

RESEARCH ON GREENHOUSE PLANTING DENSITY OF LANDSCAPE FLOWERS IN COLD REGIONS BASED ON CFD SIMULATION

基于 CFD 模拟的寒冷地区景观花卉温室种植密度研究

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ABSTRACT

As an important facility structure in China, the solar greenhouse can provide a suitable environment for plant growth and development during winter, making it a viable structure for cultivating landscape flowers in cold regions. However, the impact of crop spacing in solar greenhouses on the thermal environment had received scant attention from researchers. Therefore, computational fluid dynamics (CFD) software was used to simulate the effect of crops on the thermal environment in solar greenhouses. The results of this study show that: the presence of crops in the greenhouse has a greater influence on the temperature in the solar greenhouse along the horizontal, vertical and longitudinal directions within the ranges of (3000, 8000 mm), (300 mm, at the film) and the distance from the inner surface of the east and west walls within the range of 10,000 mm; the presence of crops in the greenhouse has a greater influence on the internal temperature of the east wall, the west wall and the north wall; The influence of different planting densities of crops in the greenhouse on the internal temperatures of the solar greenhouse in the horizontal, vertical and longitudinal directions was within the ranges of (1000 mm, at the film), (600 mm, at the film), and the distance from the inner surface of the east and west walls was within the range of 6000 mm, respectively. This study can provide a theoretical basis for the cultivation and management of flowers in solar greenhouses in cold regions.

摘要

日光温室作为中国重要的设施结构，在冬季可提供植物生长发育的适宜环境，因此可在寒冷地区的日光温室中种植景观花卉。但是针对日光温室内花卉景观种植密度对温室热环境的影响较少，因此通过 CFD 模拟手段探究不同种植密度对温室湿热环境的影响。本研究结果显示：相对于无作物温室的温度，有作物温室的温度沿横向、竖向和纵向有较大变化的区域分别为 (3000,8000) mm、(300mm, 同跨度棚膜内表面高度处) 和距离东西墙体内部表面纵向距离为 10000mm 范围内；温室内作物不同种植密度对日光室内温度沿横向、竖向和纵向的影响范围分别为 (棚膜处,1000) mm、(600mm, 棚膜处) 和距离东西墙体内部表面距离为 6000mm 范围内。该研究可为寒冷地区日光温室花卉种植和管理提供理论依据。

INTRODUCTION

As the global population continues to grow, the demand for food shows a sharp upward trend, and facility horticulture, as a highly efficient agricultural production method, provides a highly promising solution to meet this challenge, while also helping to raise the income of the population (Cheng Weiwei., 2021). Among the many forms of facility horticulture, the development of solar greenhouses in China has been particularly remarkable, and they have become one of the key indicators of the level of agricultural modernization (Chen P et al., 2020). Daylight greenhouses, with their high-yield and high-efficiency production technology, have become an important way to improve crop yield and quality (Fu G.H. et al., 2016). However, the design and construction of solar greenhouses must fully consider the local climatic conditions, and China has a vast area with significant differences in climate. Therefore, an in-depth analysis of the thermal environment of solar greenhouses in Inner Mongolia can help promote the sustainable development of the greenhouse industry in this region (Hu Q.Q. et al., 2015).

The development of agricultural facilities and computer technology has led to the emergence of Computational Fluid Dynamics (CFD) as a powerful tool in the field of thermal environment index studies (*He Z.G. et al., 2018; He Wei et al., 2022; Jia W.S. et al., 2016*). *Domenico et al., (2020)*, used TRNsys to perform simulations to select the best glazing for solar greenhouses considering different thermal phenomena, and the results showed that single pane glass/plastic materials are only recommended for tropical/hot climates, partially for dry (desert and semi-arid) climates and rarely for other climates. *Li J.C., (2015)*, explored the effect of whether tomato was grown in the greenhouse on the microclimate environment in the solar greenhouse for the winter outdoor climatic conditions in Jinan, and found that the entrance wind speed had a small effect on the wind speed of the crop canopy, and that the temperature difference in the greenhouse was small and favourable to crop growth in the north-easterly winds, but did not consider the effect of transpiration. *YU Wei et al., (2023)*, used CFD software for virtual identification and modelling of greenhouse temperature, and the results showed that the simulation results were in accordance with the temperature distribution law, indicating that the virtual and physical sensors can work together to monitor the greenhouse environment. *Du Zhenyu et al., (2023)*, used CFD method to construct a numerical model of natural ventilation daylight greenhouse, explored the movement law of indoor airflow under the condition of natural ventilation and planting crops in spring, and the change rule of indoor temperature and humidity at different moments. The results show that: crops have a greater impact on the indoor airflow field, temperature and humidity field of the solarium; the temperature of the crop area in the solarium from 11:00 to 18:00 is too high, which does not satisfy the temperature range required by the 'four-stage variable temperature management'.

