New insight on span selection for Chinese solar greenhouses using CFD analyses

Guohong Tong[a], David M. Christopher[b*], Guoqiang Zhang[c]

[a]College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China

[b]Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

[c]Department of Engineering, Aarhus University, 8000 Aarhus C, Denmark

* Corresponding author. Email: dmc@tsinghua.edu.cn

Abstract

Chinese solar greenhouses (CSG), with thin plastic films on the south roof for transmitting sun rays during the daytime and a heavy cover at night with large thermal masses in the wall, north roof and soil to retain heat, can be used to produce vegetables and flowers year round without auxiliary heating during the winter. CSG spans can be increased to increase the production area; however, although the effect of increasing the span on the inside climate has been investigated experimentally, there is still no good guidance on selecting a suitable span configuration for growers. This investigation analyzed three groups of span configurations with spans of 10 m, 12 m and 14 m. The first set of designs had all the other dimensions varied in proportion to the span width. The second set had the same dimensions for the north roof and north wall with the other dimensions varied to fit the longer spans. The third set had the same south roof with a longer north roof to fit the longer span. The analyses were based on a 12 m span CSG simulation model validated in a former study with the thermal environments predicted using computational fluid dynamics (CFD) analyses. The results show that, for the CSG with all the dimensions varied in the same proportion, the inside air temperature is highest with the 14 m span and lowest with the 10 m span. For CSG with the same north roof and north wall dimensions, the air temperature is the highest with the 12 m span and lowest with the 14 m span. For the configurations using the same south roof size, the 12 m and 10 m spans had similar air temperatures because the north wall with the 10 m span was 2 m taller than that with the 12 m span, while the 10 m span with the same north wall size as the 12 m span had the lowest temperature. Analyses of the solar heat gained, heat lost and temperature distributions for each group give good guidance for span selections for the growers.

Keywords: Greenhouse, span, heat transfer, temperature, simulation, CFD

1. Introduction

Chinese solar greenhouses (CSG) are small and simple compared with the plastic/glass covered greenhouses used in western countries. A thin plastic film covers the south roof of CSG for transmitting the solar rays during the daytime with a thermal blanket added on top during the night to retain heat. Furthermore, large thermal masses in the north wall, north roof and soil store solar heat during the day and release heat to the inside air at night. Thus, CSG can produce vegetables and flowers year round without auxiliary heating during the winter. An outside picture and the names of the CSG components are shown in Fig. 1. The span of the CSG specifically refers to the width of the soil surface. Different spans can be found in existing CSG, since there is no established building code for guiding CSG construction (Zhou, 2012). CSG spans were usually from 5.5 m to 7.5 m before 2000 (Kang, 1990; Chen, 1994; Bai et al., 2002), then enlarged to 8 - 12 m (Tong et al., 2004; Chen, 2008) after high strength materials were introduced and construction methods were improved. To increase the crop production area inside a CSG, the spans have been extended to 14 m in Jiangsu Province (Wang et al., 2012), 15 m in Shanxi Province and 24 m in Shandong Province.

