HEAT ENVIRONMENT STUDY OF PASSIVE SOLAR GREENHOUSE
/
被动式日光温室热环境研究

Zhonghua LIU [*1)], **Xin YOU** [2)], **Penghui QIAO**[2)], **Mengjun CHEN**[2)], **Weiwei CHEGN**[1)]

[1)] Shanxi Agricultural University, College of Urban and Rural Construction, Taigu/China
[2)] Shanxi Agricultural University, College of Agricultural Engineering, Taigu/China
Tel: +86-0354-6287420; E-mail: lzh6175305@163.com
Corresponding author: Zhonghua LIU
DOI: https://doi.org/10.35633/inmateh-71-24

Keywords: *Passive solar greenhouse; Thermal environment; Cold, Low temperature and high latitude regions; Temperature change rate*

ABSTRACT

Passive solar greenhouses are developing rapidly in China and they can significantly increase crop yields. In order to promote the goal of temperature control in solar greenhouses in the high-latitude region of Shanxi, China, this paper conducted experiments to determine the three-dimensional thermal environment of solar greenhouses in the region, and the results showed that: regardless of the weather, the indoor temperature at the moment of midday exceeded 30°C; the temperature in the western region rose the fastest during the daytime, and declined the fastest in the eastern region during the nighttime. This research can provide theoretical support for the construction and management of solar greenhouses in low heat and water areas at high latitudes.

摘要

中国被动式日光温室发展迅速，被动式日光温室能够大幅提高作物产量。为促进中国山西高纬度地区日光温室的温度管控目标，本文对该地区的日光温室三维热环境进行试验测定，结果显示：无论何种天气，中午时刻室内温度都超过 30℃；白天西部区域温度上升最快，夜间东部区域下降速度最快。该研究可为高纬低热少水地区的日光温室建造和管理提供理论支撑。

INTRODUCTION

Solar greenhouses are a type of greenhouse unique to China and are built to accommodate the growth and development of vegetables in winter (*Panwar N.L. et al., 2011*), with passive solar greenhouses providing more than 30% of the total supply of vegetables and fruits (*Chao et al., 2019*). China's solar greenhouses mainly rely on solar energy absorption by the walls and ground during the day to store heat, and on heat dissipation by the walls at night to maintain indoor temperatures. Solar greenhouses can effectively increase crop yields and help maintain sustainable agricultural production. Temperature is one of the most important environmental factors in solar greenhouse production (*Shamshiri R.R. et al, 2018*). All biological and chemical processes throughout the life cycle of a crop must take place under certain temperature conditions. Nowadays, with the development of facility agriculture technology, the length and span of solar greenhouses are increasing and the space inside the greenhouse is gradually expanding, leading to uneven temperature distribution inside the greenhouse (*Wei et al., 2022*), which may affect the growth status of crops in different locations inside the solar greenhouse. The study of temperature variation patterns and distribution characteristics in solar greenhouses is of great significance for optimising solar greenhouses and thermal environment regulation.

A large number of studies have been conducted on the characteristics and change patterns of temperature distribution in solar greenhouse, and most researchers have used environmental monitoring sensors to obtain temperature data from solar greenhouse, and then used different methods to achieve prediction and control of the thermal environment in solar greenhouses. *Weiwei Cheng (2022)* analysed the three-dimensional thermal environment of a sunken solar greenhouse and found that the rate of change of the thermal environment along the vertical direction of the greenhouse was the greatest.

[1] *Zhonghua Liu, Asoc.Prof.Ph.D.Eng; Xin You, M.S.Eng; Penghui Qiao, M.S.Arg; Mengjun Chen, M.S.Arg; Weiwei Cheng, Ph.D. Eng.*