Most of the existing studies have focused on the environmental effects of the presence or absence of crops in solar greenhouses on the greenhouse environment, while few in-depth studies have been conducted on how different planting densities affect the greenhouse thermal environment, which was a key factor. In recent years, in order to improve the economic return of greenhouse cultivation, more and more greenhouse growers have begun to actively explore the landscape planting mode in traditional solar greenhouses (*Shi L.J. et al., 2021*). Taking the strawberry picking garden as an example, this model cleverly integrated the two major functions of crop cultivation and tourism, opening up a new development path for the greenhouse planting industry. However, under this innovative model, how to scientifically and reasonably plan the crop layout in the greenhouse (*Sun B. et al., 2020*), not only fully exploiting the utilisation potential of the greenhouse thermal environment to achieve efficient crop growth, but also ensuring that the tourists' sightseeing experience is not interfered with, and creating a comfortable and pleasant visiting environment, has become a key issue strengthening the further development of greenhouse planting industry. In this study, CFD simulation was used to accurately analyse the impact of different planting densities on the thermal environment in solar greenhouses, and to explore the intrinsic laws, with the aim of providing scientific, systematic and solid theoretical support for the optimization of greenhouse crop cultivation, and contributing to the sustainable development of greenhouse cultivation industry and the enhancement of its comprehensive benefits.

MATERIALS AND METHODS

Solar greenhouse geometry and grid model construction

Computational Fluid Dynamics (CFD) is a comprehensive discipline that integrates several fields such as mathematical modelling, fluid mechanics and computer science. It uses numerical analysis and fluid theory and other methods to carry out in-depth calculation, simulation and analysis of fluid objects, providing a powerful tool for solving complex fluid flow problems. The structure of CFD software consists of pre-processing, solver and post-processing. The pre-processing of CFD mainly includes the construction of the geometric model and mesh delineation, and a good pre-processing can greatly improve the accuracy of numerical simulation.

A geometrical model was constructed for a common solar greenhouse around the city of Hulunbeier in Inner Mongolia, China. The greenhouse was situated in a north-south orientation and measured 80 metres in length in the east-west direction. The dimensions of the greenhouse are as follows: a span of 10 metres, a ridge height of 5 metres, an earth wall on the north side of the building that was 4.5 metres high, and trapezoidal shapes on the north, east and west walls, with a lower base width of 8 metres and an upper base width of 2 metres. The intersection of the north wall, the west wall and the ground in the greenhouse was defined as the (0,0,0) point. SolidWorks modelling software was used for 1:1 three-dimensional modelling of the solar greenhouse, as shown in Figure 1.1.

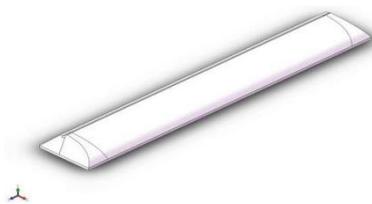


Fig. 1.1- 3D model of solar greenhouse

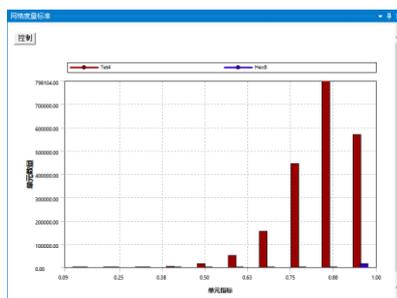


Fig. 1.2- Grid Quality

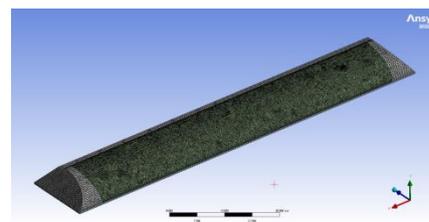


Fig. 1.3- Mesh Division

3D model meshing

Considering the boundary encryption and computational accuracy, a hybrid mesh is selected to process the model. The mesh size is 300 mm and the final mesh number was 1856226. The mesh quality is determined according to the mesh metric. The closer the mesh metric is to 1, the better the mesh quality. Grid division and grid quality were shown in Figure 1.2 and Figure 1.3.

CFD numerical modeling

Temperature change in a solar greenhouse is a dynamic and complex process influenced by factors such as construction, outdoor climate, growing conditions and internal ventilation. In order to improve the analysis efficiency and calculation accuracy, the CFD numerical model of temperature inside the solar greenhouse is reasonably simplified, assuming that the greenhouse is in a fully closed state except for the upper vent, ignoring the effect of humidity on the temperature, and that the parameters of each part of the material do not change with the temperature change.

Computational Fluid Dynamics (CFD) simulations are based on the three conservation laws of mass, momentum and energy, as well as the fundamental equations of fluid heat and mass transfer. In a confined space, the form of fluid flow is mainly affected by the Reynolds number (Re), which is manifested in two states: laminar and turbulent flow. In laminar flow, the fluid flows in layers, the flow velocity is stable, and the viscous force is dominant; while in turbulent flow, the fluid is in a disordered state, the flow velocity varies greatly, and the inertia force is dominant. The complex and dynamic fluid flow inside the solar greenhouse is usually regarded as turbulent flow. Therefore, turbulence models are widely used in the study of gas flow in greenhouses, among which the standard $k-\epsilon$ model is suitable for many scenarios and can obtain good results due to the assumption of turbulence isotropy.

