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Enhancing Crop Cooling of Greenhouse in Yangtze River Delta Region: A CFD Method Approach

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Abstract
This study addresses the challenges of inadequate air circulation and excessive internal temperatures in greenhouses within Yangtze River Delta region. The research uses experimental methods and computational fluid dynamics (CFD). Findings revealed that introducing 90° side windows significantly improved airflow and temperature distribution, whereas 45° side windows had minimal impact. Adding layers improved cooling performance at all measurement points. However, as the number of shading net layers increases, the cooling capacity changes with each additional shade net layer decreases. These findings offer a scientific basis for this region's greenhouse ventilation and shading nets using strategies for optimizing greenhouse environments.

Keywords: Greenhouse; Yangtze River Delta; Ventilation Optimization; Shading Net

1.0 Introduction

High internal temperatures and poor air circulation have posed significant challenges for greenhouse cultivation in the Yangtze River Delta, especially during summer. Existing reliance on mechanical ventilation systems leads to substantial energy consumption, elevating operational costs (Maraveas et al., 2023) (Abid et al., 2023). The region's climatic characteristics, including weak winds and high heat (Wu et al., 2024), often render natural ventilation inadequate for maintaining optimal conditions for crop growth (Al-Rikabi et al., 2023). High radiation levels further exacerbate heat buildup, causing potential crop damage. Greenhouses increasingly employ ventilation optimization and multi-layer shading nets to address these issues (He et al., 2023). However, their application requires precise scientific guidance, particularly considering the unique climatic conditions of the Yangtze River Delta.

This study expands on these observations by analyzing a fully open multi-span greenhouse in Shanghai in Yangtze River Delta conditions, which include high radiation and limited wind. Employing experimental and CFD methodologies, the research investigates ventilation optimization and the impact of shading nets on the temperature and movement of air. The findings provide theoretical references for greenhouse design and operational strategies tailored to the region's climatic challenges, as shown in Fig 1.

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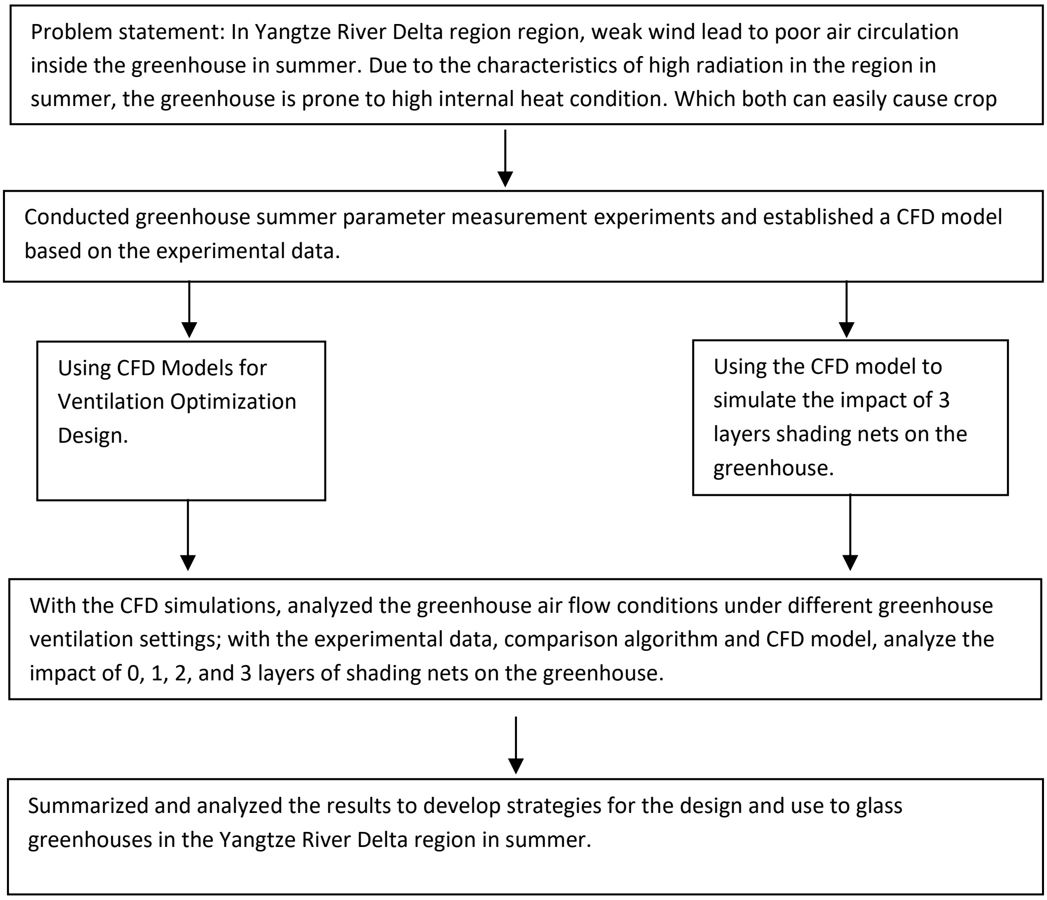


