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Simulation of Thermal Performance in a Typical Chinese Solar Greenhouse

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Abstract: A Chinese solar greenhouse (CSG) is used as a horticultural facility that provides high efficiency thermal storage performance to produce vegetables in winter. Quantifying the thermal performance of the surrounding structure including the back roof, soil, and north wall is helpful to improve the thermal performance of the CSG. The objectives of this study were to evaluate the performance of the heat transfer inside a CSG and analyze the thermal characteristics of different parts of the surrounding structures including solar gain, heat flux, and conduction heat transfer. The model was validated using experimental data from clear days and cloudy days during winter in Shenyang City, Liaoning Province, China. It indicates that the calculation method and model is valid and that EnergyPlus, which has been used in the thermal building field, can be used as a design tool to optimize solar energy storage and structure of greenhouses. The minimum temperatures of all components inside the CSG were maintained over 5 °C, even when the outside temperature reached to −22 °C, which showed good heat preservation in cold weather. Soil received the most radiation heat compared with other surfaces inside the CSG and contributed heat to the interior air to maintain air temperatures during the night.

Keywords: greenhouse; energy; simulation; solar

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1. Introduction

Due to their effective energy saving performance and usability in cold areas where night-time temperatures can be below −20 °C, Chinese solar greenhouses (CSGs) have been widely used in anti-seasonal agricultural production. CSGs enhance the use of solar energy and overcome cold temperatures, particularly in areas where heating is an essential component in other kinds of greenhouses. About 50% of the protected cultivation area is occupied by traditional Chinese solar greenhouses, making them one of the most important types of greenhouses in China.

CSGs have a south-facing front roof equipped with a removable thermal blanket to reduce heat loss at night, and walls on the north, east, and west sides. The south-facing front roof receives sunlight and is composed of transparent plastic material. Walls, which are built using bricks with heat-absorbing material on the inside and insulating material on the outside, absorb solar energy during the daytime and release energy into the greenhouse at night. Due to these unique construction techniques and materials, the thermal mechanisms of the interactions in CSGs are very different from other types of greenhouses [1–3]. The biggest difference between the solar greenhouse and other types of greenhouse is the course of energy transfer, which includes heat storage and heat preservation. The temperature inside the greenhouse is raised by solar energy, dropped due to sunset, and then maintained at a desirable temperature by the heat preservation mechanism of the greenhouse materials without an additional heating system [4,5].

Quantifying the thermal performance of surrounding structure including the back roof, soil, and north wall is helpful to improve the thermal performance of CSG. Many studies have focused on solar capture in CSGs. Yu et al. (2016) established a computational model to predict the optimal orientation for solar greenhouses located at different latitudes in China using extreme value theory [5]. Zhang et al. (2017) studied optical light transmittance characteristics of the solar greenhouse and developed a mathematical model to analyze the variations of incident angle and the transmitted light [6]. When the incident angle of the lighting surface increased from 25° to 35°, light intensity transmittance was improved by 22.8% and 20.7%, respectively [6]. Han et al. (2014) discussed the characteristics of direct solar radiation, diffuse solar radiation, and total solar radiation transmitted through the CSG [7]. Their results provide the basis for supplying theoretical solar radiation at different points within a solar greenhouse. Finally, to analyze the solar distribution and energy partition, Zhang et al. (2013) determined the solar radiation on soil wall and soil surface in a solar greenhouse [8].

However, due to the different heat gain abilities and thermal characteristics of construction materials, the heat flux variations are different in all parts of the CSG. The course of energy transfer has not been known clearly, especially under different outside climate conditions.

In the course of energy transfer, the energy is absorbed by the soil, wall, and roof at daytime and receives solar radiation energy released by the soil, north wall, and back roof at nighttime. Most heat balance models are too complex and difficult to establish in terms of both parameters and calculations, and the commercial software programs are too expensive for designers. Thus, we assumed that if we can use other simple methods to quantify the energy transfer. EnergyPlus software is used for energy analyses in buildings since it provides output parameters of thermal calculations [9]. Additionally, EnergyPlus is one of the newest freeware programs in physics of thermal building and it is widely used for building and designing HVAC systems and for dynamic simulation [10]. In heat energy balance models, environmental parameters and characteristics of construction materials can be accounted for, which allows for the prediction of temperature variations of all parts of a greenhouse. In each inside surface of a greenhouse, the incoming solar radiation is dynamic and varies with time. The greenhouse temperatures of the front roof, back roof, north wall, and soil change daily based on meteorological conditions [11]. Therefore, the thermal calculation method is necessary to predict both the temperature fluctuations and energy variations of the inside surface of greenhouses to optimize their structure and energy supply.

Thus, the objective of the present work was to develop a dynamic model to analyze thermal performance in typical CSGs using the EnergyPlus program. Moreover, this study discusses, for the first time, the energy transfer inside a greenhouse and the solar distribution on inside surfaces of a CSG in clear days and cloudy days. The overall heat balance of the greenhouse can be simulated in thermodynamics with different latitudes and weather conditions. The model can simulate temperatures of the air and greenhouse covers along with other important parameters such as the heat flux and solar radiation. Results from this study will be used to evaluate thermal performance in typical CSGs.

2. Materials and Methods

2.1. Experimental Greenhouse

The experimental Chinese solar greenhouse (CSG) had a 10 m span, 5.5 m ridge height, and was 60 m long, as shown in Figure 1. The CSG was located in Shenyang Agricultural University, at Shenyang (Latitude: 123.38 E, Longitude: 41.8 N), Liaoning Province, China. The climate belongs to continental climates. During the experimental period, no crops were grown inside the greenhouse. The north wall was a kind of composite structure, with a 0.48 m-thick layered wall with a 0.37 m-thick brick wall on the inside and a 0.11 m insulation layer outside. The north roof was 0.5 m thick and made of 4.0 mm SBS waterproof material, 0.15 m polystyrene board, and had 0.346 m of wood and Styrofoam insulation. The south roof was a 0.0015 m Po film with high optical performance, covered during the night with a thermal insulating blanket. The greenhouse environment and outside weather conditions were monitored as shown in Figure 2.

Figure 1. Exterior appearance of the Chinese solar greenhouse used in the experiment.

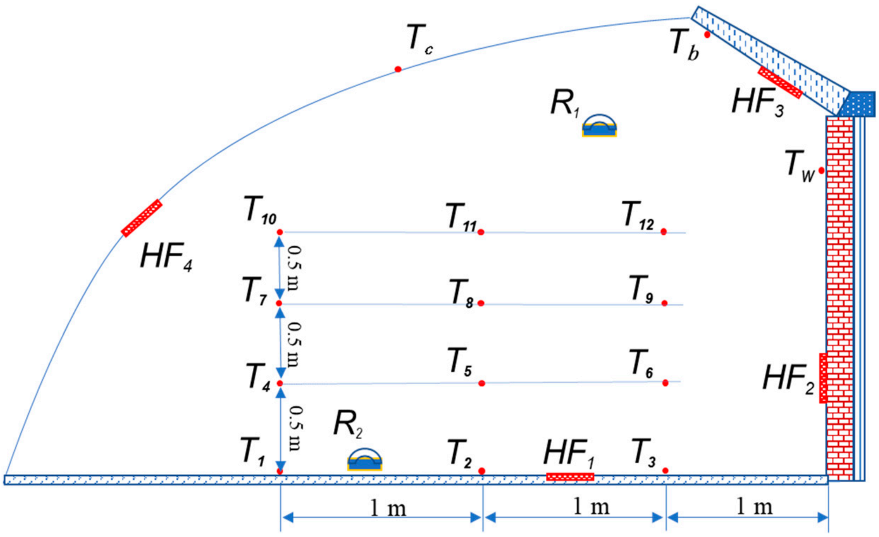

Figure 2. Distribution of sensors located inside the greenhouse for climatic parameters: temperature (*T*), radiation sensor (*R*), and heat flux plate (*HF*).

Climatic parameters outside the greenhouse were recorded by a meteorological station at a height of 10 m above the ground. The meteorological station measurement box had temperature and humidity sensors and the station also included sensors for solar radiation and wind speed and direction. Information about technical characteristics of sensors used to measure climate parameters were shown in Table 1. All sensors sampled every 10 min and recorded measurements in data loggers. Due to the uneven distribution of air temperatures inside the CSG, average values of temperature points were used as the measured values.

Table 1. Technical characteristics of sensors used to measure climate parameters.

Parameter	Sensor	Manufacturer	Range	Accuracy
T_i-Temperature	15 × RTR−71	Nikkeithermo, Inc., Tokyo, Japan	−233K~384K	±2.5%
R_s-Inside solar radiation, outside solar radiation	3 × Model MP 200	Apogee Instrument, Inc., Logan, UT, USA	360~1120 nm	±5%
HF-Heat flux	4 × HFP01 Heat flux plate	Hukseflux Thermal Sensors, Delftechpark, The Netherlands	−2000~2000 $W.m^{-2}$	−15%~5%
U_o-Outside wind speed	Anemometer 81,000	R. M. Young Company, Traverse City, MI, USA	0~50 m/s	± 0.05 m/s
U_w-Outside wind direction	Anemometer 81,000	R. M. Young Company, Traverse City, MI, USA	0~359.9°	±2°

To assess the effectiveness of the model in predicting the temperature on clear and cloudy days (the average solar radiation was lower than 200 W/m^2), simulated temperatures of the air inside the greenhouse, the inner wall face, back roof, and soil were compared with actual temperature from 27–31 December 2017 (cloudy days) and 1–6 January 2018 (clear days) as shown in Figure 3.

