Experimental research on the microclimate in the naturally ventilated multi-span greenhouse

Zhenjun Gao[1], Wenyang Li[1], Wei Li[2], Xiaoming Ding[3*]

(1. *College of Mechanical and Power Engineering, China Three Gorges University, Yichang 443002, Hubei, China*;
2. *Guangdong Modern Agricultural Equipment Research Institute, Guangzhou 510630, China*;
3. *Key Laboratory of Agricultural Facilities Structural Engineering, Academy of Agricultural Planning and Engineering, Ministry of Agriculture and Rural Affairs, Beijing 100125, China*)

Abstract: In order to further understand the changing laws of environmental factors in large multi-span greenhouses under natural ventilation conditions and the internal relations between various environmental factors, and ultimately improve the precision of microclimate regulation of large multi-span greenhouses. Taking the multi-span greenhouse with a small spire structure in the Demonstration Base of Guangdong Agricultural Technology Extension Station as the research object, under the condition of natural ventilation with butterfly-shaped windows, the changes in temperature, humidity, wind speed and solar light intensity of different monitoring planes in the greenhouse were monitored. After analyzing the monitoring data, it was found that: 1) The temperature gradient in the vertical direction in the large multi-span greenhouse is more obvious than that in the small greenhouse, and the highest average temperature difference monitored can reach 7.9°C. The velocity field in the multi-span greenhouse is always maintained within the range of 0.3-0.4 m/s, and the ambient wind speed has no effect on the airflow speed in the greenhouse. The humidity and speed in the multi-span greenhouse show good uniformity. 2) In a large multi-span greenhouse, the secondary radiation generated by the internal shading has less impact on the area near the ground, which can effectively reduce the ground temperature. 3) Under the conditions studied in this research, the temperature and humidity in the greenhouse follow the external environment as well, showing that the greenhouse design is reasonable, and the air renewal and heat exchange inside and outside the greenhouse are good during natural ventilation.

Keywords: natural ventilation, multi-span greenhouse, environmental factors, microclimate
DOI: 10.25165/j.ijabe.20241703.7073

Citation: Gao Z J, Li W Y, Li W, Ding X M. Experimental research on the microclimate in the naturally ventilated multi-span greenhouse. Int J Agric & Biol Eng, 2024; 17(3): 68–74.

1 Introduction

With the continuous development of human socio-economic and technological levels, people have higher requirements for food safety and quality[1]. It is widely used greenhouses in agricultural production because of their high yield and low cost. According to the research of Vadiee and Martin[2], the greenhouse yield is 10-20 times higher than that of outdoor gardening. Among them, the stable microclimate environment in the greenhouse, which is isolated to change the production conditions, plays a key role[3,4].

The agricultural greenhouse is a complex system with many input characteristics. Its primary function is to maintain the stability of the internal microclimate and to maintain various influencing factors such as wind speed, solar radiation, external temperature and humidity within an appropriate range. In the process of greenhouse development, many scholars have conducted extensive research on the monitoring, changing laws, simulation and regulation of the greenhouse microclimate. Ren et al.[5] established a multi-step rolling prediction model for greenhouse microclimate; Liu[6] established a greenhouse microclimate prediction model with an improved BP neural network. Ganzhur et al.[7] believes that temperature and humidity are important factors of the greenhouse microclimate, and established an automatic temperature, room temperature and humidity control system in the Matlab/Simulink environment. Ma et al.[8] established a greenhouse microclimate simulation model to analyze the 24 h temperature and light radiation changes at any location in the greenhouse. Yan et al.[9] explored the changing laws of the microclimate in the solar greenhouse under different ventilation conditions and found that the rear-slope overall window ventilation has better lighting conditions and ventilation and cooling effects than the rear-slope partitioned windows and the front roof ventilation. Edwin et al.[10] found through simulation calculations that in a multi-span greenhouse with multiple openings, the airflow has great unevenness, and the airflow entering the side windows has a great speed loss, resulting in a very uneven indoor temperature.

The above studies mostly focus on the monitoring of the microclimate of a single greenhouse and the influence of environmental factors. There are few studies on large-scale multi-span solar greenhouses. Ding et al.[11] studied the microclimate changes of single-span and multi-span plastic greenhouses and found that the humidity in the multi-span plastic greenhouses is lower and the temperature and humidity environment is more suitable for plant growth. Under natural ventilation conditions, several studies have confirmed that the number of spans has a significant impact on the ventilation rate and temperature and humidity characteristics of the greenhouse[12-16]. There is a big

Received date: 2021-09-16 **Accepted date:** 2022-12-11
Biographies: Zhenjun Gao, PhD, Professor, research interest: fluid engineering equipment, Email: 570186276@qq.com; **Wenyang Li**: Researcher, research interest: fluid engineering equipment, Email: 1012377178@qq.com; **Wei Li**: PhD, Professor, research interest: agricultural equipment, Email: 1214107350@qq.com.
***Corresponding author: Xiaoming Ding**, PhD, Professor, research interest: microbial molecular genetics. No. 41, Maizidian Street, Chaoyang District, Beijing 100125, China. Tel: 86-10-59196902, Email: xmding74@fudan.edu.cn.