In Fluent, radiation models include Rosseland model, P1 model, DTRM model, DO model, S2S model and solar radiation model. The simulation of the thermal environment of the solar greenhouse involves the radiative heat transfer processes such as the transmission of sunlight and the absorption and reflection of light by plants and soil, so the DO radiation model and the solar radiation model were preferred. In the simulation, the solar radiation calculator sets the solar orientation, irradiation intensity and material heat radiation parameters. The solar greenhouse is located at $49^{\circ}21'N$ latitude and $119^{\circ}25'E$ longitude, which is in the East 8 time zone. The solar radiation for this simulation was taken from the data at 17:00 on 26 January 2025 (a sunny day), the X-axis was reversed to due north, the Z-axis was reversed to due east in the coordinate system, the insolation coefficient was taken to be 1, and the light parameters were all set based on the solar calculator.

In CFD numerical simulation, porous media modelling is an effective tool for simulating the flow characteristics of fluids as they pass through complex regions containing solid particles or voids. In the simulation of the thermal environment of a solar greenhouse, considering the effect of the crop on air flow and heat transfer, it is a reasonable approximation to consider the crop as an isotropic porous medium. Considering the crop as a porous medium implies that structures such as the leaves and stalks of the crop are considered as a region with continuously distributed resistance. This treatment captures the crop's impedance to air flow, as well as the heat exchange process between the crop and the air.

Daylight greenhouses are subjected to differences in the distribution of solar radiation during the day, resulting in a temperature difference in the internal temperature, which leads to small changes in the air density inside the greenhouse. The Boussinesq assumption, which assumes that the air density varies so little in time and space that it can be approximated as a constant, simplifies the solution of the equations of hydrodynamics. The thermophysical parameters of the solarium envelope materials were shown in Table 1.

Boundary conditions and initial conditions

The setting of the boundary condition parameters has a great influence on the numerical simulation, and the boundary conditions and initial conditions are determined based on the experimental measured data and were set as follows:

(1) Setting of boundary conditions. The boundary conditions mainly include the setting of the boundaries of the front and rear roofs of the solar greenhouse, the east and west walls, the north wall and the soil. The interface between each part was set as a coupled wall. From 17:00 p.m. to 8:00 a.m. the next morning, the south roof was set as a layer of insulation.

(2) Setting of initial conditions. When constructing the thermal environment model of the solar greenhouse, the setting of initial conditions was a crucial step, which directly affected the accuracy and reliability of the simulation results. The experimental measurement data on 3 January 2024 were selected for model construction, and the initial temperature of the air inside the solar greenhouse was 16°C, respectively, and the outdoor temperature was applied to the outer surface of the greenhouse enclosure. In addition, the initial values of the north wall, soil, and crop surface temperatures were 22°C, 20°C, and 17°C, respectively.

Table 1

Material thermal property parameters of the solar greenhouse envelope

Parameters	PE	Wall	Soil	backward slope	Film	Crop
Densities[kg/m ³]	950	2000	1600	600	70	560
Specific heat capacity[J/(kg·K)]	1600	1050	1050	2500	1880	2100
Thermal conductivity[W/(m·K)]	0.34	0.8	0.75	0.29	0.04	0.19
Absorption coefficient	0.15	0.88	0.88	0.7	0.1	0.35
Scattering coefficient	0	0.12	0.12	0	0	0.1
Index of refraction	1.72	1.92	1.92	1.72	1.72	2.77

RESULTS AND DISCUSSION

Influence of the presence or absence of crops on the temperature distribution in solar greenhouse

Temperatures of greenhouses without crops and greenhouses with crop spacing of 1.5 m were selected for horizontal, vertical and longitudinal analyses, and temperatures of greenhouses with crop spacing of 1.5 m and 2 m were selected for horizontal, vertical and longitudinal comparisons.

Influence of the presence or absence of crops on vertical temperature changes in solar greenhouse

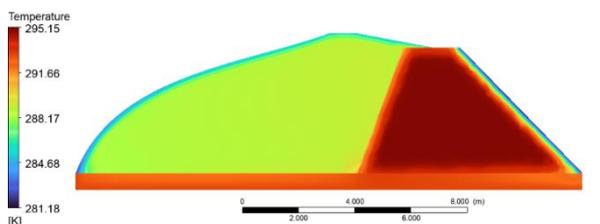


Fig. 3.1- Temperature cloud of X=36000mm north-south cross-section without crop

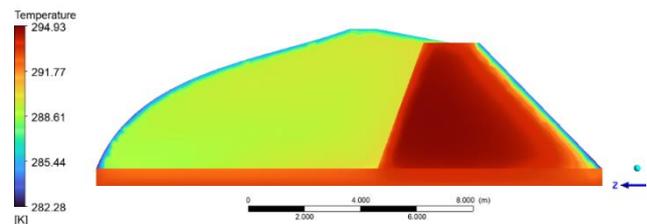


Fig. 3.2- Temperature cloud of X=36000mm north-south cross-section with 1.5m crop spacing