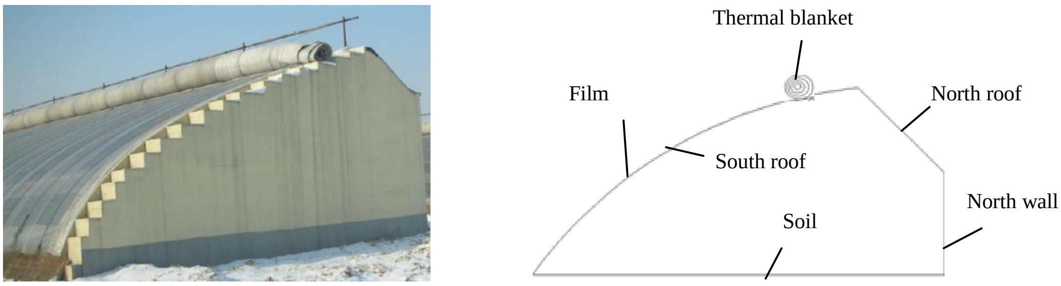


Figure 1. CSG picture and names of the components

Increasing the span increases the soil and south roof areas which changes the thermal environment inside. Thus, the effect of span changes on the interior thermal climate has become an important research topic. Kang et al. (1993) experimentally investigated the CSG inside temperatures of 6 m and 7 m spans in Anshan, Liaoning Province, with the 6 m span having higher temperatures and then suggested that smaller spans should be used in north of 40 °N. Zou et al. (1997) measured temperatures and heat fluxes for CSG with 6.9 m, 7.3 m, 8 m spans in Shaanxi Province and found that the 6.9 m span had a good thermal environment, so they recommended spans less than 7 m. The selected spans were largely related to the CSG spans used at that time. Recent studies have investigated the thermal climates in CSG built in Shaanxi Province with 8 m, 10 m and 12 m spans (Liu et al., 2012), 8 m, 9 m and 10 m spans (Liu et al.,2013) and 9 m, 10 m and 11.5 m spans (Jin et al., 2015), with the results showing that 10 m spans had higher temperatures. Others have studied the CSG thermal properties in Inner Mongolia with 8 m, 8.5 m, 9 m, 9.5 m and 10 m spans (Jiang et al., 2013) and in Gansu Province with 7 m , 8 m, 9 m, 10 m and 11 m spans (Tang et al., 2014) on site with both studies showing that the 10 m span should be selected for greenhouse construction because of its good thermal performance. All of these recent experiments were conducted on site but the CSG buildings had different walls (different heights and/or thicknesses) and/or different north roof (length and angle) sizes in each CSG set. Moreover, other differences may also have existed, such as different crop conditions, irrigation conditions, and sealing along the edges. Thus, additional studies are needed to get good conclusions for selecting the span based on comparisons of CSG with identical conditions.

Computational fluid dynamics (CFD) models have been used to optimize greenhouse configurations for near 30 years, since all the parameters in CFD models can be easily controlled to keep them the same. The commercial software Fluent was used here to analyze the effect of three spans, 10 m, 12 m and 14 m, on the interior thermal climate. These span configurations were used in three groups with all the dimensions in the first group varied in proportional to the span width, with the same dimensions for the north roof and north wall in the second group and with the same south roof size in the third group. Analyses of the solar heat gained, heat lost and temperature distributions for each group are expected to give good guidance for span selection for the growers.

2. Materials and Methods

2.1. Structures of the CSG used in investigation

The reference greenhouse was a 12 m span and 5.5 m ridge height CSG located in Shenyang, Liaoning Province, China. A 0.12 mm thick plastic film covered the south roof with a blanket placed over the film cover during the night. The north roof was 0.2 m thick and made of wood sheets, Styrofoam and other light materials. The north wall was a 0.6 m thick layered wall with a 0.36 m thick brick wall on the inside, a 0.12 m thick brick wall on the outside and a 0.12 m insulation layer in between. The 12 m span CSG structure and the inside air temperature measurement points were shown in Fig. 2.

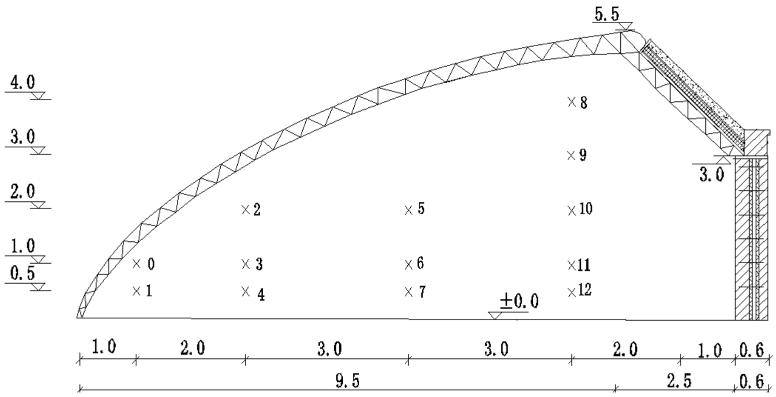


Figure 2. Air temperature measurement points with dimensions in meters

Tong et al. (2009) predicted temperatures during three clear days (Feb. 18 - 20, 2004) followed by a cloudy day (Feb. 21,2004) for this 12 m span greenhouse with the predicted values agreeing well with the experimental data. The current study investigates the effect of different spans on the inside climate after adding or subtracting 2 m from the reference 12 m span to give 10 m, 12 m and 14 m spans. These span cases, which can be found in existed commercial greenhouses, were set with different building parameters in three groups with the dimensions shown in Table 1 and the sketches shown in Fig. 3. The 14 m span case was not included in Group 3 since the same south roof in this group would result in the 14 m span having a very large amount of soil area under the north roof which would be a very poor design with this part of the soil area shaded during the days when the sun was higher in the sky.

Table 1. CSG dimensions in each group

Groups	Span	Ridge height	Height of north wall	Width of north roof	Width of film (south roof)
	10 m	4.58	2.5	2.95	9.40
Group 1	12 m	5.50	3.0	3.54	11.24
	14 m	6.42	3.5	4.13	13.14
	10 m	5.50	3.0	3.54	10.09
Group 2	12 m	5.50	3.0	3.54	11.24
	14 m	5.50	3.0	3.54	12.87
	10 m -a	5.50	5.0	0.71	11.24
	10 m -b	5.50	3.0	2.55	11.24
Group 3	12 m	5.50	3.0	3.54	11.24

