Suitability analysis of assembled solar greenhouses in northwest China based on CFD

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Abstract: Solar greenhouses in China have various structural forms. Compared with traditional solar greenhouses, the assembled solar greenhouse is not only simple in construction, convenient and fast in installation, but also improves the utilization efficiency of land and reduces the damage to the soil layer, cleverly achieving the transformation between plastic greenhouses and solar greenhouses. To determine the regions suitable for promoting modular solar greenhouses, this study adopts a combination of actual measurement and simulation methods. Based on Autodesk CFD software, a dynamic thermal model of modular solar greenhouse is established. Predictions and adaptive analysis of indoor temperature field changes at different regions are conducted in the consideration of boundary conditions such as outdoor air temperature, solar radiation on walls, and ground in various regions. The experimental results show that the change trends of measured and simulated values are basically consistent, indicating a high degree of model agreement. The maximum average deviation between the predicted and measured values of indoor air temperature is 1.53°C, the maximum average absolute deviation is 2.52°C, and the maximum root mean square is 3.74°C. The absolute coefficient ranges from 0.84 to 0.92, which indicates that the model can accurately reflect the temperature field distribution and heat exchange situation of the modular solar greenhouse at different times. This study provides a theoretical basis for the application and promotion of modular solar greenhouses and also offers a new research method for suitability simulation analysis of other types of solar greenhouses.

Keywords: assembled solar greenhouses, suitability analysis, northwest China, CFD

DOI: 10.25165/j.ijabe.20251804.9289

Citation: Wu X, Jia K, Xu H J, Li H, Zhang W H. Suitability analysis of assembled solar greenhouses in northwest China based on CFD. Int J Agric & Biol Eng, 2025; 18(4): 78–88.

1 Introduction

Sustainable agriculture is one of the most challenging issues in the context of “double carbon”. It can be classified in terms of energy utilization, environmental impact, and cost efficiency[1]. As a modern planting mode with controllable environmental conditions, facility agriculture not only alleviates the quandary of tight food supply in China, but also plays a significant role in ensuring the year-round supply of fruits and vegetables and improving farmers’ income in the “vegetable basket project”. According to data from 2022, the total area of solar greenhouse cultivation in China exceeds 2.8 million hectares, accounting for more than 80% of the world’s total facility area[2]. With the increase in population and economic development, the current demand for facilities has shifted from quantitative demand to qualitative demand, corresponding to higher energy consumption and rising costs.

The mid-latitude northwest regions of China offer particular benefits in light resources and noticeable seasonal variations for the growth of facility agriculture[3]. Due to the fact that solar greenhouses are dependent on the sun and use their enclosure structure to store heat in order to maintain the internal temperature, they are unable to reliably produce crops during the winter months when faced with unfavorable weather conditions like persistent clouds, bitterly cold temperatures, dust storms, or smog. To ensure the overwintering growth of plants, scholars have converted various energy sources such as solar energy, electricity, biomass energy, diesel, coal, and natural gas into thermal energy that can assist in heating greenhouses[4]. Among them, coal heating is favored by farmers due to its low price, ease of use, and lack of technical requirements, making it the main force for greenhouse heating. However, the emissions from coal have also put tremendous pressure on the environment. To promote the development of clean energy, improve environmental quality, and reduce pollutant emissions, China began implementing the “coal-to-electricity” policy in 2016[5]. With the adjustment of the energy structure and the increase in environmental protection requirements in recent years, this policy has become more comprehensive. To ensure year-round supply of fruits and vegetables, the most convenient method of electric heating is adopted in winter to meet the growth needs of crops. Through research and calculations, it has been found that using electric heating in greenhouses can increase production costs by 50%[6]. Therefore, selecting appropriate types of solar greenhouses based on local conditions and prioritizing the use of natural resources to achieve overwintering production have become common research goals for scientific researchers.

To achieve the aforementioned research goals and improve the environmental conditions for facility cultivation, extensive research

Received date: 2024-08-10 **Accepted date:** 2025-05-23

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has been conducted on maximizing solar energy collection and minimizing heat loss. In terms of increasing solar radiation, researchers have focused on altering the methods and timings of uncovering and covering insulation blankets, and optimizing the shape[7], angle, and azimuth[8] of the front roof to maximize the utilization of solar resources[9,10]. As for enhancing heat storage capacity, researchers have developed active and passive heat-storing walls[11]. The composition of greenhouse walls is also diverse, including single-material walls, multi-layer heterogeneous composite walls, and assembled walls that are convenient for construction and transportation[12]. While early-constructed walls contributed significantly to maintaining the thermal environment of the greenhouse, years of experience in facility production have revealed that traditional wall construction is not only labor-intensive, time-consuming, and space-consuming, but also causes irreversible damage to the soil layer. With the emergence of flexible materials, assembled solar greenhouses using flexible materials with strong thermal insulation properties as the main component have been introduced, achieving a perfect transition between solar greenhouses and plastic greenhouses. Due to the low thermal conductivity of flexible materials, heat loss within the greenhouse is significantly reduced, leading to lower energy consumption[13]. Therefore, based on the optimized roof structure, assembled solar greenhouses have been widely promoted and used in the development of China's facility agriculture.

Certainly, the performance of a greenhouse is not solely determined by its structure and materials, but also closely tied to the geographical location and climatic characteristics of a given area[14]. In practical production, Chinese Solar Greenhouse (CSG) often encounters the challenge of imbalance between its actual performance and the temperature requirements of crops. This imbalance has led to the seasonal idleness and waste of a significant number of newly built greenhouses, thereby affecting the healthy development of the greenhouse industry. Evidently, without proper theoretical simulation and analysis during the initial construction stages, the blind promotion of new-type solar greenhouses could result in significant waste of capital and resources.

The greenhouse environment is a complex, nonlinear, and dynamic system influenced by various factors such as radiation, wind speed, wind direction, temperature, and humidity[15]. The change of air temperature mainly comes from the heat exchange process between the greenhouse enclosure structure and the indoor and outdoor environment, and at the same time, air temperature significantly affects the growth, quality, and morphology of plants by influencing their photosynthesis, respiration, transpiration, as well as cell division and elongation[16]. Therefore, air temperature serves as a dominant weather parameter and a crucial indicator for assessing whether a greenhouse can meet the growth requirements of crops.

Predecessors have predicted the temperature inside solar greenhouses by establishing statistical models, neural network models, physical models, and hybrid models, among others. Ferreira et al. utilized a radial basis function neural network to model the internal temperature of greenhouses, achieving satisfactory prediction results[17]. Guerra et al. conducted a comparative study of three prediction methods (i.e., ARIMA model, AI model, and hybrid model), using weather parameters as regressors to predict RSSI. Taking into account weather parameters, the experiments demonstrated that the ARIMA model exhibited higher reliability, providing a lower average RMSE. The accuracy measurement results of the hybrid model were very close to those of the ARIMA model, but the ARIMA-ann method was simpler[18]. Zou et al. conducted verification and prediction of temperature and humidity in solar greenhouses based on the convex bi-directional extreme learning machine (C-ELM) algorithm. This prediction method exhibits higher accuracy compared to B-ELM, BP neural networks, support vector machines, and radial basis functions[19]. Because of the BP neural network algorithm's complexity, it necessitates a high sample count and intricate parameter settings. Li and his coauthors improved the BP neural network algorithm by adopting the nearest neighbor algorithm. Using the current greenhouse indoor temperature, humidity, and light intensity as inputs, and predicting the greenhouse indoor temperature 20 min later as the output, this approach not only simplifies the calculation process but also yields more accurate prediction results[20].