Jingjuan Hu (2014) used data analysis to analyse the characteristics of the changing thermal environment of a solar greenhouse in the Lishi district. *Jiangui Zhao (2019)* used the numerical filtering method to make an analysis of the environmental parameters of a solar greenhouse. At present, the most widely used software in solar greenhouse is Computational Fluid Dynamics (CFD). *Hongjun Xu (2019)* used CFD to simulate the wall temperature of a solar greenhouse and optimise its wall thickness. *Encai Bao (2018)* used CFD to simulate different rear wall ventilation in a solar greenhouse, providing a theoretical basis and experimental reference for the design of airflow circulation movement in the wall of an active thermal storage sunlight greenhouse; *Aohua Fan (2018)* used the solar greenhouse temperature field model for temperature regulation in solar greenhouses. However, due to the influence of various factors such as external meteorological conditions, wall structure parameters and production management methods on the simulation of the thermal environment in the greenhouse, there are still certain errors in the simulation of the thermal environment in the greenhouse, so other researchers use other methods to analyse the distribution of the thermal environment in the greenhouse. *Zhangyan Le (2018)* used the inverse distance weighting algorithm to model the temperature in the east-west direction of a large length solar greenhouse, and obtained the high and low value zones of the temperature in this solar greenhouse. *Junhua Zhang (2021)* used the kriging interpolation algorithm to model the canopy temperature field, obtained the temperature extrema by the differential evolution algorithm, and analysed the spatial and temporal variation patterns of the characteristic canopy temperature under different weather conditions. *Huihui Yu (2016)* used an improved particle swarm algorithm to optimize the LSSVM model for temperature prediction in a solar greenhouse.

This paper would use data analysis to study the temperature distribution and variation pattern of the solar greenhouse. The difference from previous studies was that in this experiment, a large number of temperature sensors, more intensive deployment and shorter acquisition intervals were used to study and analyse the thermal environment of the solar greenhouse. The study of the thermal environment of the solar greenhouse after intensive deployment will provide more effective information for the future deployment of temperature sensors in the solar greenhouse, contribute to the monitoring and control of temperature in precision agriculture and provide an important basis for the subsequent optimisation of the building model of the solar greenhouse.

MATERIALS AND METHODS

Experimental materials

The test solar greenhouse is a passive solar greenhouse located in Zhaozhuang Village, Zhaobi Township, Xiyang County, Jinzhong City, Shanxi Province, China, at latitude N: 37°30′, longitude E: 113°51′ and altitude 1549m above sea level. The area is located in the eastern part of Jinzhong City and the western foot of the Taihang Mountains, and belongs to the temperate and warm temperate semi-arid continental monsoon climate zone, with an annual average temperature of 9.3°C, an annual average frost-free period of 162 days, an annual average total sunshine hours of 2484.6 hours and an annual average precipitation of 572 mm.

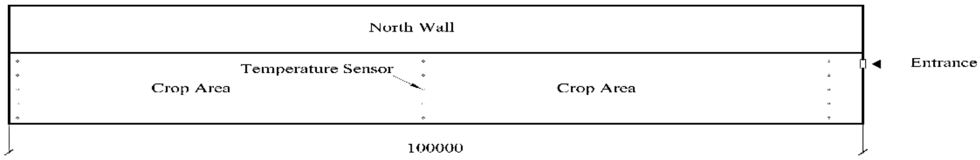
The test solar greenhouse is a sunken solar greenhouse, sunken to a depth of 1.2m, facing south, 100m long, spanning 12m, with a back wall height of 5.6m, the back wall is a trapezoidal earth wall structure, the upper and lower widths are 2m and 8m respectively, the front roof is covered with polyethylene bottomless film, the solar greenhouse has no ventilation, the insulation is used to keep warm at night in spring and winter, and in winter the insulation is lifted at around 9:00am every day, and at 16:00pm. The insulation is lifted at around 9:00 am and dropped at around 16:00 pm.

The temperature inside the solar greenhouse is measured using the RC-5 temperature recorder from Jingchuang, with a temperature range of -30°C to 70°C.Temperature measurement accuracy: in the range of -20°C, -20°C, ± 0.5°C; other ranges of 1°C. Within the temperature range of -20°C to 40°C, the accuracy is ±0.5°C and the rest is ±1°C. U disk type temperature recorder using Jingchuang RC-5 temperature recorder usb automatic data temperature and humidity recorder, built-in wide-temperature CR2032 battery, set the recording interval of 12 minutes, can be recorded continuously for 3 months, regular replacement of the built-in battery, the temperature recorder continues to record the temperature.

