Temperature variations inside Chinese solar greenhouses with external climatic conditions and enclosure materials

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Abstract: Chinese solar greenhouses enable the extension of the crop growing season in the cold climate in Northern China with little or no additional heating. The temporal variations of the air temperatures inside solar greenhouses located at three cities in North, Northeast and Northwest China were predicted by CFD simulations of the greenhouse systems using typical meteorological data. The predicted temperatures based on the meteorological data in Shenyang are quite similar to the measured temperatures. The results also show that the external air temperatures and solar radiation fluxes play more important roles for the inside temperatures as indicated by the highest inner temperature in the morning on Feb. 18 and from 10:00 to 14:00 on Feb. 19 in Beijing and by the predicted temperatures inside the greenhouse being higher in Lanzhou than those in Shenyang and Beijing during most of the day. The average daily temperature inside the greenhouse in Lanzhou was nearly 3.5℃ higher than that in Shenyang. Predicted air temperatures for various wall designs show that for single walls, the daily average interior temperatures in the aerated concrete wall greenhouse were higher than those in the brick wall and reinforced concrete wall greenhouses. However, the air temperature fluctuations were lower in the reinforced concrete wall greenhouse due to greater thermal storage capacity. The results also show that the temperatures in the layered wall greenhouses are quite similar, which coincides with the experimental results

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1 Introduction

China is a large country with large variations in the climate across the country. Solar greenhouses are used in northern climates to grow vegetables throughout the winter; however, there is a growing need to better understand the influence of the climatic conditions and the greenhouse designs on the solar greenhouse microclimate to improve the production rates. Regional climatic conditions including solar insolation, sunshine hours, percentage of sunshine, annual clear and cloudy days, and the lowest ambient temperatures have been used as estimated standards for solar greenhouse construction in China [1, 2]. These studies show that most regions of northern China are suitable for solar greenhouse production. Greenhouse enclosure materials also play an important role affecting the microclimate. To investigate the contributions of greenhouse enclosures on the microclimate, the air temperatures were measured inside greenhouses with different wall materials [3-5]. However, on-site experiments are costly and time-consuming, so numerical simulations have been used to analyze the effects of various external climatic conditions and greenhouse designs.

Numerical simulations have been increasingly used for large plastic/glass greenhouses. Zhang et al.[6] predicted the temperatures and humidities in an unheated greenhouse using a one-dimensional model. Molina-Aiz

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et al.[7] and Ould Khaoua et al.[8] simulated airflow and temperature distributions using two-dimensional models, while Fatnassi et al.[9] simulated airflow, temperatures and humidities using a three-dimensional model. However, these simulations were conducted using steady or quasi steady-state models. Chinese solar greenhouses are relatively small with a large thermal mass in the walls and with a plastic film (usually about 0.1 mm thick) covering the slanted front roof during the day with a thermal blanket added at night to keep the heat inside. Therefore, the rapidly varying solar input and the changing microclimate are much better simulated using fully time-dependent simulations. The objective of this study was to investigate the influence of external climatic conditions and wall materials on the inner temperatures for Chinese solar greenhouses using a two-dimensional time-dependent model, with hourly climate data as the boundary conditions.

2 Materials and methods

2.1 Experimental setup

2.1.1 Greenhouse and climate measurements

The air temperatures were measured in a solar greenhouse with 5.5 m ridge height, 12.6 m width and 60 m length. The greenhouse structure shown in Figure 1 included the north wall (600 mm thick with layers of brick, Styrofoam insulation and air), the north roof (200 mm thick with layers of wood, Styrofoam and other structural materials) and the transparent south surface which was made of a 0.12 mm thick polyvinyl chloride (PVC) film during the daytime covered with a 20 mm thick cotton blanket during the night.