For meteorological characteristics, however, the models indicated above did not make clear how much different environmental elements affect the temperature inside greenhouses. In response, Yang et al.[21] compared the predictive performance of RNN, LSTM, GRU, FAM-RNN, FAM-LSTM, and FAM-GRU models under different dataset splitting ratios. They proposed a FAM-LSTM model prediction method with high prediction accuracy, enabling multi-step forecasting of temperature and humidity under various horizons. Mao et al.[22] established a variable weight combination forecasting model for greenhouse climate based on BiGRU-Attention and LightGBM. After optimizing the weight coefficients for temperature, humidity, and photosynthetically active radiation (PAR) within the greenhouse, predictions were made. Experiments have proven that this variable weight combination forecasting model outperforms single forecasting models and equal-weight forecasting models in terms of accuracy and stability.

Later, researchers integrated dynamic thermal models into optimization programs, providing a new tool for finding the optimal design of solar greenhouses suitable for each climatic condition and predicting their performance[23-25]. Zhao and his team[26], based on the principle of energy balance, utilized Matlab to establish a one-dimensional transient temperature prediction model for modular-type flu-greenhouses. This model predicted the surface temperatures of various enclosure structures within the greenhouse and obtained the daily temperature variation trends of different surfaces inside the greenhouse. However, it did not simulate or explain the changes in the air temperature within the greenhouse. Zhang et al.[27] simulated the coupled nonlinear relationship between air humidity and ventilation opening size in a greenhouse using Computational Fluid Dynamics (CFD), providing a fundamental reference for controlling air temperature and humidity through ventilation openings. Meanwhile, Mao et al.[28] employed a combination of CFD simulation and measured data to model and validate the dynamic temperature and humidity within a Venlo-type greenhouse. It was concluded that the established greenhouse climate model could effectively simulate real greenhouse climates, demonstrating the feasibility of using CFD models to predict climate factors within greenhouses.

Looking back at existing research, whether it involves using simulation tools to evaluate the performance of existing or designed greenhouses in order to verify the achievement level of design goals, or optimizing the greenhouse structure based on simulation results, all these studies are premised on the completion of all greenhouse designs before proceeding with subsequent analytical research. The application of greenhouse prediction models is restricted to areas where greenhouses are already present, and it is not possible to use these models to predictably analyze the adaptability of solar greenhouses in other areas. This study, however, combines actual testing with dynamic simulation to establish a CFD model for assembled solar greenhouses. By forecasting and analyzing the application and performance of assembled solar greenhouses in northwest China, it suggests an expanded usage approach for the CFD model.

2 Overview and data collection of the test greenhouse

2.1 Overview of the test greenhouse

In this experiment, the research target is the assembled solar greenhouse located in Shaya County, Aksu Prefecture, Xinjiang (41.14°N, 82.83°E). This greenhouse faces south with a north-south orientation, and has a span of 12 m, an east-west span of 72 m, and a height of 5.2 m. The rear wall has a height of 4 m, and the frame is made of galvanized steel pipes. The wall material is sprayed cotton, as shown in Figure 1. The front roof is covered with polyethylene film. This solar greenhouse structure features an integrated assembly of the front roof frame, rear roof frame, and rear wall columns. The specifications of the solar greenhouse are as shown in Figure 2.

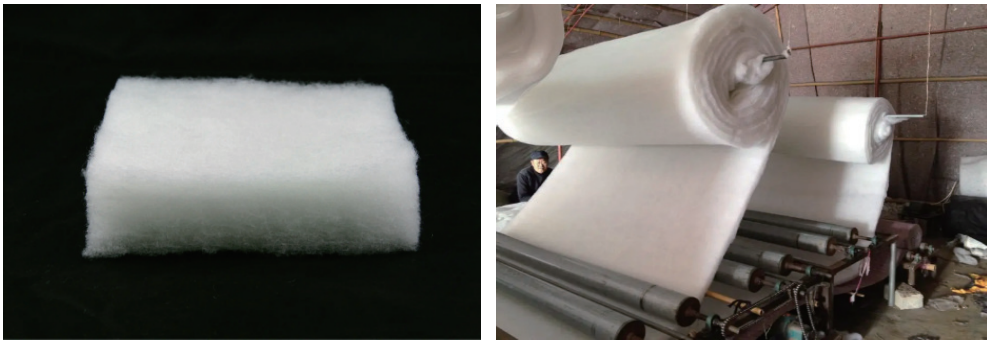


Figure 1 Exterior diagram of the greenhouse for test

Figure 2 Exterior diagram of the greenhouse for test

Within the solar greenhouse, mainly solanaceous vegetables are cultivated. Drip irrigation is adopted for watering, and thermal insulation blankets are used for nighttime insulation. On sunny days, the thermal insulation blankets of each greenhouse are opened at 10:00 and closed at 19:30. To maximize heat absorption and retention, on cloudy days, the blankets of each greenhouse are opened at 11:00 and closed at 18:30. During the entire production process, no additional heating or ventilation measures are implemented within the greenhouse.

2.2 Measurement and statistics of environmental data

From September 2021 to June 2022, data were collected on the indoor and outdoor temperature, humidity, solar radiation, soil temperature inside the greenhouse, surface temperature of the walls, and heat flux of various enclosure structures, utilizing the data loggers manufactured by Harbin Wuge Electronic Technology Co., Ltd. The temperature measurement range is from –20°C to 60°C, with an accuracy of ±0.5°C and a resolution of 0.1°C. The solar radiation intensity measurement range is from 0 to 2000 W/m^2, with an accuracy of ±3% and a resolution of 1 W/m^2. The heat flux measurement range is from –1000 to 1000 W/m^2, with an accuracy of ±3% and a resolution of 1 W/m^2. Data were recorded every 10 min. A total of 15 measurement points were arranged, as shown in Figure 3.

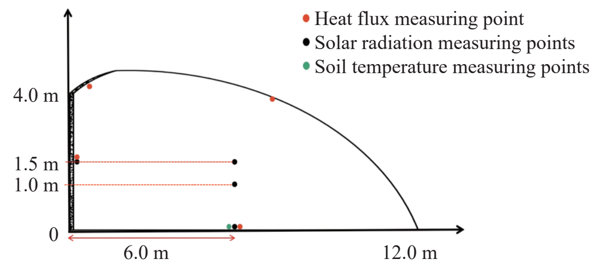


Figure 3 Distribution of environmental testing points in CSG

3 CFD model establishment and verification

3.1 Establishment of two-dimensional model of assembled solar greenhouse

Due to the significantly greater length than the span of the tested greenhouse and the notable symmetry in heat transfer phenomena, this study established a 1:1 two-dimensional geometric model of the modular solar greenhouse using Autodesk SimStudio Tools 2016 R3, based on actual measured data of the greenhouse, to reduce the demands on computational resources. The focus was placed on simulating the temperature field in the vertical cross-section located at the midpoint of the greenhouse. It is considered to accurately reflect the heat transfer process within the greenhouse. This region comprises five boundaries: the front roof, rear roof, rear wall, ground, and cold protection trench.

