Research Article

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Effect of North Wall Materials on the Thermal Environment in Chinese Solar Greenhouse (Part A: Experimental Researches)

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Abstract: In order to clarify the dependence relationship between the heat storage & preservation wall and the thermal environment, and to provide data base and theory foundation for the north wall construction of the Chinese solar greenhouse (CSG), the experimental measures has been employed to investigate the distributions of temperature, humidity and heat transfer of three different wall materials (*i.e.* perforated brick, fine coal ash brick, common clay brick). The dynamic variations of the heat-storage and heat-release processes were identified, and the thermal response characteristics were discussed. The effect of north wall materials on the thermal environment of the solar greenhouse in northern China was revealed. The results indicated that the daily heat-storage and heat-release of fine coal ash brick wall can reach $\phi_{input} = 34.5\sim130.6 \text{ W}\cdot\text{m}^{-2}$ and $\phi_{output} = -24.15\sim-45 \text{ W}\cdot\text{m}^{-2}$, respectively. The daily heat-storage time can reach $t = 5\sim8 \text{ h}$, and the wall temperature at night can be $3\sim4^\circ\text{C}$ higher than the air temperature. Moreover, the maximum indoor temperature of the fine coal ash brick wall can be maintained at $t \leq 16.7 \leq 31.1^\circ\text{C}$, the minimum humidity can be maintained at $29.75\sim45\%$. Fortunately, the construction cost is moderate, while the physical properties are obviously better than those of perforated brick and common clay brick in the CSG. The overall thermal performance of fine coal ash brick is the best of the three north wall materials, and it can make the most advantage of the heat-storage and heat-preservation performances of the CSG. As a consequence, the fine coal ash brick wall of the solar greenhouse has good promotion value in northern China and other high latitude, high altitude and long winter regions.

1 Introduction

Most areas of northern China are in the cold and freezing natural climate, and the lowest temperature in winter are mostly in the range of below zero. The application of solar greenhouse is often accompanied with large energy consumption. Moreover, the freezing damage of solar greenhouse often occurs in the northern winter. Chinese solar greenhouse (CSG) is an important agricultural facility for the year-around cultivation of vegetables and fruits in these cold regions. The CSG can achieve high-efficiency energy utilization without any auxiliary heating, so it plays a great role in the winter agricultural production in the northern China [1]. According to the statistical results until 2017, the covers of solar greenhouses in China is up to $370.1 \times 10^4 \text{ hm}^2$, accounting for 33% of the total horticultural areas in China. Why CSG has the ability of overwintering production under the severe condition without auxiliary heating? It is mainly because the enclosing body of the solar greenhouse, especially the north wall, has the capacities of heat storage and heat preservation. The north wall (*i.e.* back wall) of CSG can maintain the temperature and humidity at an appropriate level to create a suitable environment for crop growth. So the CSG construction can receive the solar radiation energy to realize self-sufficiency and reduce the cost of artificial heating [2]. The structural arrangement of the north wall has direct relationship with the thermal environment characteristics of the CSG, and the energy benefits are superior to other retaining enclosures such as soil, north roof and south roof. As the main thermal mass in the CSG, the north wall must have excellent capacities of heat storage and heat preservation while in consideration of the structural load. On the one hand, the north wall is supposed to absorb a large amount of so-

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lar radiation energy during the daytime. The heat transfer coefficient should be low, and the heat preservation and thermal insulation performance should be qualified to reduce the heat loss. On the other hand, the north wall is required a reasonable thermal inertia, which can continuously release the accumulated heat into the greenhouse. In other words, the north wall of the CSG is identified the critical heat source to increase the thermal performance at night. Therefore, the material design of the north wall is of great significance to the CSG.

At present, there are many basic researches on the heat storage and heat preservation of the north wall. Cabeza *et al.* [3], Kalnaes and Jelle [4] summarized the various kinds of composite walls used in the buildings over the past decade. The early related researches mainly utilize experimental methods. And the research ideas tend to use the reference of civil buildings. Gourdo *et al.* [5], Ren *et al.* [6], Jolanta *et al.* [7], Beshada *et al.* [8], Singh and Tiwari [9] have proposed new wall materials which can improve the heat storage & preservation properties of the north wall in the solar greenhouse. Chen *et al.* [10], Banu *et al.* [11], Kondo *et al.* [12], Heim and Clarke [13], Alawadhi [14], Critten [15], Najjar and Hasan [16] have successively studied diversified kinds of phase-change wall materials. Although these composite materials and phase-change materials can improve the thermal environment inside the solar greenhouse, the investment costs a lot in the long run. What's more, the construction is especially difficult. Therefore, the economy and practicability of general promotion are not available. Another unfortunate factor is that the high-cost active-heating greenhouses is insufficient to be introduced or manufactured in China due to the immature agricultural technology.

The recent researches has turned into the effect of thermal property of north wall on the internal environment. Since the thermal environment plays the most important role in the solar greenhouse, people gradually increase their efforts to investigate the heat storage and heat preservation of the north wall. Chen [17], Yu *et al.* [18] and Santamouris *et al.* [19] have studied the north wall thermal performance in the solar greenhouse, and discussed the heat-storage characteristics during the daytime and the heat-release characteristics at night. Jolanta *et al.* [20], White *et al.* [21] researched the thermal insulation properties of the north wall structures. Mei [22], Mihalakakou [23], Newman and Wilson [24] studied the active-heating features of the north wall. The researches of Chen *et al.* [25, 26], Zhang *et al.* [27], Chauhan and Kumar [28], Nayak and Tiwari [29], Hassanain *et al.* [30] have pointed out that passive-heating north wall can effectively reduce energy consumption and save the operating cost compared to the active-heating

