A computational model to determine the optimal orientation for solar greenhouses located at different latitudes in China

Chao Chen[a*], Yin Li[a], Na Li[a], Shen Wei[b], Fengguang Yang[a], Haoshu Ling[a], Nan Yu[a], Fengtao Han[a]

[a] *College of Architecture and Civil Engineering, Beijing University of Technology, Beijing* 100124, *P R China*

[b] *Bartlett School of Construction and Project Management, University College London (UCL), WC1E 7HB, London,UK*

[*]*Corresponding author: Chao Chen, Tel: +86 10 67391608-201; Fax: +86 10 67391608-201.*

E-mail address: chenchao@bjut.edu.cn

ABSTRACT

The orientation of solar greenhouses has a significant impact on the ability of the solar radiation energy received by the south pitched roof. In this study, based on the law of the solar trajectory and the theory of heat balance, the calculation model of the opening and closing time of the thermal insulation curtain for the south pitched roof of solar greenhouses in different latitudes is given. Using Extreme Value Theory, a method that can be used to determine the optimal orientation for solar greenhouses, i.e. to maximize the solar energy collection, has been proposed, with a consideration of impact from geographical latitude. To validate the proposed method, both simulation data (by EnergyPlus) and field measured data have been used and a good agreement has been observed. The model has been implemented to predict optimal orientations of solar

greenhouse located at nine different regions, where solar greenhouses are mainly used in the northern China.

Keywords: Solar greenhouse; Optimal orientation; Simulation; Field measurement

1 Introduction

Solar greenhouse is the local facilities agricultural architecture proposed by China, which can provide a suitable heat and humidity environment for vegetable crops by passive absorption of solar radiation (Ling et al., 2014; Wang et al., 2014; Ling et al., 2015). The orientation of solar greenhouse not only affects the sunshine time acceptable in solar greenhouse directly, but also affects the area of sunlight exposed to the walls and the ground of the solar greenhouse during the effective sunshine time (Dragicevic, 2011; Gupta and Chandra, 2002; Stanciu et al., 2016). Because of the dynamic change of solar trajectory and solar radiation intensity, it is important to determine the optimal orientation for solar greenhouses located at different latitudes, hence providing a balance between the indoor environment required by the vegetables or plants and greenhouse energy requirement.

However, the determination of the optimal orientation of greenhouse is not only directly related to the facility horticulture subject, but also closely related to the discipline of building physics and the discipline of building thermal environment. In the past, a lot of research of solar greenhouse orientation make the cultivation of vegetable crops as the center (Choi et al., 2008; Cao et al., 2009; Cheng et al., 2014). Because of the lack of support of the thermal theory of building, most of the solar greenhouse orientation is determined according to the field experience and lacks the scientific and quantitative guidance. The solar greenhouse orientation is just qualitative required by the Chinese standard of Structure and Properties Requirement for Sunlight Greenhouse and Plastic Tunnel (GB 19165-2003) CAAE. (2003): *“solar greenhouses should be facing south, and the degree of movement from the true south to the west or east should be less than 10°”*.

In the study of greenhouse orientation, many scholars have carried out a large number of studies on the orientation of the glass greenhouse with double roofs. Dragicevic (2011) have tried to find the optimum orientation of an uneven-span single shape greenhouse and concluded that an east-west orientation should be preferred at latitudes of 44ºN and 54ºN as it receives less solar radiation in summer and provides higher air inside temperatures in winter. The amount of solar radiation received by five typical greenhouses has been estimated using a mathematical model developed by Sethi (2009) and the result recommended to use east-west orientation greenhouses at all latitudes on the northern hemisphere. Gupta et al. (2012) have used three-dimensional shadow analysis in AutoCAD to determine the best orientation for greenhouses and found that an orientation of 45° movement from the true south to the west resulted in highest solar collection during winter. El-Maghlany et al. (2015) analyzed the ability of receiving solar radiation by greenhouses at different locations and orientations and proposed that east-west orientation is most suitable for northern hemisphere applications, due to the maximum amount of heat captured. Both the architectural features and the construction forms of the double roofed glass greenhouse have great differences with the solar greenhouse discussed in this study, a calculation method suitable for solar greenhouse optimal orientation is urgently needed.

Chinese scholar Wei (1999) concluded that the orientation of solar greenhouse should be 5 ° movement from the true south to the west or to the east in the northern part of China, and the same solar energy can be obtained by the solar greenhouse when the degree of movement from the true south to the west or east is same. This conclusion is based on the theory that the cumulative sunshine time of the morning is the same as the afternoon, and it ignores the influence of the dynamic change characteristics of outdoor air temperature and atmospheric transparency. Zhang et al. (2010) analyzed the influence of solar greenhouse orientation to the opening and closing time of the thermal insulation curtain for the south pitched roof, and came to conclusion that the orientation should be 6°~8° movement from the true south to the west for the overwintering planting pattern solar greenhouse, but the study did not take into account the impact of geographic latitudes. Li et al. (2003) analyzed the design principle of orientation and elevation angle of the front roof with the theory of the energy saving solar greenhouse in northwest China, and proposed that the best orientation of solar greenhouse in northwest China is true south or 5°~8° movement from the true south to the west. At Shenyang, China (41.7°N), Bai et al. (2005) studied the influence of solar greenhouse orientation on the amount of entered sunlight, and the results showed that the optimal orientation of solar greenhouse at Shenyang was 5°~6° movement from the true south to the west.