3.2 Conservation equations

The CFD simulation of the temperature field inside a greenhouse is simplified to an ideal state, assuming the greenhouse is completely airtight with no consideration of internal and external gas exchange. The walls of the greenhouse and the soil texture are considered uniform, and the impact of plants on the internal temperature and humidity of the greenhouse is not taken into account. The governing equations adhere to the laws of momentum conservation, energy conservation, and mass conservation:

$$\frac{\partial(\rho\varphi)}{\partial t}+\mathrm{div}(\rho\varphi\vec{v})=\mathrm{div}(\Gamma_{\varphi}grad\varphi)+S_{\varphi} \quad (1)$$

where, ρ is density, kg/m^3; φ is a universal variable; $\vec{v}$ is the velocity vector, m/s; Γ_{φ} is the generalized diffusion coefficient, m^2/s; S_{φ} is the source term, W/m^3. When φ is 1, the equation is continuous. When φ is u, v, w, the equation is a momentum equation. When φ is T, it is the energy equation. u, v, w is the velocity in x, y, z, three directions, m/s; T is the temperature, °C.

3.3 Grid partition

The hexagonal structural type in TRIM is adopted for mesh generation. Simulation accuracy and computing speed are closely related to mesh size. If the mesh size is too small, computations take a long time, and if it is too large, the simulation results are less accurate. As the thickness of the rear wall of the modular solar greenhouse simulated in this experiment is only 0.1 m, the basic size for the uniform meshing of the overall greenhouse domain is set at 0.05 m, generating a total of 31 504 nodes and 60 771 mesh elements, as shown in Figure 4.

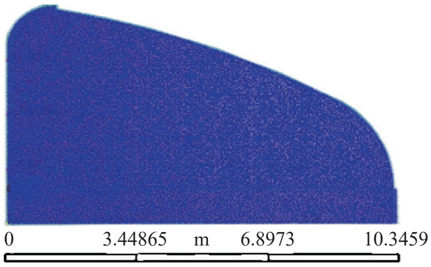


Figure 4 Model and grid partition of solar greenhouse

3.4 Boundary conditions and initial conditions

The present study utilizes environmental data from consecutive typical sunny days, spanning from January 12th to 14th, as the fundamental data for model establishment. The variations in solar radiation and air temperature are depicted in Figure 5.

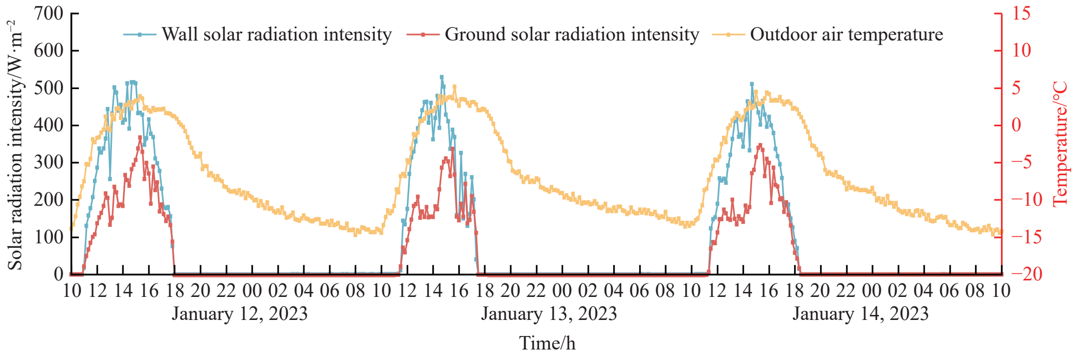


Figure 5 CFD simulation boundary conditions

Based on the actual measured environmental data, the initial temperature inside the greenhouse was set at 9.3°C, the initial wall temperature was 6.1°C, and the initial soil temperature was 11.4°C. To improve the accuracy of the model, referring to GB 50176-2016 "Code for Thermal Design of Civil Buildings", the thermal performance parameters of the enclosure structure materials such as the rear wall, front roof, rear roof, and soil of the modular solar greenhouse were calibrated. The specific values are listed in Table 1.

Table 1 Thermal property parameters of greenhouse enclosure from materials

Materials	Thickness/ mm	Density/ kg·m^{-3}	Specific heat/ J·kg^{-1}·K^{-1}	Thermal conductivity/ W·m^{-1}·K^{-1}
Polyester wadding	100	1.4	1100	0.070
Thermal insulation blanket	100	1.4	1100	1.170
Wet air	-	-	1004	0.026
Sandy soil	-	1680.0	800	0.300
PO film	-	-	-	8.900

Additionally, the heat transfer coefficients for both the rear wall and rear roof are 23 W/(m^2·K). When the thermal insulation blanket is removed, the heat transfer coefficient for the front roof is set to 8.9 W/(m^2·K), and when the blanket is covering it, it is 1.17 W/(m^2·K).

3.5 Simulation settings

To accurately calculate the heat exchange between the greenhouse wall and the air, the greenhouse air is assumed to undergo natural convection under the influence of temperature. The turbulence model employs the standard k-ε equation model. The simulation test is conducted using a computer (Lenovo Legion Y7000 2020 with Microsoft Windows 10, Intel(R) Core(TM) i5-10300H CPU @ 2.50 GHz, 16 GB of physical memory, and Intel 64-bit architecture). The simulation time step is set at 600 s, with a total of 144 steps, resulting in a total duration of 86 400 s. The solution yields a visualization of the temperature field variations within the modular solar greenhouse at different time intervals.

3.6 Model validation

In this study, the accuracy of the assembled solar greenhouse model was verified by comparing the measured and simulated values of the air temperature at the same point inside the greenhouse. The selection of the verification point for air temperature inside the greenhouse was at half the span, half the length, and 1.5 m height. The accuracy of the model was verified by introducing four evaluation indicators, including MBE, MAE, RMSE, and R^2. Among them, the maximum mean bias was 1.53°C, the maximum mean absolute bias was 2.52°C, the maximum root mean square was 3.74°C, and the absolute coefficient ranged from 0.84 to 0.92, as listed in Table 2. After comparing the actual and simulated values of indoor air temperature in a greenhouse over three consecutive days, as shown in Figure 6, it is evident that the trends of the actual and simulated values are largely consistent, demonstrating a high degree of agreement. It is believed that this model accurately reflects the distribution of temperature fields and heat exchange conditions at different times in the assembled solar greenhouse, thus serving as a solid foundation for further research.

