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Energy performance optimization of typical Chinese solar greenhouses by means of dynamic simulation

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Abstract

Over the last 20 years, several studies have been made in order to define the structure, function, and application of the Chinese solar greenhouse (CSG). This paper presents a study on the energy performances of the greenhouse envelopes used in the cold northern regions of China by means of thermal dynamic simulations. China is characterized by large variations in the weather conditions across the territory, and CSGs play a vital role for the vegetable production in the northern regions. Usually, due to the presence of three insulation walls and the use of thermal blankets during the night, CSGs enable a general extension of the crop growing season in the cold regions, with little or no additional heating requirements, depending on the weather conditions and on the cultivated crops. The dynamic simulations of the greenhouse energy performances were carried out by means of the building energy simulation program EnergyPlus. Considering the weather of the Shenyang location, the simulations were performed for three different constructions, characterized by different types and properties of glazed surfaces, opaque walls and thermal blanket, as well as ventilation of the structure, considering a free running temperature condition. Results show that when no auxiliary heating and cooling systems are used, the construction strongly influence the periods in which the internal CSG temperature stays in the optimum growing temperature range and above the lethal temperature. Further improvements on the typical CSG construction that increases its energy efficiency are possible, but imply inevitably changes in the simple characteristics and economy of the structure. The economical convenience of the solutions depends on the relation between higher costs of the structure, the market value of the cultivated crops and the improvement of the greenhouse production rate.

Keywords: dynamic simulation, energy performance, solar greenhouse

1 Introduction

China is the Country with the highest greenhouse-based vegetable production in the world. In 2010, the area encompassed by greenhouses reached over 4,7 million ha, nearly twice the area in 2004 (Yang et al., 2010). The sunlit greenhouse, also called Chinese solar greenhouse (CSG) is one of the four main type of structures adopted for the vegetable production; the other types are the low tunnels, high tunnels and multi-span greenhouses.
CSGs play a vital role in China's vegetable production, as they permit to grow warm season crop during the winter with little or no auxiliary heating in locations at latitude of 32°N to 43°N, also in the northeast regions of the Country, where the daily average temperatures in the coldest three months of the year fall below -10°C (Gao et al., 2013). The presence of additional heating systems depends on the weather conditions and on the cultivated crops. Other

advantages of CSGs are represented by the absence of CO_2 emission during the winter production, as well as significant energy savings.
The CSGs are mainly diffused in the northern cold regions of China above the Huai River, such as Shandong, Liaoning, Hebei and Gansu provinces and the Beijing area. The major species grown are warm season vegetables (>90%) such as tomato and cucumber, and some flowers and fruit trees. Exportation of those products to Korea, Japan and several European countries represent an important revenue for the growers (Gao et al., 2010). Russia, Korea and Japan have already started to use this technology (Gao et al., 2010), while in Canada, at latitude of 50°N, a series of studies on thermal performance of the passive solar greenhouse were conducted (Beshada et al., 2006).
The first simple CSG was built in 1930s, but only at the end of 1970s, with further improvements of materials and building parameters, the structure became completely passive from the energy point of view (Gao et al., 2010). The large diffusion of CSGs started in the first years of 1990s, during the 8^{th} and 9^{th} China's Five Year Plan, which promoted the CSG as a key scientific and technological project for the further development of primary sector in the Country (Tong et al., 2013). According to the statistical data of the Chinese Ministry of Agriculture, the area encompassed by CSGs reached in 2010 more than 0,8 million ha, which correspond to the 17% of the area of greenhouses devoted to vegetable production in the Country (Tong et al., 2013). If the trend of the last fifteen years will remain somehow stable, the surface occupied by CSGs will reach 1,5-1,7 million ha in 2020 (Battistel, 2013). However, during the last thirty years the CSG diffusion was not supported enough by adequate improvements of the design and technical supervision, especially in the first period. This led to the diffusion of poorly designed structures, poor quality materials and bad management (Tong et al., 2013).
Thermal performance of CSG depends on regional climatic conditions, building dimensional parameters and materials. Some studies on development, current status and effect of cross-sectional building parameters have already been made, in order to define quality and systematic building standards for CSGs (Tong et al., 2013). Measurements of inside air temperature and humidity for various locations and different CSG dimensional parameters and materials have also been made (Tong et al., 2009); however, on-site experiments are costly and time-consuming, and the results are useful only for the specific conditions of the experiments. Therefore accurate simulation models, that permit to predict the greenhouse microclimate conditions as a function of external climatic conditions and building dimensional parameters and materials, appear to be the best tools to investigate thermal performance and improve design and climate control of CSGs. Numerical simulations have been increasingly used (Fabrizio, 2012); in general, the majority of these studies used steady-state or quasi steady-state models, which don't represent the best option for the simulation of a high thermal inertia system such as CSG (Tong et al., 2008, Tong et al., 2009). Moreover, simulations obtained with multidimensional time-dependent models rarely present a full winter results of CSG thermal performance.
Given this picture, the aim of this study is to investigate the influence of different building materials on the internal temperature for CSG during the whole cold season, using a dynamic simulation model. The simulations have been performed for three structures, designed and characterized by low, medium and high energy-performances, considering a free running temperature condition.