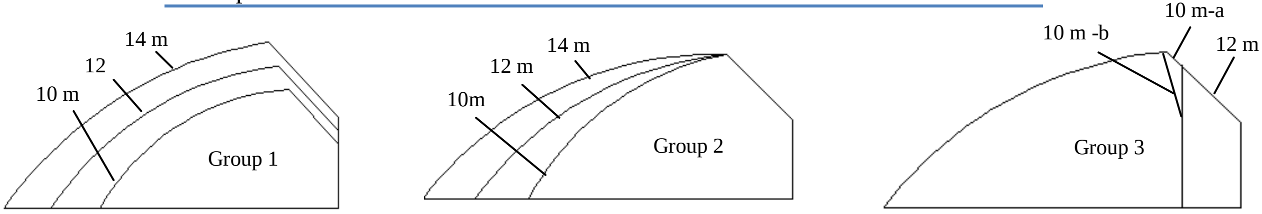


Figure 3. Sketches of the three CSG groups

2.2. Analysis methods

2.2.1.CFD simulation

The structure of the validated CFD model used by Tong et al. (2009) for the reference 12 m span CSG is shown in Fig. 4. This span selection study used the same simulation procedure and the same thermal physical parameters, such as the film transmittances for the direct and diffuse solar insolation, the air change rate in the air infiltration calculation, and the latent heat fluxes due to condensation on the film surface and due to canopy transpiration. The calculations of the total heat transfer rates on each surface were adjusted to fit the new span cases.

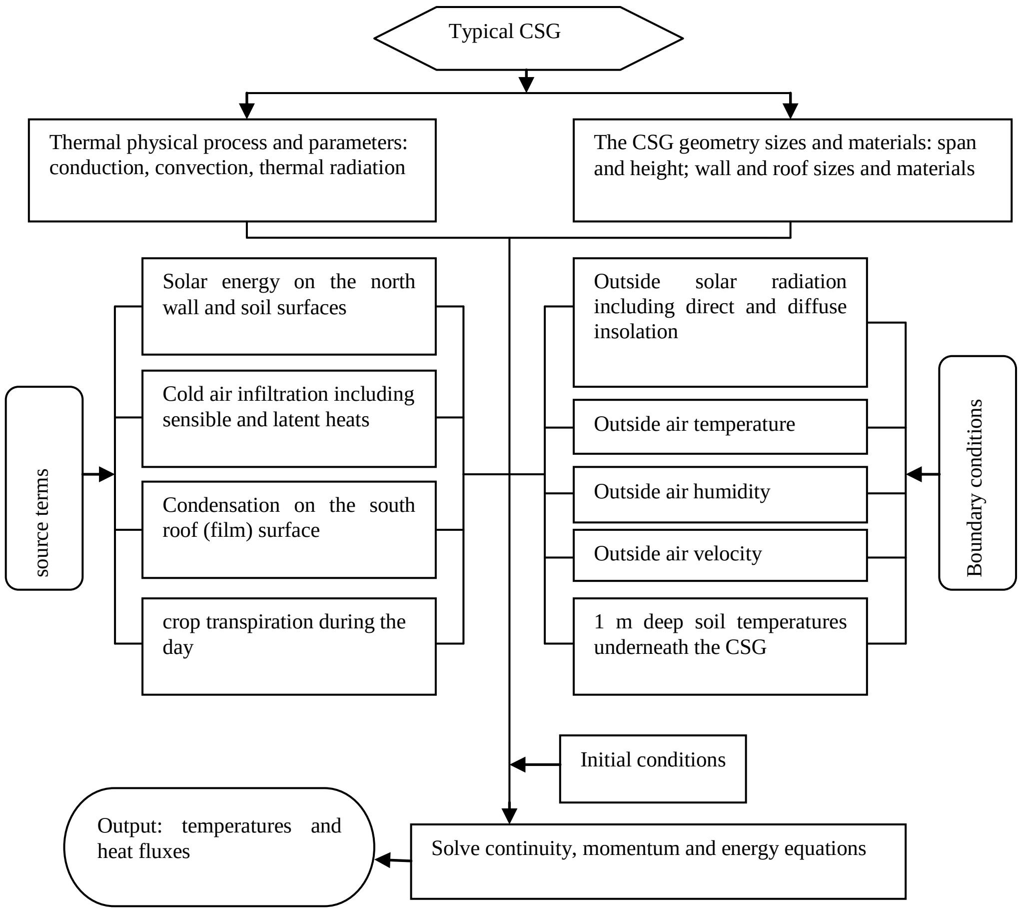


Figure 4. CSG simulation procedure and models

2.2.2.Source terms

The blanket on the CSG south roof in each design was assumed to be rolled up to the top of the south roof during the daytime. Then, the direct solar rays could reach the entire inner north wall and soil surfaces, so the direct solar heating was calculated based on the film transmittance for the direct solar rays and the amount of direct solar radiation on a horizontal surface outside the CSG. The diffuse solar radiation fluxes on the inner surfaces were calculated using view factors for each CSG structure shown in Fig. 3, with the diffuse solar heating on the surfaces then obtained based on the film transmittance for diffuse solar rays, the view factors and the amount of diffuse solar radiation on the south roof. The solar radiation reaching the north roof surface was ignored because the north roof materials had a very small thermal storage capacity due to the light materials. The sensible and latent heat due to air infiltration, the latent heat due to condensation and the latent heat due to canopy transpiration were all considered in the CFD simulations.