north wall. Some other researchers like Tong *et al.* [31], Xu *et al.* [32] and Saberian Sajadiye [33] have employed numerical simulations to predict the thermal performance of the north wall in the solar greenhouse. The north wall material has higher requirements for heat storage and heat preservation in northern China, because the natural environment is especially awful and the temperature is below zero for a long time in winter. But unfortunately, the generalized solar greenhouse limits the construction cost of the wall materials. As a result, there are very few usable wall materials for the CSG promotion in northern China. The north wall is still dominated by common clay brick, perforated brick and fine coal ash brick today. They account for more than 80% of the CSG wall materials in northern China [34]. The optimal method to research the effect of the north wall materials on the thermal environment inside the solar greenhouse is the combination of experiment measures and numerical simulations. One should firstly obtain reliable basic data by experimental testing. Secondly, the relationship between the north wall materials and the thermal environment inside the greenhouse is defined. And then the mathematical model can be established based on these results in numerical simulation. When the numerical model is verified accurate and reliable compared with the experimental data, the advantages of numerical simulation can be taken to research the flexibility of parameter variation and quantitative description. It can be seen that an important prerequisite of this methodology is to obtain the basic data through experiments and to understand the relationship between the north wall material and the greenhouse thermal environment. Nevertheless, there is no systematic research on the effect of wall materials (*i.e.* common clay brick, perforated brick and fine coal ash brick) which widely used in solar greenhouses in northern China. The previously reported experimental researches lack integrity and fail to reveal the essential relationship between north wall material and greenhouse thermal environment. It is insufficient to support the subsequent model establishment and simulation calculation. So it needs to be solved urgently.

Different north wall materials not only affect the heat-storage and heat-release characteristics of the solar greenhouse, but also directly determine the crop yield and energy consumption. In recent years, although some researchers have made some related efforts on the influence of the north wall material on the CSG thermal environment, it is far from complete and has not yet formed a complete theoretical system. Moreover, the suitable wall material property of the CSG for northern China has not yet been determined. Based on the above reasons, this study has investigated the north wall thermal performance through ex-

perimental measurements (for the thermal mathematical model of the CSG, it will be described in detail in another article of Part B using numerical simulation). The daily average heat-storage and heat-release characteristics, the heat-storage time, the maximum maintainable temperature, the humidity and the construction cost of different north wall materials in the CSG have been discussed in this experimental research. At the same time, the thermal performances of the different north wall materials can be systematically studied to provide the theory foundation for agricultural applications.

2 Experimental system and testing method

Chinese solar greenhouse in the experimental testing

The experimental CSG is located at $41^{\circ}49'N$, $123^{\circ}34'E$, facing to north and south, and the azimuth is south by west 7° . In this experimental testing, three kinds of solar greenhouses are shown in Figure 1. All the outer layer materials of the north walls are respectively the polystyrene board, and the inner layer materials are perforated brick wall, fine coal ash brick wall and common clay brick wall. The polystyrene board is an excellent thermal insulation material with low price (only 20 RMB/720 cm²), low density (only 18 kg/m³) and low heat-transfer coefficient (only 0.041 W/m·K). At present, the specific thermal insulation on the outer layer of the north wall has been widely used in the CSG [4, 17, 25–27, 31, 32]. First of all, the external insulation layer can enhance the sealing property of the north wall, reducing the thermal loss and improving the thermal insulation performance. Secondly, the maintenance and replacement of the external insulation layer are very convenient, which greatly enhances the capacity of resisting the ambient environment damage. So the building life of the CSG is prolonged. Thirdly, the thermal insulation is built at the external layer with simple structure, short construction period and low invested cost. Therefore, the north wall in the CSG mainly uses polystyrene board as thermal insulation material at the outer layer. And the three north walls in the experiments are perforated brick & polystyrene board, fine coal ash brick & polystyrene board, common clay brick & polystyrene board. The ridge height is 4m, the north wall height is 2.7m, the span is 8m, and the length is 60m. The structural framework uses arch steel truss without pillar inside. The other structural parameters and material properties of the three experimental solar greenhouses are all the same.

Figure 1: Three kinds of solar greenhouses with different north wall materials in the experimental measurements: (a) perforated brick north wall, (b) fine coal ash brick north wall, (c) common clay brick north

2.1 Main structural and material parameters of the CSG

The internal structure of the CSG is shown in Figure 2. In the experiment, the south roofs (*i.e.* lighting surfaces) of three different north walls are made of the same materials. In the daytime, the south roof uses Japanese PO film for the covering material. It is a kind of modified polyolefine composite material mainly composed of ethylene, propylene, butene and other homopolymers, with good toughness, low temperature resistance, high softening temperature, excellent thermal and light stability, and good corrosion resistance. In the night, the south roof is covered with thermal insulation material (*i.e.* three layers of composite insulation quilt): two layers of non-woven fabric and one layer of sprayed cotton in the middle. The main material properties in the experimental greenhouses are shown in Table 1 and Table 2.

Table 1: The main materials of the CSG

greenhouse structure		material	
south roof by day		Japanese PO plastic film	
south roof by night		Non-woven & sprayed cotton	
back slope		steel structure	
back roof		concrete	
north wall	perforated brick & polystyrene board	fine coal ash brick & polystyrene board	common clay brick & polystyrene board
brick wall composition	clay, shale	fine coal ash, lime	clay

Table 2: The main material property parameters of the CSG

Parameter	thermal conductivity K W/m·K	specific heat C_p J/(kg·K)	density ρ kg/m ³	experimental thickness mm	kinetic viscosity kg/(m·s)	emissivity (-)
PO plastic film	0.19	-	920~960	0.08~0.8	-	0.7
heat preservation quilt	0.037~0.095	1600	70	16~55	-	-
back roof	0.93	1050	1800	300	-	0.8
common clay brick	0.81	1050	1800	370	-	0.93
north wall						
perforated brick north wall	0.58	1061.1	1400	370	-	0.93
fine coal ash brick north wall	0.50	1050	1600	370	-	0.93
polystyrene board	0.041	2414.8	18	110	-	-
soil	0.76~1.16	1010	1500~2000	2200	-	0.92
air inside the greenhouse	0.02	1013	1.205	-	1.81×10^{-5}	-