2 Design principles of CSGs

The cross-sectional view of a CSG, with the indication of the main building elements is shown in Figure 1-A. The high energy efficiency of the CSG is related to its basic design principles, which are: the optimization of solar radiation collection; the storage of the energy collected during the day; the minimization of thermal losses.
The first aspect mainly depends on the building orientation in relation to the south, and the shape and material of the sunlit surface. Since the CSG is used to extend the growing season of crops during cold periods of the year, the glazed part of the structure is always oriented (when possible) exactly to the south. The shape and the angle of the south roof represent however the critical point for the solar energy collection, because they strongly influence

the incidence angle between the solar radiation and the sunlit surface, which determine the transmission and reflection of the solar rays through the glazed surface.

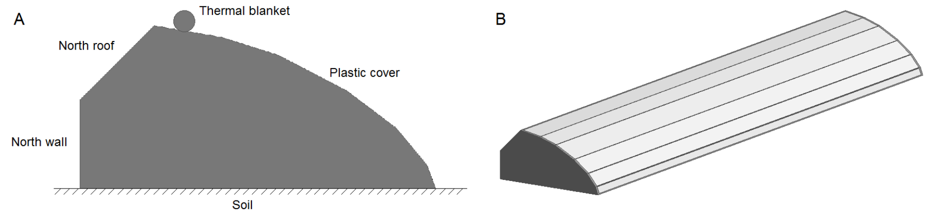

Figure 1: Profile of the CSG (A) and CSG model in DesignBuilder (B).

Many authors studied the performance of the south roof design by means of numerical models, due to the difficulties and limits of experiments. Results show that a curved shape cross-section, which correspond to the modern CSG south roof shape, guarantees better transmission of beam radiation with respect to other type of cross-section shapes (Tong et al., 2013).
As regards the second aspect, during the day the CSG receives and stores part of the energy irradiated from the sun; during the night, the internal temperature is maintained due to the cession of the thermal energy stored. Since a CSG has a south-oriented glazed surface, the north wall has heat storage function. Consequently, the amount of energy that the structure can store mainly depends on the thermophysical properties of the materials used for the inner layers of the back wall. A high volumetric heat capacity is always desirable, but the thermal conductivity, which affect the thermal energy losses during the night, must also be considered.
Finally, the last design principle of the CSG is the thermal insulation. Since the solar energy absorbed by the materials during the day is the only positive term in the energy balance of the greenhouse, it is essential to ensure a good level of insulation for the retention of the energy stored. To better protect and insulate the indoor environment, the CSG is built with three massive walls and only one single south-oriented glazed surface, which is covered during the night with an insulating thermal blanket.

3 Materials and methods

3.1 Case study description

Three different type of south-oriented CSGs, characterized by the same structural dimensions but with different envelope, cover and blanket materials were defined: a low, a medium and a high energy-performance CSG, respectively indicated as LP, MP and HP.
As regards the dimensions, the CSGs is 60 m long and 12,6 m wide, with a 5,5 m ridge height; the cross-sectional parameters are coherent with the modern solar greenhouse building standards. The thickness of the back wall, north roof and side walls are varying as a function of the structure considered for the simulation. The details on the thermal and optical properties of the materials selected for each type of structure are reported in Table1.
The LP greenhouse presents the simplest construction, with the north and side walls made of machine-rammed earth, and an inner layer of bricks added to improve the structural stability. The cover is a thin plastic film with medium optical performance, covered during the night by an economic compressed straw blanket. A ventilation rate of 1,2 ach was considered.
With respect to the LP construction, both the MP and HP greenhouse include a layered north wall and a thicker PVC (polyvinyl chloride) film. The back layered wall is made of bricks and XPS (extruded polystyrene foam) as thermal insulating material; the use of thermal insulating materials permit to halve the thickness of the north wall, reducing consequently the surface occupied by the building. The clear PVC film is characterized by better spectral performance and a higher thickness, which help to reduce thermal and ventilation losses through the glazing. Because of the higher thickness and the better tightness of fit of the PVC film, a ventilation equal to 0,7 and 0,5 volume/h was considered for the MP and HP CSG respectively. For the HP greenhouse, a reflective IR coating was also added to the blanket to minimize the radiation losses through the glazing during the night.