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(I_c - I_m) \tag{2}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|(I_c - I_m)| \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(I_c - I_m)^2} \tag{4}$$

$$R^2 = 1 - \frac{\frac{1}{n}\sum_{i=1}^{n}(I_c - I_m)^2}{\frac{1}{n}\sum_{i=1}^{n}(I_c - \bar{I})^2} \tag{5}$$

where, I_c is the calculated value of the solar radiation model of the greenhouse floor or wall, W/m²; I_m is the measured solar radiation value of the greenhouse floor or wall, W/m²; $\bar{I}$ is the average value of measured solar radiation on the ground or wall of the greenhouse, W/m²; n indicates the total amount of solar radiation data on the ground or wall of the greenhouse in one day.

Table 2 CFD model validation data

Date	MBE/°C	MABE/°C	RMSE/°C	R^2
January 12, 2022	0.95	2.2	2.9	0.91
January 13, 2022	1.53	2.52	3.74	0.84
January 14, 2022	–0.56	2.21	2.9	0.92

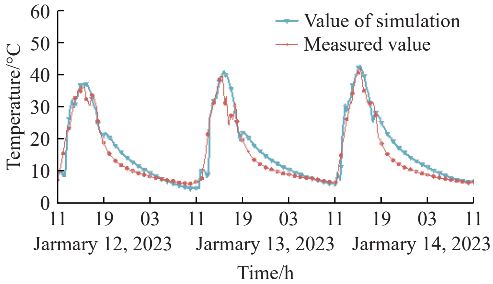


Figure 6 CFD model validation of daylight greenhouse

4 Simulation of the suitability of assembled solar greenhouses in typical areas

The performance of solar greenhouses is influenced by the climatic features of various locations in addition to the structural materials used in the structures. Although assembled solar greenhouses have demonstrated significant performance advantages during the testing period in experimental sites, this does not mean that assembled solar greenhouses are worth promoting everywhere. Therefore, based on the previously established CFD model of assembled solar greenhouses, this study simulates and analyzes the internal environment and suitability of this type of solar greenhouse in northern China. Based on the monthly averages of the previous ten years, the typical meteorological year (TMY) is presented as the foundational data for modeling. It selects a year from the data of the past ten years that is close to the average of the past ten years for each month, representing the average state of climate for many years. The data of the typical meteorological year is considered to have strong climate representativeness. The test process is shown in Figure 7.

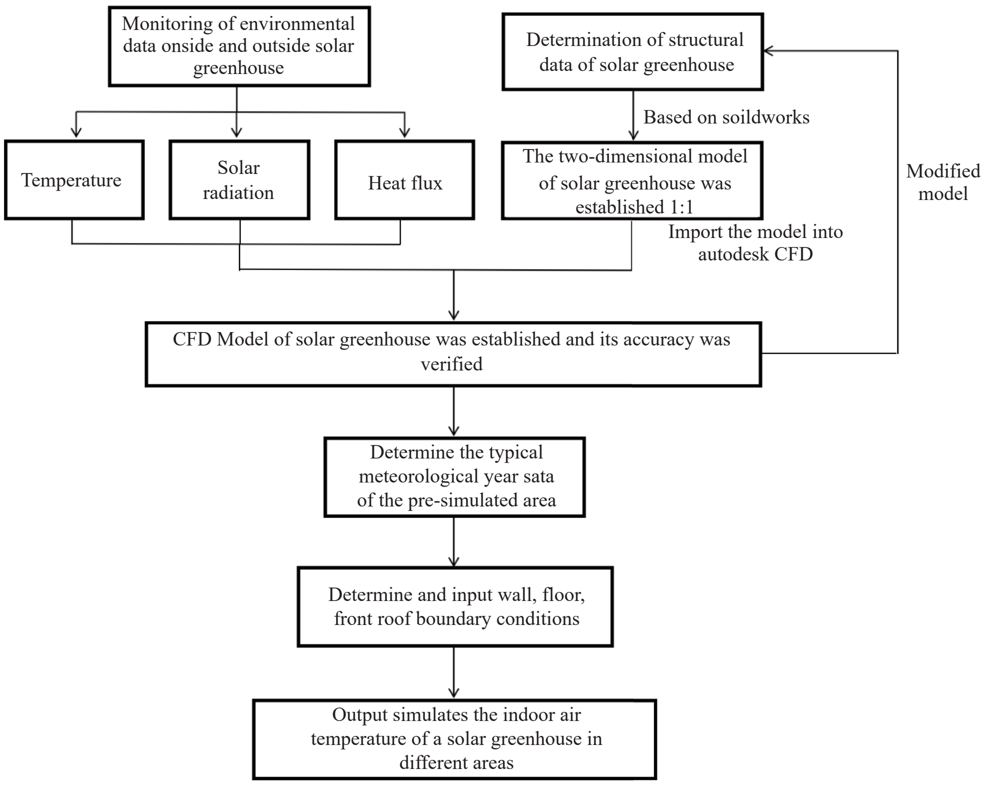


Figure 7 Establishment and suitability simulation of CFD model for packaged solar greenhouse

4.1 Selection of typical areas and sources of meteorological data

In alignment with the national plan for modern facility agriculture construction, and under the premise of ecological protection and rational resource utilization, the research focuses on the rational utilization of non-cultivated land resources such as Gobi deserts and saline-alkali lands. Therefore, this study selects 12 typical regions in northwest China, taking into account natural factors like annual sunshine duration, temperature, and precipitation, as well as socio-economic factors like total population and gross national economic output. These selected typical regions are deemed to have absolute advantages for developing facility agriculture. Utilizing the pre-established CFD model for assembled solar greenhouses, this study conducts simulation analysis on the temperature distribution within this type of greenhouse across different regions. The temperature and solar radiation data used in the simulation were obtained from the publicly accessible FTP server of NCDC (National Climatic Data Center, ftp://ftp.ncdc.noaa.gov/pub/data/noaa/isd-lite/), and the station information is presented in Table 3.

Table 3 Information of typical regional meteorological stations

Region	Weather station number	Name of place	Latitude/°	Longitude/°
Xinjiang	51 704	Artux	39.72	76.17
	52 203	Kami	42.82	93.52
	51 720	Keping	40.50	79.05
	51 818	Pishan	37.62	78.28
	51 777	Ruoqiang	39.03	88.17
	51 573	Turpan	42.93	89.20
	51 814	Yecheng	37.92	77.40
Gansu	52 679	Wuwei	37.92	102.70
Inner Mongolia	52 576	Alxa	39.22	101.68
Ningxia	53 618	Yongning	38.28	106.25
Qinghai	52 866	Xining	36.73	101.75

4.2 Definition of boundary conditions

Utilizing the established CFD model for assembled solar greenhouses, coupled with boundary conditions such as outdoor air temperature, and solar radiation on walls and ground in various regions, this study conducted predictions and adaptability analyses of indoor air temperatures in assembled solar greenhouses across different locations.

4.2.1 Reference dates and sunrise and sunset times for typical areas

During the research, this study selected the coldest day in a typical meteorological year as the subject of analysis for external air temperature. Additionally, the thermal blanket is a crucial measure to ensure the thermal environment within the solar greenhouse. However, due to China's vast territory and the significant span in longitude and latitude in the northwest regions, there are remarkable climatic variations. As a result, the time for removing and covering the thermal blanket differs slightly in each region. Therefore, in the simulation process, the determination of the removal and covering time of the thermal blanket was primarily based on the local sunrise and sunset times of that particular day, specifically one hour after sunrise and one hour before sunset. The sunrise and sunset times for various regions are listed in Table 4.