Figure 2: The structure diagram of the Chinese solar greenhouse

2.2 Experimental equipment

The temperature and humidity in the experimental CSG are recorded by using an automatic HOBO recorder produced by Onset Company in the United States. The detective data is continuously recorded at one-minute intervals, and the collected data is preserved to the output text in

the form of excel table. The instrument temperature probe is treated with radiation protection during the measurement and has a standard accuracy of $\pm 0.2^\circ\text{C}$. The other temperature measuring instruments is type-T thermocouple. The employed device has many advantages such as high measurement accuracy, fast thermal response time, high mechanical strength and good voltage resistance. The CR1000 and CR3000 data collector produced by Campbell Company are used for data acquisition. The HFP01 sensor is used to measure the heat flux data in soil, walls and other buildings, which uses a ceramic and plastic material shell produced by Hukseflux Company in the United States. The regular voltage signals are transmitted to the surrounding medium so as to collect heat flux data. The CR1000 and CR3000 data collector are used for data acquisition, too.

Table 3: Locations and contents of measuring points inside and outside the CSG

Measuring point marks	Test contents	Measuring point positions	Measuring point marks	Test contents	Measuring point positions
1	North wall surface temperature	0.50m from the surface and 0.00m from the north wall	11	South roof surface temperature	4.00m from the north wall
2	North wall surface temperature	1.35m from the surface and 0.00m from the north wall	12	South roof heat flux	4.00m from the north wall
3	Heat flux on the north wall surface	1.35m from the surface and 0.00m from the north wall	13	Back slope surface temperature	0.75m from the north wall
4	North wall surface temperature	2.25m from the surface and 0.00m from the north wall	14	Back slope heat flux	0.75m from the north wall
5	Indoor air temperature and humidity	1.00m from the surface and 1.50m from the north wall	15	Surface soil temperature	0.00m from the ground and 4.00m from the north wall
6	Indoor air temperature and humidity	1.00m from the surface and 4.00m from the north wall	16	Deep soil temperature	0.15m from the surface and 4.00m from the north wall
7	Indoor air temperature and humidity	1.00m from the surface and 6.50m from the north wall	17	Deep soil temperature	0.30m from the surface and 4.00m from the north wall
8	Indoor air temperature and humidity	It is 2.00 m from the surface and 1.50 m from the north wall.	18	Surface soil heat flux	0.00m from the surface and 4.00m from the north wall
9	Indoor air temperature and humidity	2.00m from the surface and 4.00m from the north wall	19	Outdoor air temperature and humidity	1.00m from the ground and 9.98m from the north wall
10	Indoor air temperature and humidity	3.00m from the surface and 1.50m from the north wall

Figure 3: Layout of temperature sensors and humidity sensors inside and outside the CSG

2.3 Characteristics and testing methods of experimental greenhouse management

The experimental period in this experimental investigation is the most representative severe winter in northern China from December 2016 to March 2017. The greenhouse management methods are the same for three different north walls in the experimental testing. The heat preservation quilt was rolled up at 8:30 a.m. and put down at 4:00 p.m. The heat fluxes of south roof, north wall, back slope and soil are monitored for 24 hours continuously. For the monitoring of various conventional meteorological factors, the time interval of data acquisition is 10 minutes. Figure 3 shows the layout of the detection points inside and outside

Figure 4: The locations of the measuring points in the north wall of the CSG

the greenhouse, and the corresponding relevant location information is shown in Table 3.

2.3.1 The locations and methods of the temperature and humidity measuring points

The temperature and humidity sensors in the experimental CSG are set in north to south direction. The distances from the north wall are 1.5 m, 4 m and 6.5 m, respectively. The hanging thermometer and hygrometer are 1.0 m from the indoor ground, 2 m and 3 m from the ground. Underground temperature sensors in the middle are placed in 0m, 0.15m and 0.3m depth. These sensors are evenly disposed inside and outside the CSG to capture the temperature and humidity distributions in every corner including the air, wall and soil. And this kind of the layout scheme of the sensor positions has been demonstrated reliable by many researchers [11, 12, 21, 26, 27].

2.3.2 The positions and methods of thermocouple arrangements

Figure 4 is the distribution diagram of the thermocouples. The heat flux plates are respectively arranged on the inner surface of the north wall, the inner surface of the back slope, front roof and soil surface. The arrangement positions of the thermocouples inside the walls are selected in the middle of the greenhouse (i.e. from east to west 30 meters). Therefore, the temperature of the wall cross section at different thicknesses can be measured, and the data are collected every 10 minutes. The probe distributions in the vertical direction are respectively 0.5m, 1.35m and 2.2m height above the ground. And the distances from the wall surface in the horizontal direction are 0.01m, 0.02m, 0.05m, 0.10m, 0.20m and 0.30m, respectively.

2.4 Calculation methods and formulas

The accumulated time of the instrument is slightly different from the daily timing method (24-hour timing method, unit: hour). The conversion formula between the two methods is as follows:

$$t = \begin{cases} t_{\text{time}} & (\text{first day}) \\ t_{\text{time}} + 24\text{h} & (\text{second day}) \end{cases} \quad (1)$$

where t is the accumulated time value of the instrument, t_{time} is the daily timing method.

To reflect the fluctuation range of temperature change in the CSG, the limit temperature difference between days is calculated in the experiment, and the formula is as follows:

$$\Delta T_{\text{max} - \text{min}} = T_{\text{max}} - T_{\text{min}} \quad (2)$$

where $\Delta T_{\text{max} - \text{min}}$ is the limit temperature difference value, T_{max} is daily maximum temperature of greenhouse, and T_{min} is the minimum temperature of the greenhouse during the daytime.

