Experimental validation of CFD model with the air velocity and temperature in the plant factory

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Abstract: A computational fluid dynamics (CFD) model for the closed plant factory has been developed in this study, the experimental validation of CFD model with the air velocity value was compared with the measured air temperature value. The results showed that the mean relative error of validation with the air velocity was 15%, and comparable with experimentally observed air temperature profile inside the plant factory with RMSE of 3% which shows the utility of CFD to study plant factory microclimatic parameters.

1. Introduction

Plant factory is an efficient agricultural production system that enables the annual continuous production of crops by controlling the high precision environment of horticultural facilities [1]. It can use modern science and technology to automatically control the humidity, temperature, light intensity, carbon dioxide concentration and environmental conditions of nutrient solution, so that the plant growth facility can achieve efficient production without or little affected by natural environmental conditions [2].

Computational Fluid Dynamics (CFD) technology is a tool that can accurately simulate the trend of airflow and temperature distribution in plant production systems. Huan Liu et al. [3] used Fluent 16.0 to establish a 3D model of an artificial light plant factory, and optimized the design of a variety of airflow circulation modes. Wenjian Zhu et al. [4] used Fluent software to simulate the distribution of airflow field and temperature field according to the established CFD model of a multi-span greenhouse. Fang Zhang et al [5] simulated the natural ventilation of large span greenhouse by establishing CFD model and verified the temperature measuring points. Hui Fang et al [6] established CFD model, which can predict the spatial distribution of indoor temperature in different directions of greenhouse, and provided a reference for the construction of the large span heat preservation greenhouse. Jiaoliao Chen et al [7] used CFD to simulate the temperature field distribution of a Venlo-greenhouse under the condition of hot air heating in greenhouse. Majdoubi et al [8] considered plants as porous media, regulated wind speed to change the movement of insect and tomato crops. And the greenhouse temperature field and relative humidity field were simulated by CFD and verified by experiments. Finally, the optimized greenhouse temperature and humidity conditions were obtained by simply modifying the crop row. Zhang et al. [9] based on CFD to optimize the uniformity of the indoor temperature field in plant factories. Yongbo Li
et al. [10] used CFD model to simulate the temperature field uniformity in greenhouse. Many results showed that the actual measured temperature is in high agreement with the CFD simulated temperature, which indicates that the boundary conditions set and the established CFD model are effective in many research experiments. Environmental factors affecting plant production include temperature, airflow, light, humidity and CO₂ [11], it is reasonable and feasible to use this method to simulate and optimize the temperature, humidity, CO₂ and airflow field in plant factories. But there are few reports on using airflow value to verify the CFD model.

This study developed a CFD model for the closed plant factory, the experimental validation of CFD model with the air velocity value was compared with the measured air temperature value. The results provided theoretical support for the transformation and optimization of the structure of the plant factory.

2. Materials and methods

2.1 Experimental materials

This experiment based on the artificial light plant factory. ANSYS Fluent 16.0 software was used to simulate the indoor airflow and temperature field in plant factory. The simulated value was compared with the measured value of air velocity and temperature to verify the accuracy of the model.

2.2 Experimental methods

2.2.1 Develop CFD model of the plant factory

In the ANSYS Workbench 16.0, the 3D 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; and the two sides of the wall were simplified to nine return 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 three-layer 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. Respectively two cultivation shelves were in a group and symmetrically placed. It was assumed that the fluid flow in the plant factory was continuous, steady-state, incompressible fluid, and the flow field is turbulent [12]. The peripheral protective structure of the experimental plant factory was non-transparent insulation material. 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:

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

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho g_i \tag{2}
\]

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

A standard k-ε turbulence model was used to solve the turbulent transport process of indoor air.

The computational grid was divided in the ANSYS Workbench 16.0, and the whole fluid region was divided into structured hexahedral meshing. After grid independence test, the number of grids was calculated to be 3521452, and the grid quality is excellent (Quality=0.999) [13]. Boundary conditions were shown in Table 1.
Table 1 Boundary condition setting in calculation

| Fluid: | Air |
|--------|-----|
| Indoor temperature: | Measured value 22.5 °C |
| Gravitational acceleration: | 9.81 m/s² |
| Plant cultivation shelf: | Heat insulation |
| LED light lamp plate: | Constant heat flux; Measured value 32 °C |
| Air inlet: | Temperature (22.5 °C) |
| Air outlet: | Free outflow; Gauge pressure: 0 Pa; Measured value 22.5 °C |

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.

The calculation was carried out in FLUENT 16.0 software in ANSYS Workbench. The solver was solved by separate and Simple C semi-implicit algorithm. Second order discretization schemes were used for momentum and energy, while first order discretization schemes were used for others.

2.2.2 Model validation

This experiment selected the section X=1.2m, and 4 measuring points evenly at each height Y=0.5, 1.5, 2.0m. So, there were totally 12 measuring points (V1~V12). The 12 measuring points in this section were used to measure the airflow velocity and temperature for simulation and verification. And the cross section points were shown in Figure 1. Air velocity measurement: DT-618 hand-held anemometer (±3%±0.1 m/s). Temperature measurement and recording: greenhouse doll (domestic) (measuring accuracy: 0.2°C). Data acquisition: record every 10 min.

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

2.3 Data statistics and analysis

In this study, Excel 2016 software was used for data processing and error analysis.

3. Results and discussions

3.1 Comparison of air velocity between simulated and measured values

The measured values of 12 measuring points were compared with the simulated values, and the results were shown in Figure 2. Point 4 was located near the outlet, its absolute error and relative error was the largest, respectively 1.1 m/s and 4.6%. The absolute error of Point 12 was 0.1-0.6 m/s, the relative error was 2%-35%, the mean absolute error was 0.2 m/s and the mean relative error was 15%. The airflow in the plant factory would be affected by the movement of the tester and the placement of the instrument, the air velocity simulated value was different from the measured value, but the trend was consistent, so the model was effective.
Fig. 2 Comparison of air velocity between simulated and measured values

3.2 Comparison of air temperature between simulated and measured values
The measured temperature values of 12 measure points were compared with the simulated values, and the results were shown in Figure 3. The absolute error of the 12 points was 0.2-1.1℃, the mean absolute error was 0.7℃, 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℃ and 4.6%, the temperature simulated value was different from the measured value, but the trend was consistent, so the model was effective.

Fig. 3 Comparison of temperature between simulated and measured values

4. Conclusions
The results of both airflow and temperature values simulated by CFD model have been compared with the experimental results performed during the experimental period in the plant factory. In this ventilation mode, the mean relative error of validation with the air velocity was 15%, and comparable with experimentally observed air temperature profile inside the plant factory with RMSE of 3% which show the utility of CFD to study plant factory microclimatic parameters. It was concluded that the measured temperature values of the plant factory had a better agreement with the simulated values by the CFD model compared with the validation by measured air velocity values. This study can provide a reference for airflow simulation and optimization in commercial plant factories. If large commercial plant factories adopt the same ventilation mode, the airflow uniformity needs further study, and the test results of this study cannot be directly applied.

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