Table 1: Construction properties of the three CSGs considered in the simulations

			s (mm)	λ (W/mK)	τ_{sol} ext/int	ρ_{sol} ext	ρ_{sol} int	τ_{vis} ext/int	ρ_{vis} ext	ρ_{vis} int	ε ext	ε int
Cover	LP	Plastic	2	0,20	0,59	0,11	0,10	0,60	0,12	0,10	0,90	0,89
Cover	MP	PVC	2	0,15	0,86	0,08	0,08	0,88	0,09	0,09	0,84	0,84
Cover	HP	PVC	5	0,05	0,86	0,08	0,08	0,88	0,09	0,09	0,84	0,84
Blanket	LP	Straw, compressed	36	0,09	0	0,25		0	0,25		0,9	
Blanket	MP	Thick cotton	20	0,03	0	0,25		0	0,25		0,9	
Blanket	HP	Thick cotton	35	0,03	0	0,25		0	0,25		0,5	

			s (cm)	λ (W/mK)	c_p (J/KgK)	ρ (Kg/m^3)	α_{sol} ext/int	α_{vis} ext/int	ε ext/int	Λ (W/m^{2}K)
North wall	LP	Rammed earth (ext)	150	1,35	1260	2240	0,70	0,70	0,90	0,79
		Bricks (int)	12	0,81	1050	1800	0,60	0,60	0,93	
	MP	Bricks (ext)	12	0,81	1050	1800	0,60	0,60	0,93	0,52
		XPS with CO_2 blowing	5	0,03	1400	32	0,60	0,60	0,90	
		Bricks (int)	24	0,81	1050	1800	0,60	0,60	0,93	
	HP	Bricks (ext)	12	0,81	1050	1800	0,60	0,60	0,93	0,22
		Air gap	2	0,02	1006	1,3	0,70	0,70	0,90	
		XPS with CO_2 blowing	10	0,03	1400	32	0,60	0,60	0,90	
		Bricks (int)	36	0,81	1050	1800	0,60	0,60	0,93	
North roof	LP	Bitumen (ext)	5	0,30	1000	1000	0,85	0,90	0,90	1,18
		Rammed earth (ext)	20	1,25	1260	2240	0,70	0,70	0,90	
		Miscll. wood mat. (int)	15	0,29	2070	850	0,60	0,60	0,90	
	MP	Bitumen (ext)	2,5	0,30	1000	1000	0,85	0,90	0,90	0,66
		XPS with CO_2 blowing	2,5	0,03	1400	32	0,60	0,60	0,90	
		Miscll. wood mat. (int)	20	0,29	2070	850	0,60	0,60	0,90	
	HP	Bitumen (ext)	2,5	0,30	1000	1000	0,85	0,90	0,90	0,30
		XPS with CO_2 blowing	7,5	0,03	1400	32	0,60	0,60	0,90	
		Miscll. wood mat. (int)	30	0,29	2070	850	0,60	0,60	0,90	
Side walls	LP	Rammed earth (ext)	80	1,25	1260	2240	0,70	0,70	0,90	1,27
		Bricks (int)	12	0,81	1050	1800	0,60	0,60	0,93	
	MP	Bricks (ext)	12	0,81	1050	1800	0,60	0,60	0,93	0,57
		XPS with CO_2 blowing	5	0,03	1400	32	0,60	0,60	0,90	
		Bricks (int)	12	0,81	1050	1800	0,60	0,60	0,93	
	HP	Bricks (ext)	12	0,81	1050	1800	0,60	0,60	0,93	0,31
		XPS with CO_2 blowing	10	0,03	1400	32	0,60	0,60	0,90	
		Bricks (int)	12	0,81	1050	1800	0,60	0,60	0,93	