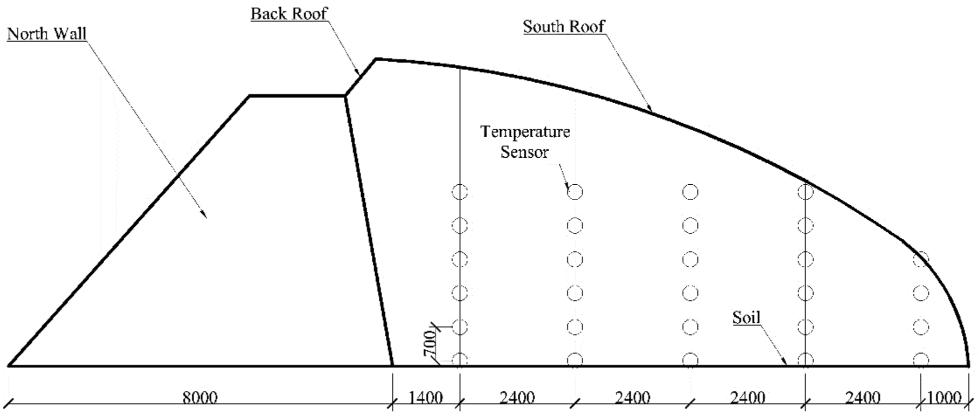
Experimental methods

In this experiment, the temperature inside the solar greenhouse was measured using the spot measurement method. Three sections of the solar greenhouse were selected to measure the temperature in the east, middle and west sides of the crop area.

The distance between the indoor measurement line and the edge of the film on the south side of the greenhouse was 1.0m, 3.4m, 5.8m, 8.2m and 10.6m, and the distance between the measurement points on the same measurement line was 0m, 0.7m, 1.4m, 2.1m, 2.8m and 3.5m respectively. There were 28 measurement points in each section, a total of 84 measurement points, and the thermometer temperature collection time interval was set at 12 min, starting on 28 December 2021 and ending on 7 February 2022, with a total of 448,308 data.



a



b

Fig. 1 - Distribution of solar greenhouse measurement points (a, plan view of solar greenhouse measurement points, b, cross-sectional view of solar greenhouse measurement points)

Data analysis

This experiment lasted 42 days, with 17 sunny days, 11 cloudy days, 8 cloudy days and 2 days of rain and snow. Since the insulation was not removed during the rainy and snowy days, the temperatures collected during the rainy and snowy days were ignored. The temperature data collected during the cloudy (January 2), sunny (January 3) and cloudy (January 4) days were collated and analysed to obtain the daily temperature change pattern and distribution characteristics of the solar greenhouse.

RESULTS

Indoor temperature

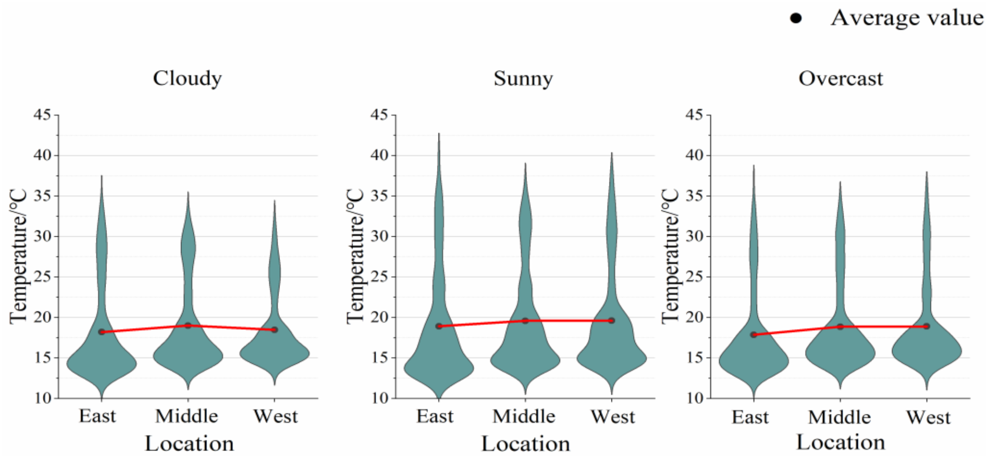


Fig. 2 - Overall analysis of solar greenhouse temperatures under different weather conditions