China has a vast territory, and the difference of climate and geographical features in different regions is great. What's more, the dynamic demand characteristics of the light and heat environment during the growth of vegetable crops are different. Therefore, it is important to form a calculation methods that can guide the optimization design of solar greenhouse orientation in different geographical latitude regions, so as to improve the efficient utilization of solar energy and improve production efficiency. In this study, a large number of theoretical analysis and experimental results about the thermal design of solar greenhouse of early research are combined. According to the heat transfer and the extreme value theory, this study regard the maximum solar radiation energy obtained from the south pitched roof of solar greenhouse as the research objective, and regard the sunshine time and sunshine quality available during the vegetable production as constraint condition, the calculation model of the opening and closing time of the thermal insulation curtain for the south pitched roof of a solar greenhouse in different latitudes is given, and a method that can be used to determine the optimal orientation for solar greenhouses in different geographical latitude has been proposed. Through the presentation of calculation method, it is expected to provide a reference for the optimization design of solar greenhouse building and the efficient utilization of solar energy.

Nomenclature

Symbols		I_{OFF}	solar radiation intensity at opening time of thermal insulation curtain, W/m^2
h	solar elevation angle, °	I_0	solar radiation constant, W/m^2

i	sunlight incidence angle, °	K_f	heat transfer coefficient of plastic sheeting, W/(m^2·°C)
n	the typical winter time for off-season vegetable production	P	Atmospheric transparency coefficient
t_i	indoor air temperature, °C	Q_1	front roof radiant heat transfer, W/m^2
t_o	outdoor air temperature, °C	Q_2	front roof convection heat transfer, W/m^2
t_1	opening time of thermal insulation curtain, h	S	total solar radiation, J
t_2	closing time of thermal insulation curtain, h	*Greek letters*	
q	daily cumulative solar irradiation, J	α	solar azimuth angle, °
A	Area of south pitched roof, m^2	γ	solar greenhouse orientation, °
I	solar radiation intensity, W/m^2	τ	plastic sheeting transparency, %
T_1	delay of the local sunrise time, min	ϕ	latitude, °N
T_2	ahead of the local sunset time, min	γ_{max}	optimal solar greenhouse orientation, °
I_d	direct solar radiation, W/m^2	δ	solar declination angle, °
I_i	diffuse solar radiation, W/m^2	ω	hour angle, °
I_{ON}	solar radiation intensity at opening time of thermal insulation curtain, W/m^2	θ	elevation of south pitched roof, °

2 Factor analysis

Maximizing solar energy received by the south pitched roof is essential when designing solar greenhouses. Comparing to using conventional heating solutions, a well-designed solar greenhouse can save a huge amount of energy, while keeping indoor thermal environment acceptable. In this section, influences of three major factors on the amount of solar energy received by a greenhouse were investigated for the later model development. The three factors are: 1) solar trajectory, determined by elevation angle (h) and azimuthal angle (α); 2) geographical latitude; and 3) opening and closing time of thermal insulation curtains on the south pitched roof.

The solar altitude angle and azimuth, as well as the annual solar motion trajectory, are dynamic. These change rules can directly influence the amount of solar radiation energy obtained by the south pitched roof of a solar greenhouse (Sethi, 2009). In the northern hemisphere, with the increase of latitude, the sunrise time becomes later, and the sunset time is earlier, hence the sunshine duration is shorter (Bahrami et al., 2016). The geographical latitude of solar greenhouses will affect the length of effective sunshine duration of solar greenhouses, thus affecting the performance of catching solar radiation from the south pitched roof.

Figure 1 shows the change rules of solar radiation intensity, indoor temperature and outdoor temperature of the solar greenhouse from December 16, 2016 to December 23, 2016 in Beijing. It reflects that the temperature difference between inside and outside of solar greenhouse reaches the peak at around 7:30am, when the sun starts to rise. According to heat balance theory, if the thermal insulation curtain is opened when the solar energy obtained is not sufficient to compensate the heat loss from the uncovered south pitched roof, it is not energy efficient. This principle is also applicable for the time of sunset, when the thermal insulation curtain needs to be closed to keep the solar greenhouse warm. Therefore, it is important to determine the best opening and closing time for the thermal insulation curtain with a consideration of solar energy obtained and building heat loss.

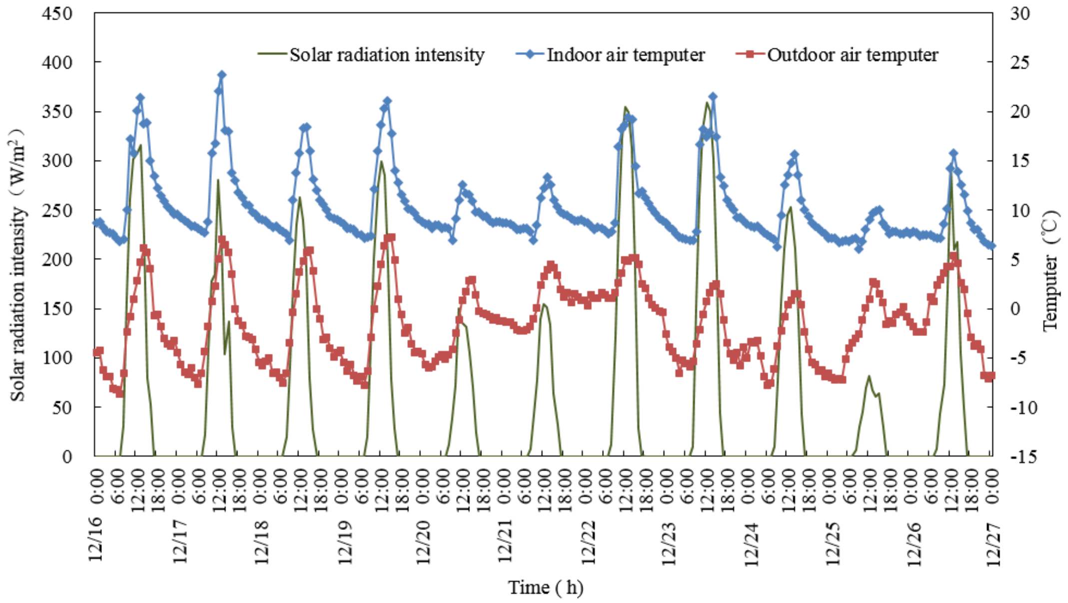


Figure 1: Change rules of solar radiation intensity, indoor temperature and outdoor temperature of the solar greenhouse in Beijing

According to the heat balance theory, to promote energy efficiency, the thermal insulation curtain should not be opened until the solar radiation energy that can be obtained through the uncovered south pitched roofs can compensate the heat lost from the uncovered south pitched roof, due to the temperature difference between the two sides of the roof (i.e. indoors and outdoors). The same principle can be used to determine the best closing time during the evening time.