2.2.3.Boundary conditions and initial conditions

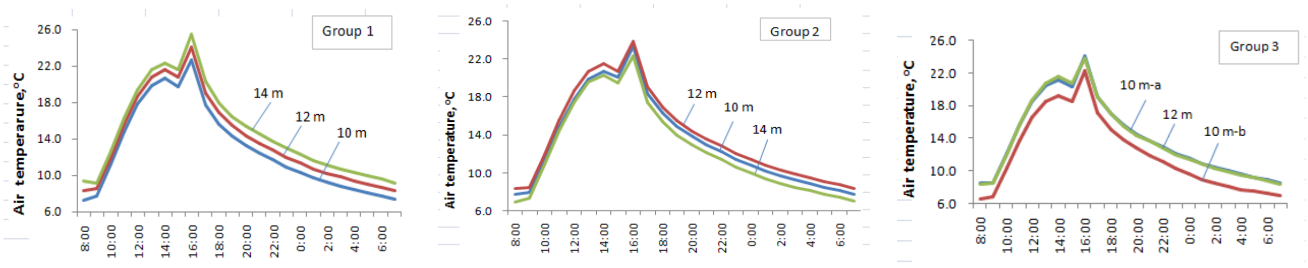
The outside climatic conditions on two clear days (Feb.18 and 19, 2004) were used as the boundary conditions for calculating the thermal climate inside the CSG in each group. The outside solar insolation fluxes, air temperatures, air humidities and air velocities for two days were used as inputs (Tong et al., 2009). The average measured soil temperature 1.0 m below the surface in the 12 m span CSG of 284K was used as the boundary condition at the soil bottom, while the two sides of the 1.0 m deep soil region were assumed to be insulated. The blankets were rolled up to the top of the south roof for all the designs at 8:00 in the morning and unrolled to cover the whole film area at 15:00 in the afternoon. The time period from 8:00 to 15:00 was defined as the daytime with 16:00 to 7:00 as the night time.

The Feb. 18 simulations were repeated several times for each CSG until the temperatures at two reference points 1.0 m above the center of the soil surface and 0.2 m below the soil surface varied by less than 0.01 ℃ between cycles. The velocities, temperatures and pressures at 0:00 on Feb. 18 were then used as the initial conditions.

3. Results

3.1. Air temperature

The air temperature is an important factor for CSG plant production, so the average air temperature is used to evaluate the CSG thermal conditions for the various spans and geometries. The average air temperatures in the CSG for each hour are shown in Fig. 5 for the various designs.



(a) Group 1 (b) Group 2 (c) Group 3

Figure 5. Hourly average air temperatures inside the greenhouses

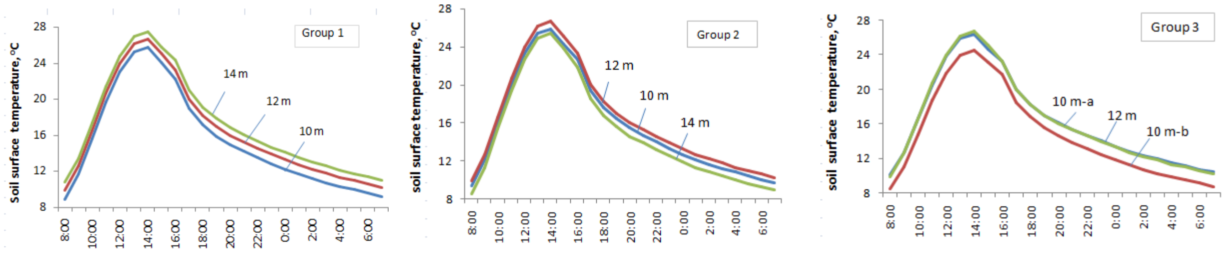
The air temperatures in Group 1 increase with increasing span as shown in Fig. 5(a) with the daily average temperature difference between the 14 m and 12 m spans of 0.9 °C while the temperature difference between the 12 m and 10 m spans was 1 °C. The temperature difference decrease as the span increases suggests that there is a limit as to how far the span can be increased to get higher inside air temperatures when all the other dimensions are varied in proportional to the span.