From Figures 3.1 and 3.2 above, in the specified parameters of $x=36000\text{mm}$, $z=0\text{mm}$, $y= (0, 5000)$ mm, the distribution law of vertical temperature was as follows: under constant working conditions, the temperature of the greenhouse with a crop greenhouse was higher than that of the greenhouse without a crop. In the range of $y=(0, 600)\text{mm}$, the temperature difference increased gradually, with a maximum temperature difference of 0.6°C , the minimum temperature difference was 0.06°C ; in the $y=(700, 4300)$ mm range, the temperature difference remained relatively stable, with a maximum temperature difference of 0.65°C ; in the $y=(4400, 4800)$ mm range, the temperature difference increased gradually, with a maximum temperature difference of 1.05°C and a minimum temperature difference of 0.65°C ; in the $y=(4900, 5000)$ mm range, the temperature difference decreased gradually, with a maximum temperature difference of 0.54°C and a minimum temperature difference of 0.04°C . The analysis indicated that the presence or absence of crops in the greenhouse exerted a negligible effect within the range of $y=(600, 4800)$ mm, yet it demonstrated a discernible effect within the ranges of $y=(0, 600)$ mm and $y=(4800, 5000)$ mm.

In the specified range of $x=36000$ mm, $z=5000$ mm, $y=(0, 3900)$ mm, the vertical temperature distribution law was as follows: under constant working conditions, the temperature of the greenhouse with crops was higher than that of the non-crop greenhouse. The temperature difference in the range of $y=(0, 100)$ mm gradually increased, and the maximum temperature difference was recorded at 0.49°C , while the minimum temperature difference was 0.06°C . In the range of $y = (200, 1200)$ mm, the temperature difference remains relatively smooth, with a maximum temperature difference of 0.48°C and a minimum temperature difference of 0.45°C . In the range of $y = (1300, 3500)$ mm, the temperature difference gradually increases, with a maximum temperature difference of 0.73°C and a minimum temperature difference of 0.46°C ; in the $y=(3600, 3900)$ mm range, the temperature difference decreased gradually, with a maximum temperature difference of 0.97°C and a minimum temperature difference of -0.12°C . The analysis indicated that the presence or absence of crops in the greenhouse exerted a negligible effect within the range of $y=(200, 3500)$ mm, yet it demonstrated a discernible effect within the ranges of $y=(0, 200)$ mm and $y=(3500, 3900)$ mm.

In the specified range of $x=36000$ mm, $z=9000$ mm, $y=(0, 1800)$ mm, the vertical temperature distribution law was as follows: under constant working conditions, the temperature of the greenhouse with a crop greenhouse temperature was indistinguishable from the temperature of the greenhouse without a crop. The temperature difference gradually increased in the range of $y = (0, 300)$ mm, with the maximum temperature difference of 0.55°C and the minimum temperature difference of 0°C . In the range of $y = (400, 900)$ mm, the temperature difference stayed relatively stable, with the maximum temperature difference of 0.66°C and the minimum temperature difference of 0.58°C . In the range of $y = (1000, 1800)$ mm, the temperature difference gradually decreases and the maximum temperature difference was 1.79°C and the minimum temperature difference was -0.13°C . From the above analysis, it can be seen that the presence or absence of crops in the greenhouse had a small effect in the range of $y = (300, 1000)$ mm, and a larger effect in the range of $y = (0, 300)$ mm and $y = (1000, 1800)$ mm.

As demonstrated in the preceding analysis, the presence or absence of crop temperature in the greenhouse exerted a lesser influence on the trellis at $x=36000$ mm and $y=300$ mm.

Effect of the presence or absence of crops on lateral temperatures in solar greenhouse

In order to explore the greenhouse, both with and without crops, the temperature along the transverse rule of change was to be analysed. For this purpose, the east-west span along the north-south cross-section was to be taken, with X set at 36000 mm, Y set at 0 mm, 1600 mm and 2400 mm, and Z set at $(-8000, 10000)$ mm on the temperature change curve.

From Figures 3.1 and 3.2 above, the change rule of temperature with crop temperature and without crop temperature at $y=0$ mm along the transverse direction was as follows: under the same working condition, the temperature of the greenhouse with crop was higher than the temperature of the greenhouse without crop; in the range of $z=(-8000,-6000)$ mm, the difference increased with the increasing of z , and the maximum difference was 0.6°C , and the minimum difference was 0.4°C ; in the range of $z=(-6000,2000)$ mm, the difference decreased with increasing z , the maximum difference was 0.8°C and the minimum difference was 0.07°C ; in the range of $z=(2000,10000)$ mm, the difference between the temperature of the greenhouse with crops and the temperature of the greenhouse without crops was maintained in the range of $(0.04, 0.07)^{\circ}\text{C}$. It can be seen that, considering the effect of the temperature difference of 0.5°C on the crop, the indoor crop had a greater effect on the internal temperature of the north wall, and a lesser effect on the temperature along the transverse direction at the soil surface of the indoor space.