Table 4 Sunrise and sunset schedule by district

Name of place	Typical weather: date of coldest day of the year	Sunrise time	Sunset time
Artux	January 11th	10:15	19:51
Kami	January 4th	9:16	18:25
Keping	January 1st	10:07	19:27
Pishan	January 5th	10:02	19:42
Ruoqiang	January 29th	9:16	19:24
Turpan	January 10th	9:33	18:48
Yecheng	January 30th	9:56	20:12
Wuwei	January 18th	8:23	18:16
Alxa	January 15th	8:14	17:58
Yongning	January 7th	8:11	17:50
Xining	January 10th	8:25	18:15

4.2.2 Calculation of solar radiation of wall and soil

As an essential envelope structure in solar greenhouses, the rear wall is significantly influenced by ambient temperature and external radiation. During the day, the wall's surface temperature rises instantly when sunlight hits it. Part of the heat is then transferred to the air through convection, and the other half is retained in the wall through conduction. At night, when the temperature inside the greenhouse is low, the heat stored in the wall is released to warm the air in the greenhouse. Therefore, during the CFD simulation process, solar radiation data on the wall surface is also required. However, the hourly solar radiation values provided by various meteorological stations represent the radiation received on a horizontal surface. There are differences between vertical and horizontal solar radiation, as vertical solar radiation is influenced by the solar altitude angle and azimuth angle, as shown in Figure 8. Consequently, this study has estimated the solar radiation received by the wall based on the ground-level solar radiation. The specific calculation method is as follows:

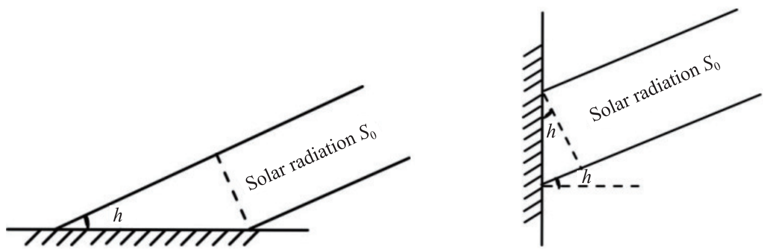


Figure 8 Relationship between solar radiation and solar elevation angle

The first step is to determine the solar declination angle, hour angle, altitude angle, and azimuth angle:

$$\delta = 23.45 \times \sin[360^\circ (284+N)/365] \tag{6}$$

$$\tau = (12-t)\times 15^\circ + (120^\circ - \psi) \tag{7}$$

$$\sin h = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\tau \tag{8}$$

$$\sin\alpha = \cos\delta \sin\tau / \cos h \tag{9}$$

where, δ is the sun declination angle, (°); N indicates the accumulated days in order of days, with 12 on January 12 and 13 on January 13; τ is the hour angle of the sun, (°); t is Beijing time, and the calculated time step is 1/6 h, h; ψ is the local longitude, (°); φ is the local latitude, (°); h is the altitude angle of the sun, (°); α is the solar azimuth, (°).

Then it is necessary to clarify the relationship between solar radiation on the wall and solar radiation on the ground:

$$S_G = S' \times T \times \sin h \tag{10}$$

$$S_W = S' \times T \times \cosh \times \cos(\alpha - \gamma) \tag{11}$$

where, S_G is the amount of solar radiation received by the ground, (W/m^2); S_W is the amount of solar radiation received by the back wall, (W/m^2); S' is the amount of solar radiation from the sun's rays through the atmosphere to the front roof surface of the greenhouse, (W/m^2). The transmittance of the front roof is 65%. In the whole simulation process, it is considered that the solar greenhouse does not perform auxiliary heating and ventilation cooling.

4.2.3 Initial conditions

All the thermal property parameters used in the prediction model are identical to those listed in Section 3.4. There are differences in sunrise and sunset times across various locations, which are taken into account when setting the time for uncovering and covering the insulation blanket, as well as the heat transfer coefficient of the front roof surface. Due to limitations in experimental conditions, it was not possible to conduct actual measurements of the wall and soil temperatures inside greenhouses in the predicted regions. In order to make the simulation results comparable, the same temperature settings for the soil and walls were applied for simulations in all regions, with the values provided in Table 5.

Table 5 Simulated initial temperature of each part inside the greenhouse

Air temperature/°C	Wall temperature/°C	Soil temperature/°C
11.7	7.1	11.6

5 Results and analysis

5.1 Analysis of the applicability of assembled solar greenhouses in Xinjiang

After simulating the temperature field of the modular solar greenhouse on the coldest day of a typical meteorological year, as shown in Figure 9, this study found the following: In Ruoqiang County, the lowest outdoor temperature during a typical meteorological year was simulated to be 49.1°C during the day, 19.18°C on average at night, and the lowest temperature at night was 11.73°C. In Keping County, during the coldest day of a typical meteorological year, the maximum temperature inside the greenhouse was 58.9°C during the day, the average temperature at night was 19.2°C, and the lowest temperature was 11.3°C, as shown in Figure 10. Taking the growth temperature requirements of several typical greenhouse crops as a reference, this greenhouse can basically meet the temperature conditions required for crop growth. However, there is an issue of excessively high daytime temperature, which can lead to phenomena such as stopped leaf growth, inability to bloom, or sprout in crops. Therefore, it is necessary to focus on timely ventilation and cooling. Based on the above analysis, the modular solar greenhouse has great promotional value in Ruoqiang and Keping. Under normal conditions of uncovering and covering the insulation quilt, crop production can safely overwinter without the need for auxiliary heating.

From the simulation of the indoor air temperature of the assembled solar greenhouse on the coldest day in the typical meteorological years in Artux, Yecheng, and Turpan, as shown in Figure 11, it is found that in Artux, the average daily temperature inside the greenhouse is 16.8°C, with an average nighttime temperature of 13.85°C and a minimum nighttime temperature of 6.8°C. In Yecheng, the average temperature inside the greenhouse throughout the day is 18°C, with a daytime maximum temperature of 43.5°C; the average nighttime temperature is 13°C, and the lowest temperature is 7.1°C, as shown in Figure 12. In Turpan, the lowest temperature at night is 6.7°C, and the highest temperature during the day is 40.6°C. Although the daytime temperature inside the assembled solar greenhouse is relatively high in three areas, as the outdoor air temperature drops, the temperature difference gradually increases, and the heat inside the greenhouse continuously dissipates. After 6:00 pm, the air temperature inside the greenhouse has dropped below 10°C, and the continuous low temperature can lead to slow crop growth and even death in severe cases. Based on the above analysis, it is believed that the assembled solar greenhouse cannot provide a suitable growth environment for plants without heating. If it is to be used in these areas, nighttime heating should be conducted during low temperatures, and insulation measures should be taken at the same time.