The average air temperatures in Group 2 shown in Fig. 5 (b) show that for this group, the air temperature is the highest in the 12 m span CSG and lowest in the 14 m span CSG. The lower air temperature in the 14 m span design occurs even though the longer span receives more solar energy, it also loses more heat from the larger transparent film area than the other two spans. Furthermore, the same dimensions for the north roof and the north wall for the greenhouses in Group 2 result in the daily average temperature difference between the 12 m span and the 10 m span CSG in group 2, 0.6 °C, being slightly lower than the temperature difference between this two spans in Group 1, 1 °C.

The three configurations in Group 3 have the same south roof size so they all receive the same amount of solar energy. Thus, the 12 m and 10 m spans have similar air temperatures as shown in Fig. 5 (c) when the north wall height with the 10 m span was 2 m taller than that with the 12 m span, Case 10 m-a. The temperature difference between these two spans was only 0.2 °C with higher temperatures in the 12 m span CSG during the daytime and higher temperatures in the 10 m span CSG during the night. Thus, these two designs had equal heat gains and nearly the same thermal storage resulting in nearly the same temperatures. However, the 10 m span with the same north wall size as the 12 m span, Case 10 m-b, had the lowest average indoor air temperature.

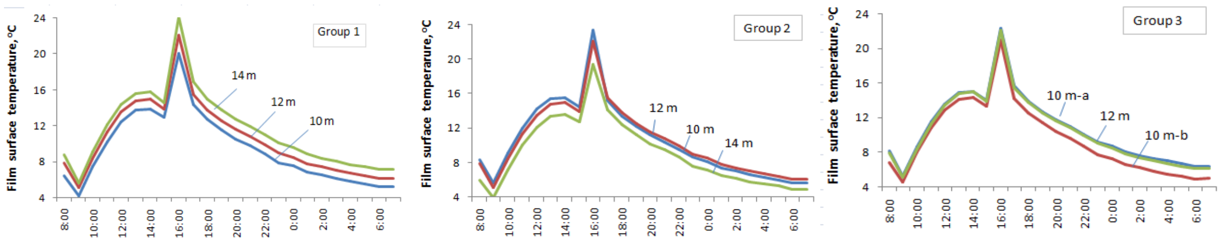
3.2. Surface temperature

The heat gains and losses through the CSG surfaces result in different surface temperatures, which then influence the inside air temperature due to the convection inside the CSG. The soil surface received most of the transmitted solar energy, about 65% (Tong and Li, 2006), with most of the heat losses through the south roof (Chen et al., 1990). The soil surface and film surface temperature variations for the CSG in each group are shown in Fig. 6.



,

(a) Soil surface temperature



(b) Film surface temperature

Figure 6. CSG indoor soil and film surface temperatures

The surface temperature variations shown in Fig. 6 follow the same trends as the inside air temperature variations shown in Fig. 5 except for the cases in Fig. 6 (b) for Group 2, where the average film surface temperature for the 10 m span is 0.7 °C higher during the daytime and 0.4 °C lower during the night than with the 12 m span and also in Fig. 6 (b) for Group 3 where film surface temperature for the 10 m span is 0.2 °C higher than for the 12 m span for the entire day. The soil surface temperature differences between the three spans in Fig. 6 (a) have nearly the same magnitudes as those in Fig. 5. Thus, the results suggest that the soil surface temperature has a large effect on the air temperature changes. Generally speaking, higher soil surface temperatures and higher film surface temperatures result in higher air temperatures.

3.3. Energy in the CSG

3.3.1.Energy transferred through the soil and north wall surfaces

The solar rays transmitted into the CSG are then absorbed by the soil and north wall surfaces. The part of the solar energy that is not for reflected is then conducted deep into the wall or the soil with the reflected radiation and thermal radiation and convection from these surfaces then transferring heat to the other surfaces or to the air. The heat transferred by all of these mechanisms and the heat transfer due to air infiltration along the soil and north wall edges were summed over 24 h and are presented as absolute values in Fig. 7.