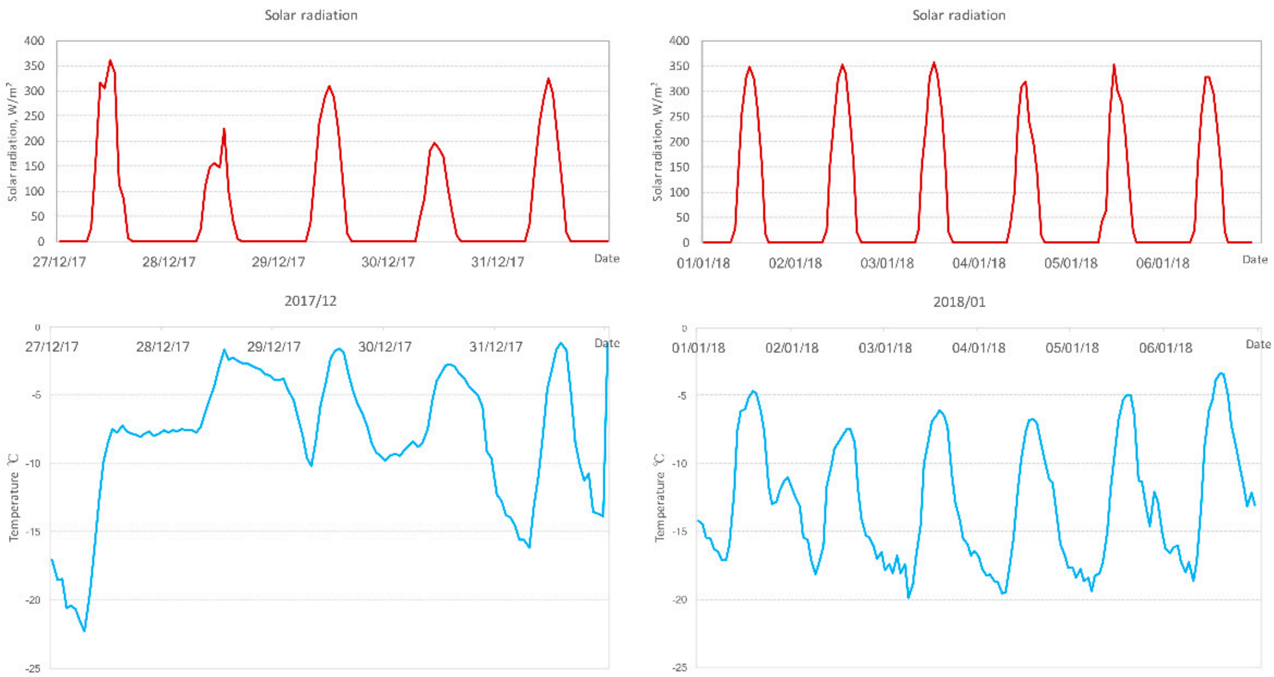

Figure 3. External climatic conditions during clear days (27–31 December 2017) and cloudy days (1–6 January 2018).

2.2. Description of the Model

A programming flow chart is designed based on the model as shown in Figure 4. In order to estimate the radiant and convective effects on each surface of the CSG, a 3D-model of CSG was established with the same size as the experimental greenhouse by using the free software Sketchup as shown in Figure 5. Each part of surroundings was individual and the sides of the CSG may be defined in different characteristics [12]. The air space was divided into outside CSG and inside CSG. The air inside the CSG was considered as the thermal zone. There is no typical material used on the greenhouse covering and thermal screen. To serve this purpose, the physical properties of surfaces, including the north wall, north roof, south roof, soil, were defined by using the pretreatment software Open Studio as shown in Table 2. This program allows to define new materials by defining new libraries of properties. The structure of each surface in the CSG was also added by defining the material of the inside layer, middle layer and outside layer as shown in Table 3. This helps us calculate the overall heat transfer coefficient of each surface by the structure and material properties.

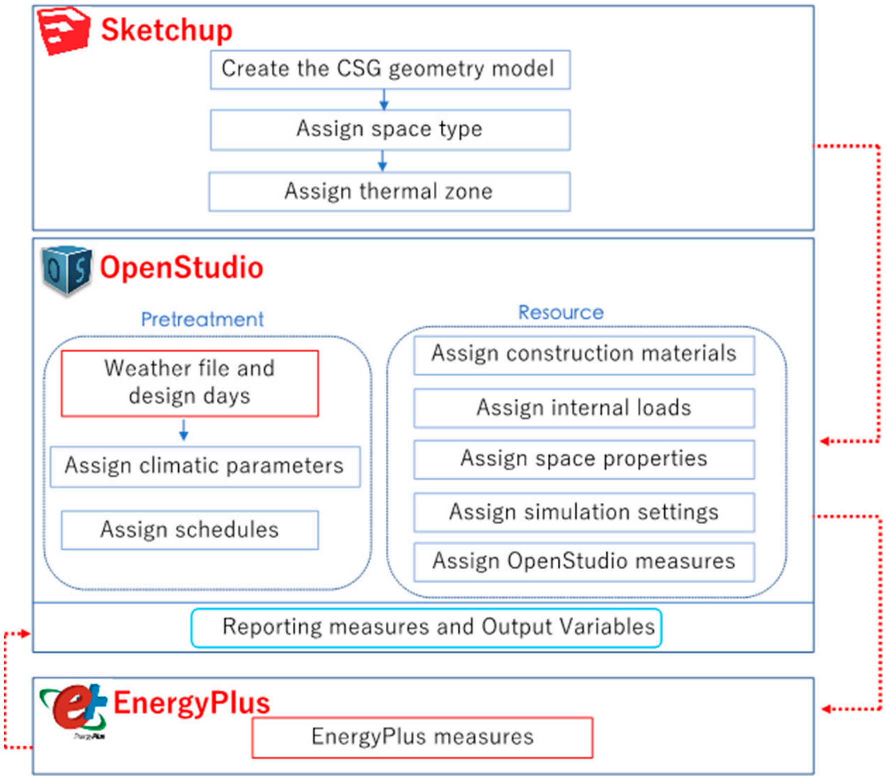

Figure 4. Flowchart for CSG simulation procedure.

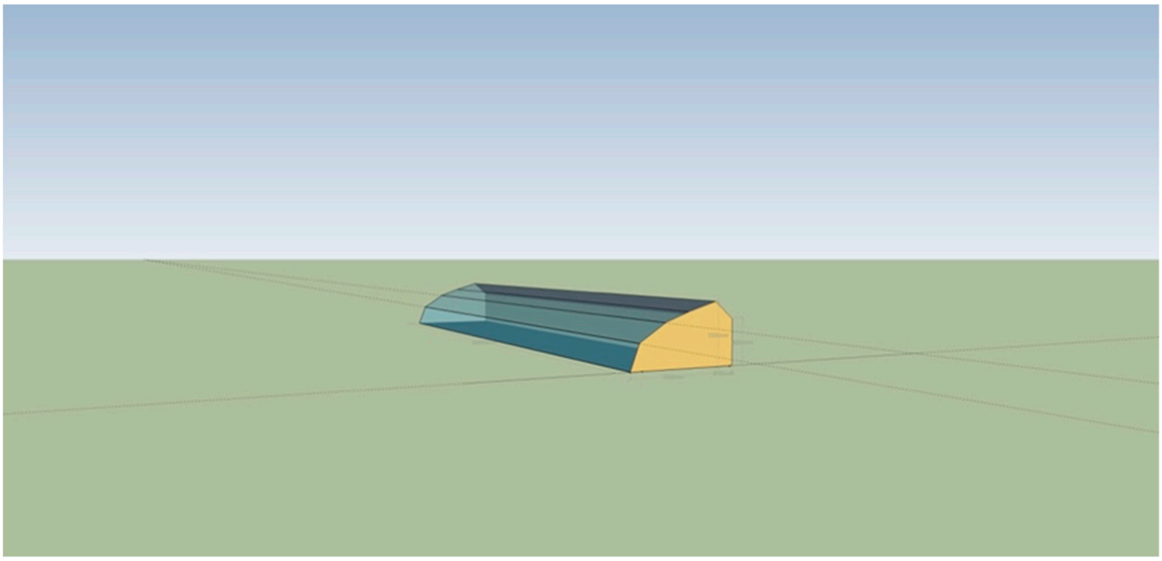

Figure 5. The geometry model of CSG in the simulation created by Skectchup.

Table 2. Physical properties of surfaces used in the simulation.

Layer Material	Thickness, L (m)	Density, P (kg m^{-3})	Specific Heat, C_p (J kg^{-1} K^{-1})	Thermal Conductivity (W m^{-1} K^{-1})
Brick	0.1016	1920	790	0.89
Insulation board	0.11	43	1210	0.03
Waterproof material	0.004	1.0	920	0.15
Wood and Styrofoam insulation	0.346	555.5	1091	0.05
Polystyrene board	0.15	8.0	1340	0.03
PE woven fabric	0.0015	40	819	0.33
Recycled cotton	0.036	10	920	0.058
Po film	0.0015	1400	1045	0.15
Soil	0.5	2000	1010	0.6
Air	-	1.3	1006	0.02

Table 3. Structural layers used in the simulation.

Structure	Inside Layer	Middle Layer	Outside Layer
North wall	Brick wall	Insulation board	
North roof	Waterproof material	Polystyrene board	Wooden formwork
Blanket	PE woven fabric	Recycle cotton	PE woven fabric
South roof	Po film	-	-

During the day, the thermal blanket was rolled up at 8:30 and rolled down at 16:30 in winter cultivation. The schematic for the thermal blanket was set in the assign schedules in the module of the Energyplus. The thermal blanket used in the simulation is the typically used thermal blanket in CSGs. Transmission loss through the south roof, north roof, back walls and soil are assumed in the simulation.

The simulation models the heat transmission among the outside air, the inside air, soil and other parts of greenhouse beginning at 8:30 with initial conditions for the inside air temperature T_i, outside air temperature T_o and temperature values in each inside surface.

2.2.1. The Energy Balance of the Greenhouse

In the CSG heat energy balance model, solar energy is the only energy from the outside as shown in Figure 6. In addition, all environmental parameters and characteristics of construction materials are accounted for the overall heat balance can be expressed as:

$$\rho V C_p \frac{dT}{dt} = Q_{gain} - Q_{loss} \quad (1)$$

The greenhouse air temperature was calculated from an energy balance, where ρ is the density, C_p is the air specific heat, V is the indoor air volume, dT is the change in air temperature for the given time period, dt is the time period (1 h), Q_{gain} is the total heat added to the system, and Q_{loss} is the total heat lost from the system.

To determine the internal energy distribution and temperature variations in the CSG, the heat balance method based on the internal faces of greenhouses was used on surrounding parts of the CSG, including the front roof, back roof, walls and soil.