For a solar greenhouse, the solar radiation energy obtained through the south pitched roof is represented by Q_1 (in W/m^2), which can be calculated using Equation 1. In order to simplify the calculation, the front roof of a solar greenhouse is treated as a tilting surface.

$$Q_1 = AI\tau \qquad (1)$$

where A is the area of the inclined plane of the front roof, in m^2; I is the solar radiation intensity of the inclined plane of the front roof, in W/m^2; τ is the transmissivity of plastic sheeting, dimensionless. According to Sun et al. (2013), the average value of τ is 0.52, due to the low solar elevation angle in the morning and evening.

Q_2 (in W/m^2) is used to represent the heat loss through the south pitched roof, which is dependent on the temperature difference between indoors and outdoors, as defined by Equation 2,

$$Q_2 = AK_f(t_i - t_o) \tag{2}$$

where K_f is the heat transfer coefficient of the plastic sheeting, in W/(m^2·℃). According to CAAE. (2012), K_f = 6.7W/(m^2·℃); t_i is indoor air temperature, in ℃; t_o is outdoor air temperature, in ℃.

In the morning, when $Q_1 \geq Q_2$, Equation 3 could be obtained. Since this moment, the thermal insulation curtain can be opened.

$$I_{ON} \geq 12.9 \times (t_i - t_o) \tag{3}$$

where I_{ON} represents the required solar radiation intensity for opening the thermal insulation curtain, under the corresponding indoor and outdoor temperature conditions, in W/m^2.

In the afternoon, when $Q_1 \leq Q_2$, Equation 4 could be obtained. Since this moment, the thermal insulation curtain should be closed to reserve energy.

$$I_{OFF} \leq 12.9 \times (t_i - t_o) \tag{4}$$

where I_{OFF} represents the required solar radiation intensity for closing the thermal insulation curtain, under the corresponding indoor and outdoor temperature conditions, in W/m^2 .

In order to determine the optimal opening and closing times for the thermal insulation curtain in winter, i.e. between November 1st and February 28th, in Beijing, the typical meteorological year data (TMY) of China from Meteorological Information Center. (2005) and field measured indoor temperature data have been used. The former data provided outdoor temperature and solar radiation intensity. Figure 2 depicts the calculated opening and closing times, as well as the sunrise and sunset times, for every ten days during the period. From the calculation, it could be found that in Beijing the opening time is about 70~80 minutes later than the sunrise time, and the closing time is about 30~40 minutes earlier than the sunset time.

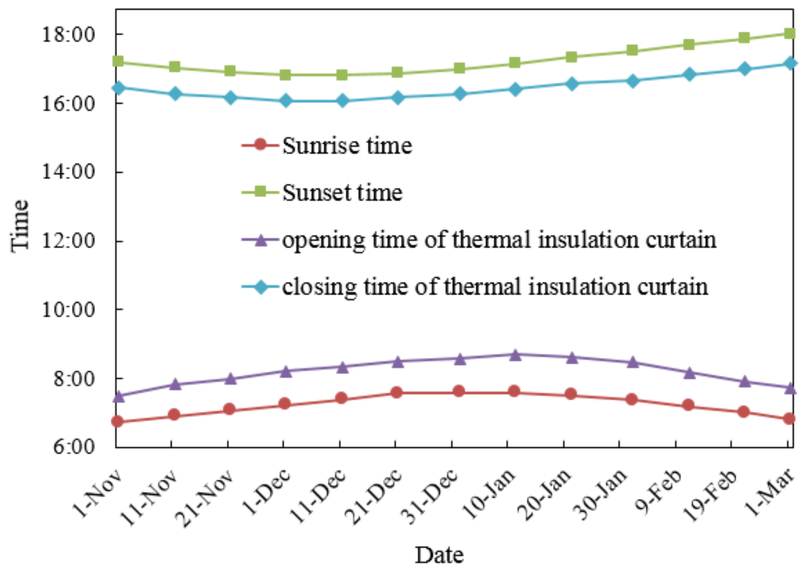


Figure 2: Opening and closing time of thermal insulation curtain during winter in Beijing

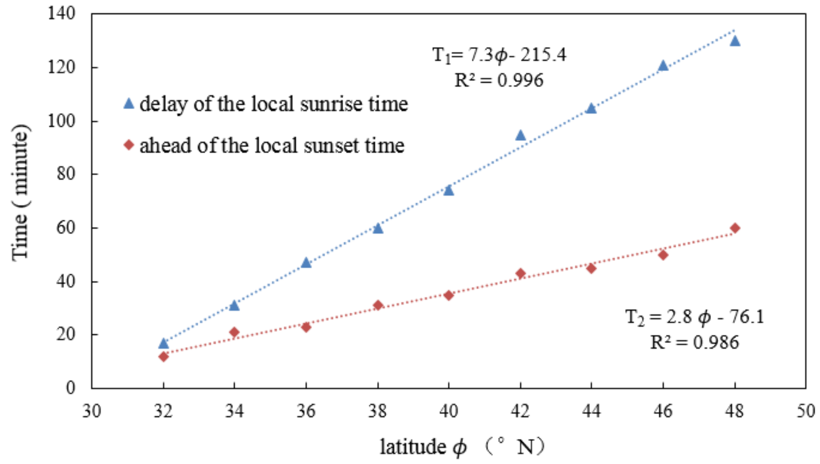


Figure 3: Relationship between geographical latitude and opening and closing time of thermal insulation curtain