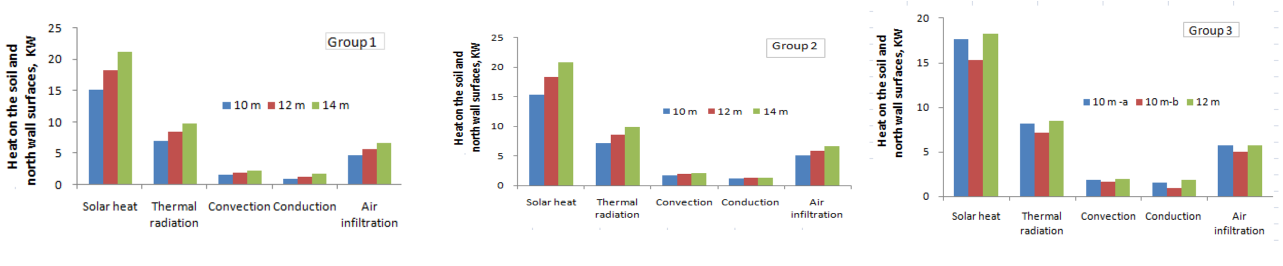


Figure 7. Heat transfer to and from the soil and north wall surfaces

Figure 7 shows that the surface convection is relatively small, around 10% - 11%, compared to the absorbed solar energy. The conduction into the surface is even smaller, only 6% - 9%. Most of the absorbed solar energy received by the soil and north wall surfaces, 45% - 48%, is then released as thermal radiation to the other surfaces. The large amounts of thermal radiation and the small amounts of convection can be explained by the closed CSG design with no ventilation inside. The very small amount of conduction heat transfer is due to the relatively poor thermal diffusivity of the soil such that the temperatures 0.5 m deep in the soil remained unchanged throughout the entire day and the insulation in the north wall. Figure 7 also shows that even for the closed CSG, air infiltration along edges of the soil and north wall absorbs 31% - 33% of the solar energy with the losses to air infiltration increasing as the span increases; thus, good edge seals are more important for all span lengths to reduce the air infiltration and retain more of the heat inside the CSG to heat the inside air.

3.3.2.Surface convection

The convection heat transfer from the surfaces to the air directly affects the air temperatures. When soil and north wall surface temperatures are higher than the air temperature, the convection heat transfer from the surfaces to the air increases the air temperature while the convection heat transfer between the inner roof surfaces and the air mostly cools the indoor air since their surface temperatures are mostly lower than the air temperature. The convection heat transfer variations during the 24 h period are shown in Fig. 8.

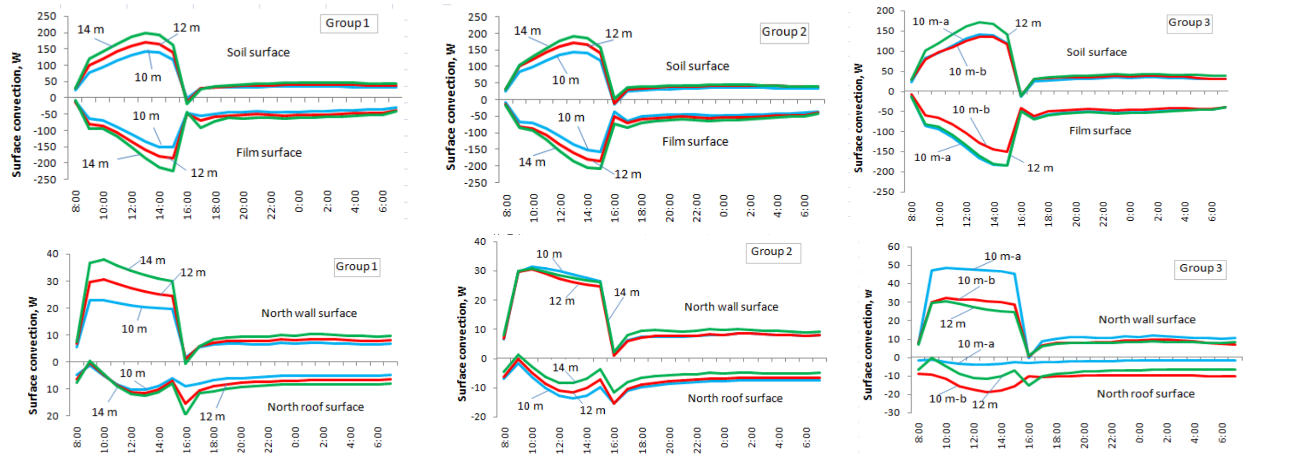


Figure 8. Surface convection heat transfer for each CSG

The surface convection heat transfer varies considerably during the day but is nearly constant during the night as shown in Fig. 8. The total convection heat transfer from the soil, film or north wall surfaces during the day, from 8:00 to 15:00, accounts for more than 60% of the total convection for the entire 24 h. The hourly convection heat transfer rates at the north roof surface change little over the 24 h period. Figure 8 also shows that during the night from 16:00 to 7:00 when the thermal blanket cover covers the film surface, the surface convection heat transfer rates are nearly constant for all the span sizes in each group. These surface convection variations during the daytime indicate that the large air temperature increases mainly depend on the surface convection variations during the daytime and that the indoor air is warmed by the convection heat transfer from the soil and north wall surfaces and cooled by the convection heat transfer to the roof surfaces with the soil provided most of the heating. Even during the night, the soil continues to provide significant heat transfer to the air that balances the heat losses through the film surface, with the north wall also providing some heating of the air at night.