As shown in Figure 2, the temperature statistics for the sunroom on cloudy (2 January), sunny (3 January) and cloudy (4 January) days showed that the extremes of temperature in the sunroom occurred in the eastern part of the crop area under different weather conditions; regardless of the weather, the temperature was more concentrated around 14°C in the eastern part of the crop area, around 15°C in the central part of the crop, and around 15.5°C in the western part of the crop area. Table 1 showed the average temperatures and diurnal temperature differences at different locations in different weather conditions, and it could be seen that on the eastern side of the crop area, the diurnal temperature differences were the greatest in the solar greenhouse, and the maximum temperatures were above 30°C, which was not suitable for the growth of temperature-loving vegetable crops such as tomatoes. The main reason for this phenomenon is that the air in the room received solar radiation after the insulation curtain was removed, causing its temperature to rise rapidly, and with the gradual increase in the sun's altitude angle, the temperature only increased rather than decreased, reaching its maximum value at around 13:00 noon, before the temperature decreased afterwards.

Table 1

Temperature in different weather conditions

Weather conditions	Cloudy			Sunny			Overcast		
Position	East	Middle	West	East	Middle	West	East	Middle	West
Average temperature (°C)	18.20	18.99	18.47	18.91	19.58	19.59	17.85	18.85	18.89
Maximum temperature (°C)	39.4	36.3	34.4	42.9	38.7	39.6	38.4	36.5	37.5
Minimum temperature (°C)	11.1	13.2	12.7	11.2	13.1	12.5	11.7	13.3	12.2
Day and night temperature difference (°C)	28.3	23.1	21.7	31.7	25.6	27.1	26.7	23.2	25.3

Daily pattern of temperature change

In this experiment, a total of 84 temperature measurement points, 28 temperature measurement points per section, were laid out in the solar greenhouse to measure the temperature change characteristics at different locations in the solar greenhouse. Due to the large number of points laid out, the temperature data of each section was collated before analysing its daily temperature change pattern, and the temperature of each measurement point at different moments was calculated using the face-weighted average temperature method, with the formula as in (1), where *T* denotes temperature and *S* denotes area.

$$\bar{T} = \frac{\sum_{1}^{n} T_i S_i}{\sum_{1}^{n} S_i} (℃) \tag{1}$$

Face-weighted average temperature is a method of measuring temperature that involves distributing temperature over a specified face and weighting the temperature on that face by the weight of its relative position to obtain an average temperature. The main advantages of this algorithm are that it accurately reflects the distribution of temperature on a specified face, independent of boundaries; it also effectively provides accurate temperature data and is a more accurate predictor of temperature change.

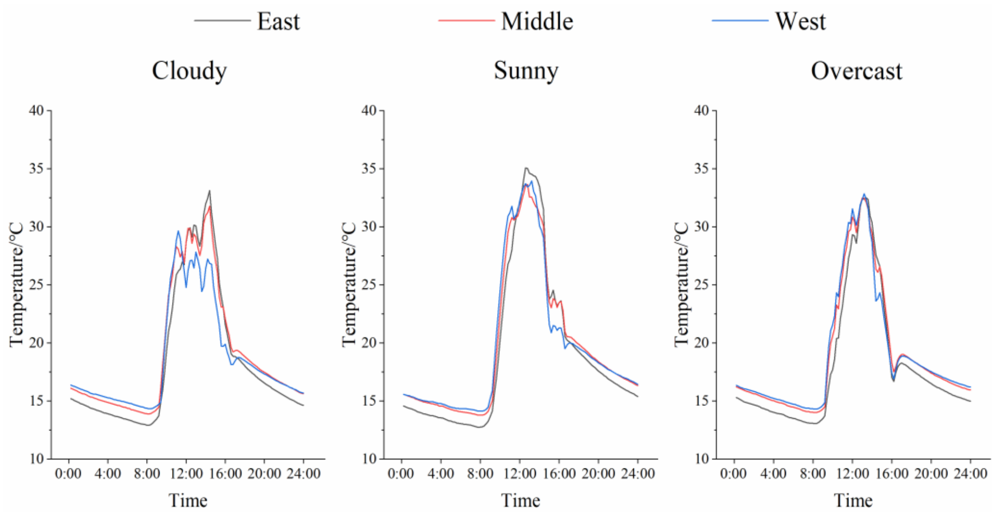


Fig. 3 - Graph of daily variation of temperature in the solar greenhouse

As shown in Figure 3, the indoor temperature reached its lowest value at around 8am, rising rapidly after the blanket was removed at 9am, slowing down after 11am, and then rising before falling gently after the blanket was put on at around 16pm; the night-time temperature in the solarium was much lower than the day-time temperature, and the highest and lowest temperatures of the day were found in the eastern part of the crop area of the solarium.