Following the same method used above, the optimal opening and closing times were calculated for various latitudes in the northern hemisphere, and Figure 3 shows the time difference between the sunrise (sunset) and the opening (closing) time. It reflects that both time differences are general proportional to the latitude, i.e. the higher the latitude, the bigger the time difference. Equations 5 and 6 define the correlation between the latitude and the time difference.

$$T_1 = 7.3\phi - 215.4 \tag{5}$$

$$T_2 = 2.8\phi - 76.1 \tag{6}$$

where T_1 is the delay to the local sunrise time, in min; T_2 is the advance to the local sunset time, in min; ϕ is latitude, in °N.

3 Model development and verification

3.1 Model development

When considering the total solar radiation penetrating into the solar greenhouse through the plastic sheeting, two components are generally used, i.e. direct radiation and diffuse radiation, in W/m^2. The total energy obtained by the solar greenhouse can be reflected by a parameter called Daily cumulative solar irradiation (q_i), in Joule, calculated by Equation 7.

$$q_i = \int_{t_1}^{t_2} \tau_t \left(I_{(d)t} + I_{(i)t} \right) A \tag{7}$$

where τ_t is the plastic sheeting transparency at t time, %; t_1 is the opening time of thermal insulation curtain, t_1 = local sunrise time + T_1/60(min), h; t_2 is the closing time of thermal insulation curtain, t_2 = local sunset time - T_2/60(min), h; $I_{d(t)}$ is the solar direct radiation intensity at t time, W/m^2; $I_{i(t)}$ is the solar diffuse radiation intensity at t time, W/m^2; A is the area of the incline south pitched roof, m^2.

Solar direct radiation intensity ($I_{d(t)}$):

Solar direct radiation falling on any plane has a close correlation with the sunlight incidence angle to this plane. When the incidence angle is known, the intensity could be calculated using Equation 8.

$$I_{d(t)} = I_0 P^{\frac{1}{\sin h_t}} \cos i_t \tag{8}$$

where I_0 is the solar radiation constant, W/m^2; P is atmospheric transparency coefficient;

h_t is solar elevation angle at t time, °; i_t is the sunlight incidence angle at t time, ° ,the angle could be calculated using Equation 9.

$$\cos i_t = \cos\theta \times \sin h_t + \sin\theta \times \cos h_t \times \cos(\alpha_t - \gamma) \tag{9}$$

where θ is tilt angle of south pitched roof of solar greenhouse, °; h_t is the angle of solar altitude at t time, °;α_t is the angle of solar azimuth at t time, °; γ is the orientation of solar greenhouse, °.

Solar diffuse radiation intensity ($I_{i(t)}$):

Solar diffuse radiation intensity going into a solar greenhouse through the plastic sheeting includes diffuse sky radiation, ground reflected radiation and atmospheric longwave radiation (Li et al., 2015), and in this study diffuse sky radiation as a key is mainly discussed (Cao et al., 2017). The diffuse radiation intensity could be calculated using Equation 10.

$$I_{i(t)} = 0.5 \times I_0 \sin h_t \times \frac{1 - P^{\csc h_t}}{1 - 1.4 \ln P} \times \cos^2 \frac{\theta}{2} \tag{10}$$

Transmissivity of plastic sheeting:

The transmissivity of plastic sheeting is a major factor influencing the amount of solar energy obtained by a solar greenhouse. Equation 11 (Chen D S, 1991) defines a correlation between sunlight incidence angle (i_t) and the transmissivity of plastic sheeting used for solar greenhouses.

$$\tau_t = 90 - 5^{(i_t - 20)/25.06} \tag{11}$$

According to the Equation (11), the influence rule of solar greenhouse orientation on the transmissivity of plastic sheeting in Beijing can be calculated, the results are shown in figure 4. It is known from figure 4 that, when changed the solar greenhouse orientation, compared with the transmissivity of the true south, the difference of the transmissivity of plastic sheeting is less than 5%. The calculation results of the whole winter are almost identical to figure 4, and the same rules can be obtained in other regions. Therefore, the influence of the solar greenhouse orientation on the transmissivity of plastic sheeting is small.

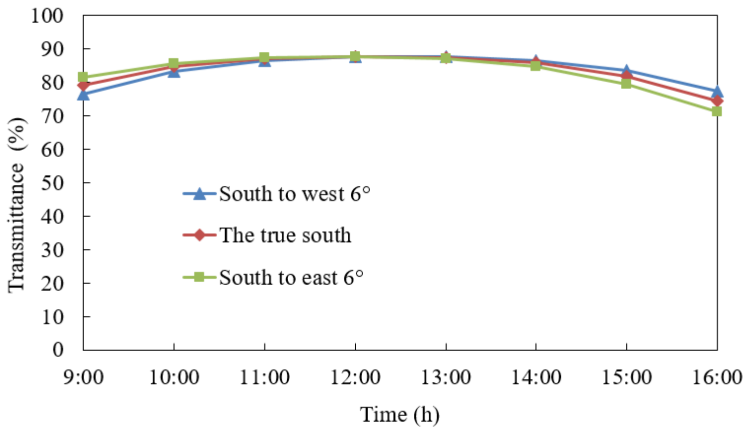


Figure 4: Change of transmittance of films with different orientations

Cumulative solar irradiation (S) through the south pitched roof:

The total solar radiation (S), in Joule, entering a solar greenhouse through plastic sheeting has been accumulated for n days, and calculated using Equation 12,

$$S = \sum_{i=1}^{n} q_i \tag{12}$$

where q_i is daily cumulative solar irradiation of the i^{th} day, in Joule; n is the typical winter time for off-season vegetable production in different place, from November 1st to February 28th next year, in day.