Nomenclature

s	thickness
λ	thermal conductivity
c_p	specific heat
ρ	density
Λ	thermal conductance
α	optical absorptance
τ	optical transmittance
ρ	optical reflectance
ε	emissivity

Subscript

vis	visible
sol	solar

The only heat gain of a passive CSG correspond to the energy received from the Sun; according to this, it is fundamental to correctly consider the optical properties of the plastic cover used for the glazed surface. For the dynamic simulations, the spectral transmission and reflection coefficients have been considered in the complete wavelength range of the solar radiation (Figure 2). The optical coefficients for the transmission and reflection of solar radiation reported in Table 1 represent the mean value in the visible solar range.

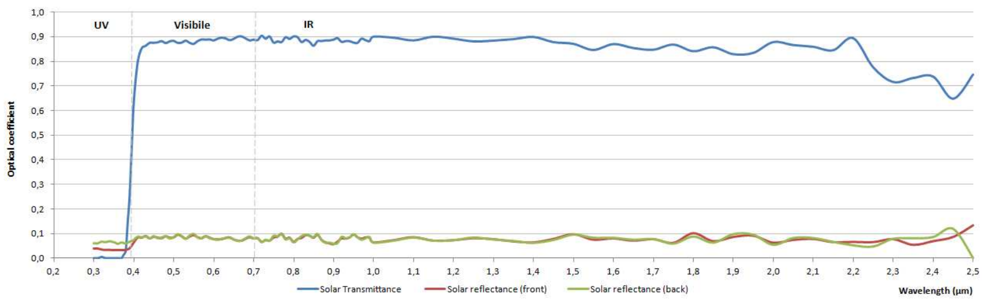

Figure 2: Spectral transmittance, internal and external reflectance of the cover used for the MP and HP CSG.

The other critical component that must be accurately consider in the CSG simulation is the thermal blanket. Depending on the period of the year, the thermal blanket can be rolled up entirely or only partially; the time at which the blanket is removed after the sunrise and rolled down again during the day depends also on the climate of the period. Nowadays, CSG operations are generally based on growers personal experience; an optimal standard thermal blanket management must be still defined.

Dynamic simulations were performed considering a complete roll up of the thermal blanket during every day of the study, in order to ensure adequate photoperiods for the crops and to avoid uneven light distribution inside the building. If this is not done, the plants could become abnormally phototropic, and will not exhibit healthy growth patterns. The time at which the blanket is removed in the morning and rolled down again in the evening was set for every month, and optimized from an energy point of view by means of dynamic simulations. It was found that delaying the removal by one hour after the sunrise and anticipating the application by one hour before sunset was the best mean monthly solution for most of the months considered in the simulation period.

3.2 Dynamic simulation software

The simulation of the greenhouse energy performance was carried out by means of the building energy simulation program EnergyPlus, which is one of the latest and freeware software in the thermal building physic field and it is widely used worldwide for building and HVAC systems design and dynamic simulation. The CSG design was reproduced using DesignBuilder, a software that provide a user interface for the EnergyPlus dynamic simulation engine. The graphical rendering of the building in DesignBuilder is shown in Figure 1-B.
Some of the properties of the materials reported in Table 1 have also been taken from DesignBuilder internal database.
The ground heat transfer and storage was simulated by considering a soil layer of 50 cm (λ=0,6 W/mK,ρ= 2050 Kg/m^3, c_p=1010 J/KgK) and by imposing monthly mean ground temperature to the adjacent layer of the ground. This monthly mean ground temperature was calculated by means of EnergyPlus Ground Heat Transfer Calculator, which is a separated tool and performs a two-dimensional ground heat transfer calculation over a long period (several years) from the weather and soil data. The results of this application are the monthly mean surface ground temperatures that can be used in association with EnergyPlus.