In cloudy weather, after the curtain was opened, the temperature showed a multi-peak change, the first time it reached the peak at around 11:00am, the temperature rise rate was west (7.5˚C/h) > central (6.81˚C /h) > east (6.46˚C/h); after that, it was affected by cloudy weather, the received solar radiation was sometimes more and sometimes less, the temperature was also sometimes high and sometimes low, at around 14:30 pm On sunny days, the temperature basically showed a single peak change, and after the insulation curtain was opened at around 9:00am, the temperature rose rapidly, and by 11:00am, the rate of temperature rise was west (8.11°C/h) > central (7.76°C/h) > east (7.07°C/h), reaching its maximum at around 13:00 noon.

On cloudy days, the temperature showed multiple peak changes, reaching its peak at around 12:00 pm due to the "lower values of solar radiation on cloudy days, with the temperature growth rate in the west (5.64°C/h) > central (5.44°C/h) > east (5.39°C/h); the temperature reached its highest value at 13:00 pm. Analysis of the data showed that the temperature in this solar greenhouse rose fastest between 9am and 11am, as the sun first shone directly on the western wall after the curtain was lifted and some areas in the eastern part of the crop area were shaded by the eastern wall, resulting in a faster rise in temperature in the western part of the crop area than in the eastern part. After 12 noon, due to the change of the sun's altitude angle, the solar radiation received by the western part of the crop area gradually decreased, and at around 13:00, the temperature reached its highest value. After that, due to the decrease of the sun's altitude angle, the solar radiation received by the solar greenhouse also gradually decreased, and the temperature gradually decreased, as the western part of the crop area was shaded by the western hill wall, resulting in the fastest temperature decrease in this area, and by 16:00, the western part of the crop area ;By 16.00 pm, the temperature in the western part of the crop area had reached its lowest value compared to the other two areas, and after the insulation curtain was put on, the temperature in the solarium first rose slightly and then continued to decrease slowly.

In cloudy weather, from the afternoon when the curtains were covered to 8am the following day, the rate of temperature drop in the solarium was east of the crop zone (0.51°C/h) > central (0.48°C/h) > west (0.3°C/h); in sunny weather, from the afternoon when the curtains were covered to 8am the following day, the rate of temperature drop in the solarium was east of the crop zone (0.67°C/h) > central (0.62°C/h) > west (As the eastern part of the crop area is farther away from the eastern wall, it can only get a small amount of heat radiated from the eastern wall at night, while the western side of the crop area is near the western wall, the heat radiated from the western wall could effectively act on the western part of the crop area at night, slowing down the temperature drop in this area.

The graph also showed that the trend of temperature changes in the solarium varied from day to day due to varying weather conditions. In cloudy weather, the temperature in the solarium exceeded 30°C at 13:30-14:30, in sunny weather, at 10:30-14:30, and in cloudy weather, at 11:30-14:00.