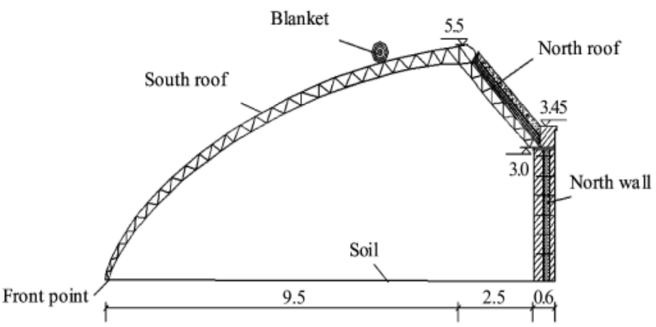


Figure 1 Profile of the solar greenhouse with dimensions in meters

The solar insolation and the air temperatures and humidities inside and outside the greenhouse were measured during the winter and spring from 2003 to 2005 in Shenyang[10]. The solar insolation rates were measured on horizontal surfaces inside and outside the greenhouse. The measured temperatures included the air temperatures at various locations inside and outside the greenhouse, the inner soil temperatures at various depths in the soil, and the inner surface temperatures of the north wall, north roof and the cover on the south roof. The relative humidities, absolute humidities, dew point temperatures and mixing ratios 1 m above the ground across the greenhouse were also measured inside and outside the greenhouse.

2.1.2 Regions selected for modelling

Chinese solar greenhouses are mainly used in northern China. Shenyang (41.77°N) lies in northeast China in a mild zone with a continental climate, with average annual temperatures of 6℃ to 11℃ and monthly average temperatures in the coldest month of −18℃ to −15℃. Beijing (39.95°N) lies in north central China in a typical warm and mild zone with a subhumid and continental monsoon climate, with average annual temperatures of 10℃ to 12℃ and monthly average temperatures in the coldest month of −7℃ to −4℃. Lanzhou (36.05°N) lies in northwest China in a mild zone with a monsoon climate, with average annual temperatures of 4℃ to 14℃ and monthly average temperatures in the coldest month of −14℃ to 3℃.

2.1.3 Wall materials

The walls of typical Chinese solar greenhouses have large thermal capacities to store heat during the day for release during the night. The influence of the wall materials on the thermal environment inside the greenhouse was analyzed for a single layer wall made of brick, reinforced concrete or aerated concrete and for a layered wall with layers of brick and insulation or with layers of aerated concrete and insulation, with wall thicknesses of 60 cm and the same insulation layer material (Figure 1).

2.2 Numerical simulations

2.2.1 Governing equations

The general conservation equation was given by Versteeg and Malalasekera[11]:

$$\partial(\rho\varphi)/\partial\tau + div(\rho\varphi\vec{v}) = div(\Gamma_\varphi grad\varphi) + S_\varphi \qquad (1)$$

Where ρ is the fluid density in kg/m^3; $\vec{v}$ is the velocity vector in m/s; Γ_φ is the diffusion coefficient in m^2/s; φ represents the dependent variable in the conservation equations with the continuity equation for φ=1, the conservation of momentum equations for $\varphi = v_x$, v_y and v_z and the conservation of energy equation for $\varphi = T$. S_φ are the source terms.

2.2.1 Numerical method

The two-dimensional simulation area included the greenhouse air space, the enclosure and the soil to 1.0 m deep under the greenhouse. The system was simulated by solving the time-dependent, two-dimensional laminar conservation equations for the velocity and temperature fields. The analysis also included the thermal radiation heat transfer between the interior surfaces inside the greenhouse assuming that the air was transparent to the thermal radiation and between the outer surfaces and the sky. The solution method was the same as in Tong et al[10].

2.2.2 Boundary conditions

The boundary conditions of the model include the solar radiation to all the exposed interior and exterior surfaces, the external air temperatures and velocities, and the soil temperature 1.0 m below the soil surface, where the temperature was assumed to remain unchanged. The heat loss due to air infiltration was also included in the boundary conditions. The method for including the boundary conditions was given by Tong et al.[10]

The influence of the external climate conditions on the temperatures inside the greenhouse were based on the external climatic data for February 18 and 19 (clear days) taken from typical meteorological data for Shenyang, Beijing and Yinchuan[12]. The external solar radiation fluxes on horizontal surfaces, typical air temperatures, typical air relative humidities and air velocities for the three cities are shown in Figure 2. The effects of the various wall materials on the temperatures inside the greenhouse were based on the measured external climate conditions in Shenyang for comparison to the experimental results.