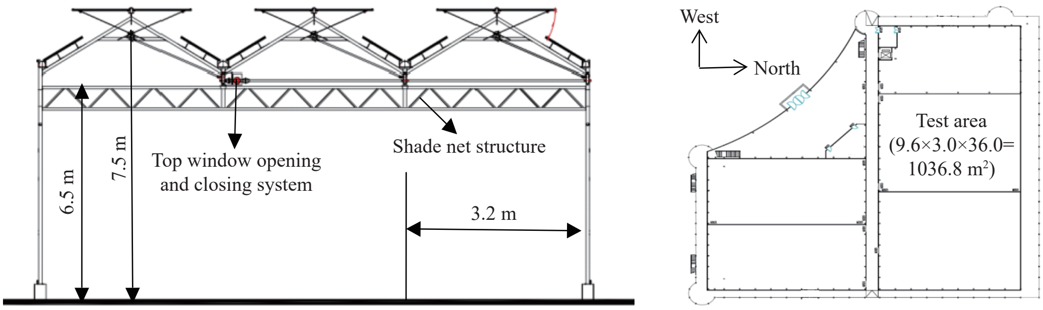
difference between the multi-span greenhouse and the single-span greenhouse in the microclimate characteristics. Most of the literature only studies the characteristics of one or two environmental factors in the greenhouse, which is not enough to reflect the characteristics of the microclimate in the greenhouse. Mashonjowa et al.[17] and Davies[18] pointed out that the design and climate control of the greenhouse should take full account of local conditions, and the control and management of the complex climate in the greenhouse require aim observational data. Therefore, all environmental factors in the greenhouse need to be taken into consideration. Considering the complexity of the coupling between various environmental factors in the greenhouse, it is difficult to get accurate results with the Computational Fluid Dynamics (CFD) method[19-23]. Therefore, this research uses experimental methods to study the distribution characteristics of the microclimate in the multi-span solar greenhouse under natural ventilation conditions. The data obtained will provide a reference for further optimizing the microclimate regulation in the multi-span solar greenhouse and guide the normal commissioning of the experimental greenhouse.

2 Materials and methods

2.1 Test greenhouse

The experimental greenhouse is a butterfly-shaped window glass greenhouse newly built in 2019 at the Demonstration Base of Guangdong Agricultural Technology Extension Station. It is in Kemulong, Tianhe District, Guangzhou (113°24′E, 23°11′N). 30 m above sea level, east-west direction, sitting north facing south. It is in the subtropical monsoon climate zone, with long summers and warm winters, and abundant rainfall. It showed the location and structure of the test greenhouse in the test base in Figure 1.

The main body of the test greenhouse adopts a multi-span small spire structure, and the mainframe adopts light hot-dip galvanized steel materials. The greenhouse skylight device rotates around the special aluminum alloy profile of the roof and uses an electric torque to control the top window opening mechanism. The maximum opening angle reaches 45°. The greenhouse is equipped with 1.5 m electric vertical lifting side windows. Each greenhouse has a side window that connects to the environment. There is an internal shading system in the greenhouse, and aluminum foil insulation film with a shading rate of 60% is used to adjust the intensity of the light in the greenhouse. Combined with the ventilation window, it can improve the natural cooling effect of the greenhouse. The greenhouse roof is covered with 4 mm thick diffuse reflective glass+AR coating, the light transmittance is above 93%, the surrounding is covered with 5 mm thick single-layer tempered glass, and a safety film is attached. The light transmittance is above 90%, and the partition wall is covered with 4 mm thick diffuse reflective glass+AR coating, light transmittance is above 93%. Insect proof nets are installed in the vents.The tested greenhouse size parameters are listed in Table 1.



a. Butterfly window structure b. Layout of the test base

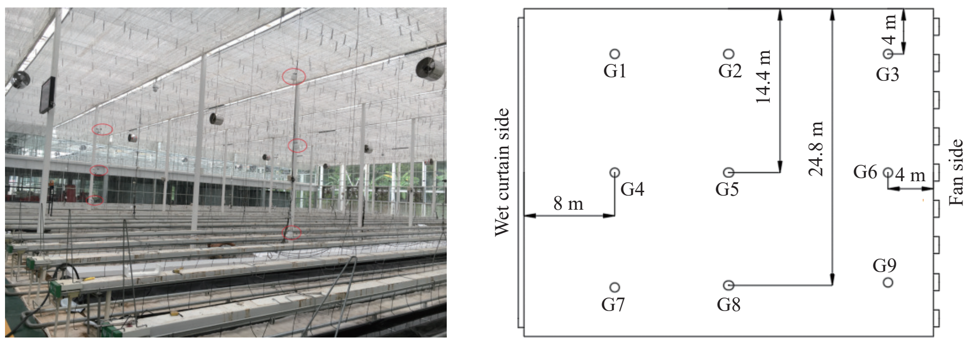
Figure 1 Schematic diagram of the layout and structure of the experimental greenhouse