Indoor temperature distribution on the coldest day

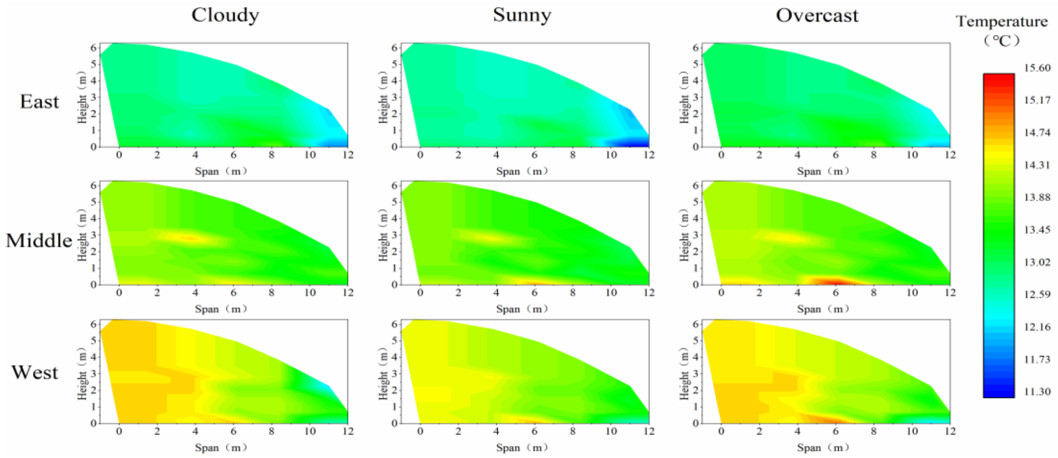


Fig. 4 - Cross-sectional temperature distribution of the solarium during extreme low temperatures

The indoor temperature reached its lowest value at around 8am and the cross-sectional temperature distribution is shown in Figure 5. As shown in Figure 4, the temperature distribution in this solar greenhouse is not uniform during extreme low temperatures. Under different weather conditions, the overall temperature in the crop area of the heliotrope at 8am showed a phenomenon of high temperatures in the west and low temperatures in the east. Along the span of the heliotrope, there was a basic trend of high temperatures in the north and low temperatures in the south, except for the ground temperature, with the lowest temperatures in the solar greenhouse located in the southernmost part of the eastern part of the crop area near the ground. It was obvious from the graph that the relationship between the magnitude of the temperature inside the solar greenhouse at the lowest temperature was cloudy > overcast > sunny. The difference in the minimum temperature of the next day was mainly due to the weather conditions of the previous day affecting the heat absorption values in the room, which is transferred to the solar greenhouse at night as the heat source of the solar greenhouse through radiation and convection, increasing the temperature inside the solar greenhouse. During the day, the heat absorbed by the solar greenhouse on a sunny day was greater than that absorbed on a cloudy day, so the temperature inside the solar greenhouse was higher on a cloudy day (4 January) than on a sunny day (3 January) and on a cloudy day (2 January) when the insulation had not been removed at 8am.

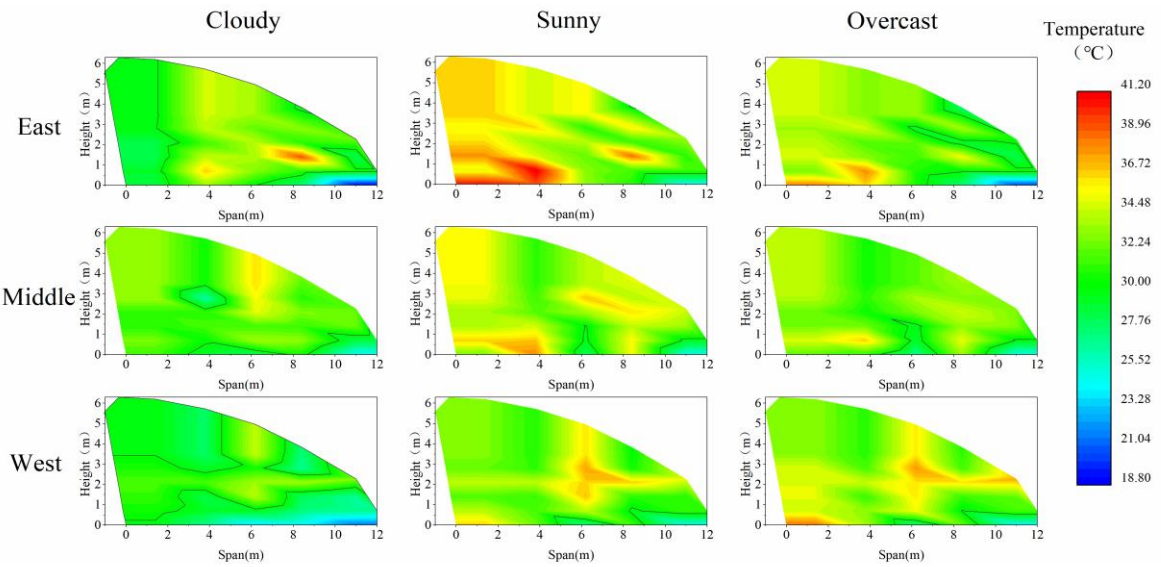


Fig. 5 - Cross-sectional temperature distribution of the solarium during extreme heat