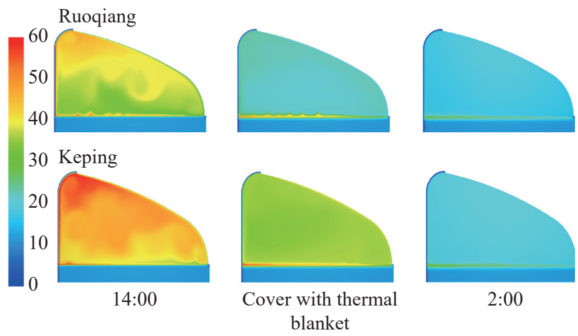


Figure 9 Variation of temperature field (°C) of assembled solar greenhouse in Keping and Ruoqiang area at different times

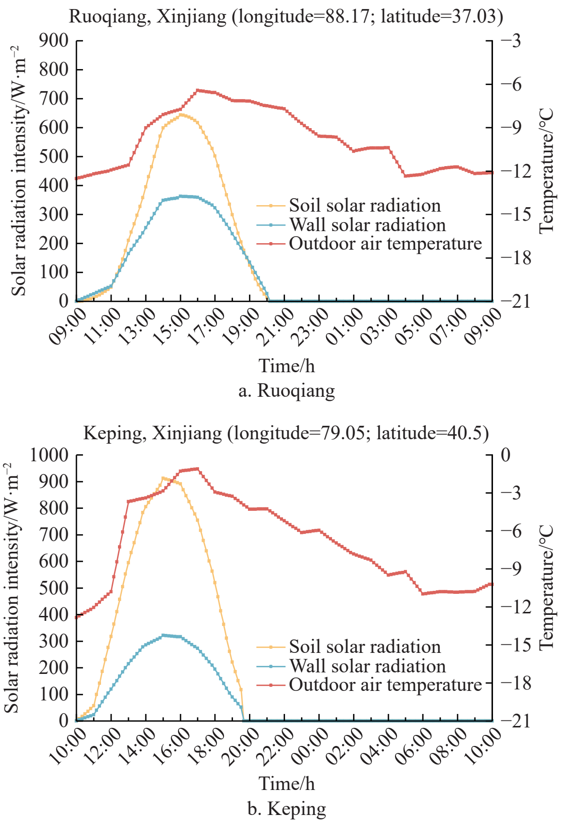


Figure 10 CFD simulation boundary conditions

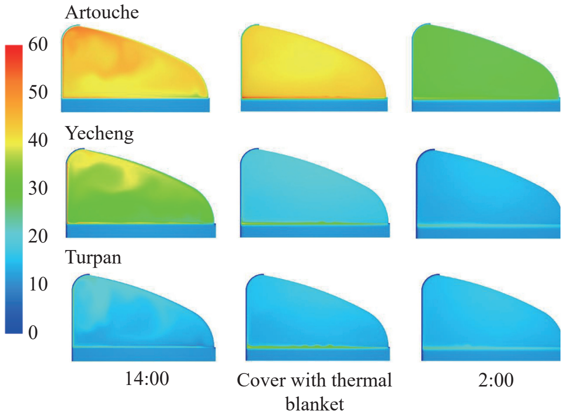
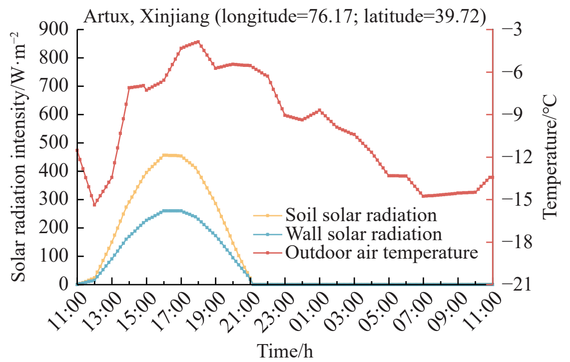
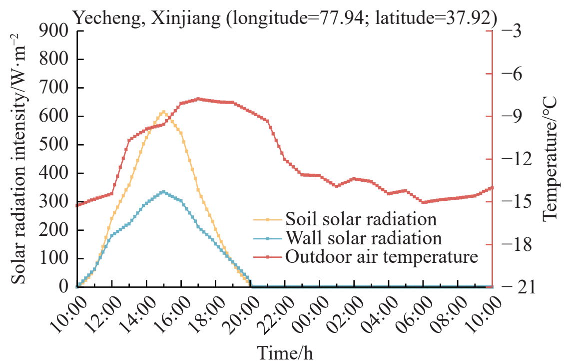


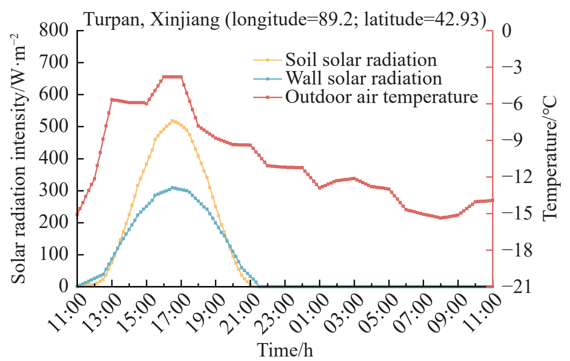
Figure 11 Variation of temperature field (°C) of assembled solar greenhouse in Artux, Yecheng, and Turpan area at different times



a. Artux



b. Yecheng



c. Turpan

Figure 12 CFD simulation boundary conditions

The Hetian region of Pishan County in Xinjiang's southern region is known for its abundant sunlight resources, and considered as an advantageous area for the development of facility agriculture. However, through the simulation of the assembled solar greenhouse in this area, it has been found that such greenhouses are not suitable for promotion in this area. During the coldest day of a typical meteorological year, the average nighttime air temperature inside the greenhouse is 8.66°C, with a minimum temperature of 2.23°C. While the region enjoys ample daytime sunlight, the assembled solar greenhouse lacks heat storage capacity in its rear wall. Despite the high amount of solar radiation entering the greenhouse during the day, it is unable to store sufficient excess heat for use at night. As the outside temperature averages –25.1°C at night, creating a significant temperature difference between indoors and outdoors, the assembled solar greenhouse, characterized by rapid heating and cooling, results in lower temperatures inside the greenhouse during the night. These low temperatures can cause chilling injury to crops, affecting their growth and development.