In order to evaluate the influence of the external environment, the heat-release performance and the speed rate of reaction temperature, the daily heating rate and cooling rate of the greenhouse must be calculated. The specific calculation methods are as follows:

$$k_{Tup} = \frac{|T_{\text{start}(up)} - T_{\text{end}(up)}| \Delta t_{up}}{\Delta t_{up}} \quad (3)$$

$$k_{Tdown} = \frac{T_{\text{start}(down)} - T_{\text{end}(down)} \Delta t_{down}}{\Delta t_{down}} \quad (4)$$

where k_{Tup} and k_{Tdown} are the daily heating rate and daily cooling rate of the greenhouse. $T_{\text{start}(up)}$ and $T_{\text{end}(up)}$ are the temperature starting and ending values in the heating stage. $T_{\text{start}(down)}$ and $T_{\text{end}(down)}$ are the temperature starting and ending values in the cooling stage. Δt_{up} is the required time to heat up. Δt_{down} is the required time to cool down.

In order to evaluate the thermal performance of each experimental greenhouse, the maximum average temperature and the lowest average temperature are calculated. The average heating rate and average cooling rate are analyzed. The time range of the average heating rate is from 8:30 a.m. to 1:00 p.m., and the corresponding time range of the average cooling rate is from 1:00 p.m. to 6:00 a.m. of the next day. The specific calculation methods of the average heating rate and the average cooling rate are calculated as follows:

$$\bar{\varphi}_{\text{top}} = \frac{(\bar{T}_{13:00} - \bar{T}_{8:30})}{7.5} \quad (5)$$

$$\bar{\varphi}_{\text{down}} = \frac{(\bar{T}_{13:00} - \bar{T}_{6:00})}{17} \quad (6)$$

where $\bar{\varphi}_{\text{top}}$ is average heating rate of the CSG, $\bar{\varphi}_{\text{down}}$ is the average cooling rate. $\bar{T}_{13:00}$ is the air average temperature of greenhouse at 1:10 p.m. for 10 consecutive days. $\bar{T}_{8:30}$ is the air average temperature of greenhouse at 8:30 a.m. for 10 consecutive days (the temperature when picking up curtain). $\bar{T}_{6:00}$ is the air temperature of greenhouse at 6:00 a.m. for 10 consecutive days.

In order to study the heat-storage and heat-release performance of the north wall, the heat flux (per unit time and per unit area) is measured by heat flux sensor, and the calculation method of heat flux along the vertical direction of the wall is expressed as follows:

$$q = \frac{t_1 - t_{n+1}}{\sum_{i=1}^n \frac{b_i}{\lambda_i A}} \quad (7)$$

where q is the heat flux at the measuring points. t_1 and t_{n+1} are respectively the temperatures in front and back of the measuring points. b_i is the wall thickness of the i layer. λ_i is the thermal conductivity of the wall. A is the contact area of the measuring point.

The relative humidity of the air in the greenhouse is an important meteorological factor to evaluate the microclimate of the greenhouse in the agricultural facilities. The high or low air relative humidity will become a common obstacle factor in the production. The relative humidity of the air used in the experiment is the ratio of absolute humidity to highest humidity, and the air humidity value represents the saturation level of the water vapor in the greenhouse. The specific calculation formula is as follows:

$$Rh = \frac{\rho_w}{\rho_{w,\max}} \cdot 100\% \quad (8)$$

where Rh is air relative humidity, ρ_w is the absolute humidity of the greenhouse. $\rho_{w,\max}$ is the maximum humidity.

3 Experimental results and analysis

3.1 The heat-storage and heat-release characteristics of three north walls

3.1.1 The heat-storage and heat-release characteristics of the north wall under the condition of sunny day

The energy conversion modes in the CSG consist of the heat-storage and the heat-release processes of the north wall and the soil. The energy transfer forms in solar greenhouse are composed of solar radiation, heat conduction of the enclosures, natural and forced convection inside and outside the greenhouse, and so on. The heat generated by the greenhouse at night comes from the heat release from the walls and the soil. The instantaneous heat-release energy of the wall is collected by setting the heat flux plate at the height of 0.5m, 1.35m and 2.25m above the ground, so the arithmetic mean value of the heat flux at each moment is obtained.

Figure 5 displays the daily variation of instantaneous heat flux of different wall materials under sunny days. As shown in Figure 5(A), the positive heat flux indicates that the north wall of the greenhouse is in the heat-storage state (ϕ^+). The north wall of greenhouse B is the first to store heat ($t = 2.5\text{h}$, 8:30 a.m.). The second is the greenhouse C ($t = 3.3\text{h}$, 9:18 a.m.) and the third is the greenhouse A ($t = 3.5\text{h}$, 9:30 a.m.). The heat-storage characteristics are mainly related to the structural feature, thermal conductivity, specific heat capacity and other physical parameters of the north wall. The thermal resistance and specific heat capacity of the three kinds of wall materials are closed to each other, but the wall structure of fine coal ash brick is more conducive to the accumulation of solar radiation energy. So the heat-storage performance is the best. After 8:30 a.m., the thermal preservation quilt of the south roof is opened, and the heat flux of the north wall increases rapidly under the solar radiation, but the time period of reaching the peak value of the three greenhouses are slightly different. The north wall of greenhouse A reaches the maximum $\phi^+ = 119.5 \text{ W}\cdot\text{m}^{-2}$ at $t = 7.3\text{h}$ (i.e. 1:18 p.m.). The north wall of greenhouse B reaches the maximum $\phi^+ = 130.6 \text{ W}\cdot\text{m}^{-2}$ at $t = 7\text{h}$ (i.e. 1:00 p.m.). The north wall of greenhouse C reaches the maximum $\phi^+ = 101.5 \text{ W}\cdot\text{m}^{-2}$ at $t = 6.8\text{h}$ (i.e. 0:48 p.m.). In addition, the negative heat flux indicates that the north wall is in a heat-release state (ϕ^-). After 4:00 p.m., the instantaneous heat flux of the north wall of three greenhouses gradually changed from positive to negative value. With the decrease of the ambient temperature, the solar radiation is weakened and the inter-