4. Discussion

The temperatures and heat fluxes inside the three groups of CSG with the 10 m, 12 m and 14 m spans were investigated in this study. In the first of these three groups, the dimensions of the span, ridge height, north wall height and north roof width all had the same proportions. Some existing CSG buildings are built in this way but do not strictly have the same proportions. The proportions in Kang et al. (1993) were 0.85 - 0.9 for 6 m and 7 m span buildings with the 6 m span having higher temperatures, while the studies of Tao et al. (2002) with proportions of 0.68 - 0.8 for 6 m and 8 m spans and the studies of Liu et al. (2013) with proportions of 0.72 - 0.8 for 8 m and 10 m spans both showed that the larger spans had higher temperatures. However, in another study by Tang et al. (2014) with proportions of 0.86 - 0.98 for 8 m, 9 m, 10 m and 11 m spans showed that the 10 m span had the highest temperature with the 9 m span having the second highest temperatures with the 11 m span having the lowest temperature. Furthermore, the measured results for the 8 m, 10 m and 12 m spans in the study by Liu et al. (2012) with proportions of 0.67 - 0.87 and the 9 m , 10 m and 11.5 m spans in the study by Jin et al. (2015) with proportions of 0.87 - 0.96 showed that the largest spans in both studies, even with thicker walls, had the lowest temperatures with the 10 m span recommended in both studies. Thus, for spans less than 10 m, the conclusions from these studies except for Kang et al. (1993) agree with the data in Fig. 5 (a) in this study that the inside air temperatures increase with increasing span. However, for spans longer than 10 m, the conclusions are less definitive, including the results of this study. This suggests that the uncertainties may be important in experimental studies.

The different spans with the same north roof and north wall sizes, Group 2 in this study, were used in the experimental studies of Yang et al. (2009) for 7 m and 7.5 m spans and in Liu et al. (2013) for 9 m and 10 m spans, with higher air temperatures with the smaller span in the first study but with the larger span in the second study. The air temperatures in the 12 m span in group 2 were higher than in the 10 m and 14 m spans in this study, which agrees with Liu et al. (2013). The third group used in this study, different CSG designs with the same south roof size, has not been considered in the literature.

When all the spans in the three groups are compared together, the 14 m span design in group 1 has the highest daily average air temperature of 287.76 K and an air temperature at 7:00 the next morning of 282.18 K, with the second highest daily average air temperature of 286.87 K in case 10 m-a with an air temperature at 7:00 the next morning of 281.48 K. The reference 12 m span ranked the third with an daily average air temperature of 286.84 K and an air temperature at 7:00 the next morning of 281.35 K. These comparisons of the spans in the three groups show that 14 m span design in group 1 had highest air temperatures. However, with the results in Group 3, this study recommends the larger span with all the dimensions increased in the same proportions plus a higher north wall.

The simulations in this study used winter conditions, which is the normal production time inside CSG. The leaf area index (LAI) of the crops inside the reference 12 m span was very small, so much of the solar insolation was absorbed by the soil. If the LAI is higher, the heat gains and losses to the soil surface may be quite different. Thus, the effects of crops with different LAI need further study. Furthermore, the span selection analysis in this study focused only on comparing the temperatures, with other parameters such as the humidity and air velocity perhaps also being important parameters.

5. Conclusions

The temperatures and heat fluxes were predicted in Chinese Solar Greenhouses with 10 m, 12 m and 14 m spans in three groups with dimensions that were either all proportional or had the same north roof and north wall sizes or the same south roof size. The predictions used detailed 2D CFD simulations of the internal greenhouse environment. The analyses show that:

(1) In the first group, the CSG with all the dimensions varied in the same proportion, the inside air temperature is highest with the 14 m span and lowest with the 10 m span. The air temperature increases as the span increases, but the temperature differences between the 12 m span and 14 m spans are smaller than those between the 10 m span and 12 m spans. The south roof film surface temperatures vary in the same way between spans.

(2) In the second group, the CSG with the same north roof and north wall dimensions, the air temperature is highest with the 12 m span and lowest with the 14 m span. The larger span receives much more solar energy but also loses more heat through the south roof. The south roof film surface temperatures vary in the same way except that the film surface temperature for the 10 m span is 0.7 °C higher than that for the 12 m span during the daytime.

(3) In the third group, the CSG with the same south roof dimensions, the 12 m span had similar air temperatures with the 10 m span when the north wall with the 10 m span was 2 m taller than that with the 12 m span, while the 10 m span with the same north wall size as the 12 m span had the lowest temperature. The results show that the same solar energy input with the same heat storage area results in the similar inside air temperatures.

(4) The convection heat transfer rates on the north wall and the soil surfaces are 10% - 11% of the absorbed solar insolation heat flux with the thermal radiation fluxes from these surfaces equal to 45% - 48% of the absorbed solar insolation heat flux.

(5) The convection heat transfer is most important during the daytime. The inside air temperature mainly depends on the balance of the convection heat transfer from the soil and north wall to the air and the heat losses due to convection to the south roof film surface during the daytime.

