Simulation research on airflow distribution performance of solar greenhouse heating system in northwest China

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Abstract. Combined with the structure of the solar greenhouse, this paper proposed a new type of solar greenhouse heating and ventilation system with the framework of the solar greenhouse as the carrier of heating and ventilation. The system's return air mode, tuyere type, tuyere installation position and aperture ratio were determined by computational fluid dynamics (CFD). The results showed that: 1) When the inlet wind speed was 10m/s and the temperature was 37°C, using the upper return air method, the average temperature of the greenhouse crop area increases by 14.7°C, which was greater than 1.3°C of the lower return air and 2.3°C of the middle return air, the heating effect was the best. 2) Based on the nozzle and slot-type tuyere, five kinds of air outlets were designed. It was found that the use of the nozzle-type air outlet could promote the circulation effect of the airflow in the greenhouse and send more heat to the crop area. 3) When the aperture ratio was controlled at 1.5, the number of air outlets has little effect on the greenhouse heating effect.

1. Introduction

The research on the regulation of the humid and hot environment of solar greenhouses in northwest China is relatively weak, and the problem of crop freezing damage has not been effectively solved [1, 2]. Taking into account factors such as heating costs and environmental protection, the use of solar energy and auxiliary heating facilities to heat greenhouses has become the mainstream [3]. At present, many scholars have done a lot of research on the heat storage part of the heating system, but less research on the greenhouse airflow organization during the heat release process, resulting in uneven heat distribution in the greenhouse, and some crops cannot be heated. In order to solve the above problems, the airflow organization of the greenhouse should be designed. In order to improve the growth environment of the plant factory, Zhang [4] and Liu [5] established a pipeline air supply system in the plant factory to provide a good wind speed environment for the growth of crops, but did not consider the temperature factors that affect the growth of crops. Therefore, this paper established a pipeline heating system to control the wind speed environment and temperature environment of the greenhouse.

2. Materials and methods

2.1 Experimental setup

The experiment was carried out in the campus of Lanzhou Jiaotong University (latitude 36°05′N, longitude 103°88′E). The solar greenhouse is facing south, extending from east to west, with a length of 7m and a span of 6.88m. The height of the ridge is 3.4m, the thickness of the back wall is 1.32m, and the height is 2.6m. The front sloping roof is covered with a polyethylene-vinyl acetate (EVA) film with a thickness of...
of 0.12m. A variable frequency fan was installed inside the greenhouse to drive the circulation of the airflow.

2.2 Measuring point layout

In the experiment, T-type thermocouples were arranged in three directions, as shown in Fig. 1, and the data was recorded every five minutes. In order to obtain accurate outdoor weather parameters, the PC-4 weather station was arranged on the south side of the greenhouse 2m away from the greenhouse.

![Fig. 1. Schematic diagram of measuring point layout.](image1.png)

2.3 CFD modeling and meshing

Use Gambit6.3 to create a 1:1 3D model according to the actual greenhouse size, and the grid independence of the model was verified under three grid numbers of 255470, 567125, and 1025457, and the air temperature error analysis in the greenhouse was selected. After calculation, the maximum relative errors were 9%, 7% and 6% respectively, which ensures the reliability of the calculation results.

![Fig. 2. 3D model of the experimental greenhouse.](image2.png)

2.4 Parameter design and calculation method

A typical sunny day was used to verify the test, and the measured data from 8:00 am to 20:00 pm on Sept. 28, 2021 was used as the boundary condition. On the test day, the shed was opened for ventilation at 11:00 in the morning and closed at 16:00 in the afternoon. On the day of the test, the highest temperature of the outdoor environment was 29.3°C, which appeared at 3:45 pm, and the lowest temperature was 11.3°C, which appeared at 7:20 am. The maximum illuminance of solar radiation was 819W/m².

![Fig. 3. Comparison of measured temperature and simulated temperature.](image3.png)

The north wall and soil of the greenhouse were set as constant temperature boundary conditions, 12°C and 7°C respectively, the east and west walls were set as adiabatic boundary conditions, the front and rear slope roofs were set as convective boundary conditions, and the convective heat transfer coefficient was 9.8W/(m²·K) and 10W/(m²·K). The outdoor temperature was 7°C, and the indoor initial temperature was 10°C.

It can be seen from Fig. 3, that the simulated temperature in the greenhouse was consistent with the measured temperature change curve with time, in which the maximum absolute error of temperature was 2.6°C, and the average absolute error was 0.6°C.

3. Analysis of simulation results

3.1 Comparison of return air forms

Fig. 4 showed the temperature field and velocity field of the three types of return air. The average temperature of the crop growing area at 0.3m was 24.7°C, which was 14.7°C higher than the initial temperature. The average temperature of the greenhouse in Case2 was 11.3°C, and the average temperature of the crop growing area under 0.3m was 12.3°C, which was 2.3°C higher than the initial temperature. The average temperature of the Case3 greenhouse was 13.1°C, and the average temperature of the crop growing area at 0.3m was 11.3°C. Compared with the initial temperature of the greenhouse, the temperature was increased by 1.3°C.
Observing the velocity field, the average wind speed in the crop area using case1 can reach 0.3 m/s. Appropriate wind speed can promote the growth of crops and increase the rate of photosynthesis. The others fail to form a good air circulation in the greenhouse, heat flow cannot be delivered to the crop area at the bottom of the greenhouse and it causes a lot of energy waste. Therefore, the optimization of the ventilation system will be simulated by the way of case1.