By substituting Equations 7 to 11 into Equation 12, Equation 13 could be obtained,

$$S = \sum_{i=1}^{n}\int_{t_1}^{t_2} \tau_{tn} \times [I_0 P^{\mathrm{csch}_t}(\cos\theta \times \mathrm{sinh}_t + \sin\theta \times \mathrm{cosh}_t \times \cos(\alpha_t - \gamma)) + \frac{1}{2} \times I_0 \,\mathrm{sinh}_t \times \frac{1-P^{\mathrm{csch}_t}}{1-1.4\ln P}\cos^2\frac{\theta}{2}] \times A dt \tag{13}$$

where τ_{tn} is the transmissivity of plastic sheeting of the true south solar greenhouse at *t* time, according to the analysis results of figure 4, in order to simplify the calculation, the transmissivity of plastic sheeting of the solar greenhouse is simplified to the true south direction, %;

The optimal orientation of a solar greenhouse should ensure the most amount of solar energy obtained through the south pitched roof, during daytime. To achieve this requirement, *S* in Equation 13 should be maximized. According to the extreme value theory (Zhang et al., 2015), when S at its peak value, $dS/d\gamma=0$. Therefore, to determine the optimal solar greenhouse orientation $\gamma_{\max}$, Equation 14 could be used.

$$\gamma_{\max} = \arctan \frac{\sum_{i=1}^{n} \int_{t_1}^{t_2} \tau_{tn} P^{\mathrm{csch}_t} \cosh_t \sin \alpha_t dt}{\sum_{i=1}^{n} \int_{t_1}^{t_2} \tau_{tn} P^{\mathrm{csch}_t} \cosh_t \cos \alpha_t dt} \tag{14}$$

When the typical winter time for off-season vegetable production (n), the atmospheric transparency coefficient (P) and the latitude (ϕ) of region of the solar greenhouse are known, solving Equation 14 can give the optimal solar greenhouse orientation.

In fact, the atmospheric transparency coefficient P in Equation (14) is usually calculated according to the statistics of the measured data (Yan et al., 1986). Figure 5 is the change rules of atmospheric transparency coefficient in different weather conditions based on the statistical calculation of meteorological parameters of the typical meteorological years in Beijing. It can be seen that, in the sunny day, the atmospheric transparency coefficient is lowest at the morning and increased gradually at the afternoon. In the cloudy day and overcast, atmospheric transparency coefficient is affected by the cloud amount, but the general trend is that the atmospheric transparency coefficient is greater in the afternoon than the morning. The atmospheric transparency coefficient of other geographical regions also has the same rule. The greater the atmospheric transparency coefficient, the greater the solar radiation get from the south pitched roof of solar greenhouse. So the orientation of solar greenhouse in northern China should be set in the south to west.

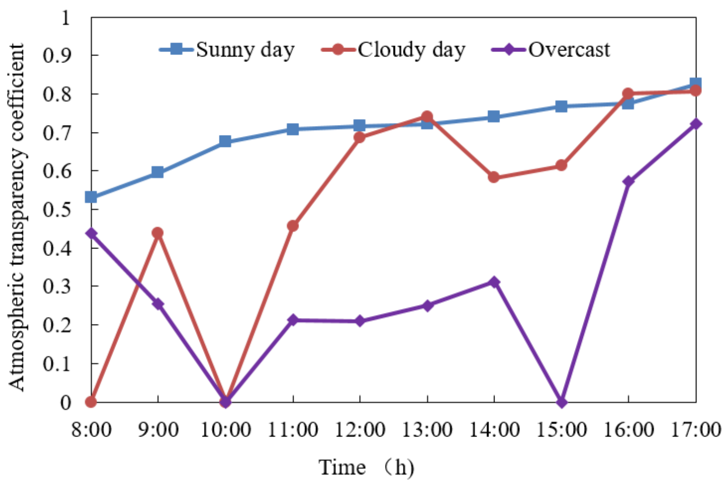


Figure 5: Change rules of atmospheric transparency coefficient in different weather

When set the typical winter time for off-season vegetable production as November 1st to February 28th of next year. According to the Equation (14), the optimal orientation of solar greenhouse in different geographic latitude can be calculated (Fig. 6). The opening and closing time of thermal insulation curtain can be calculated by Equation (5) and (6). The parameters of the atmospheric transparency coefficient P and the solar angle are calculated according to the typical meteorological year (TMY) in China.

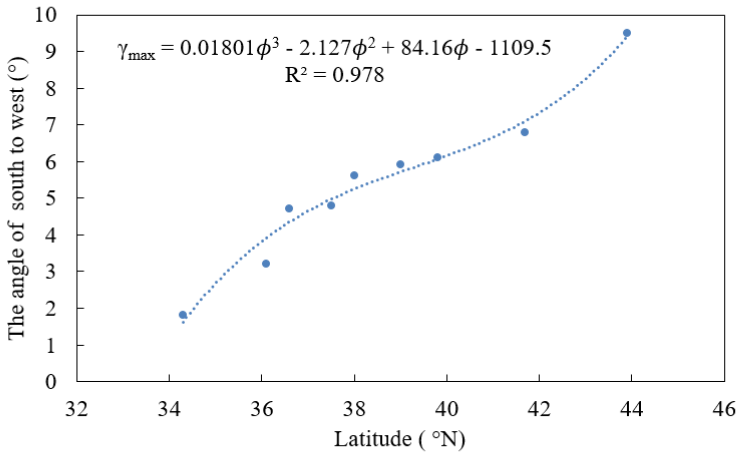


Figure 6: Optimum orientation values of solar greenhouse buildings in different latitudes

According to the calculated results of Figure 6, the fitting relationship between the optimum orientation of the solar greenhouse and the geographical latitude can be obtained in Equation (15). According to the Equation (15), the optimum orientation of solar greenhouse in different geographic regions can be easily calculated.