The change rule of temperature at $y=1600$ mm between the temperature with crop and the temperature without crop along the transverse direction was as follows: in the range of $z=(-6000, -2000)$ mm, the temperature of the greenhouse without crop was higher than the temperature of the greenhouse with crop; in the range of $z=(-6000, -5000)$ mm, the difference increased with the increased of z , and the maximum difference was 1.1°C , and the minimum difference was 1.0°C ; in the range of $z=(-5000, -2000)$ mm, the difference decreased with z , with a maximum difference of 0.6°C and a minimum difference of 0.3°C ; in the $z=(-1000, 9000)$ mm range, the temperature of the greenhouse with crops was higher than that of the greenhouse without crops; in the $z=(-1000, 0)$ mm range, the difference increased with z , with a maximum difference of 0.6°C and a minimum difference of 0.03°C ; in the range of $z = (0, 3000)$ mm, the difference decreased with increasing z , with a maximum difference of 0.62°C and a minimum difference of 0.45°C ; in the range of $z = (4000, 8000)$ mm, the difference stayed in the range of $(0.46, 0.64)^{\circ}\text{C}$ with increasing z ; in the range of $z = (8000, 9000)$ mm, the crop-free greenhouse temperature was higher than the temperature of the greenhouse with crops, with a temperature difference of 0.15°C . This shows that indoor crops had a greater effect on the interior of the wall at 5000 mm from the inner surface of the wall and on the interior space at 8000 mm from the inner surface of the wall.

The change rule of temperature at $y=2400$ mm between the temperature with crop and the temperature without crop along the transverse direction was as follows: in the range of $z=(-5000, -2000)$, the temperature of the greenhouse without crop was higher than the temperature of the greenhouse with crop, and the difference decreases with the increasing of z , with the maximum difference being 1.44°C and the minimum difference being 0.29°C ; in the range of $z=(-1000, 8000)$ mm, the temperature of the greenhouse with crop was higher than the temperature of the greenhouse without crop, in the range of $z=(-1000, 2000)$ mm, the difference decreased with increasing z , the maximum difference was 1.0°C , and the minimum difference was 0.53°C ; in the range of $z=(3000, 7000)$ mm, the difference was maintained in the range of $(0.60, 0.69)^{\circ}\text{C}$. In the range of $z=(7000, 8000)$ mm, the difference increased with increasing z and decreased with a maximum difference of 0.69°C and a minimum difference of 0.05°C . It was evident that indoor crops had a significant impact on the interior of the wall at 1000 mm from the inner surface of the wall and on the interior space at 7000 mm from the inner surface of the wall.

In summary, the presence or absence of crops in the greenhouse had a large effect on the temperature of the north side wall, and within the crop layer, the effect was larger at a distance of 3000 mm to 8000 mm from the inner surface of the north side wall.

Effect of the presence or absence of crops on longitudinal temperatures in solar greenhouse

To investigate the effect of crop presence on the longitudinal temperature distribution inside the greenhouse, an analysis was conducted along the east–west cross-section of the north–south span. Temperature variation curves were examined at $Z = 5000\text{mm}$, $y = 0$ mm, 1600 mm and 2400 mm, $x = (-8000, 80000)$ mm

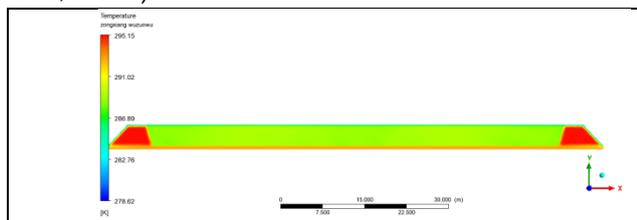


Fig. 4.1 - Temperature cloud of $Z=5000$ mm east-west cross-section without crop

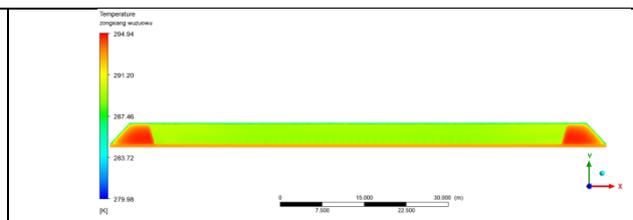


Fig. 4.2- Temperature cloud of $Z=5000$ mm east-west cross-section with 1.5 m crop spacing

As can be seen from Figure 4.1 and Figure 4.2, the change rule of temperature along the longitudinal direction of the greenhouse with and without crop temperature at $y=0$ mm was as follows: under the same working condition, the temperature of the greenhouse with crop temperature was higher than that of the greenhouse without crop temperature; within the range of $x=(-8000, -5000)$ mm, the temperature difference increased gradually with the increase of x , and the maximal temperature difference was 1.21°C ; within the range of $x=(-5000, 72000)$ mm range, the minimum temperature difference was 0.01°C , and the maximum temperature difference was 0.21°C ; in the $x=(72000, 78000)$ mm range, the temperature difference increased slowly as x increased, and the minimum temperature difference was 0.21°C , and the maximum temperature difference was 1.22°C ; in the $x=(78000, 80000)$ mm range, the temperature difference decreased gradually, the minimum temperature difference was 0.75°C and the maximum temperature difference was 1.22°C . It can be seen that, considering the effect of temperature difference of 0.5°C on the crop, the indoor crop has a greater effect on the temperature of the east and west walls, and a smaller effect on the temperature along the longitudinal direction at the soil surface of the indoor space.