The temperature in the solar greenhouse reached its highest value at around 13:00 in the afternoon on sunny and cloudy days, and at around 14:30 in the afternoon on cloudy days, with the cross-sectional temperature distribution shown in Figure 5. The lowest temperatures were located in the southern part of the crop area, near the ground, with the highest temperatures occurring in different sections of the crop area at different locations due to weather and location. In the western part of the crop area, the highest temperatures are in the middle of the solarium under different weather conditions: in the middle of the crop area. In sunny and cloudy weather, the maximum temperature is at ground level around 4 m near the back wall, and in cloudy weather the maximum temperature occurs in the middle of the solarium. In the eastern part of the crop area, on sunny and cloudy days, the maximum temperature was at ground level about 4 m near the back wall, and on sunny day there were small areas of high temperatures similar to those in cloudy weather, at a position 8 m from the back wall of the solar greenhouse; overall, the maximum temperature in the solar greenhouse was at a position 4 m near the back wall in the eastern part of the crop area. The main reason for this phenomenon is that from the morning after the uncovering of the curtain to 12 noon, as the sun's altitude angle gradually increases, the intensity of radiation also gradually increases, and the solar radiation received by the west wall gradually decreases, resulting in a gradual increase in temperature from west to east. At the same time, due to the large temperature difference between the inside and outside of the solarium, heat exchange occurs between the vicinity of the film and the outside world, making the temperature of the solarium high in the north and low in the south. Because of the uneven solar radiation received by the solar greenhouse during drizzly weather, the location of the highest temperatures differs from that of sunny and cloudy days. It can also be seen in Figure 5 that the temperature in most areas of the solarium exceeds 30°C in different weather conditions.

Discussions

The main object of this paper is to study a solar greenhouse in Xiyang County, Jinzhong City, Shanxi Province. By measuring its temperature and analyzing its daily temperature change pattern under different weather conditions and temperature distribution during extreme temperatures, we found that the rate of temperature rise, rate of temperature fall and temperature distribution in this solar greenhouse varied under different weather conditions in winter, and the maximum temperature exceeded 30°C, which would seriously affect the growth and development of temperature-loving crops. At this stage, most of the solar greenhouses in China are facing the problem of temperature increase and decrease.

At present, most of the solar greenhouses in China are facing the problem of low temperatures at night in winter, which leads to low-temperature disasters for vegetable crops, while the solar greenhouse studied in this paper has the problem of high daytime temperatures in winter, which is not suitable for the growth and development of temperature-loving vegetables. This is similar to the findings of *Lv Huanhuan (2021)*, both of which showed that high daytime temperatures in solar greenhouses may cause high temperature stress on vegetables and affect their yield. To address this problem, ventilation could be applied to this solarium according to different weather conditions. Proper ventilation could not only reduce the temperature in the solarium, but also effectively regulate the humidity and CO_2 concentration in the solarium to meet the requirements for normal crop growth in the solarium. If the ventilation is opened at around 10am on a sunny day, it can effectively reduce the rate of temperature rise in the solarium and lower the temperature in the solarium at the same time.

In this experiment, temperature data was only collected and analysed for the internal temperature of the solar greenhouse, which clearly showed the pattern of daily temperature changes and the distribution characteristics of the solar greenhouse, but to optimise the thermal environment of the solar greenhouse, the light intensity, humidity, soil and wall surface and internal temperature of the solar greenhouse should also be considered. In future studies, these data should be collected together with the temperature inside the solar greenhouse in order to obtain a more rational analysis of the thermal environment in the solar greenhouse and to better manage and optimize it.

CONCLUSIONS

In this paper, measurements of light were not covered in this article, and the coupling between light and temperature is not clearby. By selecting different weather conditions to analyse the trends of the thermal environment and the characteristics of temperature distribution in the solar greenhouse, the following conclusions were obtained:

Under different weather conditions, the maximum and minimum temperatures in this solarium were located in the eastern part of the crop area, and the maximum temperatures were all higher than 30°C, which was not conducive to the growth and development of temperature-loving vegetables.

The time to reach the maximum temperature in this solar greenhouse varied in different weather conditions, and the rate of change varied from location to location.

