹ | Density /kg·m⁻³ | Thickness /mm | Construction position                   |
|------------------------|----------------------------------|-------------------------------------|-----------------|---------------|----------------------------------------|
| Color steel laminboard | 0.04                             | 1.4                                 | 15              | 100           | East wall, West wall, North wall and North roof |
| PVC film               | 0.11                             | 0.1                                 | 1380            | 0.1           | South roof                             |
| Thermal insulation blanket | 0.04                           | 1.4                                 | 15              | 50            | South roof                             |
| Hydrogels             | 1.28                             | 0.88                                | 1460            | Semi-infinite | Ground                                 |
| Rammed earth          | 1.16                             | 1.01                                | 2000            | 40            | Heat storage wall                      |
| Gravel                | 1.51                             | 0.92                                | 2300            | 40            | Heat storage wall                      |
| Water                 | 0.58                             | 4.2                                 | 1000            | 40            | Heat storage wall                      |
| PCM                   | variable                         | variable                            | 740(liquid)     | variable      | Heat storage wall                      |
|                        |                                  |                                     | 825(solid)      |               |                                        |
2.2. Meteorological conditions

The outdoor temperature fluctuations in Xi'an area are shown in Figure 2 based on the local typical year winter weather data from the National Meteorological Administration of China. In this study, the local weather data from January 12 to January 18, when the outdoor temperature is the lowest in winter was selected for simulation. Figure 3 shows the hourly changes in outdoor air temperature and southward solar radiation in Xi'an from January 12 to January 18.

2.3. Mathematical model and solution method

In this study, the heat transfer process of the wall containing PCM was calculated by the finite difference method, and the heat balance method attached to the finite element software Design Builder was used for simulation calculation.

3. Results and discussion

3.1. The influence of phase transition temperature on the lowest temperature in the solar greenhouse

The effect of different phase transition temperatures on the lowest indoor temperature of the solar greenhouse at different times was simulated in this study. The simulation results are shown in Figure 4. It can be seen from Figure 4 that the influence of the phase change temperature on the daily minimum temperature in the solar greenhouse is to increase and then decrease. Thence, the indoor minimum daily temperature can be significantly increased by constructing a PCM with a suitable phase change temperature. The reasons for the above phenomenon can be explained as the following: The condition for the continuous process of the PCM releasing heat to the solar greenhouse at night is that there is a certain temperature difference between the surface of the PCM and the indoor air. Therefore, if the phase change temperature of the PCM is too low, it will release heat only if the temperature in the solar greenhouse is lower than the phase change temperature. However, if the phase change temperature is too high, the time period during which the indoor temperature of the solar greenhouse is higher than the phase change temperature will be shorter, resulting in insufficient phase change of the PCM [8]. This will reduce the amount of solar energy stored by the PCMs, resulting in lower night temperatures in the solar greenhouse. Simulation analysis results show that the best phase change temperature for using PCMs under this working condition is 11 °C.
3.2. Influence of latent heat value of PCM on average temperature in solar greenhouse

The effect of the PCM with different latent heat values on average indoor temperature of the solar greenhouse was simulated. The simulation results are reported in Figure 5.

It can be seen from Figure 5 that the average indoor temperature increases as the latent heat value of the PCM increases when the latent heat value is less than 140 kJ/kg. When the latent heat value of the PCM is greater than 140 kJ/kg, the increase in the latent heat value has negligible effect on the average temperature in the solar greenhouse. This is because the amount of heat storage of the PCM is affected by the solar radiation intensity in the area where it is used. The indoor temperature of a solar greenhouse cannot be further increased by using PCM with a larger latent heat value when the latent heat value exceeds the maximum amount of solar energy that can be stored. Therefore, considering the economy and advantages, a reasonable latent heat value of the PCM should be selected to increase the indoor temperature of the solar greenhouse. The simulation results show that the reasonable latent heat value of the PCM should be greater than 140 kJ/kg under this working condition to effectively increase the indoor temperature of the solar greenhouse.

3.3. The effect of thermal conductivity of PCM on the indoor temperature amplitude of solar greenhouse

In order to explore the influence of PCM with different thermal conductivity on the temperature adjustment performance of solar greenhouses, this study simulated the influence of PCM with different thermal conductivity on the temperature amplitude of solar greenhouses. The results of the simulation are calculated in Figure 6.

It can be seen from the simulation results in Figure 6 that the temperature difference between day and night in the solar greenhouse decreases with the increase of the thermal conductivity of the PCM. However, when the thermal conductivity of the PCM is greater than 0.4 W/(m·℃), the thermal conductivity has a very weak effect on the temperature difference between day and night in the solar greenhouse. The reason for the above phenomenon is that the increase of the thermal conductivity of the PCM will result in the rapid accumulation of heat energy in the PCM, alleviating the increase or decrease of the indoor temperature extreme point, thereby reducing the indoor temperature fluctuation. In addition, according to literature reports [9], the thermal conductivity of most PCM is between 0.1 W/(m·℃)-0.4 W/(m·℃). Increasing the thermal conductivity of the PCM will increase the manufacturing cost of the PCM. Therefore, it is most economical and advantageous to use a PCM with a thermal conductivity of 0.4 W/(m·℃) for this working condition.
3.4. Comparison of temperature regulation performance of PCM and other building materials in solar greenhouse

In order to evaluate the influence of PCM and common building materials on the temperature of solar greenhouse. This study simulated the effects of rammed earth, gravel, water and PCM as heat storage on the indoor temperature of the solar greenhouse. The simulation results are shown in Figure 7.

As shown in Figure 7, rammed earth, gravel, water, and PCM are used as heat storage bodies to have a certain adjustment effect on the indoor temperature of the solar greenhouse. The minimum temperature of the solar greenhouse increased by 0.46 °C, 0.47 °C, 0.56 °C, 1.95 °C, and the average temperature increased by 0.02 °C, 0.03 °C, 0.07 °C, and 1.15 °C, respectively. The simulation results show that PCM used in solar greenhouses have better heat storage capacity than traditional materials, and effectively increase the minimum and average indoor temperatures. The lowest indoor temperature in the solar greenhouse using PCM as heat storage materials in winter increased by 32.97%, and the average temperature increased by 12.51%. This has an obvious positive effect on the healthy growth of crops in winter. In addition, the use of PCM to store a large amount of solar energy resources reduces the consumption of fossil energy in the solar greenhouse, which is of positive significance for energy saving, emission reduction and environmental protection [10].

4. Conclusion

Through the simulation and analysis of the influence of phase change materials with different thermal physical parameters on the indoor temperature of the solar greenhouse, the following conclusions are obtained in this study:

1) The lowest indoor temperature in the solar greenhouse increases first and then decreases with the increase of the phase transition temperature. The influence of PCM with different latent heat values on the average indoor temperature of the solar greenhouse increases first and then stabilizes. Increasing the thermal conductivity of PCM can reduce the temperature range of the solar greenhouse, but the increase in thermal conductivity has little effect on the indoor temperature when the thermal conductivity is greater than 0.4 W/(m·°C).

2) It is the most economical and reasonable to use PCM with a phase change temperature of 11 °C, a latent heat value of 140 kJ/kg, and a thermal conductivity of 0.4 W/(m·°C) in solar greenhouses in Xi'an. This will increase the minimum indoor temperature in the solar greenhouse in winter by 32.97% and the average temperature by 12.51%.
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