Figure 5: Daily variation of instantaneous heat flux of different wall materials under sunny days (Observation time: from 6:00 a.m. to 6:00 a.m. the next day, 24 h)

nal temperature of the greenhouse is accordingly reduced. In order to maintain the heat balance of the greenhouse, the wall is changed from heat-storage to heat-release. The north wall of greenhouse A and greenhouse C are the first to realize heat release ($t = 10$ h, 4:00 p.m.), and then is the greenhouse B ($t = 10.2$ h, 4:12 p.m.). After 8:00 p.m., the north wall heat-release of greenhouse B tends to be stabilized, and the heat-release of greenhouse B is the largest among the three kinds of wall materials ($\phi^- = 50 \text{ W}\cdot\text{m}^{-2}$). The heat-release characteristics are directly related to the crop growth in the CSG at night. The excellent heat-release characteristics of fine coal ash brick wall are helpful to create the best growth environment for crops. As shown in Figure 5(B) and Figure 5(C), four typical moments of $t = 3.0$ h, $t = 6.8$ h, $t = 9.5$ h and $t = 11.45$ h have been selected in the experimental measurements. These four typical time correspond to the heat-release valley, the heat-storage peak and the transition stage of the north wall. As shown in Figure 5(C), the difference of heat storage among the three greenhouse north wall materials is the largest at $t = 6.8$ h (i.e. 0:48 p.m.). The difference of heat release among the three greenhouse north wall materials is the greatest at $t = 11.45$ h (i.e. 5:27 p.m.).

3.1.2 The heat-storage and heat-release characteristics of the north wall under the condition of cloudy day

Figure 6 displays the daily variation of instantaneous heat flux of different wall materials under cloudy days. As shown in Figure 6(A), due to the lack of heat source in the greenhouse, the wall heat-storage time (only 3~5h) is shorter than that in sunny days. Greenhouse B has the longest heat-storage time and greenhouse C has the shortest heat-storage time. The heat-storage fluxes of the north wall in greenhouse A and greenhouse C reach the maximum $\phi^+ = 20.7 \text{ W}\cdot\text{m}^{-2}$ at $t = 6.9$ h (i.e. 0:54 p.m.). Nevertheless, the heat flux of the north wall in greenhouse B reaches the maximum $\phi^+ = 34.5 \text{ W}\cdot\text{m}^{-2}$ at $t = 6.8$ h (i.e. 0:48 p.m.). In cloudy days, the solar radiation energy is much less than the sunny days, so the heat mass entering the greenhouse is less. As a consequence, the temperature in the greenhouse is much lower than that of sunny days. In the conditions of solar radiation energy absence under cloudy days, the heat-storage performance of the perforated brick wall and the common clay brick wall is more obvious, and external wall will lose more energy than that of the fine coal ash brick wall. Most of the time period of the three north walls is in the heat-release state in the condition of cloudy day. The north wall heat-release of the greenhouse B is the maximum (i.e. $\phi^- = 24.15 \text{ W}\cdot\text{m}^{-2}$), and the greenhouse C is the minimum (i.e. $\phi^- = 17.25 \text{ W}\cdot\text{m}^{-2}$). The amount of heat accumulated by the fine coal ash brick

Figure 6: Daily variation of instantaneous heat flux of different wall materials under cloudy days (Observation time: from 6:00 a.m. to 6:00 a.m. the next day, 24 h)

north wall is the most in the daytime, so the amount of heat released at night is also the most. The north walls of greenhouse A and greenhouse C are the first to release heat (*i.e.* $t = 8.4\text{h}$, 1:24 p.m.), and then is greenhouse B (*i.e.* $t = 9.4\text{h}$, 3:24 p.m.). After 9:00 p.m., the heat flux of the north wall tends to be stable. As shown in Figure 6 (B) and Figure 6 (C), four typical moments of $t = 4.0\text{h}$, $t = 6.9\text{h}$, $t = 10\text{h}$ and $t = 11.6\text{h}$ are selected respectively. These four typical moments also correspond to the heat release valley, the heat storage peak and the transition stage of the north wall, respectively. As shown in Figure 6(C), the heat-storage difference of the three north wall materials is the largest at $t = 6.9\text{h}$ (*i.e.* 0:54 p.m.). The north wall materials of three greenhouses are in the conversion stage of heat-storage and heat-release at $t = 11.6\text{h}$ (*i.e.* 5:36 p.m.). The amount of solar radiation on cloudy days is the weakest, which is almost only scattering radiation. The north wall of fine coal ash brick also has better heat storage and heat preservation capacities under cloudy conditions.

To further compare the heat releasing difference of the north wall materials, the heat-release characteristics of the three greenhouses in the whole winter are comprehensively evaluated. The contribution of the monthly average released heat of the three kinds of north walls to the greenhouse is displayed in Figure 7. According to the results of heat-release test, the heat-release capacities of the three north walls increase month by month. The most obvi-

Figure 7: Comparison of the average released heat of three kinds of greenhouse walls in winter

ous increasing is greenhouse B and the growth rate is 22%. The average monthly released heat of greenhouse A and greenhouse C is closed to each other. In January, February and March, the average monthly heat-release capacity in the three greenhouses is: greenhouse B > greenhouse A > greenhouse C.

Figure 8: The heat-storage and heat-release rule of perforated brick wall: (a) Temperature variation of different cross sections of the north wall (b) Variation of surface temperature and air temperature (observation time: 6:00 a.m. to the next day 6:00 a.m.)