This heat balance is generally modeled with four coupled heat transfer components:

(1) Short-wave radiation absorption and reflectance, meaning the incident solar radiation entering through CSG windows.
(2) The longwave radiation interchange, including the absorption and emittance of low temperature radiation sources, such as all other surfaces.
(3) Convection to the air.
(4) Conduction through the CSG element.

The equations for the walls, back roofs, soil and front roofs are presented in Sections 2.2.2–2.2.5.

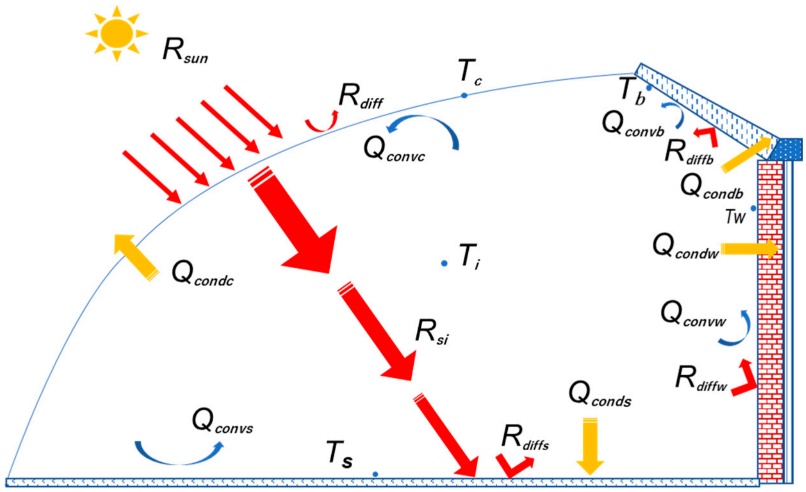

Figure 6. Illustration of the overall heat balance in the CSG.

2.2.2. Inner Surface Energy Balance of the Wall

The temperature of the inner face of the greenhouse wall was calculated from an energy balance (Equation (2)) as shown in Figure 7, where ρ_ω is the compound wall density, C_ω is the compound wall specific heat, V_ω is the compound wall volume, T_w is the compound wall temperature change for the given time period, dt is the time period (1 h), R_{siw} is the incident solar radiation to the wall, Q_{condw} is the conduction energy from the inner wall surface to the outdoor air, Q_{convw} is the convective energy exchange between the inner wall surface and the indoor air, and Q_{lwxw} represents the absorption and emittance of low temperature radiation sources.

$$\rho_w V_w C_w \frac{dT_w}{dt} = R_{siw} - Q_{lwxw} - Q_{convw} - Q_{condw} \quad (2)$$

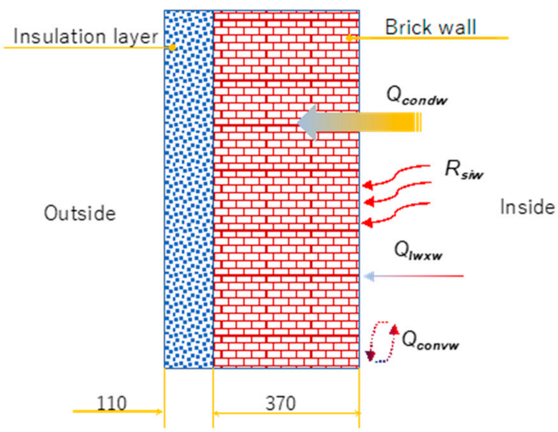

Figure 7. Heat transfers in the greenhouse wall (unit, mm).

2.2.3. Inner Surface Energy Balance of the Back Roof

The temperature of the inner face of the greenhouse back roof was calculated from an energy balance (Equation (3)) as shown in Figure 8, where ρ_b is the back roof density, C_b is the back roof specific heat, V_b is the back roof volume, T_b is the temperature of back roof change for the given time period, dt is the time period (1 h), R_{sib} is the incident solar radiation to the back roof, Q_{condb} is the conduction energy from the inner wall surface to the outdoor air, Q_{convb} is the convective energy exchanged between the inner wall surface and the indoor air and Q_{lwxb} represents the absorption and emittance of low temperature radiation sources.

$$\rho_b V_b C_b \frac{dT_b}{dt} = R_{sib} - Q_{lwxb} - Q_{convb} - Q_{condb} \tag{3}$$

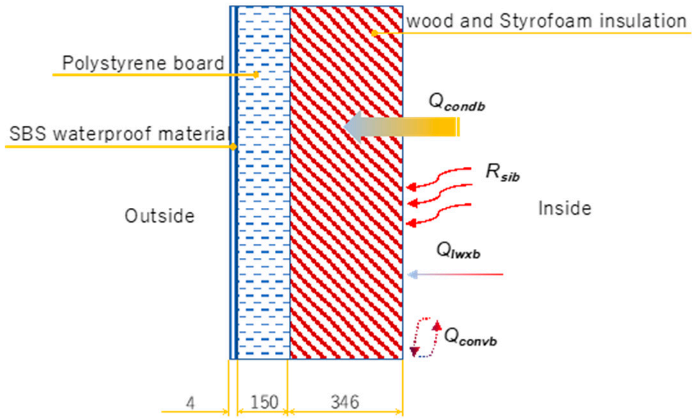

Figure 8. Heat transfers in the greenhouse back roof (unit, mm).

2.2.4. Inner Surface Energy Balance of Soil

The greenhouse soil temperature was calculated from an energy balance (Equation (4)) as shown in Figure 9, where ρ_s is the soil density, C_s is the soil specific heat, V_s is the soil volume, T_s is the soil temperature change for the given time period, dt is the time period (1 h), R_{sis} is the incident solar radiation to the soil, Q_{conds} is the conduction energy from the soil to the outdoor air, Q_{convs} represents the convective energy exchange between the soil and the indoor air and Q_{lwxw} represents the absorption and emittance of low temperature radiation sources. The soil layer 50 cm near the surface was closely related to the soil surface temperature, which was stable below 50 cm.

$$\rho_s V_s C_s \frac{dT_s}{dt} = R_{sis} - Q_{lwxs} - Q_{convs} - Q_{conds} \tag{4}$$

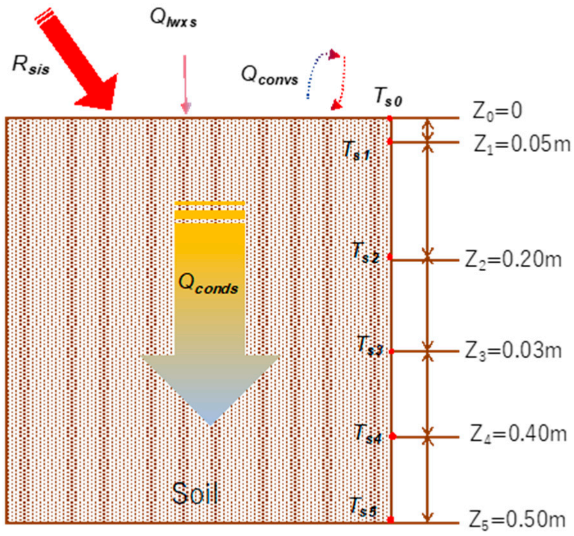

Figure 9. Heat transfers in the greenhouse soil.

2.2.5. Inner Surface Energy Balance of the Front Roof

During the day, the thermal blanket was rolled up and the front roof was covered by a Po film. At night, the thermal blanket was rolled down to mitigate inside heat loss. Therefore, the solar radiation (R_{sic}) is zero and the thermal conductivity of the front roof increased. The thermal blanket in the CSG was taken as an exterior shade outside the film and shade properties were set based on the operation schedule.

$$\rho_c V_c C_c \frac{dT_c}{dt} = R_{sic} - Q_{lwxc} - Q_{convc} - Q_{condc} \tag{5}$$

The greenhouse air temperature was calculated from an energy balance (Equation (5)) as shown in Figure 10, where ρ_c is the film density, C_c is the film specific heat, V_c is the film volume, dT_c is the air temperature change for the given time period, dt is the time period (1 h), R_{sic} is the incident solar radiation to the film, Q_{condc} is the conduction energy from the film to the outdoor air, Q_{convc} represents the convective energy exchange between the film and the indoor air and Q_{lwxc} represents the absorption and emittance of low temperature radiation sources.

The effective density of the thermal blanket and walls used in the calculations was calculated as the average over all the layers:

$$\rho_{eff} = \frac{1}{D \sum_{layers} \rho_i d_i} \tag{6}$$

where D is the total layer thickness in m, d is the individual layer thicknesses in m, ρ is the material density in kg m^{-3} and i is the layer number.

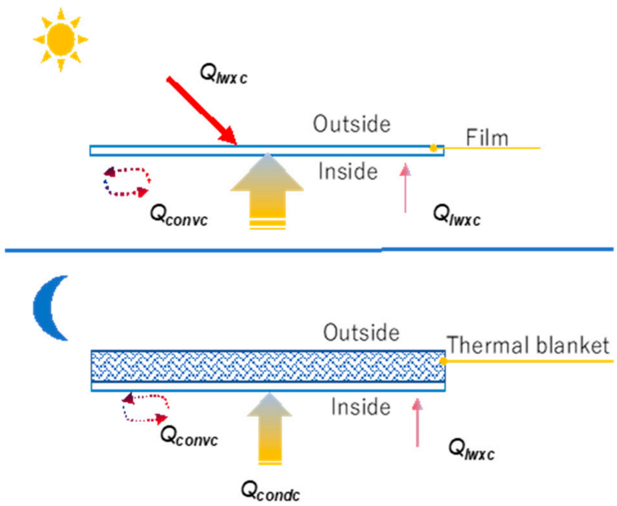

Figure 10. Heat transfers in the greenhouse front roof.

The effective specific heat was calculated as the weighted average of the specific heats of individual materials:

$$C_{p,eff} = \frac{1}{\left(\rho_{eff} D\right) \sum_{layer} \rho C_{p,i} d_i} \tag{7}$$

The effective thermal conductivity K_{eff} was calculated so that the equivalent thermal resistance would be the same as for the series of individual layers:

$$\frac{D}{K_{eff}} = \sum_{layers} \frac{d_i}{k_i} \tag{8}$$

3. Results

3.1. Model Validation

3.1.1. Temperature Variations

Solar radiation was the only energy that reached inside the greenhouse, so the temperature inside the greenhouse varied with daily solar variation. The simulation results and were shown in Figures 11–14. Fluctuations of all simulated temperatures were consistent with measured temperatures for cloudy days and clear days. Minimum temperatures of all components inside the CSG were maintained over 5 °C, even when the outside temperature reached to −22 °C, which showed good heat preservation in cold weather. The determination coefficients of simulated temperatures with measured data were R^2 = 0.89–0.95 and R^2 = 0.86–0.93 for cloudy days and clear days, respectively. The best result was obtained for soil temperature at R^2 = 0.95 on clear days.

