Climatic factors affecting plant growth include temperature, humidity, and airflow environment. A vital factor of plant ecological environment is the airflow environment, which affects the growth of plants in the plant factory. The growth of horticultural crops is directly affected by the airflow environment in plant factories. In this experiment, a three-dimensional model was established for an indoor artificial light plant factory using computational fluid dynamics (CFD) to simulate the airflow field distribution in the plant factory, the measured value and the simulated value of air velocity were in good agreement, only 10% of the cultivation area was in the range of suitable growth air velocity. The optimization design of airflow field in the plant factory will be developed.
and development process of plants. The suitable air velocity of plant leaves can regulate the microenvironment, while reducing water condensation to avoid high wet diseases, promote crop growth and increase stress resistance, and ultimately improve product quality [8].

It is greatly important to study the relationship between crop growth and airflow motion states in plant production systems. The indoor microclimate can be directly regulated by ventilation in plant production systems. The appropriate airflow velocity in the greenhouse can not only improve the environmental analysis conditions of cash crops, such as working temperature and humidity, but also help to improve the photosynthesis, respiration and transpiration of crops. The optimum air velocity of indoor potted pepper was about 0.8 m·s⁻¹, no wind or high wind velocity was not conducive to the pepper growth [9].

In the CFD research of plant factories, Zhang et al. [10] establish a three-dimensional model of the single-layer cultivation area of the closing plant factory, simulate and verify the airflow environment of the single-layer cultivation area, optimize the design of the airflow circulation system. Lim et al. [11] established a three-dimensional CFD model for plant factories, analyzed the airflow field by setting different air outlets. A non-standard and achievable turbulence model is used in the model calculation, and it is assumed that the gas in the plant factory is three-dimensional, steady-state, incompressible turbulence. Baek et al. [12] took artificial light plant as the research object. The ventilation mode includes the opening of internal fan, exhaust fan and air conditioning system. They constructed the CFD model in different ventilation modes, and obtained the optimal ventilation mode by comparative analysis. Huan Liu et al. [13] used CFD to establish plant factory environment model, and through analyzing indoor temperature field and airflow field, the ventilation optimization scheme was designed. It is reasonable and feasible to use Fluent methods to simulate and optimize the airflow field in plant factories.

This experiment simulated and verified the airflow field of indoor artificial light plant factory by using CFD, 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
(1) ANSYS Fluent 16.0 software was used to simulate the indoor airflow in plant factory.
(2) The simulated value was compared with the measured value of air velocity to verify the accuracy of the model. The airflow uniformity was studied by this model.

2.2 Experimental methods

2.2.1 Establish CFD model of indoor artificial light plant factory
(1) Establish CFD geometric model
In the ANSYS Workbench 16.0, 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; 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.

(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 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:

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

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

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

A standard k-ε turbulence model was used to solve the turbulent transport process of indoor air, and
the flow near the wall adopted the standard wall function method.

(3) Numerical simulation

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) \(^{[14]}\). Boundary conditions
were shown in Table 1.

| 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: 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 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 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\(^{-1}\)),
data acquisition: record every 10 min.

Fig. 1 The measuring points at the section X=1.2m
2.2.3 Simulation of the airflow uniformity in the plant factory
The experiment introduced the Fluent calculation results into CFD, simulated and obtained the airflow distribution of the plant factory, and analyzed its uniformity.

2.3 Data statistics and analysis
In this experiment, 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⁻¹ and 4.6%. The absolute error of Point 12 was 0.1-0.6 m·s⁻¹, the relative error was 2%-35%, the mean absolute error was 0.2 m·s⁻¹ 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](image)

3.2 Analysis of airflow uniformity
By experimental verification, it was concluded that the average absolute error between the simulated value and the measured value of the air velocity measuring points was 0.2 m·s⁻¹, the average relative error was 15%. And the model was correct, which can be used for the analysis of the airflow uniformity.

As shown in Figure 3, the airflow entered the room vertically from the upper inlet and aggregated at the inlet, forming eddy and rotational flow at the ground of the plant factory. The model results showed that the minimum air velocity was close to 0 m·s⁻¹, the maximum air velocity in the lower cultivation area near the inlet, was 0.4 m·s⁻¹; the air velocity in 90% of the cultivation area was less than 0.3 m·s⁻¹, the cultivation area in the range of comfortable air velocity of plant growth (0.3-1.0 m·s⁻¹) was 10%, and the average air velocity in the cultivation area was 0.15 m·s⁻¹. And the distribution of the airflow was not uniform.

![Fig. 3 The airflow velocity distribution at interface Z=2.0 m](image)
4. Conclusions
It was concluded that in this ventilation mode, the airflow of the plant factory entered the room vertically from the upper inlet, accumulated at the inlet, and formed eddy and rotational flow at the ground of the plant factory, which was consistent with the research results of Huan Liu et al. Under the current ventilation mode, only 10% of the cultivation area was in the range of suitable growth air velocity (0.3-1.0 m·s⁻¹). The later study will optimize the design of the ventilation scheme based on this CFD model to improve the indoor airflow uniformity of plant factories. This study can provide a reference for airflow simulation and optimization in commercial plant factories.

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