3.2 The response regularities of the internal temperature to the heat-storage and heat-release characteristics of different north wall materials

3.2.1 Effect of heat-storage and heat-release of perforated brick wall on greenhouse temperature

Figure 8(a) is the heat-release distribution in the north wall of greenhouse A at night (i.e. 6:00 p.m. to the next day 6:00 a.m.). For greenhouse A, the heat-release thickness of the north wall at 6:00 p.m. is 15cm, but the heat-release thickness at 9:00 p.m. is 20cm. After that, the heat-release thickness of the north wall is equal to or greater than 30 cm at 0:00, 3:00 and 6:00 in the morning. The heat-release temperature is gradually attenuated over time, suggesting that the solar energy accumulated in the north wall is transferred to the indoor environment. The high-temperature region of the north wall is mainly concentrated on the surface of 5cm near the inner wall, indicating that the heat accumulated in the brick wall tends to conduct to the outside. Therefore, it is critical important to increase the insulation property of the north wall in the solar greenhouse. It can be seen from Figure 8(b) that the air temperature in the greenhouse is higher than the surface temperature of the north wall during the time period of $t = 0\text{h}\sim 10\text{h}$ (i.e. 6:00 a.m. to 4:00 p.m.), indicating that the greenhouse wall is in the heat-storage stage due to the warming effect of the solar radiation. When $t = 10\text{h}$ (i.e. 4:00 p.m.), the air temperature inside the greenhouse is $2\sim 3^\circ\text{C}$ lower than the wall surface

temperature, so the wall is in the heat-releasing stage at night.

3.2.2 Effect of heat-storage and heat-release of fine coal ash brick wall on greenhouse temperature

Figure 9(a) is the rule of heat-release in the north wall of greenhouse B at night (i.e. 6:00 p.m. to the next day 6:00 a.m.). The heat-release thickness of the north wall at 6:00 p.m. is 15cm and at 9:00 p.m. is 20cm. Like greenhouse A, the heat-release thickness of the north wall is greater than 30 cm at 0:00, 3:00 and 6:00. The heat-releasing high-temperature region is concentrated on 5~10cm of the inner wall near surface, so the distribution range of the heat-storage source inside the north wall body is wider than that of greenhouse A. Meanwhile, the heat preservation performance of the north wall in greenhouse B is satisfied to the CSG. As illustrated in Figure 9(b), the air temperature is $2\sim 3^\circ\text{C}$ higher than the wall surface temperature during the time period $t = 5\sim 6\text{h}$ (i.e. 11:00 a.m. to 12:00 a.m.), suggesting that the north wall is in the heat-storage stage. For the time period of $t = 0\sim 5\text{h}$ (i.e. 6:00 a.m. to 11:00 a.m.) and $t = 6\sim 24\text{h}$ (i.e. 12:00 a.m. to the next day 6:00 a.m.), the north wall is in the heat-release stage, and the air temperature inside the greenhouse is lower than the wall surface temperature. The temperature difference between them is especially noticeable at night. The heat release ability of the wall is significant and lasting, and the surface temperature of the north wall is $3\sim 4^\circ\text{C}$ higher than the indoor air temperature.

Figure 9: The heat-storage and heat-release rule of fine coal ash brick wall: (a) Temperature variation of different cross sections of the north wall (b) Variation of surface temperature and air temperature (observation time: 6:00 a.m. to the next day 6:00 a.m.)

Figure 10: The heat-storage and heat-release rule of common clay brick wall: (a) Temperature variation of different cross sections of the north wall (b) Variation of surface temperature and air temperature (observation time: 6:00 a.m. to the next day 6:00 a.m.)

3.2.3 Effect of heat-storage and heat-release of common clay brick wall on greenhouse temperature

Figure 10(a) is the rule of heat-release in the north wall of greenhouse C at night (i.e. 6:00 p.m. to the next day 6:00 a.m.). The heat-release high-temperature region of the north wall is mainly concentrated on the 3cm of the inner wall, which indicates that the accumulated heat in the north wall is more conductive to the outside. Therefore, greenhouse C needs to enhance the wall insulation. According to Figure 10(b), the difference between air temper-

ature and wall surface temperature is insignificant, and the heat-storage effect of wall is not obvious before $t = 5.2$ h (i.e. 11:12 a.m.). Under the effect of solar radiation, the indoor air temperature is obviously higher than that of the north wall in the period of $t = 5.2\sim 11.3$ h (i.e. 11:12 a.m. to 5:18 p.m.). After $t = 11.3$ h (i.e. 5:18 p.m.), the air temperature at night is $2\sim 3^{\circ}\text{C}$ higher than that of the wall surface, and the wall is in heat-release stage.

3.3 The response regularities of internal thermal environments to external environmental conditions of three north wall materials

3.3.1 Response regularities of air temperature to heat-storage and heat-release characteristics of different north wall materials