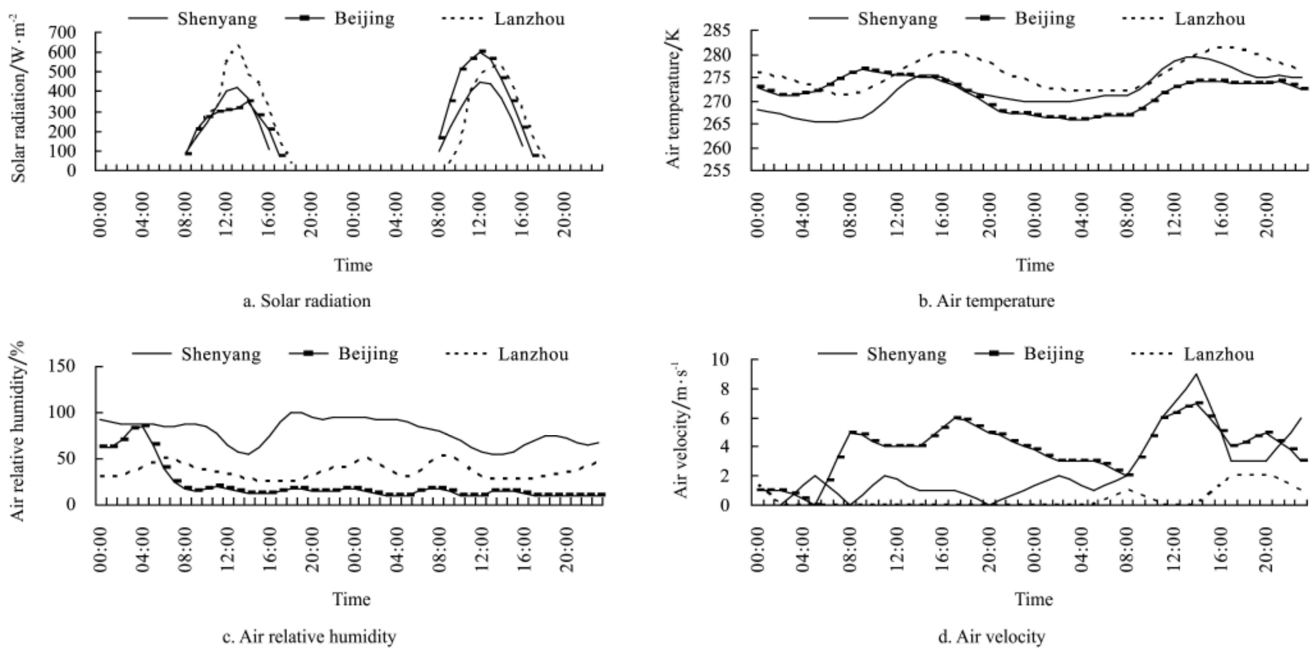


Figure 2 External climatic data taken from typical meteorological data for Shenyang, Beijing and Lanzhou on Feb. 18 and 19[12]

3 Results

3.1 Validation of the simulation based on the typical meteorological data

The interior air temperatures in the middle of the greenhouse at a height of 1 m were simulated based on the typical meteorological data for February 18 and 19 with clear sky for comparison with measured data for the same two days in 2004 and 2005 in Shenyang. The results are shown in Figure 3.

The predicted temperature variations based on the typical meteorological data agree well with the measured temperatures for 2004 and 2005 as shown in Figure 3, especially during the nighttime in 2004. The measured temperatures during the daytime in 2004 were somewhat higher than in 2005 especially on Feb. 18 most likely due to a somewhat sunnier day in 2004 than in 2005.

3.2 Temperature variations in three different cities

The predicted temperatures in the middle of the greenhouse shown in Figure 4 at a height of 1 m above the soil were calculated based on the typical meteorological data for clear days on February 18 and 19 in 2004 and 2005 for Shenyang, Beijing and Lanzhou.