The change rule of temperature at $y=1600$ mm along the longitudinal direction was as follows: in the range of width of the east and west walls, the temperature of the greenhouse without crops was higher than that of the greenhouse with crops; in the range of $x=(0, 72000)$ mm, the temperature in the greenhouse with crops was higher than that in the greenhouse without crops; in the range of $x=(0, 2000)$ mm, the difference of temperature was 1.2°C ; in the range of $x=(2000, 18000)$ mm range, the temperature difference gradually decreased, the maximum temperature difference was 1.2°C , and the minimum temperature difference was 0; in the $x=(18000, 34000)$ mm range, the temperature difference gradually increased, the maximum temperature difference was 0.51°C , and the minimum temperature difference was 0; in the $x=(34000, 40000)$ mm range, the temperature difference stayed constant, the temperature difference was 0.51°C ; in the range of $x=(40000, 56000)$ mm, the temperature difference decreased gradually, the maximum temperature difference was 0.51°C , and the minimum temperature difference was 0; in the range of $x=(56000, 72000)$ mm, the temperature difference decreased gradually, the maximum temperature difference was 1.45°C , and the

minimum temperature difference was 0. From the above analysis, it can be seen that, in the range of crop layers, the presence or absence of crops in the greenhouse has a greater effect on the temperature of the inner side of the east and west walls and on the temperature within the range of 10,000 mm from the longitudinal distance of the east and west walls.

The change rule of temperature at $y=2400$ mm along the longitudinal direction was as follows: in the range of the width of the east wall and the west wall, the temperature in the crop-free greenhouse was higher than the temperature in the crop greenhouse, and with the increase of the distance from the surface of the indoor wall, the temperature difference was gradually increasing, and the maximum temperature difference was 2.4°C , and the minimum temperature difference was 0.99°C ; in the range of $x=(0,72000)$ mm, the temperature in the crop greenhouse was higher than the temperature in the greenhouse without crops; in the range of $x=(0,18000)$ mm, the temperature difference gradually decreased, the maximum temperature difference was 1.3°C , and the minimum temperature difference was 0.07°C ; in the range of $x=(18000,22000)$ mm, the temperature difference stayed unchanged, and the temperature difference was 0.07°C ; in the range of $x=(22000,54000)$ mm, the temperature difference gradually increased, the maximum temperature difference was 0.66°C , the minimum temperature difference was 0.04°C ; in the range of $x=(54000,72000)$ mm, the temperature difference gradually decreased, the maximum temperature difference was 1.47°C , the minimum temperature difference was 0.04°C . From the above analysis, it can be seen that, the presence or absence of crops in the greenhouse had a greater impact on the temperature inside the east and west walls, and it has a greater impact on the temperature inside the wall at the longitudinal distance between the wall of 10000 mm and (34000,40000) mm range had a greater effect on the temperature.

Therefore, from the above analysis, it can be seen that the presence or absence of crops in the greenhouse had a greater effect on the temperature inside the east and west walls, and on the temperature within a distance of 10,000 mm from the surface of the wall, taking into account the effect of a temperature difference of 0.5°C on the crop.

Influence of different planting densities of crops on the temperature distribution in solar greenhouses

The study respectively simulated the temperature variation patterns in solar greenhouses with crop spacings of 1500 mm (actual) and 2000 mm. For the simulations, the temperature data at 17:00 on 26 January 2024 were selected as the initial boundary conditions. The temperature distribution maps at 08:00 were then analysed comparatively to assess the differences.

Influence on the vertical temperature of solar greenhouses

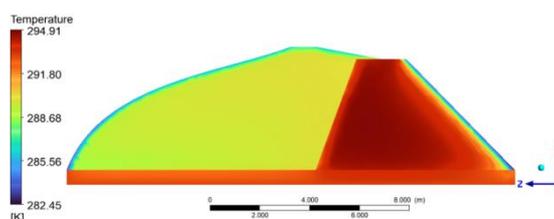


Fig. 5- Temperature cloud of $X=36000$ mm north-south cross-section with 2.0 m crop spacing

In order to investigate the vertical effect of different crop planting densities (1.5 m and 2 m, respectively) on the temperature in the greenhouse, $x=36000$ mm was taken in the greenhouse, and the difference in temperature between the crop planting density of 2 m and the temperature of the crop planting density of 1.5 m was analysed according to the difference in the height y when z was 0 mm, 5000 mm, and 9000 mm, respectively.