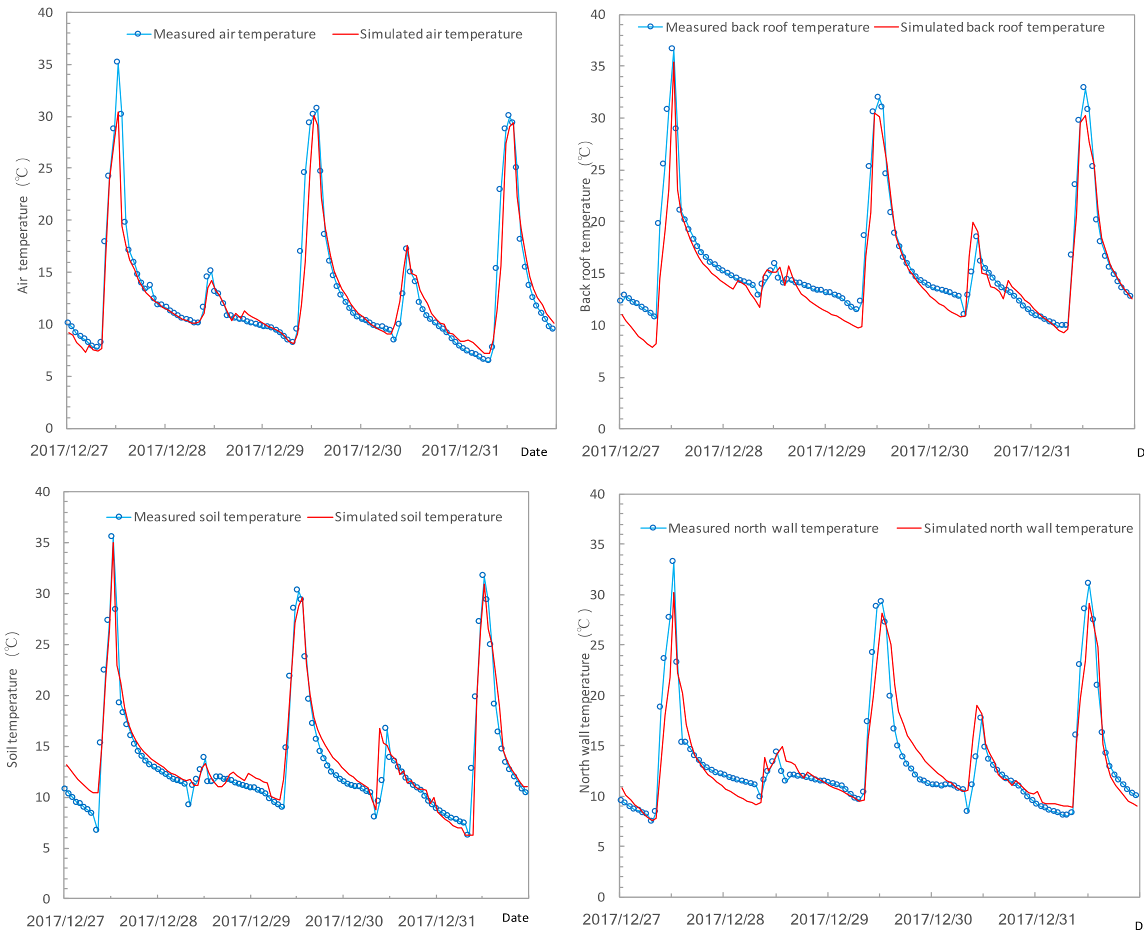

Figure 11. Comparisons of simulated and measured temperature variations during cloudy days.

The maximum air temperature difference between simulated and measured values appeared at noon with a range of 1.8–2.4 °C for the clear days, which was a little higher than on a cloudy day, which had a range of 1.1–1.6 °C. This was because the simulated data was the average temperature inside the greenhouse and the consistency of air temperature on cloudy days was higher than that on sunny days.

On clear days, there were obvious periodic changes of daily air temperatures inside the greenhouse. The maximum air temperatures were over 30 °C at noon and the minimum air temperatures were above 12 °C at night. Air temperature decreased rapidly after sundown, but due to the high thermal insulation of the greenhouse material surroundings, the air temperature inside the greenhouse was maintained over 12 °C, indicating that the CSG could maintain vegetable production.

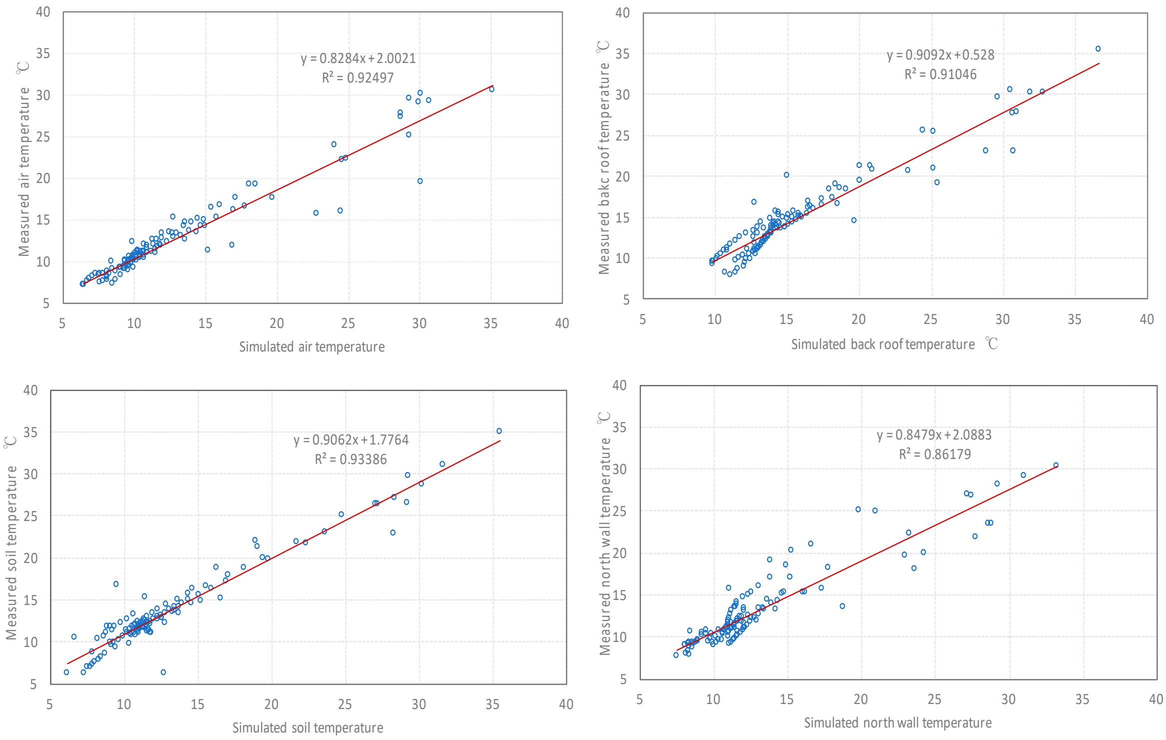

Figure 12. Relationship between simulated and measured temperature variations during cloudy days.

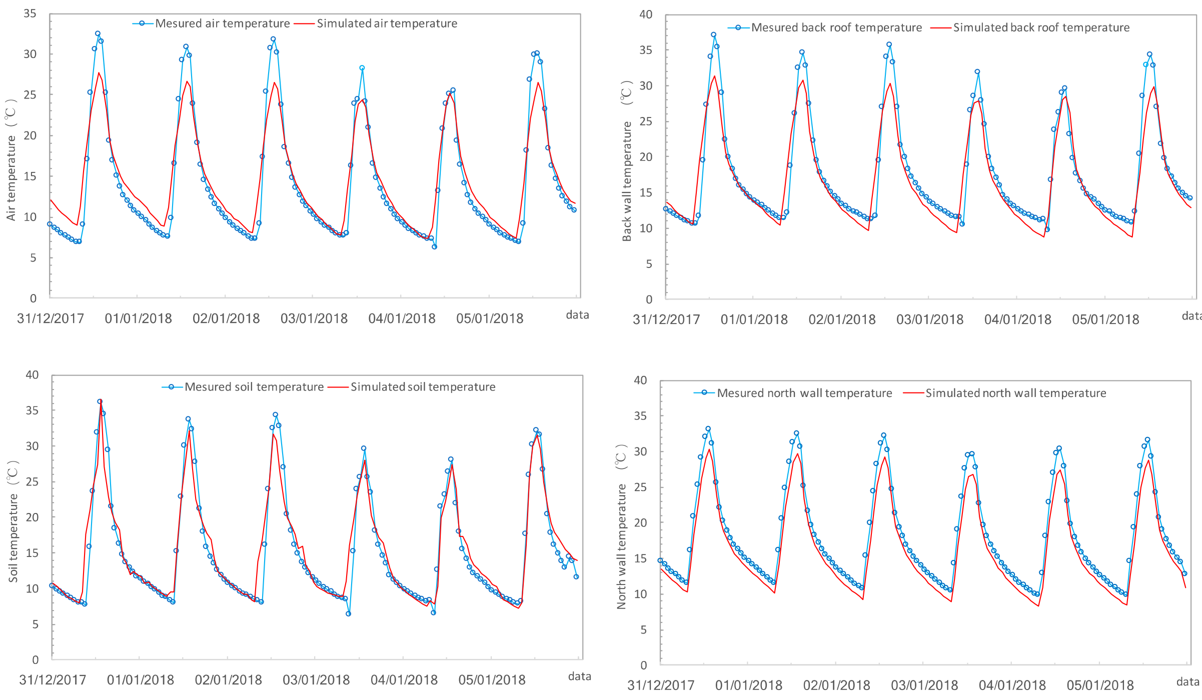

Figure 13. Comparisons of simulated and measured temperature variations during clear days.