The external air temperature and the solar radiation both strongly affect the inside temperatures. The greenhouse in Beijing has the highest interior temperature in the morning on Feb. 18 which is 1.5℃ higher than that in Shenyang and 1.1℃ higher than that in Lanzhou when the average external temperature from 6:00 to 11:00 in Beijing was 8.7℃ higher than that in Shenyang and 3.4℃ higher than that in Lanzhou. Beijing also had the highest interior temperatures from 10:00 to 14:00 on Feb. 19 due to the higher solar insolation than that in Shenyang or Lanzhou. For most of the rest of the time, the predicted temperatures inside the greenhouse in Lanzhou were higher than those in Shenyang and in Beijing because of the higher outside temperatures and higher solar insolation in Lanzhou. The average daily temperature inside the greenhouse in Lanzhou was nearly 289.5 K while in Shenyang was only 286 K and that in Beijing was between the two.

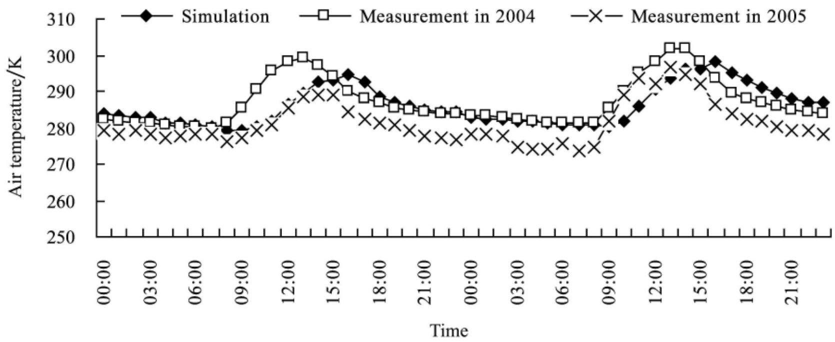


Figure 3 Simulated and measured air temperatures inside a Chinese solar greenhouse in Shenyang on February 18 and 19 in 2004 and 2005.

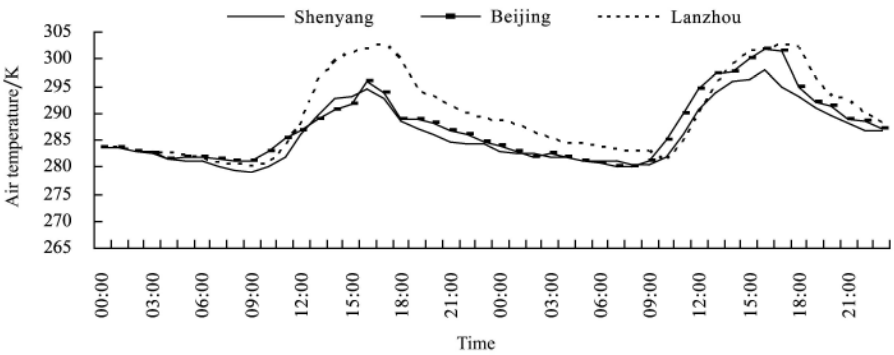
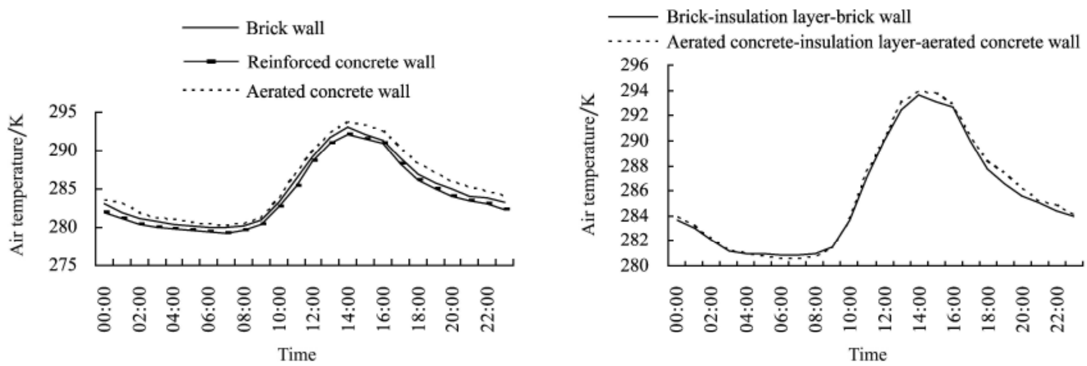


Figure 4 Predicted air temperatures inside Chinese solar greenhouses in Shenyang, Beijing and Lanzhou on February 18 and 19 in 2004 and 2005

3.3 Temperature variations for various wall materials

The variations of the temperatures inside the greenhouses for various wall materials were predicted based on the measured external climatic conditions on Feb. 18, 2004 in Shenyang.