3.3 Validation of the simulation

In order to predict reliable results with the dynamic simulation model, a validation of the model itself was done. The best way to check the accuracy of model results is to compare them with measurements made on real structures. Tong et al. (2009) recorded solar insolation on the ground, inside and outside temperatures and relative humidity for a south-oriented CSG located in Shenyang (latitude of 41.8°N). The indoor measurements were taken in the cross-section centre of the greenhouse during three consecutive sunny days, and a last cloudy day.
The measurements made by the authors were selected as a reference to confirm the reliability of model results; the internal air temperature of the CSG studied by Tong et al. was simulated and compared to the measurements made by the authors during the four days.
The CSG where the measurement were performed was a “modern” type of solar greenhouse, which correspond to the design which find diffusion after 1996; the structure is characterized by the presence of arc-shaped zinc-coated steel frames as a replacement of the vertical steel pillars (Gao et al., 2010). The greenhouse construction included a 600 mm layered north wall, made of bricks and XPS foam as a thermal insulating material, a north wall made with layers of wood and XPS. The glazed south oriented surface was made of 0,12 mm PVC film, covered with a 20 mm thick cotton blanket during the nighttime. The CSG was 60 m long and 12,6 m wide, with a 5,5 m ridge height.
In order to simulate the same external conditions of the authors, the typical weather file of Shenyang, downloaded from the U.S. Department of Energy, was modified using the Weather Statistics and Conversion tool of EnergyPlus. The same management of the thermal blanket was also reproduced. The authors reported that the blanket was rolled half way up from 8:00 to 15:00 during the sunny days, and from 8:00 to 13:00 during the last cloudy day. According to the farmer’s experience, halving the opening and anticipating the application of the blanket with respect to the sunset time is the most effective way to reduce the heat losses from inside the greenhouse.
Because of the high thermal inertia of the CSG, a sufficient warm-up time must be taken into account before starting the comparison of the results with the reference data; according to this, a period of two days was considered a sufficient time. The comparison of the simulated and measured temperature for the last sunny day and the cloudy day is shown in Figure 3.
The simulated temperature variation agrees well with the measured data for both the two days. During the third sunny day, the simulation slightly under predicts the internal temperature before the sunrise, and slightly over predicts the solar energy free gain.
The highest simulated temperature overcomes by 1,8°C the maximum measured temperature, and as a consequence, in the successive hours of the afternoon and almost until the end of the day, the simulated temperatures remain higher than the data. The lower under prediction and maximum over prediction of the simulated temperatures remain always higher

than -1,5℃ and lower than 1,8℃ respectively, with a mean hourly difference of -0,36℃ and 1,00 standard deviation.

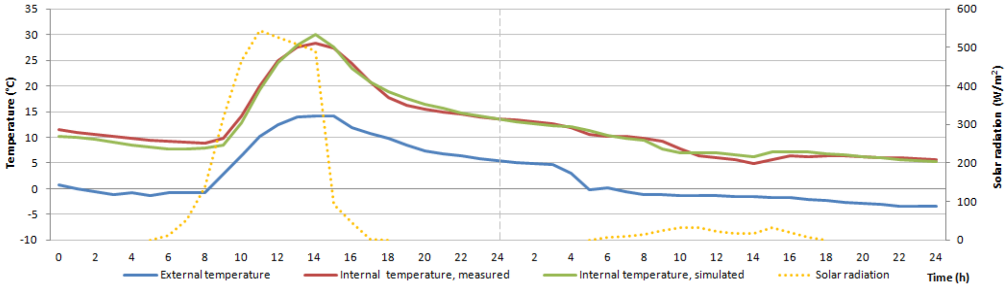

Figure 3: Simulated and measured temperature profiles inside the CSG, 3rd and 4th day.

As regards the cloudy day, it can be observed that the simulation slightly anticipate the internal temperature reduction that occur few hours later the removal of the thermal blanket with respect to the measurements. Even in this second day, during the irradiation of the sun, the simulated temperatures slightly overcome the experimental data. The differences between the simulated temperature and measurements remain however inside the -1,5℃ ÷ 1,5℃ interval for the whole day, with a mean hourly difference equal to 0,15℃ and 0,74 standard deviation.

3.4 Simulations outline

CSGs are mainly diffused in northern China, in locations above 32°N latitude. The capital of the Liaoning province, Shenyang (latitude of 41.8°N) was chosen as the site for the investigation of CSG thermal performance, because of the hard climate of the region and high latitude of the location. The average temperature in the coldest month of the year goes from -18℃ to -15℃.

A complete thermal model and a full winter dynamic simulation was created and performed for the LP, MP and HP CSG, in order to study the potential performance of the buildings during the cold period of the year for the considered location. The simulations were performed always considering a free running temperature condition: the study of the passive energy performance requires in fact to consider the absence of any form of auxiliary heating and cooling systems.