The average daily air temperature difference between simulated and measured data was 1.2 °C on clear days and 1.8 °C on cloudy days. These errors were in the range of other researchers. Tong and David (2009) found simulated average temperature differences of around 1.0 °C on clear days and 1.5 °C on a cloudy day in a 12 m span by 5.5 m solar greenhouse using CFD [13]. Du et al. (2012) divided a greenhouse into small sections to simulate temperature variation and found a simulation error of the air at 1.5 °C [14]. Hassanein et al. (2015) examined the impact of using solar energy for underground biogas digesters and simulated the temperature variations in a solar greenhouse [15]. The range of results observed in the simulation had differences of 0.15 °C during the sunny day and 0.34 °C during the cloudy day.

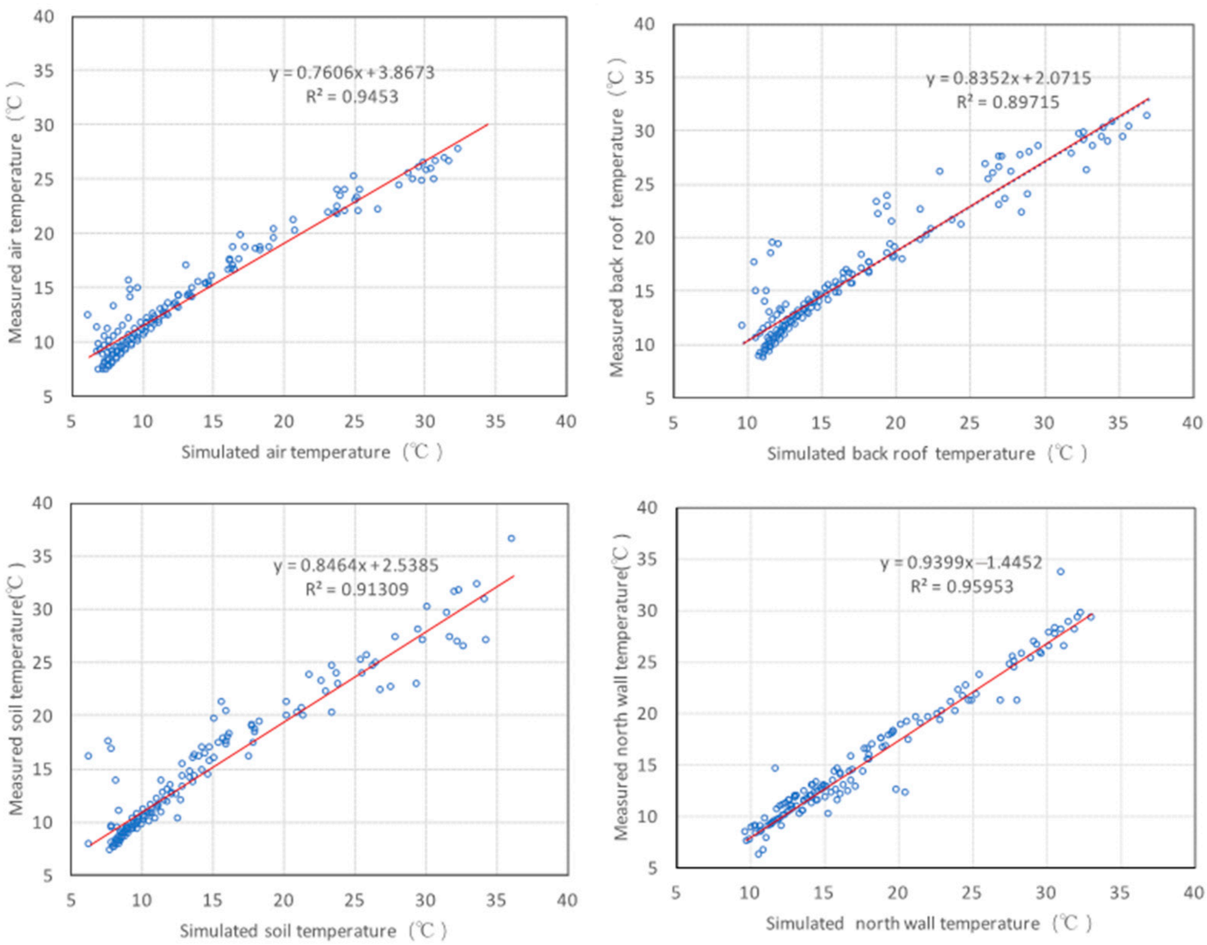

Figure 14. Relationship between simulated and measured temperature variations during clear days.

The back roof is important in constructing the appropriate geometry of the greenhouse and increasing the thermal capacity of the whole greenhouse. Measured values of the temperature at the back roof were 1.5−2.2 °C higher than those simulated at the peak of the air lines. The average temperature difference was almost the same as that reported by Meng et al. [16].

The maximum temperature difference between simulated values and measured values in soil was about 1.5 °C, which was less than in other parts of the greenhouse, since a constant temperature was assumed at 0.5 m. Determination coefficients on cloudy and clear days were consistent at 0.93 and 0.91, respectively. These coefficients were similar to those found by Audberto et al. (2017) in soil temperature simulations conducted in April and May [17]. Meng et al. (2009) also obtained similar results with a soil temperature error of ±1.4 °C [16]. Consistency between the simulation and validation data emphasized that the simulation results or model could be used to predict the soil temperature in a CSG.

The simulated surface temperatures on the inside of the north wall were consistent with the temperature measurements on clear days with R^2 = 0.95. The model used in the present work included different discharge coefficients such as thermal absorption, solar absorption, and visible absorption. The model also focused on the incident solar radiation to the wall and the conduction energy from the inner wall surface to the air, which are the biggest differences between solar greenhouses and other types of greenhouses. The use of solar absorption and visible absorption improved the estimation of north wall temperature. Other greenhouse temperature prediction models used different coefficients. Tong et al. (2014) discussed the effect of an insulation layer on the dynamic thermal performance of wall configurations using the moisture transfer coefficient for a layered wall [18]. Zhang et al. (2016) established a comprehensive evaluation model including the parameter of absolute heat flux to achieve the best wall thickness [19]. Du et al. (2012) used the heat transfer coefficients of the north wall in the heat expression model to simulate air and soil temperatures [14].

The temperature inside the wall surface was higher than the air temperature, which shows that the wall absorbed the solar energy transmitted through the greenhouse and that this energy can be returned to the air during the night. Similar results were reported from previous studies in solar greenhouses [10,11,18,20].

3.1.2. Heat Flux Variations in the Greenhouse Construction Materials

Due to the different heat gain abilities and thermal characteristics of construction materials, the heat flux variations are different in all parts of the CSG. The solar heat portion of the energy is absorbed by the soil, wall and roof at daytime and receives solar radiation energy released by the soil, north wall and back roof at nighttime.

During 27–31 December 2017, there were two cloudy days on the 29th and 30th, which showed solar radiation inside the greenhouse below 150 w/m^2.Variations of heat flux on the back roof, soil, and north wall were consistent with measured temperatures for sunny days and cloudy days. Based on the experimental greenhouse conditions, the simulated heat loss from the greenhouse is shown in Figures 15–18 The soil received the maximum amount of solar energy compared with the back roof and the north wall. At daytime, the main heat loss was from the soil and it fluctuates with solar variation and temperature differences between indoor and outdoor. The maximum heat flux at daytime was above 80 W/m^2 and the average heat release was near 20 W/m^2 at night after the thermal blanket was rolled down. It is obvious that the heat loss decreased with the thermal blanket. After sunset, there was no heating resource inside the greenhouse, but the heat loss was in a stable state. The soil and walls continue to act as an energy reservoir supplying energy to the air in the greenhouse.

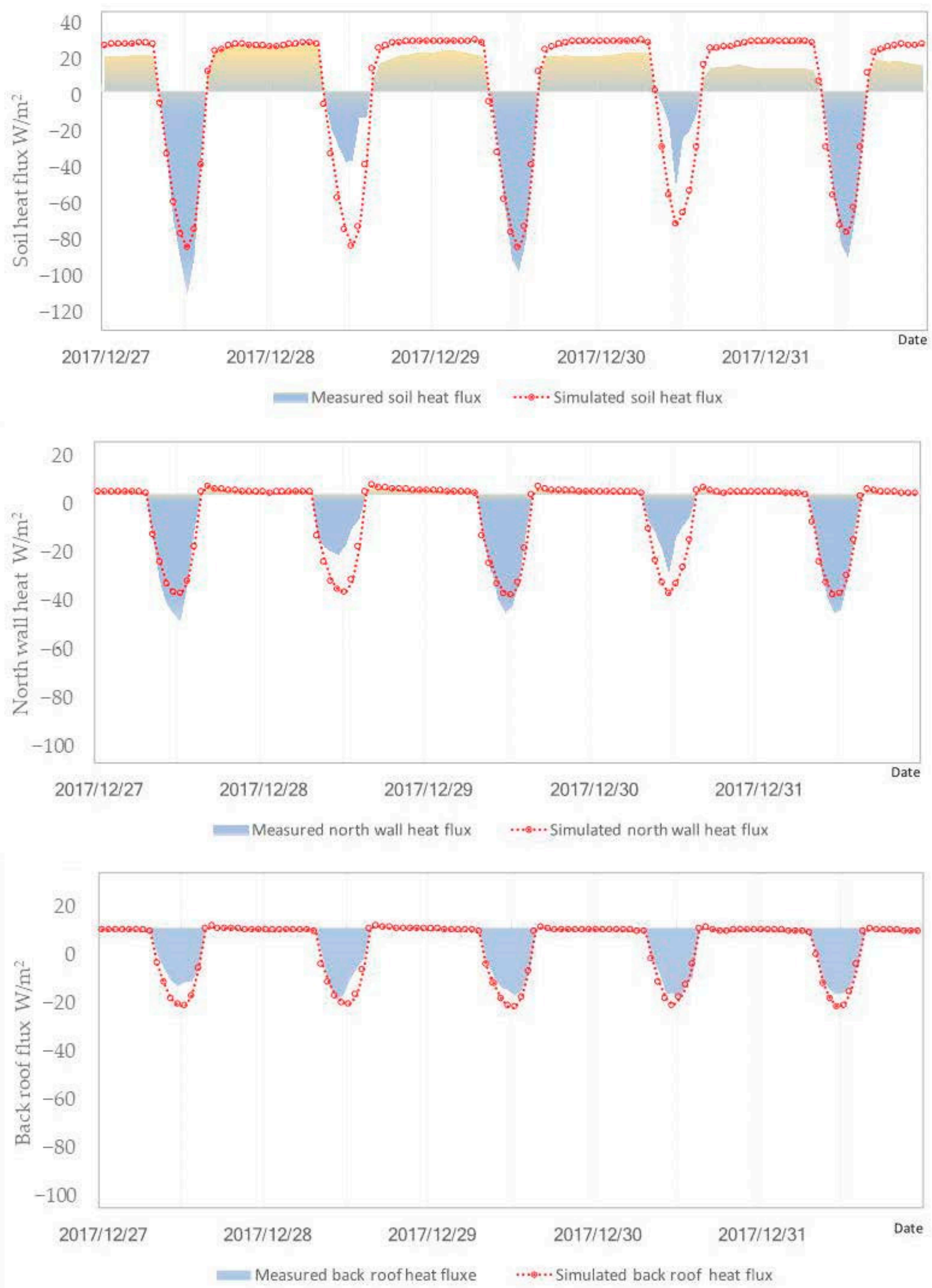

Figure 15. Comparisons of simulated and measured heat flux variations during cloudy days.