The results in Figure 5a for the single layer walls show that the daily average interior temperatures in the aerated concrete wall greenhouse were 0.7℃ higher than those in the brick wall greenhouse and 1.4℃ higher than those in the reinforced concrete wall greenhouse.



a. Single layer walls b. Layered walls

Figure 5 Predicted air temperatures inside Chinese solar greenhouses with single and layered walls in Shenyang on Feb. 18, 2004

However, the air temperature fluctuations throughout the entire day in the reinforced concrete wall greenhouse were the lowest of the three greenhouses due to its greater thermal storage while the air temperatures in the aerated concrete wall greenhouse fluctuated the most. Thus, the air temperatures in the reinforced concrete wall greenhouse decreased more slowly than that with the other two types of greenhouse walls before the blanket was removed in the morning. The temperatures in the two types of layered wall greenhouses shown in Figure 5b are quite similar, which coincides with the experimental results [13].

4 Discussion

The greenhouse system was simulated by solving the time-dependent, two-dimensional laminar flow conservation equations based on the finite volume method. Typical meteorological data were used in the boundary conditions to predict the inside air temperatures, with reasonable agreement with measured data for two years. Then, the air temperatures in greenhouses with the same materials and designs but located in three cities in North, Northeast and Northwest China were predicted to show that both the outside air temperatures and the solar radiation strongly influence the inside air temperatures. This illustrates why various types of greenhouses have been developed in different parts of China and why different greenhouse designs need to be optimized for different climate regions [14, 15]. The model in this study can be utilized to accurately predict the microclimate greenhouses in various regions and with various designs.

The results show that the wall material influences the interior air temperatures only for the single wall designs using a brick wall, reinforced concrete wall or aerated concrete wall greenhouse. In the greenhouses with layered walls made of high thermal capacity materials on both the inside and the outside with an insulating layer (Styrofoam) in between, the air temperature variations were much smaller.

The variation of the microclimate in the solar greenhouse is very difficult to predict due to its complex structure with the heavy walls on the north side and north roof, the soil, the transparent surface on the south side during the day and the thick cotton cover at night. All of these absorb the solar insolation and then transfer heat to the inside air and lose heat to the outside. Therefore, the exact boundary conditions are difficult to accurately specify. Although this model agrees well with the measured data, the heat and mass transfer mechanisms for the solar greenhouse need further investigation to find more accurate models for the microclimate inside the greenhouse.

5 Conclusions

The predicted temperatures based on typical meteorological data agreed reasonably well with measured data for cold days in Shenyang in February, 2004 and 2005. The agreement was especially good during the nighttime when the temperatures are the coldest.

The external air temperature and solar insolation both strongly influence the inside temperatures. The inside temperatures were simulated using typical meteorological data for clear days on February 18 and 19 for Shenyang, Beijing and Lanzhou. Beijing had the highest interior temperature of the three locations in the morning on Feb. 18 and from 10:00 to 14:00 on Feb. 19 because of the higher temperature or solar radiation in Beijing during that time. However, for most of the time, the predicted temperatures inside the greenhouse in Lanzhou were higher than those in Shenyang and in Beijing with the average daily temperature inside the greenhouse in Lanzhou nearly 3.5℃ higher than that in Shenyang.

Analysis of the temperature variations for various wall materials suggests that the air temperatures inside single layer wall greenhouses vary greatly with the largest temperature difference between designs reaching 2°C. However, the temperature differences in the layered wall greenhouses are quite small, which agrees with experimental measurements.

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