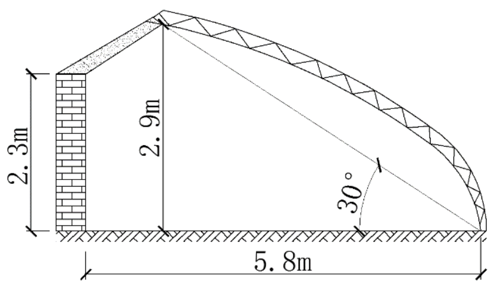
$$\gamma_{max} = 0.01801\phi^3 - 2.127\phi^2 + 84.16\phi - 1109.5 \quad (R^2=0.978) \qquad (15)$$

3.2 Model validation

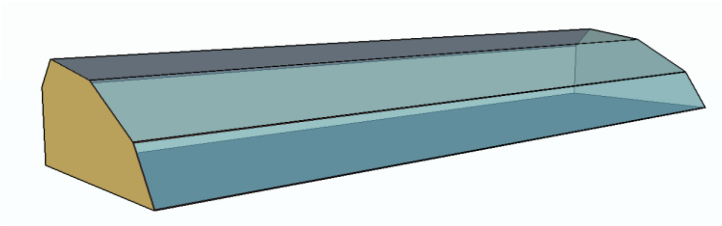
In order to validate the proposed model above, both simulation data and field measured data have been used. The validation methods and results have been introduced in Section 3.2.1 and Section 3.2.2 respectively.

3.2.1 Validation using simulation results

The simulation model used for the validation was developed according to a solar greenhouse located in the rural part of Beijing, China, as introduced in Ling et al., (2016). It has a length of 27m, a span of 5.8m, a ridge height of 2.9m, a north wall height of 2.3m, a front roof elevation of 30°, graphically shown in Figure 7a. The simulation work was carried out by EnegyPlus, a major dynamic building performance simulation tool (NREL.2015), and Figure 7b has shown the model developed in EnergyPlus.



a. Solar greenhouse structural diagram



b. Solar greenhouse simulation model

Figure 7: Solar greenhouse structure and simulation model

The calculation time was between 1st November and 28th February, typical winter time in Beijing for off-season vegetable production. The weather data were coming from the typical meteorological year as introduced before already. During the simulation period, the opening and closing times of thermal insulation curtain of the solar greenhouse have been calculated by Equations 5 and 6.

Using Equation 15, the calculated optimal solar greenhouse orientation was 6.2° movement from the true south to the west. Figure 8 has shown the predicted solar radiation obtained by the solar greenhouse, through the plastic sheeting. The simulation work was carried out for various solar greenhouse orientations, the negative value of the orientation represent the degree movements from the true south to the east, and the positive value of the orientation represent the degree movements from the true south to the west. The simulation results clearly show that at the orientation of 6° movements from the true south to the west, the obtained solar was at the peak value, demonstrating the accuracy of the proposed model in this study.

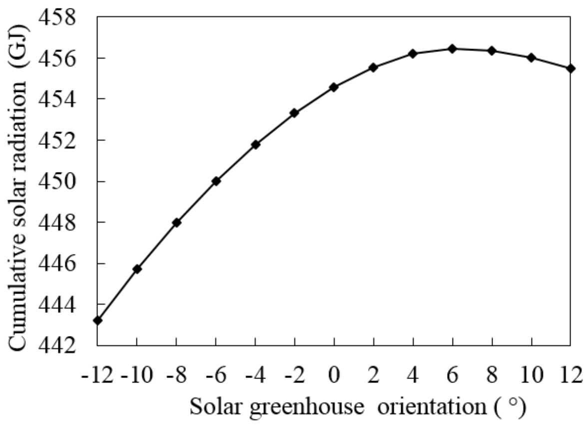


Figure 8: Relationship between cumulative solar radiation and solar greenhouse orientation by simulation

3.2.2. Validation using field measured data

In this study, field measured data have been used to validate the proposal method as well. To do that, five testing greenhouses, smaller than the one shown in Figure 4a (with a scale of 1:4), was developed. During the test, the five testing greenhouses set as different orientation: 12° movements from the true south to the west, 6° movements from the true south to the west, the true south, 6° movements from the true south to the east, 12° movements from the true south to the east. The measurement of solar radiation was carried out at three positions indoors, uniformly arranged along the length of the solar greenhouse, as shown in Figure 9. During the test period, the opening and closing times of thermal insulation curtain of the solar greenhouse have been set as Equations 5 and 6.

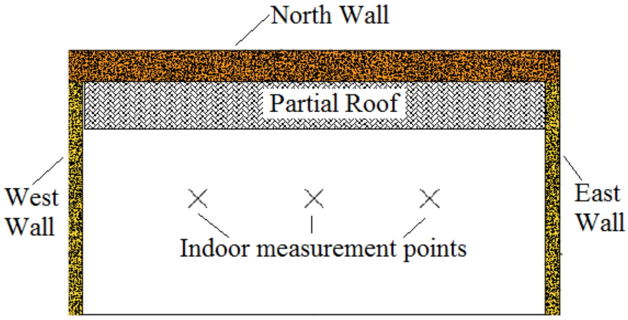


Figure 9: Testing solar greenhouse and arrangement of measuring points

Solar radiation was measured by TBQ-2 radiometers, with a measurement range between 0 and 2000W/m^2, measurement accuracy of ±2%. The measurement interval was selected to be 1 minute and the measurement duration was from 01/11/2014 to 28/02/2015.