Taking $z=0$ mm, the temperature difference between the temperature at a crop planting density of 2 m and the temperature at a crop planting density of 1.5 m was analysed. Only when $y = (0, 800)$ mm, the temperature of crop planting density of 1.5 m was greater than the temperature of crop planting density of 2 m, the maximum difference was 0.2°C , and the minimum difference was 0.01°C ; when $y > 800$ mm, the temperature of crop planting density of 2 m was greater than the temperature of crop planting density of 1.5 m. The maximum temperature difference was 0.27°C and the minimum temperature difference was 0.15°C within the $y = (900, 4700)$ mm interval; when $y = (4800, 5000)$ mm, which is located in the vicinity of the film, the temperature difference gradually increases, and the maximum temperature difference was 0.69°C .

Taking $z=5000$ mm, the temperature difference between the temperature at a crop planting density of 2 m and the temperature difference at a crop planting density of 1.5 m was analysed. When $y = (0, 500)$ mm, the maximum difference in temperature between the two was 0.49°C ; when $y = (600, 1800)$ mm, the temperature difference between the two was more than 0.5°C , and the maximum temperature difference was 0.59°C ; when $y = (1900, 3400)$ mm, the maximum difference in temperature between the two was 0.49°C ; and when $y = (3500, 3900)$ mm, the maximum temperature difference between the two temperatures was 5.02°C and the minimum difference was 0.55°C .

Taking $z=9000$ mm, the temperature difference between the temperature at a crop planting density of 2 m and the temperature at a crop planting density of 1.5 m was analysed. When $y=(0, 1200)$ mm, the maximum temperature difference between the two temperatures was 0.3°C , and the minimum temperature difference was 0.23°C ; when $y=1300$ mm, the temperature difference between the two temperatures was the largest, which was 1.35°C ; when $y=1400$ mm, 1500 mm, the temperature of crop planting density of 1.5 m was greater than that of crop planting density of 2 m, and the difference in temperatures was 0.49°C respectively, 0.44°C ; when $y = (1600, 1800)$ mm, which was located in the vicinity of the film, the maximum difference in temperature was 0.59°C .

In summary, in the greenhouse when $x=36000$ mm, the temperature of crop planting density of 2 m was generally higher than the temperature of planting density of 1.5 m. However, there existed localized areas of contrast, where the temperature of crop planted at a density of 1.5 m was higher than the temperature of planted at a density of 2 m only at $z=0$ mm, $y<800$ mm, and at $z=9000$ mm, $y=1400$ mm, and 1500 mm. Further analysis showed that within the planting area, the effect of planting density on temperature was significant when $y>600$ mm, and the temperature difference could be up to 0.5°C or more. In addition, the effect of planting density on temperature was particularly pronounced in the area within 400 mm from the film, with lower temperatures near the film and larger temperature differences, especially at $z=5000$ mm, where the temperature difference at the film was the largest, reaching 5.02°C .

Influence on transverse temperature in solar greenhouses

The present study investigates the change rule of temperature along the transverse direction in the greenhouse with different planting densities. This study selected the data of different heights in the east-west spanning north-south direction in the greenhouse, and analysed the temperature within $z=(-8000, 10000)$ mm at $x=36000$ mm, $y=0$ mm, 1600 mm, and 2400 mm.

From the above figure, it can be seen that under the same working condition, in the greenhouse with crop planting densities of 2 m and 1.5 m respectively, the transverse temperature distribution pattern within $z=(-8000, 10000)$ mm at $x=36000$ mm and $y=0$ mm was as follows: the temperature difference within $z=(-8000, -5000)$ mm gradually increases, the maximum temperature difference was 0.1°C , and the minimum temperature difference was -0.02°C ; The difference in temperature values within $z=(-5000, -1000)$ mm remains unchanged, with a temperature difference of 0.05°C ; the temperature difference at $z=0$ mm was -0.26°C ; the difference in temperature values within $z=(0, 4000)$ mm remained unchanged, with a temperature difference of -0.06°C ; the difference in temperature values within $z=(4000, 8000)$ mm gradually increased, with a maximum temperature difference of 0.4°C ; the difference in temperature values within $z=(8000, 9000)$ mm gradually decreased, with a minimum temperature difference of 0.36°C ; and the temperature difference at $z=10000$ mm film was 0.72°C .

The change rule of temperature at $y=2600$ mm along the transverse direction was as follows: the temperature difference gradually decreased within $z=(-6000, -4000)$ mm, with the maximum temperature difference of -0.18°C and the minimum temperature difference of -0.01°C ; the difference in temperature values within $z=(-4000, -2000)$ mm stayed the same, with a temperature difference of 0.01°C ; the difference in temperature values within $z=(-2000, 3000)$ mm gradually increased, with the maximum temperature difference was 0.3°C ; the difference in temperature values within $z=(3000, 8000)$ mm gradually decreased, with a minimum temperature difference of 0.22°C ; and the temperature difference at $z=9000$ mm film was 0.58°C .

The change rule of temperature at $y=2400$ mm along the transverse direction was as follows: in $z = (-5000, -2000)$ mm within the temperature difference remained unchanged, the temperature difference was 0.03°C ; in $z = (-2000, 1000)$ mm within the difference in temperature values gradually increased, the maximum temperature difference was 0.29°C ; in $z = (1000, 7000)$ mm within the canopy gradually decreased, the minimum temperature difference was 0.21°C ; and the temperature difference at $z=8000$ mm film was 0.75°C .