Figure 11 exhibits the indoor and outdoor temperature distributions of three different north wall materials in the sunny day. When the external environment temperature reaches the peak (i.e. $t = 12.54\text{h}$, $T_{\text{fine(out)}} = 0.3^\circ\text{C}$), the internal temperature reaches the maximum value. Greenhouse B reaches the peak firstly ($t = 12.16\text{h}$). And then is greenhouse C ($t = 12.33\text{h}$). The last is greenhouse A ($t = 12.92\text{h}$). The comparison can be expressed as $T_{\text{max(B)}} = 35.1^\circ\text{C} > T_{\text{max(A)}} = 31.1^\circ\text{C} > T_{\text{max(C)}} = 26.9^\circ\text{C}$. The peak value of internal temperature in greenhouse B is the largest, indicating that the instantaneous endothermic capacity of pulverized coal ash brick wall is the strongest. In the period of $t = 7.6\sim 17.1\text{h}$, the internal temperature variations of the three greenhouses are the same, which is consistent with the external temperature changing trend. It's worth noting that the temperature curve is unimodal. All the south roof quilts of three greenhouses are opened at 8:30 a.m. in the morning. As the increase of the solar height angle after $t = 7.6\text{h}$, the indoor temperature is obviously affected by the external temperature rising. The greenhouse A and the greenhouse B have the same heating rate (i.e. $k_{T(A)up} = k_{T(B)up} = 5.2^\circ\text{C/h}$). The heating rate of greenhouse C is smaller (i.e. $k_{T(C)up} = 4.4^\circ\text{C/h}$). It indicates that the fine coal ash brick wall and the common clay brick wall have the same thermal buffering capacity, but the response of the perforated brick wall to the ambient temperature changing is the weakest. The solar altitude angle decreases gradually after $t = 13.3\text{h}$ (since 1:18 p.m.), the cooling rates of the three greenhouses are obviously higher than that of external ambient temperature (i.e. $k_{T(B)down} = 3.3^\circ\text{C/h} > k_{T(C)down} = 3.2^\circ\text{C/h} > k_{T(A)down} = 2.9^\circ\text{C/h} > k_{T(out)down} = 1.3^\circ\text{C/h}$). The temperature drop slows down at night after $t = 17.1\text{h}$ (since 5:06 p.m.). At the same time, the temperature variations of greenhouse B and greenhouse C exhibit multi-peak distributions. The lowest internal temperature of the three greenhouses appears at $t = 7.6\text{h}$ (i.e. 7:36 a.m.), and the comparison can be expressed as $T_{\text{min(A)}} = 5.18^\circ\text{C} < T_{\text{min(C)}} = 5.9^\circ\text{C} < T_{\text{min(B)}} = 11.1^\circ\text{C}$. In the daytime, the solar energy is stored inside the north wall to raise the temperature. At night, the heat in the north wall is released, and the wall temperature decreases. It can be seen that no

Figure 11: Effect of the north wall material on the indoor temperature in the sunny day

Figure 12: Effect of the north wall material on the indoor temperature in the cloudy day

matter daytime or night, greenhouse B heat is basically balanced, the fine coal ash brick wall stores the most amount of heat during the daytime and releases the most amount of heat at night.

Figure 12 shows the indoor and outdoor temperature distributions of three different north wall materials in the cloudy day. Due to the high cloud covering, the solar radiation intensity is weakened. As a consequence, the temperature difference inside and outside the greenhouse is reduced, and the limit temperature in the three greenhouses correspondingly decreases. The comparisons can be expressed as $\Delta T_{\text{max-min(A)}} = 11.2^\circ\text{C}$ (cloudy) $< \Delta T_{\text{max-min(A)}} = 25.9^\circ\text{C}$ (sunny), $\Delta T_{\text{max-min(B)}} = 9.1^\circ\text{C}$ (cloudy) $< \Delta T_{\text{max-min(B)}} = 24^\circ\text{C}$ (sunny) and $\Delta T_{\text{max-min(C)}} = 8.8^\circ\text{C}$ (cloudy) $< \Delta T_{\text{max-min(C)}} = 21^\circ\text{C}$ (sunny). Meanwhile, the heating rate of internal and external environment is smaller than that of sunny day. The internal heating rates of the three kinds of north wall mate-

Figure 13: Effects of different north wall materials on heating rate and cooling rate of the CSG (greenhouse A: perforated brick wall, greenhouse B: fine coal ash brick wall, greenhouse C: common clay brick wall, out: external environment, top: heating rate, down: cooling rate)

materials are basically the same (i.e. $k_{T(A)up} = 2.4^{\circ}\text{C/h}$, $k_{T(B)up} = 2.3^{\circ}\text{C/h}$ and $k_{T(C)up} = 2.3^{\circ}\text{C/h}$). There is no significant difference in the peak indoor temperature between greenhouse A and greenhouse C (i.e. $T_{\max(A)} = 16.6^{\circ}\text{C}$ and $T_{\max(C)} = 16.3^{\circ}\text{C}$). The time of the outdoor temperature peak (i.e. $t_{\max(out)} = 13.68\text{h}$) lags behind that of the indoor temperature peak (i.e. $t_{T\max(A)} = 12.92\text{h}$, $t_{T\max(B)} = 12.16\text{h}$ and $t_{T\max(C)} = 12.16\text{h}$).

Figure 13 illustrates the effects of different north wall materials on heating rate and cooling rate of the CSG. As discussed above, the heating process is in the morning, and the cooling process is in the afternoon and evening. The higher the heating rate is, the faster the thermal response of air temperature to external climate is, and the solar energy absorption by the north wall is insignificant. The higher the cooling rate is, the worse the thermal inertia is, and the heat-storage performance of the north wall is worse. As shown in statistical results, the average heating rate (i.e. $\bar{\varphi}_{topA} = 5.008^{\circ}\text{C/h}$) and the average cooling rate (i.e. $\bar{\varphi}_{downA} = 1.356^{\circ}\text{C/h}$) are both higher and the temperature fluctuation is more greatly in greenhouse A. The average heating rate and the average cooling rate of greenhouse B are about the same as those of greenhouse C (i.e. $\bar{\varphi}_{topB} = \bar{\varphi}_{topC} = 4.382^{\circ}\text{C/h}$ and $\bar{\varphi}_{downB} = \bar{\varphi}_{downC} = 1.304^{\circ}\text{C/h}$). But they are smaller than the greenhouse A. It indicates that the north wall of greenhouse B and greenhouse C have better heat storage. The thermal properties of different north wall materials are different. For example, the thermal conductivity, the specific heat and so on. Due to the various thermal properties of the wall materials, the thermal preservation can be different under the same thermal resistance. In the cloudy days, the average heating rate and average cooling rate of the three greenhouses decrease significantly, which tend to be slower compared with the

sunny days (i.e. fine days). And the heating/cooling rate of greenhouse A is the most obviously among the three greenhouses. The temperature fluctuation of greenhouse B is the smallest. The heating rate and cooling rate are respectively $\bar{\varphi}_{topB} = 1.936^{\circ}\text{C/h}$ and $\bar{\varphi}_{downB} = 0.639^{\circ}\text{C/h}$, which demonstrates that the heat-storage inertia of greenhouse B is significant.