The period selected for the simulations was from the start of November to the end of March, which are the months when the outside temperature starts and stops to fall under 0℃ respectively. The typical data weather file considered for the simulations in Shenyang was provided by the U.S. Department of Energy, in the Weather Data Sources section; the weather file for Shenyang is both available in ASHRAE International Weather for Energy Calculations (IWEC) and Chinese Standard Weather Data (CSWD) formats.

The quantitative comparison of the thermal performance of the CSG types requires the definition of suitable performance indexes. Crops are characterized by optimum growing temperature intervals during daytime and nighttime; therefore, a complete optimum temperature range can be identified. When the internal CSG temperature falls outside this range, the difference between the internal temperature (t_i) and the maximum or minimum optimum growing temperature ($t_{g,max}$ and $t_{g,min}$ respectively) can be calculated. The summation of the hourly differences above the maximum temperature of the optimal range and below the minimum temperature of the optimal range represents the overheating degree hours and overcooling degree hours chosen as performance indexes of the building. The differences were calculated to be always positive; therefore, a lower value of the indexes represent a lower overheating and overcooling of the CSG.

Overheating index

$$I_{oh} = \sum_j \left(t_i - t_{g,\max}\right)_j \quad \text{when } t_i > t_{g,\max} \quad [℃h]$$

Overcooling index

$$I_{oc} = \sum_j \left(t_{g,\min} - t_i\right)_j \quad \text{when } t_i < t_{g,\max} \quad [°Ch]$$

4 Results and discussion

Predicted internal air temperature for the LP, MP and HP CSG during the cold period of the year in Shenyang are shown in figure 4, 5 and 6 respectively.
A temperature of 0°C can be considered as a general lethal temperature for the crops cultivated inside the CSG. For the LP CSG, it can be observed that the internal temperatures start to fall below 0°C from the beginning of December to the half of February; therefore, the low-performance CSG will be unable to guarantee the minimum required temperature in the corresponding period, if no auxiliary heating systems are used.
In order to compute the overheating and overcooling performance indexes, an optimum temperature range must be defined. The interval 10°C ÷ 25°C was selected, because it represents a good reference temperature range for horticultural crops cultivated in CSGs, like tomato and cucumber. The indoor temperature appears to fall below the minimum optimum growth temperature almost for all the period considered in the simulation. A total of 315°Ch and 22602°Ch overheating degree hours and overcooling degree hours were calculated respectively.

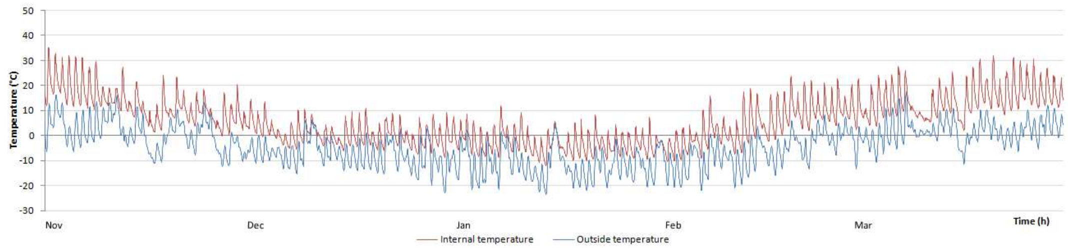

Figure 4: Simulated temperature profile for the LP CSG during the cold season.

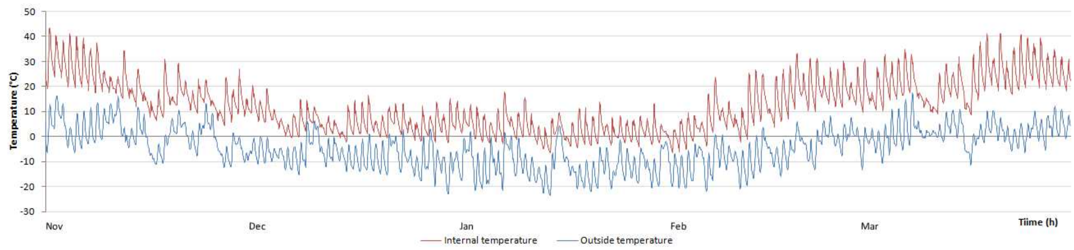

Figure 5: Simulated temperature profile for the MP CSG during the cold season.