Table 1 Tested greenhouse size parameters

Multi-span greenhouse	Span-length/m	Span number	Number of bays	Shoulder height/m	Ridge height/m	Area/ m²	Inner shading height/m
Size parameters	9.6	3	9	6.5	7.5	1036.8	5.7

2.2 Test method and arrangement

From June to July 2020, the experimental greenhouse will be selected for testing and on-site layout of the flow field in the greenhouse, select sunny weather for data monitoring from August 12 to 26. Adjust the recording data of monitoring points in August. As shown in Figure 2, the three-dimensional flow field monitoring points in the multi-span greenhouse are respectively arranged at three heights of 0.6, 2.5 and 4.5 m. The plane area where each monitoring height was located G1-G9 was evenly arranged, and 9 sampling points were positioned, with the sampling points being situated 4 m away from the surrounding walls. The outdoor weather data monitoring point is 5 m away from the side wall of the test greenhouse, with no obstacles to, 1.5 m above the ground. It showed



a. Real scene sampling points b. Distribution of sampling points

Figure 2 Schematic diagram of the layout of environmental sampling points in the greenhouse that the window opening method used in the test in Figure 1. The top window is fully opened 45°+side window, and the internal sunshade is turned on at 09:00.

During the test, the 27 monitoring points and outdoor monitoring points in the multi-span greenhouse collected data at 06:00, and the data collection interval was 1 h. Each monitoring point simultaneously recorded the temperature, humidity, solar radiation intensity and air velocity in the multi-span greenhouse until 18:00.

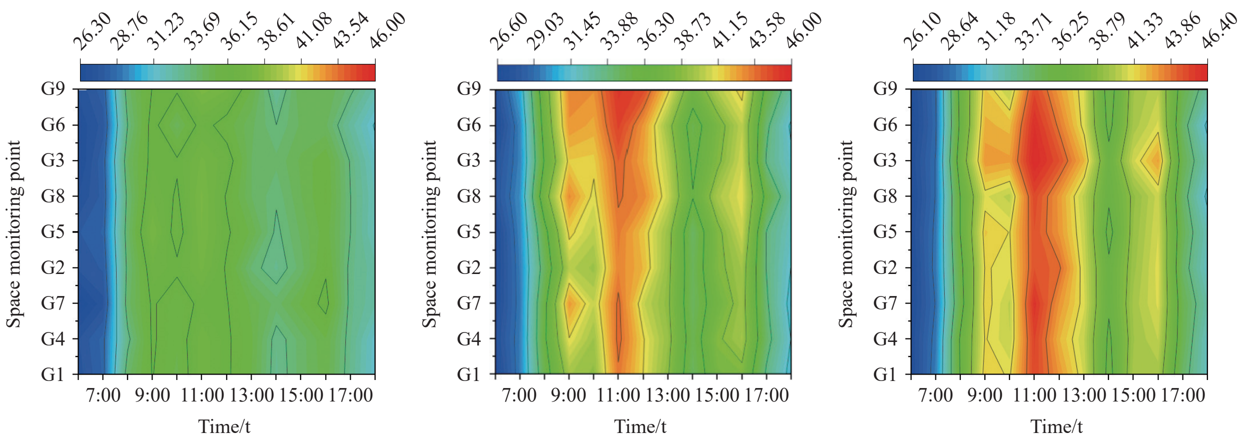
3 Results and analysis

3.1 Temperature changes in the greenhouse

To facilitate the analysis of the test results, the temperature change data of the different monitoring planes at each time in the test greenhouse in the form of the temperature contour cloud map shown in Figure 3. Figures 3a-3c show the temperature distribution and changes at different times of the monitoring points at the three monitoring heights. Compared with Figure 2b, G1G4G7 - G2G5G8 - G3G6G9 are the monitoring points in the greenhouse from south to north. It can be seen from the figure that the temperature gradient in the vertical direction in the multi-span greenhouse is very obvious.

The higher the position, the higher the temperature. The temperature near the ground is much lower than the temperature at the height of 2.5 and 4.5 m. In the contour cloud chart, it can be seen that the temperature level in the greenhouse is distributed in steps at every moment, and the stratification is more obvious when the temperature is lower. In Figures 3b and 3c, there is a local fault in the high temperature area from 9:00 am to 10:00 am, which is considered to be the short-term effect of opening the sunshade in the greenhouse at 9:00. The highest temperature of each monitoring point in a day appears between 11:00-12:00. As the monitoring position increases, the enclosed area of the temperature contour becomes smaller, the smaller the temperature unevenness in the local area. The stepped distribution of temperature in the greenhouse has become more and more obvious with time.