In summary, the transversal air temperature distribution in the greenhouse was positively correlated with the planting density in the greenhouse, and the air temperature in the greenhouse with a planting density of 2

m was higher compared to the air temperature with a planting density of 1.5 m. The indoor air temperatures varied greatly in the range of 1 m near the film at the same height, with a difference value of more than 0.5°C; the wall temperatures varied greatly in the range of 1 m near the interior and exterior of the room, but with a difference of less than 0.25°C.

Impact on longitudinal temperature in solar greenhouses

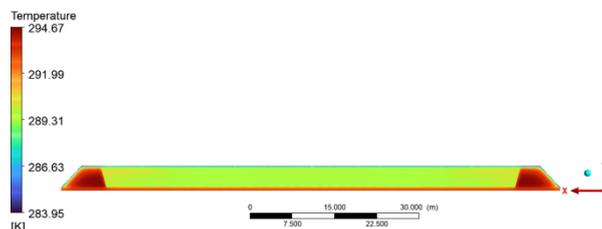


Fig. 6- Temperature cloud of Z=5000 mm east-west cross-section with 2.0 m crop spacing

In order to investigate the different crop spacing in the greenhouse on the indoor temperature along the longitudinal rule of change, the north-south span along the east-west cross-section was analysed, and the crop spacing of 2 m and 1.5 m, z=5000 mm, y=0 mm, 1600 mm, 2400 mm, x=(-8000,80000) mm at the temperature change curve was analysed.

From figures 4.2 and 6 above, under the same working condition, the greenhouse temperature of 2 m crop spacing and 1.5 m crop spacing at y=0 mm along the longitudinal rule of change was: in the range of east-west wall, the temperature of 2 m spacing was lower than 1.5 m spacing by 0.06°C on average; in the range of (1000,72000) mm, the temperature of 2 m spacing was higher than that of 1.5 m spacing, with the maximum temperature difference of 0.59°C and the minimum of 0.02°C. The temperature difference at 0 m was the largest at 3.19°C; in the range of (x=1000,72000) mm, the temperature difference was in fluctuation with the increase of x, with an average of 0.29°C, and the maximum was 0.59°C at 14000 mm, and the minimum was 0.02°C at 65000 mm; the temperature difference in the range of x=(73000,79000) mm did not vary much and averaged -0.07°C. Overall, crop spacing had a greater effect on temperatures in the range of 6000 mm and (10000, 16000) mm from the east-west wall and a smaller effect on temperatures within the wall.

The change rule of temperature along the longitudinal direction at y=1600 mm was as follows: in the range of east-west wall, the temperature of 2 m spacing was lower than that of 1.5 m spacing by 0.03°C on average; in the range of (0,73000) mm, the temperature of 2 m spacing was higher than that of 1.5 m spacing by 0.30°C on average. In the range of x=(0,73000) mm, the temperature difference was in a fluctuating state with an average of 0.30°C; in the range of x=(74000,79000) mm, the temperature difference decreased from -0.02°C to -0.07°C. Overall, crop spacing had a greater effect on the temperature within 6000 mm from the east-west wall and a lesser effect on the temperature within the east-west wall.

The change rule of temperature along the longitudinal direction at y=2400 mm was as follows: in the range of east-west wall, the temperature of 2 m spacing was lower than that of 1.5 m spacing by 0.03°C on average; the temperature difference increased with the increase of distance from the inner surface of the wall, and the maximum temperature difference was 0.29°C, and the minimum was 0.18°C. Within the range of x=(0,73000) mm, the temperature difference was in a fluctuating state, with an average difference of 0.24°C, and within the range of x=(74000,78000) mm range, the temperature difference increased from -0.04°C to -0.17°C. In conclusion, crop spacing had a small effect on the temperature inside the east-west wall and a large effect on the temperature within 5000 mm from the east-west wall.

Thus, from the above analysis, it can be seen that crop spacing has less effect on the temperature of the east and west walls, but more effect on the temperature within a distance of 6000 mm from the wall.

CONCLUSIONS

(1) The presence or absence of crops in the greenhouse has a greater influence on the temperature in the solar greenhouse along the horizontal, vertical and longitudinal directions within the ranges of (3000,8000) mm, (300 mm, at the film) and the distance from the inner surface of the east and west walls within the range of 10,000 mm;

(2) The presence or absence of crops in the greenhouse has a greater influence on the internal temperature of the east wall, the west wall and the north wall. The presence or absence of crops in the

greenhouse has a greater effect on greenhouse temperature than the density of crops grown in the greenhouse has on greenhouse temperature;

(3) The effect of different planting densities on the temperature of the greenhouse was less significant than that of different planting methods. The influence of different planting densities of crops on the internal temperatures of the solar greenhouse in the horizontal, vertical and longitudinal directions was within the ranges of (1000mm, at the film), (600 mm, at the film), and the distance from the inner surface of the east and west walls was within the range of 6000 mm, respectively.

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