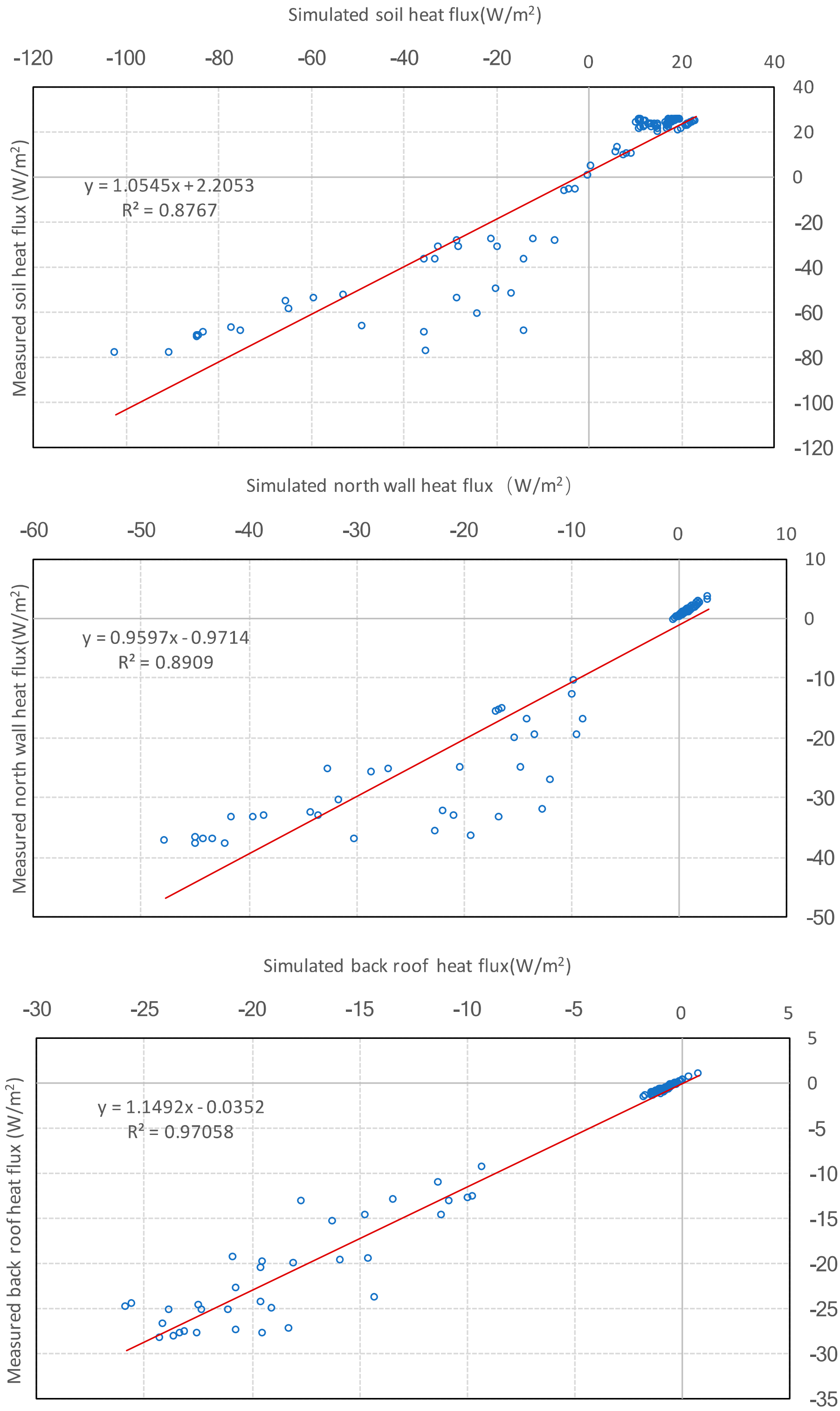

Figure 16. Relationship between simulated and measured heat flux variations during cloudy days.

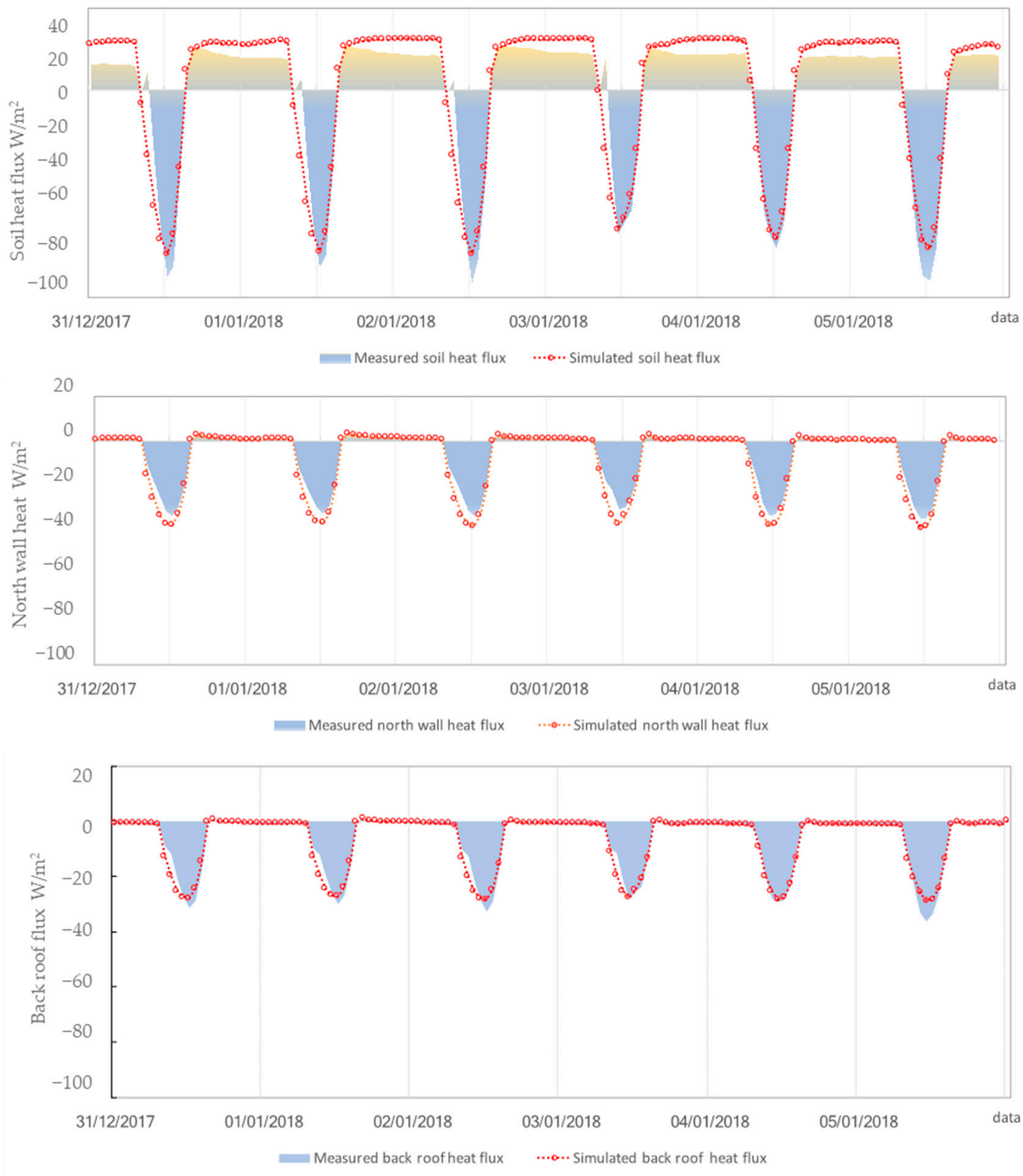

Figure 17. Comparisons of simulated and measured heat flux variations during clear days.