The maximum temperature in the solarium was around 4 metres from the back wall in the eastern part of the crop area and the maximum temperature exceeded 30°C in most areas of the crop area. periods, which were related to the indoor light and temperature.

ACKONWLEDGMENTS

I am very grateful to the College of Urban and Rural Construction for their help during the experiment and for the Shanxi Agricultural University Doctoral Start-up Fund(2023BQ06).

REFERENCES

[1] Aohua Fan (2018). Research on CFD simulation of winter solar greenhouse temperature field and uniform temperature regulation system（冬季日光温室温度场 CFD 模拟与均温调控系统研究）. *Northwest University of Agriculture and Forestry Science and Technology*, Xi′an /China.

[2] Chao Chen, Nan Yu, Fengguang Yang et al (2019). Theoretical and experimental study on selection of physical dimensions of passive solar greenhouses for enhanced energy performance[J]. *Solar Energy*, Vol.191, pp.46–56, Beijing/China.

[3] Encai Bao, Zou Zhirong, Zhang Yong (2018). CFD simulation of heat transfer from rear walls of active thermal storage daylight greenhouses with different airflow directions（主动蓄热日光温室不同气流方向后墙传热 CFD 模拟）. *Journal of Agricultural Engineering*, Vol.34(22), pp.169-177, Xi′an /China.

[4] Hongjun Xu, Yanfei Cao, Yanrong Li et al (2019). CFD-based determination of the thickness of heat storage layer in sunlight greenhouse walls（基于 CFD 的日光温室墙体蓄热层厚度的确定）. *Journal of Agricultural Engineering*, Vol.35(04), pp.175-184, Xi′an /China.

[5] Jiangui Zhao, Zhiwei Li, Wenjun Li et al (2019). Testing and analysis of spatial and temporal distribution of environmental parameters in sunlit greenhouse tomato cultivation（日光温室番茄种植环境参数时空分布测试与分析）. *Shanxi Agricultural Science*, Vol.47(12), pp.2172-2176, 2181, Taiyuan/China.

[6] Jingjuan Hu, Guisheng Fan, Yanjuan Gao (2014). Experimental study on the characteristics of air temperature change in overwintering heliotrope greenhouses（越冬期日光温室空气温度变化特性的试验研究）. *Journal of Taiyuan Engineering*, Vol.45(04), pp.490-495, Taiyuan/China.

[7] Junhua Zhang, Kai-Cheng Shen, Dan-Yan Chen, et al (2021). Analysis of spatial and temporal variation of canopy temperature in a solar greenhouse based on the Internet of Things（大长度日光温室东西方向的温度变化特征）. *Journal of Agricultural Machinery*, Vol.52(07), pp.335-342, Xi′an /China /China.

[8] Lv Huanhuan, Niu Yuanyi, Zhang Man, et al (2021). Trend analysis of light intensity and air temperature and humidity in daylight greenhouses（日光温室光照强度与空气温湿度变化趋势分析）. *Journal of Agricultural Machinery*, Vol.52(S1), pp.410-417, Beijing/China.

[9] Panwar N.L., Kaushik S.C., Kothari S. (2011). Solar greenhouse an option for renewable and sustainable farming. *Renew Sustain Energy Rev*，Vol.15, pp.3934-3945, India.

[10] Shamshiri R.R., J. W. Jones, K. R. Thorp et al (2018). “Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: a review,” *Int. agrophysics*, Vol.32(2), pp.287-302, United States.

[11] Weiwei Cheng, Zhonghua Liu (2022). Study on the change rate of the indoor temperature of a sunken solar greenhouse [J]. *INMATEH-Agricultural Engineering*, Vol.68 (3), pp. 119-126, Taiyuan/China.

[12] Yu H., Chen Y., Hassan S.G. et al (2016). Prediction of the temperature in a Chinese solar greenhouse based on LSSVM optimized by improved PSO[J]. *Computers and Electronics in Agriculture*, Vol.122，pp.94-102, Beijing/China.

[13] Zhangyan Le, Minghua Shi, Qucheng Wei, et al (2022). Characteristics of temperature variation in east-west direction of large-length daylight greenhouses[J]. *Guizhou Agricultural Science*, Vol.50(08), pp.94-102, Guizhou/China.