(6) The validations of the temporal air temperature derivatives with time from the CFD models with the experimental values show that the simulation model can successfully predict the air temperatures and heat fluxes for the 10 m, 12 m and 14 m spans.

(7) The simulation results show that the larger span with all the dimensions varied in the same proportion plus a higher north wall is the preferred design.

Acknowledgements

This work was supported by the National High-tech R&D Program of China (863 Program) under contract number 2013AA102407.

References

Bai, Y., T. Wang, G. Tong, W. Liu, 2002. Experimental research on energy saving of solar greenhouse of type north east of China -type Liaoshen I solar greenhouse. Energy Conservation Technology, 20 (1), 21-23 (in Chinese with English abstract).

Chen, D., 1994. Advance of the research on the architecture and environment of the Chinese energy-saving sunlight greenhouse. Transactions of the CSAE, 10 (1), 123-129 (in Chinese with English abstract).

Chen, D., H. Zheng, B. Liu, 1990. Comprehensive study on the meteorological environment of the sunlight greenhouse, 1. preliminary study on the thermal effect of the wall body and covering materials. Transactions of CSAE, 6 (2), 77-81(in Chinese with English abstract).

Chen, Q., 2008. Progress of practice and theory in sunlight greenhouse. Journal of Shanghai Jiaotong University (Agricultural Science), 26 (5), 343–350 (in Chinese with English abstract).

Liu, Y., Z. Zou, X. Hu, Z. Bian, Y. Wang, 2013. Analysis of light and temperature conditions of sunlight greenhouses with different span lengths in central Shaanxi plain. Journal of Northwest A&F University (Nat. Sci. Ed.), 41(2), 108-116 (in Chinese with English abstract).

Liu, Y., Z. Zou, G. Jiang, 2012. Effects of span on solar greenhouse's air temperature and tomato growth and analysis of simulation. Journal of Northwest A&F University (Nat. Sci. Ed.), 40 (1), 204-209 (in Chinese with English abstract).

Jiang, W., Y. Wang, L.Yue, Y. Jin, Y. Li, J. Wang, Y. Xie, Q. Wang, J. Qian, Y. Gao, 2013. Comparative analysis of comprehensive performance with different span greenhouse in Chifeng city sloping land. Inner Mongolia Agricultural Science and Technology, 6, 24-27(in Chinese with English abstract).

Jin, X., Z. Zou, X. Zhao, 2015. The span effect on montanic solar greenhouse. Journal of Agricultural Mechanization Research, 2, 146-150,154(in Chinese with English abstract).

Kang, S., 1990. Development and improvement for Chinese solar greenhouses in Anshan. Transactions of the CSAE, 6 (2), 101-102 (in Chinese).

Kang, S., Y. Dai, S. Fang, K. Wei, 1993. Energy-saving solar greenhouse lighting surface shape and height and span. China Vegetables, 1, 6-9 (in Chinese).

Tang, Z., J. Xie, J. Yu, Z. Feng, J. Lyu, 2014. The study on the warming and thermal insulation properties in the solar greenhouse with different span. Journal of Gansu Agricultural University, 49 (6), 60-63(in Chinese with English abstract).

Tao Z, Li M, Bian M, Zhan J. 2002. The design for the solar lean-to greenhouses in cold areas. China Vegetables, 2, 19-21(in Chinese with English abstract).

Tong, G., B. Li, 2006. Simulation of solar radiation on surfaces of a solar greenhouse. Journal of China Agricultural University, 11 (1), 61-65 (in Chinese with English abstract).

Tong, G., D.M. Christopher, B. Li, 2009. Numerical modelling of temperature variations in a Chinese solar greenhouse. Computers and Electronics in Agriculture, 68 (1), 129-139.

Tong, G., T. Li, T. Wang, Y. Tomoharu, Y. Bai, 2004. Experimental research on micro- climate environment in a large - scale solar greenhouse. Journal of Huazhong Agricultural University, Supp., 67-73 (in Chinese with English abstract).

Wang, J., J. Wang, J. Sun, S. Guo, 2012. Structure configuration and parameters of solar greenhouse in northern Jiangsu province. China Vegetables, 18, 89-98 (in Chinese with English abstract).

Yang, J., Z. Zou, Z. Zhang, Y. Wang, Z. Zhang, F. Yan, 2009. Optimization of earth wall thickness and thermal insulation property of solar greenhouse in Northwest China. Transactions of the CSAE, 25 (8), 180-185(in Chinese with English abstract).

Zhou, C., 2012. Research process of greenhouse standardization in China. China Vegetables, 18,15-20 (in Chinese with English abstract).

Zou, Z., J. Li, N. Wang, Y. Liu, H. Li, H. Li, 1997. Analyse on variations of temperature and quantity of heat in solar greenhouse. Acta Agriculturace Boreali-occidentalis Sinica, 6 (1), 58-60 (in Chinese with English abstract).