Figure 4 shows the same trends in temperature changes both inside and outside the greenhouse. The maximum and minimum values of the curves correspond perfectly to each other. In some measure, it shows that the ventilation effect produced by the butterfly-shaped window in the experiment is better.



a. 0.6 m b. 2.5 m c. 4.5 m

Figure 3 Contour cloud map of different monitoring plane temperatures in the greenhouse

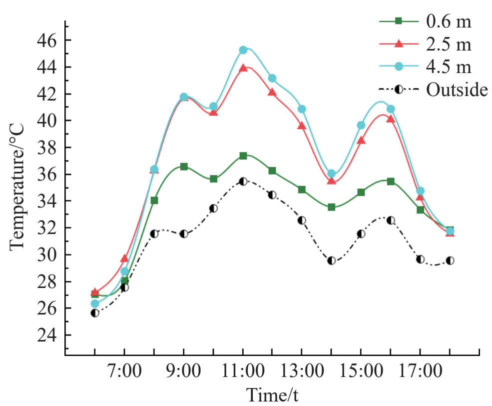
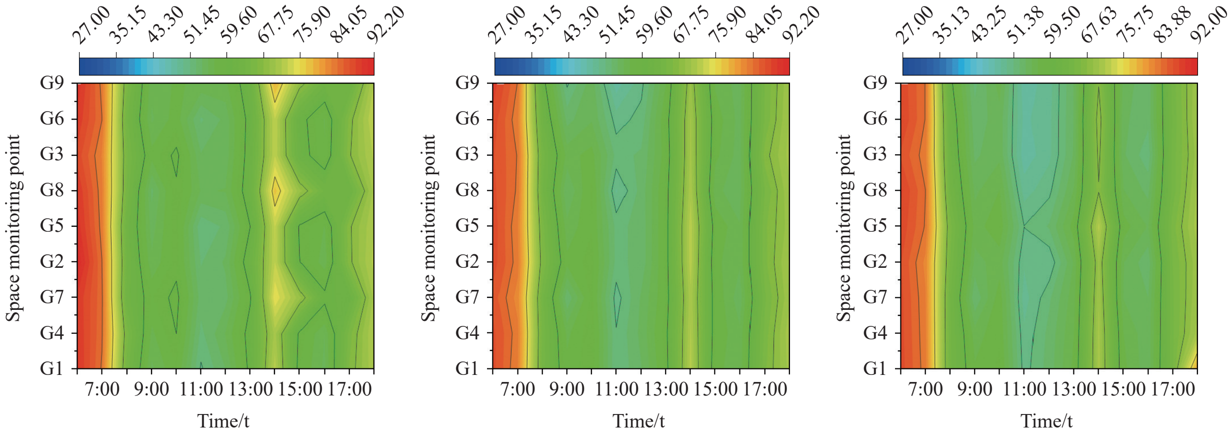


Figure 4 Average temperature and outdoor temperature changes at different monitoring heights in the greenhouse at each time

With the continuous change of the temperature outside the greenhouse, the temperature response in the multi-span greenhouse is relatively rapid. It can be seen that the average temperature of different monitoring planes in the greenhouse dropped by 1°C-2°C from 9:00 to 10:00 from Figure 4, which is consistent with the phenomenon of the above contour-line map. The average temperature of the two monitoring planes of 2.5 m and 4.5 m in the greenhouse is very close. In both high temperature periods of 8:00-12:00 and 13:00-14:00, the difference between the temperature near the ground and the temperature at 2.5 m and 4.5 m is most clear. Before starting the internal shading, the temperature rise at 2.5 m and 4.5 m is 2.16 times the height of 0.6 m. After adding the sunshade nets, the outdoor ambient temperature rose by 3.9°C and 3.0°C respectively in the two periods, the 0.6 m height in the greenhouse rose by 0.8°C and 1.9°C, and the temperature at 2.5 m and 4.5 m rose by 2.2°C, 2.5°C and 4.6°C, 4.8°C. The temperature building up at 2.5 m and 4.5 m is about 3 times that at 0.6 m. It shows that the internal shading has a certain cooling effect on the area near the ground. From 9:00 to 17:00, the temperature at 0.6 m in the greenhouse is always between 33.4°C and 37.4°C, while the maximum outdoor temperature fluctuation is 5.9°C, showing that the temperature uniformity in the crop growing area in the multi-span greenhouse is favorable.

3.2 Humidity changes in the greenhouse

Relative to the temperature inside and outside the greenhouse, the relative humidity distribution of different monitoring planes in the whole multi-span greenhouse at each time is relatively even. It can be seen from Figure 5 that there is no significant difference in the vertical direction between the relative humidity near the ground and the height of 2.5 m and 4.5 m.



a. 0.6 m b. 2.5 m c. 4.5 m

Figure 5 Humidity changes at different monitoring heights in the greenhouse

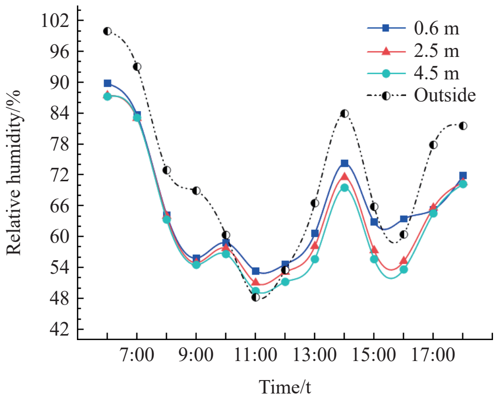


Figure 6 Average relative humidity and outdoor humidity changes at different monitoring heights in the greenhouse at each time

The humidity in the greenhouse is the heaviest in the early morning. The humidity level in the greenhouse decreases rapidly from 07:00 to 08:00. There are obvious humidity gradients in the three monitoring planes. After 08:00, the humidity change in the greenhouse is stable, and the humidity change mainly changes along the time axis. Spatial changes do not affect the relative humidity distribution on the same monitoring plane. In Figure 5, there are many enclosed areas with contour lines at a height of 0.6 m, and the relative humidity unevenness is slightly higher than that at 2.5 m and 4.5 m.