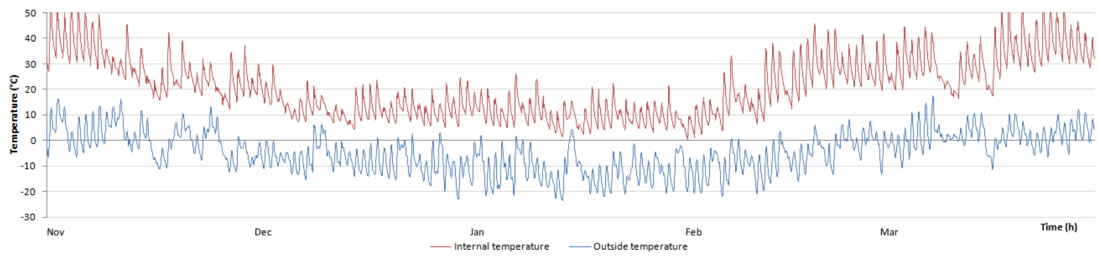

Figure 6: Simulated temperature profile for the HP CSG during the cold season.

Results for the MP CSG show a sensible increase of the internal CSG temperature. From the half of February to the half of November, the lower inside temperature remains always higher than 10°C, which corresponds to the reference minimum optimum growing temperature for the crops. During the coldest months, the mean internal temperature stays above 0°C; however, from the half of December to the end of January, the hourly temperature starts to fall regularly below 0°C. The number of overheating degree hours and overcooling degree hours were equal to 2595°Ch and 10841°Ch respectively.

Results for the HP CSG show a further increase of the mean internal temperature, that appears to stay always over the minimum lethal temperature of 0℃ for the whole cold season. In other words, the building can be considered as a fully passive energy structure for the entire year for the selected location. The internal temperature remains always higher than the reference optimum growing temperature from the 10th of February until the first week of December. The number of overheating degree hours and overcooling degree hours were equal to 11680℃h and 1991℃h respectively.
The comparison of the performance indexes is shown in Figure 7. Results show that a LP construction does not represent the best solution for the Shenyang location: without any form of auxiliary heating, the internal temperature will fall below the minimum optimum growth temperature almost for all the period considered in the simulation, while from the beginning of December to the half of February it will be impossible to cultivate because the internal temperature will systematically fall below 0℃. With respect to the LP CSG, the MP construction permits to halve the overcooling degree hours and reduce by one month the period in which it will be not possible to cultivate (half of December to the end of January).

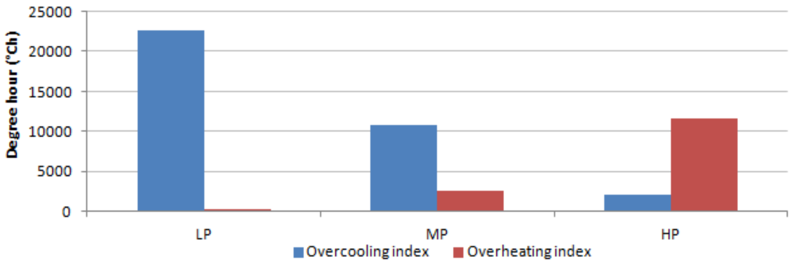

Figure 7: Comparison of the three performance indexes for the three CSGs.

The HP construction permits to further reduce the overcooling degree hours by 91% and 82% with respect to the LP and MP construction respectively. From the energy point of view, the HP CSG appears to be the only construction that allows to use the CSG for the whole winter; problems such as the freezing of the blanket and irrigation difficulties must however be considered if the cultivation are grown even during the coldest periods of the year.
Regarding the overheating of the CSG, it must be noted that a fixed ventilation rate was considered in the simulations. During the cold periods of the year, if the internal temperature becomes too high, it will be sufficient to partially lift up the plastic cover and let the colder outside air come in. During the summer, growers lift up completely the plastic cover, and if needed use a shading device. In this sense, the overheating degree hours do not represent necessarily a cooling energy demand for the building in the period selected for the simulations.

5 Conclusions

The results show that a further improvement on the typical solar greenhouse construction that increases its energy efficiency are possible, but imply inevitably changes in the simple characteristics and economy of the structure. On the other hand, a more complex design guarantees a higher minimum internal temperature during the cold season, which allows to eliminate any auxiliary heating systems or cultivate different and more valuable crops, like ornamental plants and cut flowers. The economical convenience of the solutions depends on the relation among higher costs of the structure, the market value of the cultivated crops and the improvement of the greenhouse production rate.

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