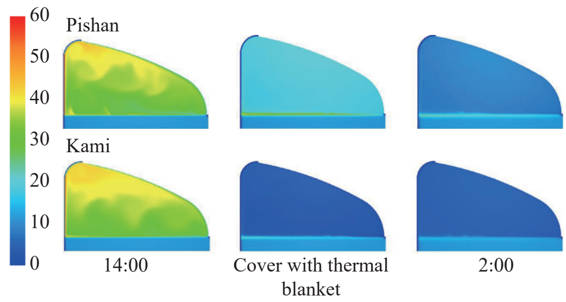
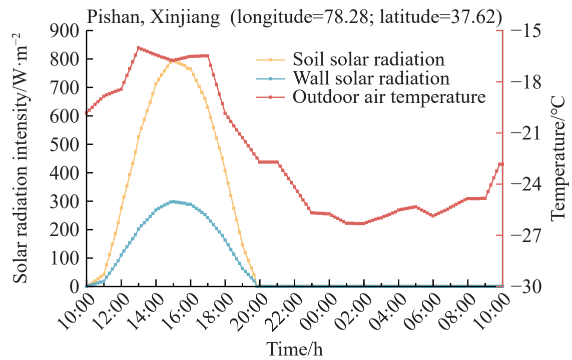
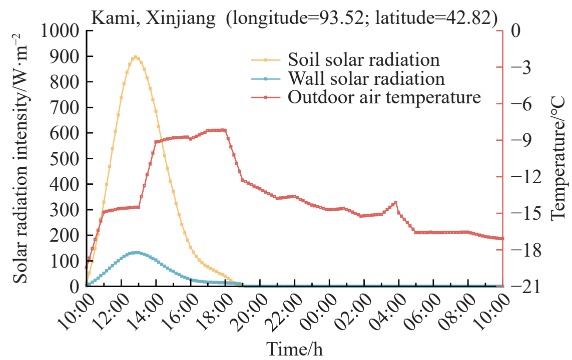


Figure 13 Variation of temperature field (°C) of assembled solar greenhouse in Pishan and Kami areas at different times

Kami, located in the eastern Xinjiang region, experiences relatively cold winters. According to simulation results in Figure 13, the temperature inside the assembled solar greenhouse in Kami is no longer suitable for crop growth after 15:00. While the solar radiation is high during midday, causing a rapid rise in temperature inside the greenhouse, the assembled solar greenhouse is unable to store the excess heat, as shown in Figure 14. Furthermore, the sunset in Kami occurs earlier than in the southern Xinjiang region, resulting in a rapid drop in air temperature inside the greenhouse. To ensure the safe overwintering of plants, continuous heating



a. Pishan



b. Kami

Figure 14 CFD simulation boundary conditions throughout the night is necessary. Compared to the HM-120-55tw sightseeing solar greenhouse, a new type promoted in Kami, the assembled solar greenhouse lacks the value for promotion in this region.

5.2 Adaptability of packaged solar greenhouse in northwest China

Longitude and latitude both have an impact on climate change when taking location into account, although in different ways. For example, latitude largely affects solar radiation, but longitude predominantly affects the seasonal changes and spatial distribution of climatic elements like temperature and precipitation. One of the most important natural heat sources for establishing a thermal environment in solar greenhouses is sun radiation. Inside solar greenhouses, the temperature of the air is directly influenced by the amount of solar radiation. Based on this theory, it is believed that there are significant similarities in the suitable types of solar greenhouses in different regions at the same latitude. Through the analysis in the previous section, this study concludes that the suitable latitude for the development of assembled solar greenhouses should be around 38° North. To verify this conclusion, this study has further simulated and analyzed the adaptability of assembled solar greenhouses in Inner Mongolia, Ningxia, and Gansu.

It is found that there is a certain regularity in the suitability of solar greenhouses in terms of latitude. The assembled solar greenhouse has good adaptability only in Alxa, Inner Mongolia, with an indoor air temperature of 20°C during the day and an average air temperature of about 12°C at night. Similar in latitude to Ruoqiang, Xinjiang, the built solar greenhouse in Alxa, Inner Mongolia, performs similarly. Nevertheless, Qinghai, Ningxia, and Gansu are not good places to construct the assembled solar greenhouse, as shown in Figures 15 and 16. Its unsuitability is primarily due to the low evening temperature, as the graph indicates. It is extremely detrimental for plant growth for the built solar greenhouse's nighttime temperature to go below 5°C in these three areas, as shown in Figure 17. As of right now, the assembled solar greenhouse's performance is comparable to that of a similar latitude solar greenhouse in Pishan County, Xinjiang. It is believed that the suitable latitude for the development of assembled solar greenhouses is around 39° North.