Figure 10 reflects the influence of the solar greenhouse orientation on the cumulative solar energy flow of the ground during the testing period. It could be observed that 6° movements from the true south to the west provided the highest cumulative solar energy flow of the ground during the testing period, complying with the calculated angle by the proposed method.

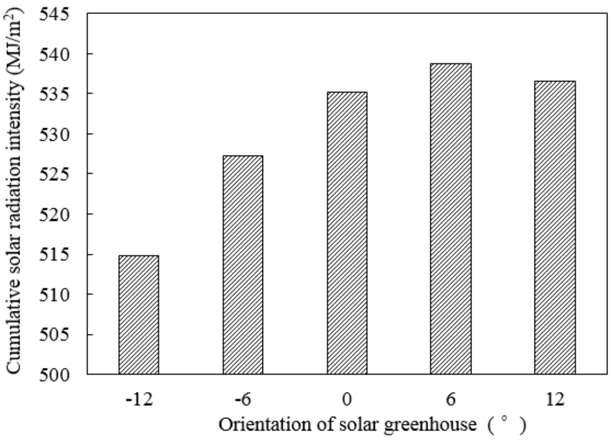


Figure 10: Relationship between cumulative solar radiation energy flow of the ground and the orientation during test period

4 Model application and case analysis

4.1 Model application

The calculation model provided in this study can be applied to the practical application accurately and conveniently. The model was used to determine the optimal orientation when placing the solar greenhouse at nine locations in the northern part of China, where solar greenhouses are mainly used. The locations included Xian, Lanzhou, Xining, Shouguang, Yinchuan, Shijiazhuang, Beijing, Shenyang and Urumqi, which have different latitudes but good solar resources. The calculated optimal orientation for solar greenhouses have been listed in Table 1 as well, with a visualization in Figure 11. In Figure 11, the symbol SW means the degree of movement from the true south to the west.

Table 1 Calculated optimal orientation for solar greenhouses at various locations in China

City	Latitude （°N）	Degree of movement from the true south
Urumqi	43.9°	9.7° to west
Shenyang	41.7°	7.3° to west
Beijing	39.8°	6.2° to west
Shijiazhuang	38.0°	5.4° to west
Yinchuan	37.9°	5.4° to west
Shouguang	37.5°	5.1° to west
Xining	36.6°	4.5° to west
Lanzhou	36.1°	4.0° to west
Xian	34.3°	1.6° to west

Figure 11: Calculated optimal orientation for greenhouses at various locations in China

It could be clearly found from Table1 and Figure 11 that the optimal orientation is dependent on the latitude of the solar greenhouse, i.e. the higher the latitude, the bigger movement needed from the true south. There are two reasons: 1) Atmospheric transparency coefficient is the key parameter which affects the solar radiation obtained by the front roof of solar greenhouse, and according to the above research, atmospheric transparency is greater in the afternoon than in the morning. In order to make full use of the solar energy, the orientation of solar greenhouse should be set in the south to west. 2) With the increase of latitude, the outdoor temperature is lower, and according to heat balance theory, the opening time of the thermal insulation curtain should be delayed, but the closing time of the thermal insulation curtain is not obvious change. So the sunshine time in the morning period of the solar greenhouse is obviously shorter than that in the afternoon.

4.2 Case analysis

According to the actual investigation, the orientation of solar greenhouse in Yinchuan is 12° movements from the true south to the west, which is based on the traditional experience. But the calculation model provided the optimal orientation is 5.4° movements from the true south to the west. The cumulative solar radiation intake of the solar greenhouse with different orientations is calculated by the EnergyPlus software. The size of solar greenhouse structure is shown in Figure 7a, the critical period of crop growth is set from November 1st to February 28th next year, the optimal opening and closing times of the thermal insulation curtain can be calculated by the formula (5) and formula (6), and outdoor temperature is based on the typical meteorological year data (TMY) of Yinchuan, China. The results of the calculation are shown in Table 2. Compared with the experience value, the solar greenhouse based on the optimal orientation can increase the solar radiation intake about 3.7GJ.

Table 2 Comparison of the solar radiation intake of solar greenhouse with the orientation experience value and the calculated value

Orientation of solar greenhouse	12° movement from the true south to west	5.4° movement from the true south to west	Amount of increase
the solar radiation intake of solar greenhouse（GJ）	544.0	547.7	3.7

5 Conclusions

On the northern hemisphere, the orientation of solar greenhouses has a significant impact on the amount of solar radiation received through the south pitched roof, hence influencing both indoor environment and heating energy requirement. Therefore, selecting the optimal orientation is essential when designing a solar greenhouse. In this study, based on the law of the solar trajectory and the theory of heat balance, the calculation model of the opening and closing time of the thermal insulation curtain for the south pitched roof of solar greenhouse in different latitudes is given. Using Extreme Value Theory, a method that can be used to determine the optimal orientation for solar greenhouses, i.e. to maximize the solar energy collection, has been proposed, with a consideration of impact from geographical latitude. Some main findings from the study include:

1) A method to determine the optimal opening and closing times of the thermal insulation curtain has proposed. With the increase of latitude, the opening time of the thermal insulation curtain should be delayed, and the closing time of the thermal insulation curtain is not obvious change. So the effective sunshine time of the solar greenhouse in the morning is shorter than that in the afternoon.

2) A calculation model has provided that can be used to determine the optimal orientation for solar greenhouses, with a consideration of the latitude of the application, and the optimal orientations of solar greenhouses in the northern part of China have provided, where solar greenhouses are mainly used. According to the results of this study, the optimal orientation is dependent on the latitude of the solar greenhouse, i.e. the higher the latitude, the bigger movement needed from the true south.

3) In order to ensure the efficient production of anti-seasonal vegetables in winter, duration and quality of sunshine obtained by solar greenhouses should be considered.