Figure 6 is a data diagram of the average relative humidity inside and outside the greenhouse at different monitoring heights at each time. From the figure, it can be found that the humidity inside and outside the greenhouse drops rapidly from 07:00, and the relative humidity of each monitoring plane in the greenhouse reaches the extreme point at the same time at 09:00. At the height of 0.6-4.5 m in the greenhouse, the relative humidity dropped by 33.9%, 32.5%, and 32.7%, respectively. The consistency and following ability of the outdoor relative humidity and the relative humidity of the three indoor monitoring heights are better than the temperature changes in Figure 4. Taking the humidity outside the greenhouse as the standard, the relative humidity differences of the three vertical heights of 0.6 m, 2.5 m, and 4.5 m in the greenhouse are 7.15%, 8.38%, and 9.09%, respectively. Combined with the humidity change characteristics of Figures 5 and 6, the internal shading does not directly affect the humidity in the multi-span greenhouse. Relative humidity is less affected by spatial factors in the greenhouse, but it changes drastically with the outdoor environment during natural ventilation.

3.3 Intensity of the sunlight

Figure 7 shows the change of solar radiation intensity in the multi-span greenhouse under the condition of natural ventilation during the sunny day. It can be seen that the solar radiation intensity in the greenhouse has increased sharply from 08:00 to 09:00. When the internal sunshade is turned on at 09:00, the solar radiation intensity of the monitoring plane in the greenhouse drops again at 07:00 to 08:00. After that, the solar light intensity has remained at a low level, showing that the shading-nets has a significant effect on reducing the solar radiation intensity.

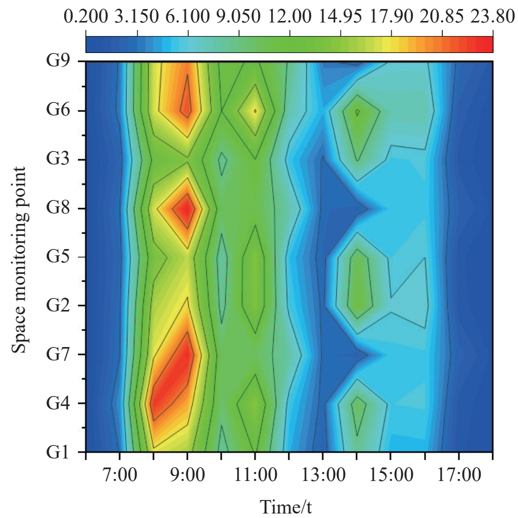


Figure 7 Contour cloud map of solar radiation intensity at 1.5 m in the greenhouse

Before the shading is turned on, the contour area with the highest solar radiation intensity in the figure corresponds to the five monitoring points G4, G7, G8, G6, and G9, namely the southeast area of the greenhouse. After the internal shading is turned on at 09:00, although the solar radiation intensity in the greenhouse has dropped significantly, it can still be seen that the center of the area with the highest light intensity gradually moves down as the time changes, it shifts to the middle area of the multi-span greenhouse.

Figure 8 shows the changes in solar light intensity at distinct moments in the three sampling points in the greenhouse and the monitoring point outside the greenhouse at a height of 1.5 m. Considering the symmetrical relationship of the greenhouse space, the monitoring data of G3, G5, and G7 are analyzed, and it is found that before the shading net is turned on, as the outdoor environment light intensity increases sharply, the light intensity of the three monitoring points G3, G5, and G7 has been increased respectively, which were 14.3, 16.3, and 23.1 klx. In connection with Figure 8, G7 is in the southeast corner of the greenhouse, G5 is in the central area of the greenhouse, and G3 is in the northwest corner of the greenhouse. The direction of sunlight affected the distribution of solar light intensity in the greenhouse.

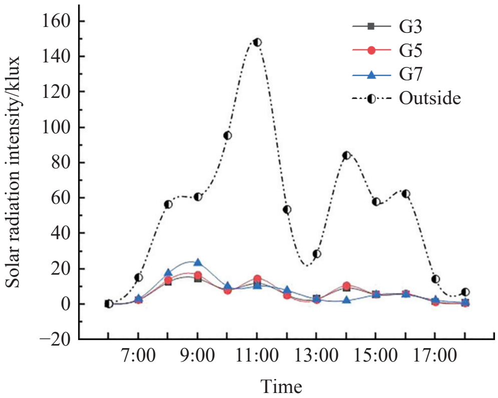


Figure 8 Changes in the average solar radiation intensity at different monitoring heights in the greenhouse at each moment

After turning on the internal shading, the changing trend of the solar light intensity in the greenhouse becomes very gentle. Before and after opening the shading net at the three monitoring points of G3, G5, and G7, the average light intensity are 6.58 klx, 7.66 klx, 10.24 klx and 5.70 klx, 6.04 klx, 5.30 klx, respectively. In contrast, the intensity of sunlight in a day is concentrated in the middle of the greenhouse. After the internal sunshade is turned on, the uniformity of the intensity of the sunlight distribution in the greenhouse becomes better. The average light intensity of G3, G5, and G7 are 6.02, 6.62, and 7.06 klx.