3.3.2 Response regularities of air relative humidity to heat-storage and heat-release characteristics of different north wall materials

Figure 14 shows the relationship between temperature and humidity in the greenhouse B between December 2016 and March 2017. It can be found from the diagram that the variation of air relative average humidity is opposite to that of air temperature change. The changes in the air relative humidity will directly affect the growth and development of the plants. And it may even cause diseases.

Figure 15 describes the humidity relationship between the internal air and the outdoor environment in the sunny day. The relative average humidity curves in the three greenhouses are like a unimodal funnel. The relative air humidity reaches the maximum at $t = 7.2\text{h}$ (i.e. 7:12 a.m.). Then the heat preservation quilt on south roof is rolled up, and the indoor air temperature rises. So that the air humidity decreases rapidly with the temperature increase. The humidity reaches the lowest value at $t = 13.6\text{h}$ (i.e. 1:36 p.m.). As the heat preservation quilt is put down again, the humidity gradually increases with the decrease of temperature after $t = 19.2$ (i.e. 7:12 p.m.). The humidity remains at a high level until the heat preservation quilt is opened in the next day. Generally speaking, higher relative average

Figure 14: The temperature and humidity distributions of greenhouse B (observation time period: December, 2016 to March, 2017)

Figure 15: Humidity relationship between the indoor air and the outdoor air with different north wall materials in the sunny day

Figure 16: Humidity relationship between the indoor air and the outdoor air with different north wall materials in the cloudy day

humidity is easy to induce crop diseases in the CSG. The relative humidity of greenhouse A and greenhouse C maintains above 85% for most of the time period (i.e. 0:00 a.m. to 8:30 a.m.). So they are not suitable for crop growth compared with greenhouse B.

Figure 16 shows the humidity relationship between the internal air and the outdoor environment in the cloudy day. Due to the weakening of solar radiation intensity, the humidity of the external environment increases in cloudy days. The greenhouse A and the greenhouse C maintain the relative humidity above 84.5% for most of the time period (i.e. 0:00 a.m. to 8:30 a.m. and 5:00 p.m. to 12:00

p.m.). The relative average humidity curves in greenhouse A and greenhouse C present unimodal funnel distribution. But the humidity distribution in greenhouse B is lower (i.e. greenhouse B < greenhouse A < greenhouse C). Moreover, the relative average humidity in greenhouse B at night rises again obviously in comparison with greenhouse A and greenhouse C.

As an important energy storage structure in the CSG, the north wall is the main heat source in the greenhouse at night, and it is also an important facility to maintain the temperature at night. Although the external environment in winter goes against to the crop growth, we can create a

suitable growth environment for spontaneous regulation by the north wall. The key of this kind of spontaneous regulation is the heat-storage and heat-release characteristics of the north walls (*i.e.* heat storage flux ϕ^+ and heat releasing flux ϕ^-). The heat transfer characteristics of the north wall depend on the material, which are also related to the compensation of temperature and the adjustment of humidity. Due to the generalized use of CSG in northern China, the selection of the north wall materials must take into account of the economic benefits. Therefore, low construction cost is an indispensable factor in the north wall construction. The three different wall materials investigated in this investigation (*i.e.* perforated brick, fine coal ash brick, common clay brick) are all energy-saving building blocks which is advocated by the state. All of them are suitable for the north wall of the CSG. However, in terms of construction cost, the perforated brick is the lowest (*i.e.* 22, 100 RMB). The price of fine coal ash brick is moderate (*i.e.* 34, 100 RMB). The application of fine coal ash brick not only has good heat storage & preservation characteristics in sunny and cloudy days, but also meets the requirements of national energy saving and emission reduction. In a word, the fine coal ash brick can be widely popularized and applied as the north wall in the CSG and other similar passive solar greenhouses. To sum up, the fine coal ash brick wall has good promotion value for the high latitude, high altitude and long winter regions.

4 Conclusions

The present experimental investigation has studied the effect of north wall material on the thermal environment in the CSG. The main conclusions are as follows:

1. The peak indoor temperature of greenhouse B is higher than that of greenhouse A and greenhouse C on both cloudy and sunny days. Despite the atmospheric counter-radiation in cloudy days, the minimum temperatures in greenhouse B and greenhouse C are basically constant at night, and the greenhouse B can maintain the thermal environment at a high level.
2. The indoor temperature fluctuation of greenhouse A is remarkable in sunny days. But the heat storages of greenhouse B and greenhouse C are better. The temperature fluctuation of greenhouse B is the smallest in cloudy days, indicating the fine coal ash brick has better thermal inertia property than the perforated brick and common clay brick.
3. In sunny days, the north wall material of greenhouse B is the fastest to store heat and the greenhouse A is the slowest. In cloudy days, the heat storage time of greenhouse B is the longest, and greenhouse C is the shortest. Moreover, the heat release of greenhouse B is the greatest, and the greenhouse C is the smallest.
4. The relationship between the average relative humidity is: greenhouse B < greenhouse A < greenhouse C. Moreover, the recovery rate of the relative humidity in greenhouse B at night is obviously slower. The humidity level of greenhouse B is more beneficial to crop growth.
5. Using fine coal ash brick wall as the north wall can give full play to the heat storage & preservation performance because it realizes the efficient utilization of light energy and consumes moderate construction cost. This kind of north wall has good promotion value for the high latitude, high altitude and long winter regions.

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