According to the results of this study, the orientation when placing the solar greenhouse should be South by West in the northern China.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (No. 51578012 and No. 51368060) and National Key Research and Development Program of China (Project No. 2016YFC1101301).

References

Bahrami, A., Okoye, C.O., Atikol, U., 2016. The effect of latitude on the performance of different solar trackers in Europe and Africa. Appl Energ 177, 896-906.

Bai, Y., Liu, W., Wang, T., Tong, G., 2005. Analysis of Orientation Influenced Sunlight in Solar Greenhouse. Transactions of the Chinese Society of Agricultural Machinery 36(2), 73-84.

Cao, F., Li, H.S., Yang, T., Li, Y., Zhu, T.Y., Zhao, L., 2017. Evaluation of diffuse solar radiation models in Northern China: New model establishment and radiation sources comparison. Renew Energ 103, 708-720.

Cao, W.A., Li, Y.A., Bai, Y.B., 2009. Relationship Between Azimuth Angle of Solar Greenhouse and inside Temperature. Journal of Agricultural Mechanization Research 31(05), 183-184+189.

CAAE, Structure and Properties Requirement for Sunlight Greenhouse and Plastic Tunnel (GB 19165-2003), Beijing, Standards Press of China, 2003.

CAAE, Design rule for fan-pad cooling system in greenhouse (NYT 2133-2012) , Beijing, Standards Press of China, 2012.

Chen D S. Technology of the energy-saving sunlight greenhouse in China. Proceedings of international symposium on applied technology of greenhouse, held in Beijing, China, 7-10 October 1991: 41-49

Cheng, R., Yu, K.Q., Wang, S.X., 2014. Experimental Study of Sunlight Greenhouse Azimuth Influenced on Plants Growth. Journal of Agricultural Mechanization Research(11), 185-187.

Choi, Y.H., Kang, N.J., Park, K.S., Chun, H., Cho, M.W., Lee, S.Y., Um, Y.C., 2008. Effect of Greenhouse Orientation on the Environment of Greenhouse and the Growth and Yield of Tomato and Oriental Melon. Korean J Hortic Sci 26(4), 380-386.

Dragicevic, S.M., 2011. Determining the Optimum Orientation of a Greenhouse on the Basis of the Total Solar Radiation Availability. Therm Sci 15(1), 215-221.

El-Maghlany, W.M., Teamah, M.A., Tanaka, H., 2015. Optimum design and orientation of the greenhouses for maximum capture of solar energy in North Tropical Region. Energ Convers Manage 105, 1096-1104.

Gupta, M.J., Chandra, P., 2002. Effect of greenhouse design parameters on conservation of energy for greenhouse environmental control. Energy 27(8), 777-794.

Gupta, R., Tiwari, G.N., Kumar, A., Gupta, Y., 2012. Calculation of total solar fraction for different orientation of greenhouse using 3D-shadow analysis in Auto-CAD. Energ Buildings 47, 27-34.

Li, D.H.W., Lou, S.W., Lam, J.C., 2015. An Analysis of Global, Direct and Diffuse Solar Radiation. Clean, Efficient and Affordable Energy for a Sustainable Future 75, 388-393.

Li, J., Zou, Z.R., Yang, X., Chen, X.H., 2003. Analysis and Discussion and Application on Solar Greenhouse about Azimuth Angle and Lighting Surface Angles. Acta Agriculturae Boreali-occidentalis Sinica 12(2), 105-108.

Ling, H.S., Chen, C., Guan, Y., Wei, S., Chen, Z.G., Li, N., 2014. Active heat storage characteristics of active-passive triple wall with phase change material. Sol Energy 110, 276-285.

Ling, H.S., Chen, C., Qin, H., Wei, S., Lin, J., Li, N., Zhang, M.X., Yu, N., Li, Y., 2016. Indicators evaluating thermal inertia performance of envelops with phase change

material. Energ Buildings 122, 175-184.
Ling, H.S.A., Chen, C., Wei, S., Guan, Y., Ma, C.W., Xie, G.Y., Li, N., Chen, Z.G., 2015. Effect of phase change materials on indoor thermal environment under different weather conditions and over a long time. Appl Energ 140, 329-337.
Meteorological Information Center, m.i.c.o.C.M.A., 2005. Special meteorological data set for analysis of thermal environment in China. China Construction Industry Press.
NREL, EnergyPlus, 2015 https://energyplus.net/.
Sethi, V.P., 2009. On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation. Sol Energy 83(1), 21-38.
Stanciu, C., Stanciu, D., Dobrovicescu, A., 2016. Effect of greenhouse orientation with respect to E-W axis on its required heating and cooling loads. Enrgy Proced 85, 498-504.
Sun, Z.H., Cao, X.M., Liu, Z.C., Lei, Y.P., Liu, Y.L., 2013. Determination of Agricultural Weather Forecast Index in Time for Curtain-Rolling for Solar Greenhouse. Chinese Agricultural Science Bulletin 29(8), 129-134.
Wang, J.W., Li, S.H., Guo, S.R., Ma, C.W., Wang, J., Jin, S., 2014. Simulation and optimization of solar greenhouses in Northern Jiangsu Province of China. Energ Buildings 78, 143-152.
Wei, W.D., 1999. Industrialized and efficient agriculture. Liaoning Science and Technology Press.
Yan, Q.S., Zhao, Q.Z., 1986. Thermal process of building. China Construction Industry Press.
Zhang, L.H., Liu, J., Zhang, R.Z., Wei-Gen, X.U., 2010. Study on Azimuth of Sunlight Greenhouse. Acta Agriculturae Jiangxi 22(5), 85-89.
Zhang, Y.P., Zhang, Y., Shi, W.X., Shang, R., Cheng, R., Wang, X., 2015. A new approach, based on the inverse problem and variation method, for solving building energy and environment problems: Preliminary study and illustrative examples. Build Environ 91, 204-218.