3.4 Velocity field distribution

In the experiment, the data found that no matter how the wind speed outside the greenhouse changes, the wind speed in the multi-span greenhouse always remains between of 0.3-0.4 m/s. It is believed that under natural ventilation conditions, the speed loss of ambient air entering through the side windows and the butterfly-shaped windows of the roof is relatively large, and the impact on the microclimate of the greenhouse is small. The air renewal inside the multi-span greenhouse is mainly affected by the heat flux density[24,25]. Thus the influence of external environmental wind speed on the crops in the greenhouse can be ignored.The average speed change at each time in the greenhouse is shown in Figure 9.

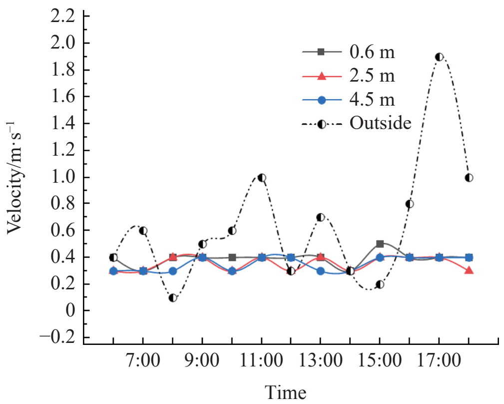


Figure 9 Average speed change at each time in the greenhouse

3.5 Correlation analysis of external environmental factors

The above test data undergo further processing to analyze the correlation between environmental parameters within each monitoring plane in the greenhouse and the external greenhouse environment, yielding the following data table. Table 2 selects the three main environmental factors of temperature, humidity and solar irradiance for analysis, and obtains the average value, standard deviation, and standard error of the difference between the internal and external environmental parameters of the greenhouse and the correlation between the internal and external environmental factors of the greenhouse.

Table 2 Correlation of climate and environmental factors inside and outside multi-span solar greenhouse

Environmental Factors	Height/ m	Error average	Standard deviation	Standard error	Environmental relevance
Temperature/°C	0.6	2.58	1.176	0.3262	0.928
	2.5	5.800	2.661	0.7382	0.952
	4.5	6.269	3.215	0.8917	0.958
Relative humidity/%	0.6	5.738	6.061	1.681	0.939
	2.5	7.946	5.155	1.430	0.962
	4.5	12.438	5.850	1.622	0.962
Solar radiation intensity/klx	1.5	45.485	37.733	10.465	0.640

It can be seen from the table that the overall correlation between the humidity inside and outside the multi-span greenhouse is the largest, with a maximum correlation of 0.962. The relative humidity in the greenhouse is most obviously affected by the outside environment of the greenhouse. The solar radiation intensity in the multi-span greenhouse is affected by the shading-nets, and the correlation with the outside environment of the greenhouse is only 0.640. The higher the location, the more obvious the correlation between the microclimate conditions and the outdoor environment. As the altitude increases, the temperature correlation changes from 0.928 to 0.958, and the relative humidity correlation changes from 0.939 to 0.962. The relative humidity inside and outside the greenhouse has the same correlation at 2.5 m and 4.5 m.

4 Discussion

This study did not carry out a long-period experimental analysis of changes in the monthly average environmental factors, but focused on the temperature, humidity, solar irradiance, and wind speed inside and outside the greenhouse each time of the day. Ignore changes in macroscopic laws, but analyzing each parameter is more pertinent. Data collection for this experiment under normal conditions of natural ventilation of the multi-span greenhouse will yield more representative baseline data.

Soni et al.[26] studied the vertical temperature distribution in a naturally ventilated greenhouse, and found that the highest temperature difference between a height of 2.5 m and a height of 0.5 m in a single greenhouse without crops is 5.9°C. In this research, the maximum average temperature difference between 2.5 m and 0.6 m is 6.5°C, and the maximum temperature difference between a single monitoring point is 8.3°C. The test site of Soni is in Bangkok, Thailand (latitude 14°04′N, longitude 100°37′E), which has a tropical monsoon climate. The length, width, and height of the greenhouse are 6.0 m, 3.0 m, and 3.2 m, respectively. The conditions are similar, and the temperature changes are the same. However, Soni et al.[26] did not study other environmental factors in the greenhouse. Zhao et al.[27] mainly compared the temperature and humidity difference between the front span and the back span of a double multi-span greenhouse in Nanjing, and analyzed the uniformity of temperature and relative humidity at a height of 2 m inside and outside the greenhouse. Yu and Zhang[28] clarified the cooling characteristics and related principles of internal shading. Although internal shading alone cannot reduce the overall temperature level in the greenhouse, in the multi-span greenhouse studied in this article, the area near the ground is weakly affected by the secondary radiation of the shading net, and the cooling effect is more obvious.