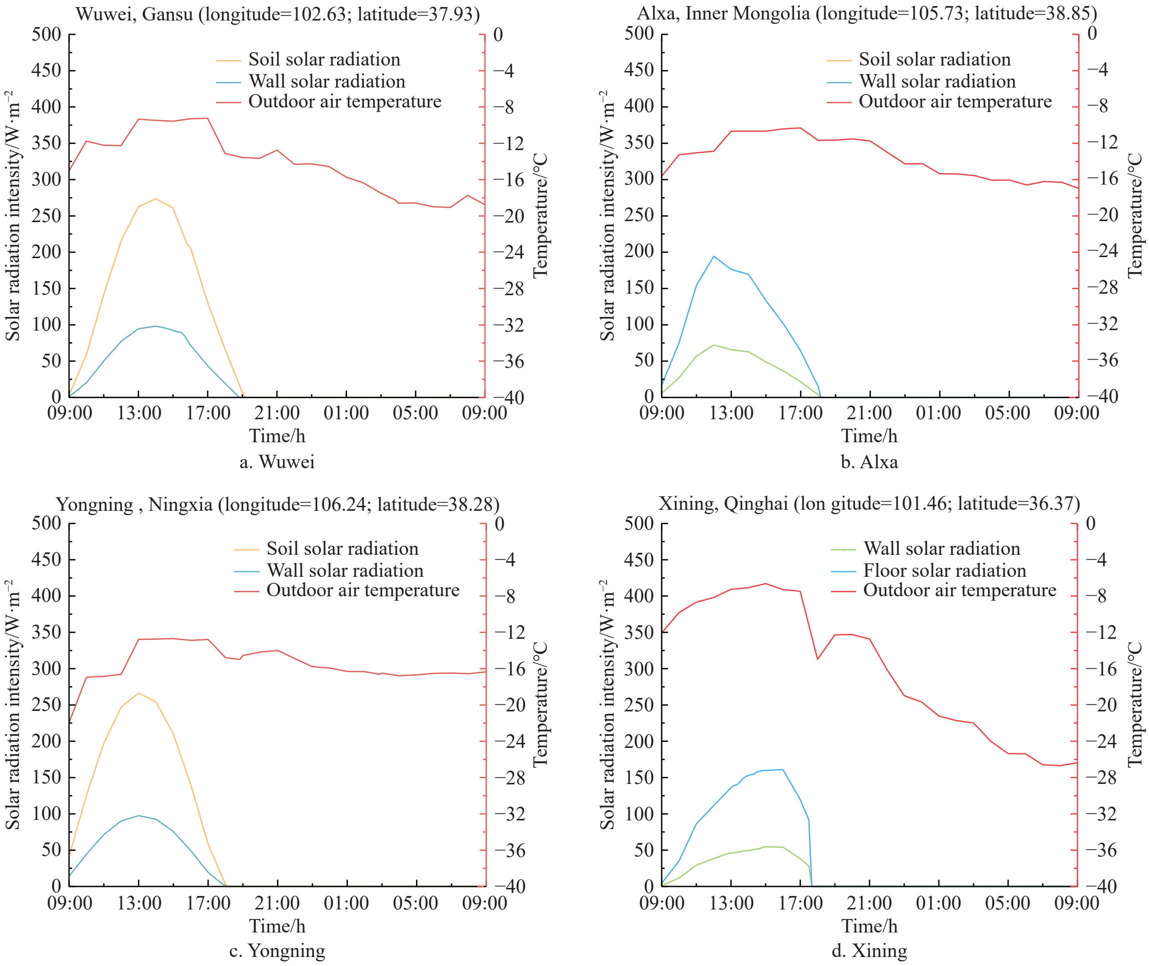


Figure 15 CFD simulation boundary conditions in northwest China

6 Discussion

The Autodesk CFD software is widely applied in solar greenhouses, encompassing simulations of airflow conditions, temperature, and humidity fields within the greenhouse[29,30]. Consequently, this study has established a model for modular solar greenhouses using CFD software and verified its accuracy, concluding that the model can accurately reflect the changes in the temperature field within the greenhouse at different times. From the simulated indoor air temperature curve, there is a brief phase of sharp temperature fluctuations, which is attributed to the practice of uncovering and covering the insulation blanket in daily management. To maximize the utilization of solar radiation resources, this process is not done in a single step, but rather in intervals based on external temperature and solar radiation changes. As the data recording interval in this experiment is 10 min, there are

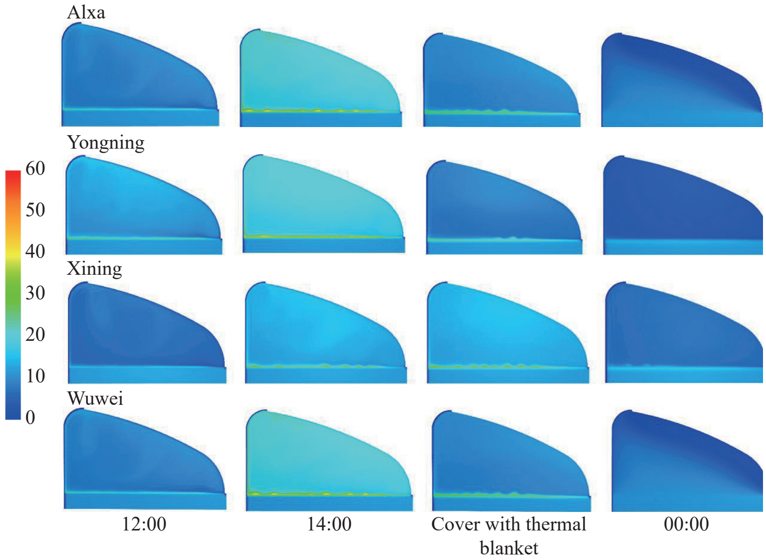


Figure 16 Variation of temperature field (°C) of assembled solar greenhouse in northwest China at different times

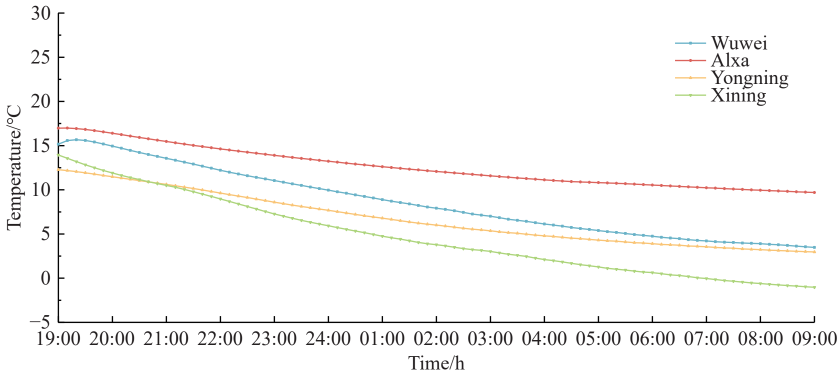


Figure 17 Night temperature variation of assembled solar greenhouse in different regions

abrupt changes in the heat transfer coefficient of the front wall during this process. This phenomenon also occurs due to the large temperature difference between indoors and outdoors during the uncovering and covering process. Therefore, in subsequent studies, the energy-saving method of uncovering and covering the insulation blanket and its impact on the heat transfer coefficient of the front wall should be taken into account to set the heat transfer coefficient of the front wall more precisely, thereby reducing errors.

Furthermore, due to experimental limitations, the coefficients for modular materials were only estimated by referencing the "Thermal Design Code for Civil Buildings" without actual measurements, resulting in some vagueness in their determination. Moreover, the greenhouse was assumed to be in an ideal state, and the model was simplified. Since the initial data for model establishment was obtained when the crops were in the seedling stage, it is considered that the crops have a relatively small impact on the thermal environment in the greenhouse, and the heat in this part is ignored. Meanwhile, no ventilation was carried out in the greenhouses during the experiment. Therefore, it is considered that the solar greenhouse is in an ideal sealed state, and the exchange of gases inside and outside the greenhouse and the uniform texture of the soil on the walls are not taken into account. To further improve the model's accuracy, future studies should more accurately measure and determine the structural parameters and physical properties of the greenhouse. Additionally, plants transfer energy to the environment primarily through conduction, convection, radiation, and latent heat of evaporation[31]. Since the crops in the greenhouse were in the seedling stage during the experimental measurement period, their impact on the thermal environment within the greenhouse was considered minimal and therefore neglected. However, in subsequent studies, the heat transfer aspects of crops to the environment should be fully considered.

Lastly, in evaluating the suitability of solar greenhouses, it is crucial to consider the overall climate conditions and basic climatic factors of the region. Researchers typically take into account multiple limiting factors such as temperature, light, wind, and snow[32]. While this study primarily focused on simulating the adaptability of modular solar greenhouses based on temperature and solar radiation, using indoor air temperature as a metric to determine the greenhouse's suitability in a given region, soil temperature is also a crucial factor. However, due to variations in soil properties across different regions, no field investigation was conducted on soil properties during the adaptability evaluation, and hence, no simulation of the soil environment was performed.

7 Conclusions

This study utilized the assembled solar greenhouse in the desert region of Xinjiang as the experimental greenhouse and constructed a two-dimensional dynamic thermal environment CFD simulation model for this solar greenhouse through a combination of experimentation and CFD numerical simulation. After verifying the accuracy of the model, an adaptability simulation was conducted for regions in northwest China that have the potential for developing Gobi agriculture based on the established CFD model of the assembled solar greenhouse. Through simulation, it was found that although the assembled solar greenhouse possesses strong heat preservation properties, due to its lack of heat storage structure, it cannot effectively store the excess heat inside the greenhouse during the daytime, resulting in excessively low nighttime temperatures that cannot meet the normal growth requirements of crops. Therefore, its promotion is geographically limited. The results indicate that the modular solar greenhouse is more suitable for promotion near the latitude of 39°N. This study not only provides theoretical support for the application and promotion of assembled solar greenhouses, but also introduces a new research method for the adaptability simulation analysis of other types of solar greenhouses.

Acknowledgements

This work was supported by the Key Research and Development Program Project of Xinjiang Uygur Autonomous Region (Grant No. 2022B02032 and Grant No. 2023B02024) and the National Natural Science Foundation of China (Grant No. 32260437).

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