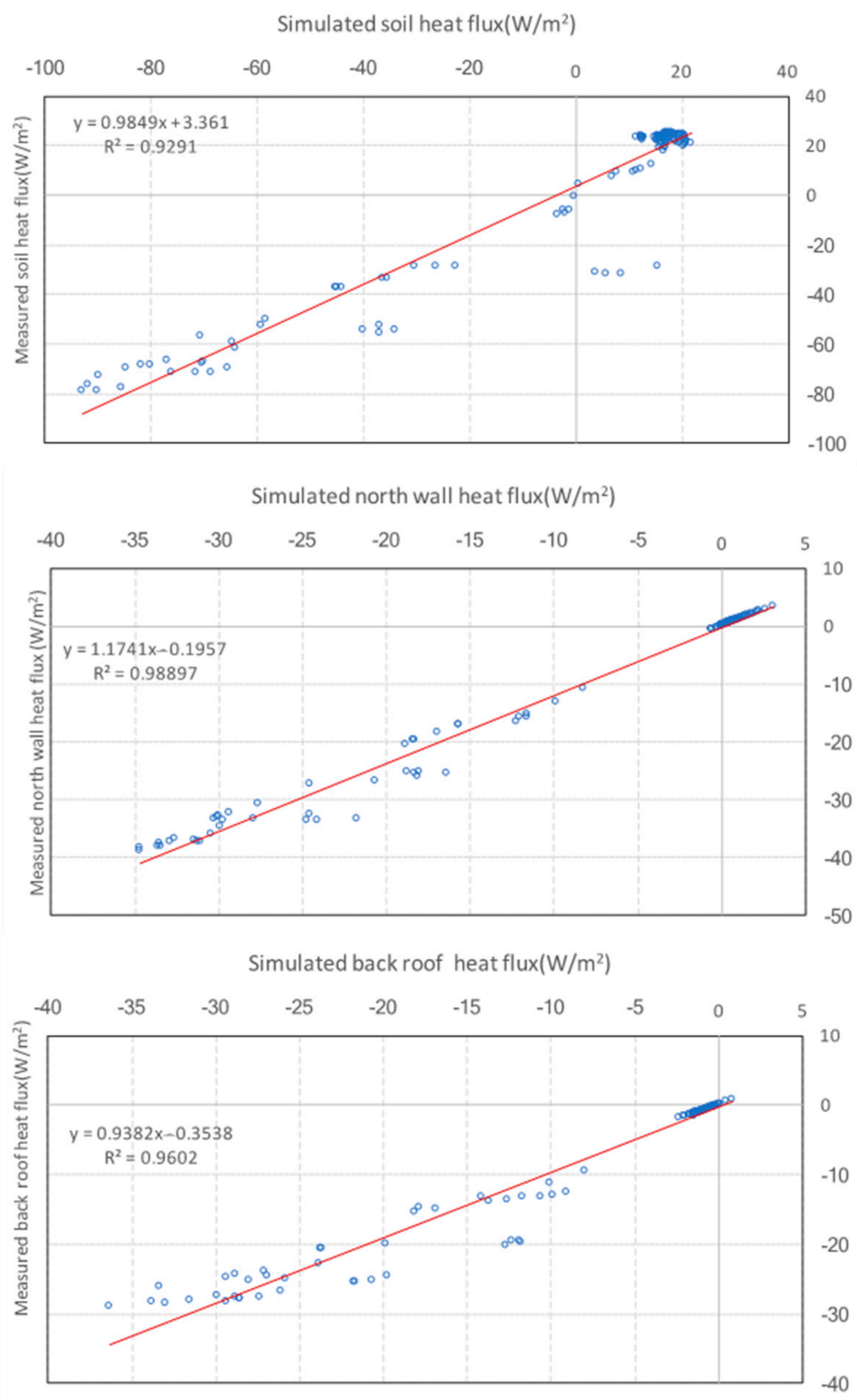

Figure 18. Relationship between simulated and measured heat flux variations during clear days.

3.2. Simulation Research

3.2.1. Solar Radiation Gain on the Inside Surfaces of the Greenhouse

Considering the position, geometry, and materials of the greenhouse, the solar radiation energy received by the soil, north wall, and back roof were simulated by using the experimental greenhouse. The inside surface solar radiation varies considerably with the solar radiation outside during the day. On clear days, the solar fraction of the soil was about 100 W/m^2 at noon as shown in Figure 19. The second highest absorption is the north wall and the back roof had the lowest absorption.

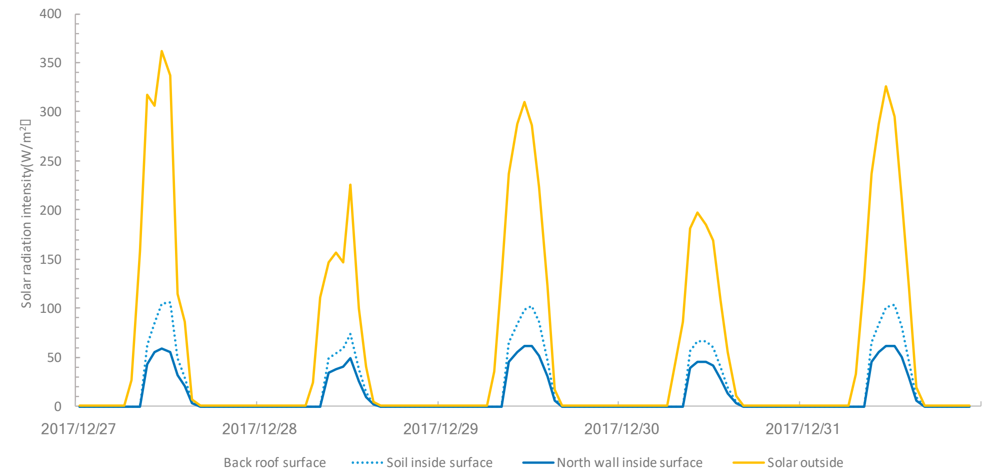

Figure 19. Solar radiation heat gain rate inside the surfaces of the CSG on cloudy days.

On cloudy days, the sequence of the energy distribution was the same as that on clear days, but the decrease in quantity of energy is obvious. The solar energy received by the soil was about 70 W/m^2 and the north wall absorption was below 50 W/m^2. The simulated results are consistent with the solar radiation data of simulated surfaces in another heat calculation study [19].

Compared with the outside solar energy, the solar energy reaching the inside face of the CSG is only a part of the energy received by the greenhouse. This suggests that to obtain maximum solar radiation and heat gain, the surface areas of the surfaces exposed to the sun should be increased.

3.2.2. Conduction Heat Transfer on the Inside Surfaces of the Greenhouse

Solar energy is transmitted into the greenhouse and then absorbed by the soil, north wall, and other surfaces. The daily conduction heat transfer variations on the soil, back roof, and north wall surfaces are in Figures 20–22. The surface conduction heat transfer varied with the solar radiation at day time and remained nearly constant.

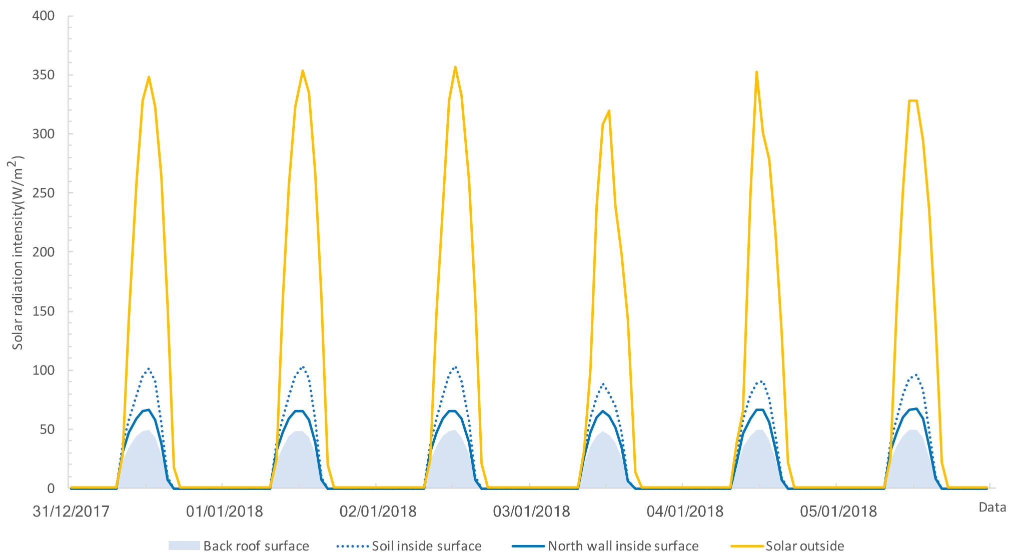

Figure 20. Solar radiation heat gain rate inside the surfaces of the CSG on clear days.

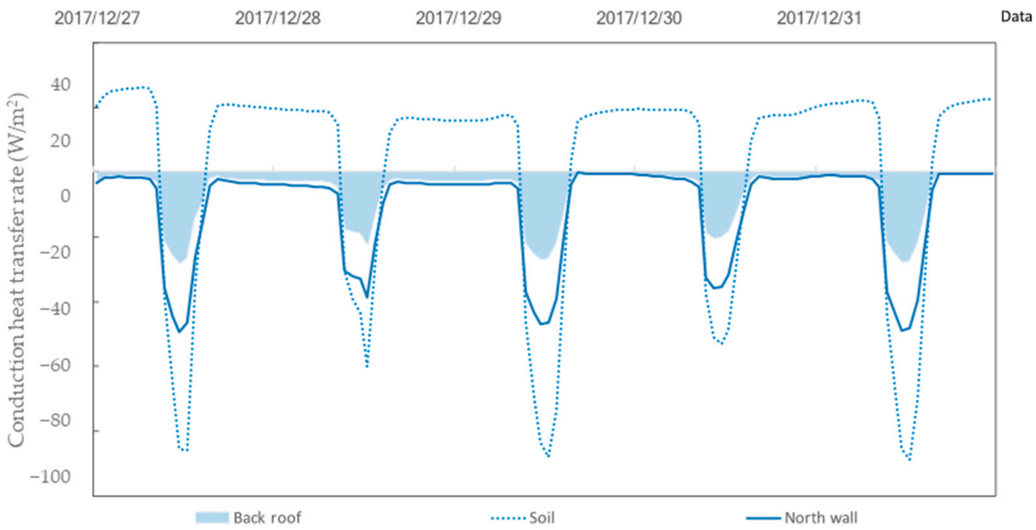

Figure 21. Conduction heat transfer on the inside surfaces of the CSG on cloudy days.

