Temperature field simulation using CFD in the plant factory

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Abstract: This experiment was developed by Computational fluid dynamics (CFD) technology. A three-dimensional model was conducted for an indoor artificial light plant factory to simulate the temperature field distribution. The results showed that the average absolute error of simulated temperature and measured temperature was 0.7℃, and the average relative error was 3%. The growth indexes of Brassica chinensis in the artificial light plant factory were measured. The uniformity of airflow field in the cultivation area should be further studied for the structural optimization of the plant factory.

1. Introduction

Plant factory is an efficient agricultural production system that enables the annual continuous production of horticultural crops by controlling the high precision environment[1-2]. Closed artificial light plant factory mainly uses artificial light such as LED lamp to provide the light source for plants, which are generally equipped with air conditioning, nutrient solution system, multi-layer cultivation rack and so on[3]. Energy and resource consumption in closed plant factory is minimized, artificial light source is fully utilized and proper environmental regulation can be carried out to provide suitable growth conditions for plants, so high quality, low cost and high added value plants as vegetables and flowers can be produced in closed plant factory[4].

Computational Fluid Dynamics technology can accurately simulate the trend of temperature distribution in plant production systems. Many results[4-7] showed that the actual measured temperature value is in high agreement with the simulated value using CFD. Therefore, it is reasonable and feasible to use this method to simulate and optimize the temperature field in plant factories[6].

The most important factor in plant factories is temperature[7]. In order to ensure the effective growth and development of crops, suitable temperature conditions must be provided. The effect of general evaluation temperature on plants is mainly through three basis point temperatures: the lowest temperature, the highest temperature and the optimum temperature. At the optimum temperature, plant growth and physiological activities can be carried out normally, and have a high rate of photosynthesis product accumulation[8-10].

Brassica chinensis originated in China, high temperature and dry conditions will make it difficult to grow normally[10]. Because the ventilation of plant factory is generally air-conditioned circulating air, the cultivation frame is multi-layer, and its top is very close to the roof, which makes the air circulation
blocked\(^{[11]}\), the growth of Brassica chinensis in artificial light plant factories could be influenced by its uneven temperature. In this experiment, a three-dimensional model of indoor artificial light plant factories was constructed by CFD, and its temperature field was simulated and verified. The growth index of Brassica chinensis was measured.

2. Materials and methods

2.1 Experimental materials

This experiment was conducted in the artificial light plant factory in Chengdu city, and the variety of test Brassica chinensis is "special Brassica chinensis" provided by Jintian Seed Industry.

2.2 Experimental methods

2.2.1 Establish CFD model of indoor artificial light plant factory

(1) Establish CFD geometric model

In the Design modeler of Workbench 18.1, the three-dimensional geometric model of plant factory was established (4800mm(Length)×2800mm(width)×2600mm(height)); the top inlet was simplified to a side length of 400mm square; two sides of the wall were simplified to nine vents(600mm×200mm). The air circulation was carried out by means of upper air and return air on two sides.

Simplification of LED artificial light: the LED light board was located at the top of the stereoscopic cultivation shelf, and it was simplified to a square heat flux plate of 650mm×650mm.

Simplification of the stereoscopic cultivation shelf: there were four stereoscopic cultivation shelves, each consisting of three-layer plates, each plate with a specification of 1500mm×700mm, the height of the shelf plate was 500mm. Two cultivation shelves were in a group and symmetrically placed.

(2) Calculate the aerodynamic model

It was assumed that the fluid flow in the plant factory was continuous, steady-state, incompressible fluid, and the flow field is turbulent. The temperature of the plant factory interior wall, the three-dimensional cultivation shelf outer wall and air outlet fin was uniform and constant (type 1 boundary conditions), the LED light lamp plate was considered as a hot plate (type 2 boundary conditions), assuming that the door sealing is good and the air leakage is not considered.

The equations of mass, momentum and energy conservation were applied in the model construction:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)
\]

\[
\frac{\partial}{\partial x_i} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = \frac{\partial}{\partial x_j} \left[ -p \delta_{ij} + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho g_i \quad (2)
\]

\[
\frac{\partial}{\partial x_i} (\rho C_T T) + \frac{\partial}{\partial x_j} \left( \rho u_i C_T T \right) - \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial T}{\partial x_j} \right) = S_T \quad (3)
\]

(3) Numerical simulation

The computational grid was divided in the MESH Workbench 16.0, and the whole fluid region was divided into structured hexahedral meshing. Since the temperature gradient of the boundary layer at the lamp board, inlet and outlet of LED light source in the plant factory changes greatly, the grid should be properly encrypted and the quality should be controlled according to the Equi Angle Skew standard. After grid independence test, the number of grids was calculated to be 3521452, and the grid quality is excellent (Quality=0.999)\(^{[12]}\).

Boundary conditions were set in Boundary Conditions of FLUENT showed in Table 1.

The inner flow field was divided by the hexahedral wall of the plant factory, the heat dissipation of the LED light plate was defined as a constant value, and the plant cultivation shelf had no airflow infiltration and no heat transfer\(^{[5]}\).
Table 1 Boundary condition setting in calculation

| Fluid: Air            |
|----------------------|
| Indoor temperature: Measured value 22.5 °C |
| Gravitational acceleration: 9.81 m·s⁻² |
| Plant cultivation shelf: Heat insulation |
| LED light lamp plate: Constant heat flux; Measured value 32 °C |
| Air inlet: Velocity (Measured value); Temperature (22.5 °C) |
| Air outlet: Free outflow; Gauge pressure: 0 Pa; Measured value 22.5 °C |

(4) Initial conditions and solutions
The pressure-velocity coupling equation was solved by using Simple C semi-implicit algorithm, and the discrete solver was used to solve 3D steady-state values of each conservation equation.