Local conditions should be considered in the greenhouse design and climate control process. Therefore, it is necessary to conduct a full-scale field test on a specific greenhouse to get reliable data support[28]. In this study, to control the influencing factors of various environmental factors of the microclimate of the multi-span greenhouse, and get more universal analysis results with fewer interference factors. No crops were planted in the greenhouse during the test period. Combining the environmental data obtained above, it can be predicted that when crops are planted in the multi-span solar greenhouse, and when the plant height and coverage area of the crops are large, part of the heat radiation will be converted into latent heat due to the transpiration of the plants[29]. A better greenhouse environment will be obtained near the ground of the greenhouse than in this experiment, and the thermal environment in areas higher than the ground will also be improved to a certain extent.

5 Conclusions

Through the experimental study of the large-scale multi-span solar greenhouse in South China in August, the butterfly-shaped window was adopted, and the changes of various internal environmental factors under normal natural ventilation conditions in each link, and the following conclusions were obtained:

1) Microclimate characteristics of large-scale multi-span greenhouses: affected by climatic conditions, the highest temperature in the solar greenhouses in southern China on sunny days can reach 45°C. The vertical temperature gradient in large-scale multi-span greenhouses is more obvious than the difference between single-span greenhouses and small-scale greenhouses. The humidity difference between inside and outside the greenhouse under natural ventilation is about 8%, and the vertical humidity difference in the greenhouse is within 2%. The velocity field in the multi-span greenhouse is mainly affected by the heat flow density inside the greenhouse. The ambient wind speed does not affect the airflow velocity in the greenhouse. The humidity and speed in the multi-span greenhouse show good uniformity.

2) Evaluation of the overall performance of the butterfly-shaped window ventilation in the greenhouse: after the internal sunshade is turned on, the average light intensity in the greenhouse is 6.1 klx, which is much greater than the light intensity required for the normal growth of plants. In a large multi-span greenhouse, the secondary radiation generated by the internal shading has little effect on the area near the ground, which can effectively reduce the ground temperature. Under the condition of natural ventilation, the temperature and humidity inside the greenhouse are most obviously affected by the external environment. The two have an obvious correlation, showing that the greenhouse design is reasonable. The air renewal and heat exchange inside and outside the greenhouse are good during natural ventilation.

3) Suggestions for improvement from the results: to more effectively control the temperature in the greenhouse, the temperature in the greenhouse can be kept stable during the high temperature period in summer with external shading. The air humidity at night in the environment is significantly higher than that during the day by about 30%. When the humidity conditions at night affect the growth of the total crops in the greenhouse, the top windows can be closed in time and only the side windows are used for ventilation. At the same time, the internal circulation ventilation is strengthened to maintain good air circulation in the plant canopy area and avoid plant diseases caused by condensation.

In summary, according to the different climatic and geographical conditions in different regions, the construction forms and operating strategies of the greenhouse should also be different. The research object of this study is the large-scale multi-span solar greenhouse completed in 2019. Detecting the changing characteristics of the greenhouse microclimate, assessing its ventilation performance and proposing corresponding operating suggestions, can prepare for normal production in the future.

Acknowledgement

This work was financially supported by the National Key Research and Development Program of China (No. 2017YFD0701500) and the Open Project of the Key Laboratory of Agricultural Facilities Structural Engineering of the Ministry of Agriculture and Rural Affairs (No. 202003).

[References]

[1] Villagran E, Bojacá C. Experimental evaluation of the thermal and hygrometric behavior of a Colombian greenhouse used for the production of roses (*Rosa* spp). Ornamental Horticulture, 2020; 26: 205–219.

[2] Vadiee A, Martin V. Energy management in horticultural applications through the closed greenhouse concept, state of the art. Renewable and Sustainable Energy Reviews, 2012; 16: 5087–5100.

[3] Xue X. How far is my country's modern greenhouse from the world's advanced level. Vegetable, 2019; 4(5): 6–12. (in Chinese)

[4] Sarkodie S A, Strezov V, Weldekidan H, Asamoah, E F, Owusu, P A, Doyi I N Y. Environmental sustainability assessment using dynamic autoregressive - Distributed lag simulations — Nexus between greenhouse gas emissions, biomass energy, food and economic growth. Science of The Total Environment, 2019; 668: 318–332.

[5] Ren S G, Liu X, Gu X J, Wang H Y, Xu H L. Multi-step rolling forecast model of greenhouse microclimate based on R-BP neural network. Chinese Agricultural Meteorology, 2018; 39(5): 314–324. (in Chinese)

[6] Liu X. Research on greenhouse microclimate prediction model based on improved BP neural network. Master dissertation. Nanjing Agricultural College, 2017; 86p. (in Chinese)

[7] Marina G, Alexey G, Andrey K, Denis F. Automation of microclimate in greenhouses. E3S Web of Conferences, 2020; 210: 05004.