3.2 Comparison of tuyere types

The slot type tuyere and spout were suitable for public buildings with large space or tall workshops with allowable fluctuation range of room temperature greater than or equal to 1°C. Therefore, based on these two types of tuyeres, we designed five kinds of tuyere, as shown in Fig. 5, and the size of the tuyere in Table 1.

It can be seen from the Table 1 and 2 that the case 1 and case 3 performances were better. Compared with other types of tuyeres, these two types of tuyeres had good performances in terms of the heating capacity of the greenhouse and the fluidity of the airflow. It was worth mentioning when using type c for air supply, the heating effect of the inlet wind speed of 10 m/s was greater than that of 11 m/s and 12 m/s. Further illustrated that a reasonable airflow organization and circulation can play a positive role in the energy saving of the greenhouse.

![Temperature and velocity distributions for the three cases](image)

**Fig. 4.** Temperature and velocity distributions for the three cases. (case1 was upper return air, case2 was below return air, case3 was middle return air)

| Type | Nozzle diameter (mm) | Number of groups |
|------|----------------------|------------------|
| a    | 30                   | 4                |
| b    | 24                   | 4                |
| c    | 20                   | 4                |
| d    | 200×10               | 1                |
| e    | 1000×5               | 4                |

**Fig. 5.** Schematic diagram of the air outlet.

| V (m/s) | Case1 | Case2 | Case3 | Case4 | Case5 |
|---------|-------|-------|-------|-------|-------|
| T (°C) | V (m/s) | T (°C) | V (m/s) | T (°C) | V (m/s) | T (°C) | V (m/s) |

**Table 1.** Air outlet size summaries.

**Table 2.** Summary of simulation results for four inlet wind speeds.
3.4 Comparison of different aperture ratios

This Study had indicated that when the aperture ratio was about 1.5, it was conducive to the uniform air supply of the pipeline. Therefore, in this design, the aperture ratio was controlled around 1.5. By changing the number and diameter of the air outlets, four air supply schemes were determined, and the dimensions are shown in Table 3. Fig. 6 showed a schematic diagram of the layout of the air outlet.

| Table 3. Air outlet size summary. |
|---------------------------------|
| Diameter(mm) | Number | Area(m²) | Aperture ratio |
|----------------|--------|----------|----------------|
| 15             | 17     | 1.766x10⁴ | 1.53           |
| 20             | 9      | 3.14x10⁴  | 1.60           |
| 25             | 6      | 4.906x10⁴ | 1.50           |
| 30             | 4      | 7.065x10⁴ | 1.44           |

Fig. 6. Schematic diagram of the air outlet.

From the simulation results summarized in Table 4, it can be seen that when the aperture ratio was controlled at about 1.5, the number of orifices had little effect on the heating effect of the ventilation system. When the inlet wind speed was 12m/s, the highest temperature rises to 3.3°C of scheme a, and the lowest temperature rises to 3°C of scheme d, a difference of only 0.3°C. And under the four schemes, the wind speed in the crop area was maintained above 0.15m/s, which can meet the wind speed conditions required by the crop area. Combined with the data in the table and taking into account the difficulty of the actual operation of the project, the aperture ratio of the ventilation system was set at 1.53.

| Table 4. Summary of Simulation Results. |
|----------------------------------------|
| Index | Num | 9m/s | 10m/s | 11m/s | 12m/s |
| crop area | 4 | 7.4 | 7.6 | 8.1 | 8.3 |
| temperature | 6 | 7.4 | 7.6 | 7.9 | 8.2 |
| °C | 9 | 7.4 | 7.6 | 7.8 | 8.1 |
| wind speed | 17 | 7.3 | 7.7 | 7.8 | 8.0 |
| m/s | | | | | |
| crop area | 4 | 0.19 | 0.18 | 0.19 | 0.2 |
| m/s | 6 | 0.17 | 0.19 | 0.18 | 0.17 |
| | 9 | 0.17 | 0.16 | 0.15 | 0.18 |
| | 17 | 0.16 | 0.17 | 0.18 | 0.17 |

4. Conclusions

The main conclusions are as follows: 1) The location of the return air outlet had a great influence on the heating effect, and it was better to set the return air outlet above the greenhouse. 2) The use of air outlets in the form of nozzles can increase the air supply distance and promote the circulation of airflow in the greenhouse. The air supply speed of the slit tuyere attenuated too fast, which had a poor heating effect on the greenhouse, and the wind speed in the crop area was only 0.02m/s. 3) When the aperture ratio was similar, the number of air supply ports had little effect on the heating capacity of the greenhouse.

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