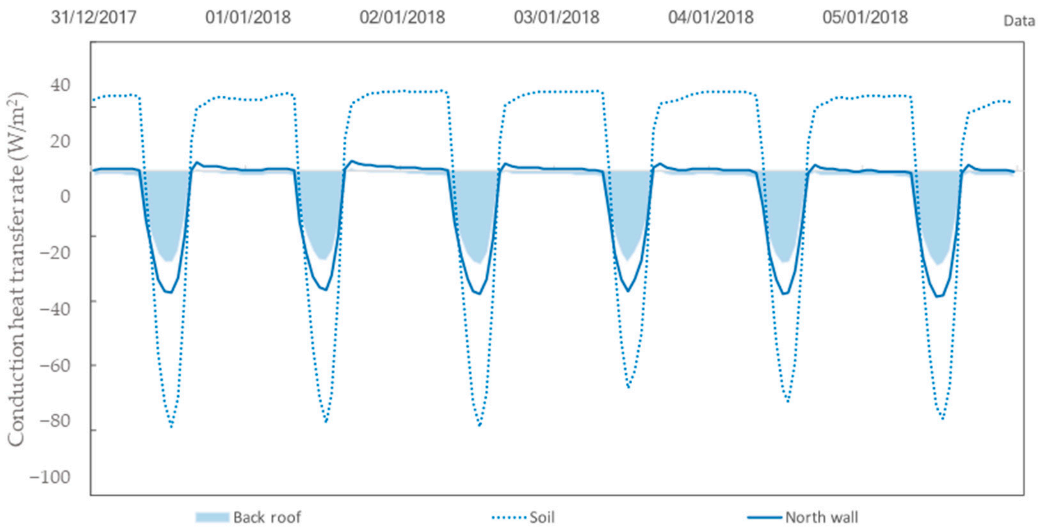

Figure 22. Conduction heat transfer on the inside surfaces of the CSG on clear days.

The soil conduction flux indicated that the soil layer was transferring heat upwards, thus positively contributing to the soil surface energy balance on both clear and cloudy days. On clear days at night, the soil conduction flux remained at 20 W/m^2, suppling energy to compensate for the energy loss of the greenhouse. These results confirmed those of Baille et al. (2006), who reported a night energy balance of an air-heated greenhouse in mild-winter climatic conditions where the soil conduction flux was maintained at 19 W/m^2 [21]. These estimates were consistent with those of Garzoli and Blackwell (1981), who reported a positive heat contribution from the soil in a greenhouse heated by the direct burning of propane gas [22]. The average values of soil conduction flux in February (19.2 W/m^2) and March (16.5 W/m^2) were equivalent to an energy release from the soil, during a 12 h night period, of about 0.9 and 0.7 MJ/m^2, respectively.

3.2.3. Convection Heat Transfer on the Inside Surfaces of the Greenhouse

The variations of convection heat transfer were similar to conduction variations, but the values were relatively small. The maximum convection heat transfer in soil was not over 20 W/m^2 (Figures 23 and 24) at day time and the convection heat transfer was not over 10 W/m^2 at night. The convection heat transfer on the back roof and north wall were smaller than those of the soil on clear and cloudy days. These convection variations indicated that in the relatively enclosed CSG during winter, convection heat transfer accounted for 10–11% of the absorbed solar energy. The indoor air was warmed by the convection heat transfer from the soil, north wall and back roof and the soil provided most of the heating.

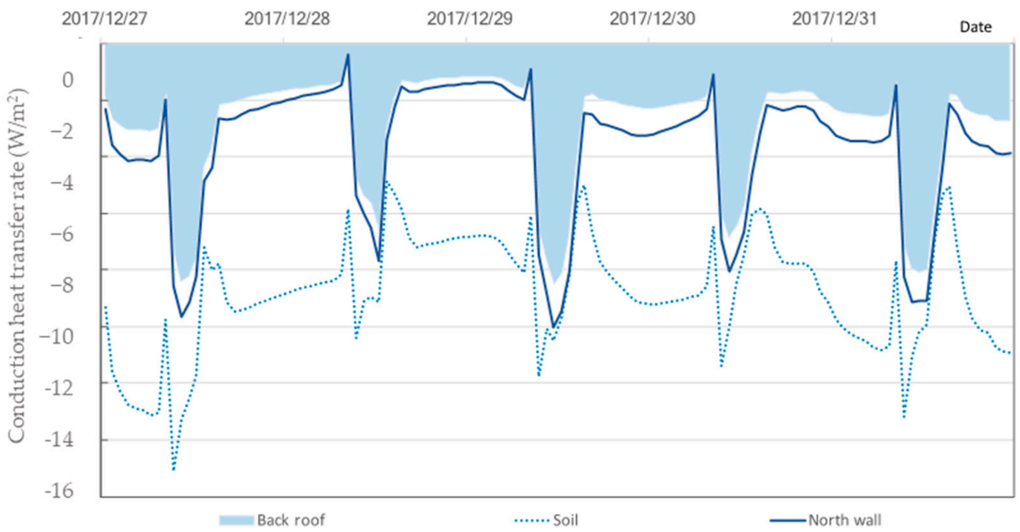

Figure 23. Convection heat transfer on the inside surfaces of the CSG on cloudy days.

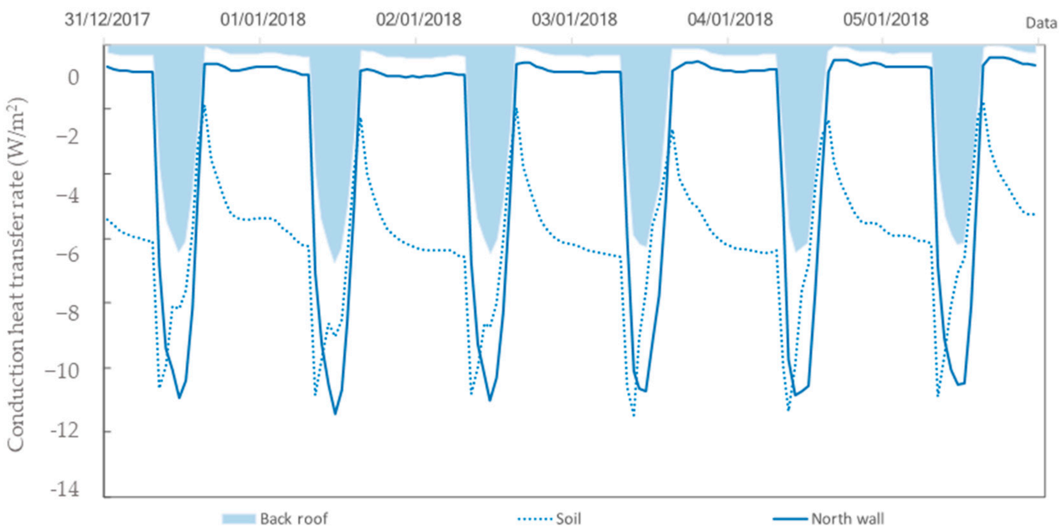

Figure 24. Convection heat transfer on the inside surfaces of the CSG on clear days.

4. Discussion

The model provided in this study can be applied to accurately and conveniently assess the thermal performance of the CSG. By including output for different parameters such as inside face temperature, energy reaching the greenhouse and heat loss, the energy distribution combined with thermal characteristics of the CSG can be predicted dynamically. Predictions of these characteristics are critical for optimizing the structural materials and geometry of the greenhouse. The temperature properties can be studied using different climate data and different construction materials.

Consistency between the simulation and validation data emphasized that the simulation results or model could be used to predict the temperature. The average daily air temperature difference between the simulated and measured data was 1.2 °C on clear days, while the temperature difference was 1.8 °C on cloudy days. These results were within the range observed in other studies.

Simulation and modeling for different locations can be conducted easily using a location weather data file and the software used in the present study (Sketch Up, Open Studio, and EnergyPlus). Comparison of the simulated and measured data for cloudy and clear days showed that greater errors in the estimation of inside air temperature occurred at noon. This was due to the uneven distribution of air temperatures inside the solar greenhouse, making simulation of that time more irregular. Despite the ambient temperature changing from −5 °C to −20 °C, the inside of the CSG remained approximately 10 °C without heat, indicating that the thermal effect of the north wall, back roof and blanket could limit energy released to the outside.

Based on the simulation data, the solar radiation heat could be absorbed by the inside surfaces of the greenhouse and the soil supplied as input heating energy at night. In some studies of greenhouse energy balance, the values of soil heat transfer were assumed to be relatively small and thus neglected [23]. This assumption may be valid in the case of greenhouses with high-density crops, where the soil is largely shaded by the canopy, and in which the relative weight of the soil flux contribution is small. On the contrary, in greenhouses with low leaf area crops and no heating, the soil energy storage and release over a 24 h cycle is far from negligible [24]. Thus, the planting schedule and leaf area index management of crops inside greenhouses should also be considered with the whole heat balance of the greenhouse.

The optimum greenhouse design is usually to capture the maximum solar energy during the winter and improve the inside air temperature [25,26]. Due to the importance of the soil temperature not only in maintaining the inside air temperature but also in cultivation, thermal protection for soil should be included, especially at night. Future work can involve improving the solar radiation received through the south roof and reducing heat transmission. In addition, further economic analysis that considers the thermal material characteristics of surroundings in the greenhouse and surface radiation properties should be conducted.

A dynamic model of a Chinese solar greenhouse (CSG) was developed in this study, based on energy balance equations using EnergyPlus. This model allowed us to estimate the air, soil, north wall, and back roof temperatures, the construction heat flux and the heat gain of inside surfaces of the greenhouse. The model considered the whole course of heat transmission including heat conduction, heat convection and heat radiation. The geometry and thermal characteristics of the surrounding material and the effect of the application of a thermal blanket were also included in the model. The simulation results showed that the model predicted the performance of the greenhouse consistent with measured data. It indicates that the calculation method and model is valid and that EnergyPlus, which has been used in the thermal building field, can be used as a design tool to optimize solar energy storage and structure of greenhouses.

5. Conclusions

To evaluate the performance of the heat transfer in CSGs, a dynamic model of a Chinese solar greenhouse (CSG) was developed in this study by using EnergyPlus. By combining the use of pretreatment software and EnergyPlus, it showed a high flexibility in the calculation of the energy transfer in the CSG as well as potential for application in other building structures.

By simulating the energy transfer of the inside of a greenhouse and analyzing the thermal characteristics of different parts of the surrounding structures, it can be found that minimum temperatures of all components inside the CSG were maintained over 5 °C, in both clear days and cloudy days, which showed good heat preservation in cold weather. Soil received the most radiation heat compared with other surfaces inside the CSG and contributed heat to the interior air to maintain air temperatures during the night. In order to obtain more comprehensive and practical predictions from greenhouse models, different thermal materials and surface radiation characteristics parameters should be discussed in addition to considering the material cost in future studies.

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