[8] Ma D, Carpenter N, Maki H, Rehman T U, Tuinstra M R, Jin J. Greenhouse environment modeling and simulation for microclimate control. Computers and Electronics in Agriculture, 2019; 162: 134–142.

[9] Yan L L, Jing H W, Bao E C, Cao D F, Pan T H, Shen T T, et al. The influence of different natural ventilation methods on the performance of solar greenhouse. Journal of China Agricultural University, 2020; 25(3): 71–78. (in Chinese)

[10] Villagrán E A, Gil R, Acuña J F, Bojacá C R. Optimization of ventilation and its effect on the microclimate of a colombian multispan greenhouse. Agronomía Colombiana, 2012; 30(2): 282–288.

[11] Ding X T, Jin H J, Zhang H M, Yu J Z. Comparative study on the temperature, room temperature and humidity environment of single-span greenhouse and multi-span plastic. Shanghai Journal of Agriculture, 2011; 27(2): 96–101. (in Chinese)

[12] Espinoza K, López A, Valera D L, Molina-Aiz, F D, Torres, J A, Peña, A. Effects of ventilator configuration on the flow pattern of a naturally - ventilated three-span Mediterranean greenhouse. Biosyst. Eng., 2017; 164: 13–30.

[13] Baeza E J, Pérez-Parra J J, Montero J I, Bailey, B J, López, J C, Gázquez, J C. Analysis of the role of sidewall vents on buoyancy-driven natural ventilation in parral-type greenhouses with and without insect screens using computational fluid dynamics. Biosyst. Eng., 2009; 104(1): 86–96.

[14] Liu Y C, Zou R Z, Hu X H, Bian Z H, Wang Y. Analysis of light and temperature environment of different span solar greenhouses in Guanzhong Area, Shaanxi Province. Journal of Northwest Sci-Tech University of

Agriculture and Forestry (Natural Science Edition), 2013; 41(2): 108–116. (in Chinese)
[15] Liu Y F. Research on the performance of solar greenhouses with different spans. Northwest A&F University, 2012. (in Chinese)
[16] Jin X H, Zou Z R, Zhao X. Influence of span on the performance of mountain solar greenhouse. Agricultural Mechanization Research, 2015(2): 146–150. (in Chinese)
[17] Mashonjowa E, Ronsse F, Milford J R, Pieters, J G. Modelling the thermal performance of a naturally ventilated greenhouse in Zimbabwe using a dynamic greenhouse climate model. Solar Energy, 2013; 91: 381–393.
[18] Davies R. The impact of globalization on local communities: a case study of the cut-flower industry in Zimbabwe (No. 13). International Labour Office, Southern Africa Multidisciplinary Advisory Team, 2000.
[19] Hao F L, Shen M W, He Y, Feng L. Multi-factor comprehensive CFD steady-state simulation analysis in a single plastic greenhouse. Journal of Agricultural Machinery, 2014; 45(9): 297–304. (in Chinese)
[20] Li Y X, Li B M, Li Z, Ding T. CFD numerical simulation of natural ventilation and cooling of venlo greenhouse in summer. Journal of China Agricultural University, 2004; 6: 44–48. (in Chinese)
[21] Zhou W, Li Y B, Wang X C. Predictive control of greenhouse temperature based on CFD unsteady state model. Journal of Agricultural Machinery, 2014; 45(12): 335–340. (in Chinese)
[22] Shen M W, Hao F L. Steady-state simulation of natural ventilation flow field in multi-span plastic greenhouse-The influence of the top window configuration on the flow field in the greenhouse. Journal of Zhejiang University (Engineering Science Edition), 2007; 4: 668–672. (in Chinese)
[23] Tong G H, Li B M, David M C, Yamaguchi, Z. Preliminary study on simulating the temperature environment of sunlight greenhouse by CFD method. Journal of Agricultural Engineering, 2007; 7: 178–185. (in Chinese)
[24] Hou Y C, Li H, Li A G. Experimental and theoretical study of solar chimneys in buildings with uniform wall heat flux. Solar Energy, 2019; 193: 244–252.
[25] Yang C Q, Gao T; Li A G. Gao X. Buoyancy-Driven ventilation of an enclosure containing a convective area heat source. International Journal of Thermal Sciences, 2021; 159: 106551.
[26] Soni P, Salokhe V M, Tantau H J. Effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouses. Biosystems Engineering, 2005; 92: 469–482.
[27] Zhao Z, Li X, Wang J, Guo S Y, Lan D, Ni M Y. Preliminary study on the microclimate of the new multi-span solar greenhouse. Journal of Northwest Sci-Tech University of Agriculture and Forestry (Natural Science Edition), 2020; 48(5): 88–98. (in Chinese)
[28] Yu J C, Zhang X F. The cooling effect of multi-span greenhouses covered by shading nets in Jianghuai area. Chinese Agricultural Meteorology, 2004; 4(3): 56–58. (in Chinese)
[29] Sun W T, Zhou B, Xu F, Shang C, Lu C G, Guo W Z. Performance of positive pressure fan-pad cooling system and cooling load model for Chinese solar greenhouse. Transactions of the CSAE, 2019; 35(16): 214–224. (in Chinese)