(5) Steady-state calculations
The calculation was carried out in FLUENT 16.0 software. The solver was solved by separate and Simple C semi-implicit algorithm.

2.2.2 Measurement point selection
This experiment selected the section X=1.2m, and 4 measure points evenly at each height Y=0.5, 1.5, 2.0m. So, there were totally 12 measure points (V1~V12). The 12 measure points in this section were used to measure the temperature for simulation and verification. And the cross section points were shown in Figure 1.

![Fig. 1 The measure points at the section X=1.2m](image)

2.2.3 Simulation of the temperature field uniformity in the plant factory
The experiment introduced the calculation results of Fluent into CFD, simulated and obtained the temperature distribution of the plant factory, and analyzed its uniformity.

2.2.4 Determination of growth status of Brassica chinensis
On December 25, 2019, the Brassica chinensis seeds were sowed in the greenhouse by soaking and sprouting, and the size of the seed plate was (54cm×18cm). The seedling substrate was mixed in the ratio of mixed rock to vermiculite was 1:3, and the Hoagland nutrient solution was poured 2~3 times every day. The four-leaf seedlings with the same growth and strong growth were selected and transferred into the artificial light plant factory. On January 11, 2020, samples were taken to determine the growth indexes of Brassica chinensis.

2.3 Determination method

2.3.1 Method for determining temperature values
(1) Temperature measurement and recording: greenhouse doll (domestic) (measuring accuracy: 0.2°C)
(2) Data acquisition: record every 10 min.

2.3.2 Method for determining the growth indexes of Brassica chinensis
(1) The main root length, plant height and petiole length were measured by straightedge.
(2) The fresh weight of the plant was measured after washing and drying with distilled water.
(3) The dry weight of the plant was measured after drying at 105°C for 15 min and constant weight at 75°C.
(4) The seedling index was calculated according to the method of Zhenxian Zhang et al. (Seedling index $\text{Seedling index} = \text{stem diameter/ plant height} \times \text{whole plant dry mass}$ \cite{13}.
(5) Leaf area was calculated by formula of $\text{Single leaf area} = \text{length} \times \text{width} \times 0.7007$.

2.4 Data statistics and analysis
In this experiment, Excel 2010 software was used for data processing and error analysis.

3. Results and discussions

3.1 Comparison of air temperature between simulated and measured values
The measured air temperature values of 12 measure points were compared with the simulated values, and the results were shown in Figure 2. The absolute error of the 12 points was 0.2-1.1°C, the mean absolute error was 0.7°C, the relative error was 0.9%-4.6% and the mean relative error was 3%. Point 4 was located near the outlet, its absolute error and relative error was the largest, respectively 1.1°C and 4.6%. The airflow in the plant factory would be affected by the movement of the tester and the placement of the instrument, the temperature simulated value was different from the measured value, but the trend was consistent, so the model was effective.

![Fig. 2 Comparison of temperature between simulated and measured values](image)

Fig. 2 Comparison of temperature between simulated and measured values

3.2 Analysis of temperature field uniformity
By experimental verification, it was concluded that the average relative error between the simulated value and the measured value of temperature measurement point was 3%. And the model was correct, which can be used for the analysis of the temperature field uniformity. Figure 3 was a cloud diagram of temperature field Z=2.0 section in this model. The model results showed that the simulation value of the temperature closed to the LED lamp board was large, the maximum can reach 30.5°C. The temperature field distribution was more uniform under the stereoscopic cultivation frame and at the passage in the plant factory. In the cultivation area, the maximum temperature value was 26°C, the minimum value was 23°C, and the average value was 25°C, which can meet the growth demand of Brassica chinensis.

![Fig. 3 The temperature distribution at interface Z =2.0m](image)
3.3 Analysis of the growth indexes of Brassica chinensis

The measurement data were shown in Table 2. According to the measurement data of growth status of Brassica chinensis, the growth status of Brassica chinensis in the indoor artificial light plant cultivation area was characterized by the strong plant and shallow root system. In general, the growth condition of Brassica chinensis in the cultivation area was good, which proved that the temperature range of indoor artificial light plant was suitable for the growth of Brassica chinensis.

| Plant height (cm) | Main root length (cm) | Petiole length (cm) | Leaf area (cm) | Fresh weight (g) | Dry weight (g) | Stem diameter (cm) |
|------------------|-----------------------|---------------------|----------------|---------------|---------------|-------------------|
| 15.72±           | 17.44±                | 4.92±               | 31.94±         | 19.125±       | 1.755±         | 0.2556±           |
| 1.875            | 1.694                 | 0.725               | 13.866         | ±3.871        | 0.422          | 0.0692            |

4. Conclusions

This experimental study showed that the measured temperature values had a high agreement with the simulated values in the plant factory. The average absolute error was 0.7℃ and the average relative error was 3%, which indicated that the CFD model established in this experiment was correct. Under this ventilation mode, the temperature field distribution in the cultivation area of Brassica chinensis was more uniform, and its temperature range was suitable for the growth demand.

For plant growth, the uniformity of airflow field is as important as that of temperature field. The uniformity of airflow field in the cultivation area of Brassica chinensis under this kind of ventilation mode should be further studied to provide a reference for the structural optimization of plant factories.

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