Fig 1: Research process

2.0 Literature Review

Existing research underscores the critical role of greenhouse ventilation structures in optimizing airflow. Studies indicate that well-designed side windows can enhance airflow patterns, creating a conducive microenvironment for crops. For instance, Kittas demonstrated that baffled side windows outperform roll-up alternatives in improving airflow fields using the CFD method (Kittas & Bartzanas, 2007). Similarly, Akrami emphasized the importance of vent placement in regulating airflow and temperature within greenhouses (Akrami et al., 2020).

Shading nets, another vital component of greenhouse systems, are pivotal in controlling temperature and humidity. They offer energy-saving benefits while improving crop quality and greenhouse environmental performance (Ghoulem et al., 2019) (Shukla & Kumar, 2024). Studies by Willits and Peet demonstrated the effectiveness of shading nets in reducing radiation, aiding in cooling, and moisture retention(Willits & Peet, 2000). Further, Ahmed M. and Abdel-Ghany analyzed the effects of shading net configurations on radiation and temperature distribution, providing essential references for simulation models (Abdel-Ghany et al., 2015) (Abdel-Ghany & Al-Helal, 2011). Santorini, in a study on multi-span greenhouses, showed that low permeability screens optimized the temperature distribution (Santolini et al., 2022).

Shi, in a study for Botanical Garden, investigated the minimum shading area required for different outdoor temperatures under no wind weather in summer, and he fitted the correlation curves to guide the shading control for the proper thermal conditions (Shi et al., 2023). Keshi found that external shading has excellent cooling and homogenizing properties. In addition, based on the investigations on the effect of external shading height, he showed that external shading nets are suitable to be installed within 1 meter above the roof in his experimental region (KeShi et al., 2014).

Many scholars have studied greenhouse cooling measures and ventilation optimization (Mao & Li, 2025) (Fatnassi & Poncet, 2025); however, due to regional climate differences, when a region's agricultural greenhouse faces problems, it is still necessary to conduct a lot of research based on the region's climate conditions. So that the management strategy can adapt to the local climate. In previous studies, some scholars have used a combination of experimental and CFD research methods to study greenhouses and achieved good results, which shows that these methods are practical tools in this research area.

3.0 Methodology

3.1 Experiment Object

A commercial greenhouse in Shanghai, China's Jinshan District, served as the site of the study. Three spans made up the greenhouse, oriented north-south, and measured 41.1 m in length by 28.8 m in width. The height of its ridges and eaves was 5.3 and 4.3 meters, respectively, and its skylight had a 52° opening angle. The greenhouse had two layers of indoor shading nets at 4.0m and 4.5m. There was no ventilation equipment on the east and west walls, and there were fans on the north wall with dimensions of 1.38 m× 1.38 m positioned at a height of 0.32 m, and there was a wet curtain on the south wall at a height of 0.4 m. The width of the wet curtain was 1.5 m. The positive X-axis was oriented eastward for greenhouse modeling. The northwest corner of the greenhouse served as the origin, and the Z-axis positive direction was determined to be positive southward, as shown in Fig 2.

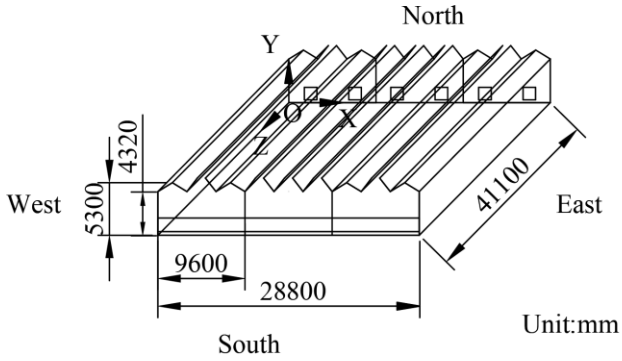


Fig 2. Greenhouse geometric model

3.2 Experimental Procedure

The experiment was conducted in early August, which was characterized by high radiation and weak winds typical of the Yangtze River Delta summer. Experiment conditions included opening the rear fan cover on the north wall so the external airflow could enter the greenhouse through the fan opening. Additionally, air vents were installed on the south wall through the dry-wet curtain's ventilation holes. The opening degree of the skylight was 52.4°. The middle span of the greenhouse was measured for humidity and temperature. Sensors (ZDR-3WIS automatic temperature recorder) were positioned at three heights: 0.7 m, 1.3 m, and 2.2 m, representing crops and high zones, respectively. The field of crops was defined as the 0.5-1.5 m range. Two vertical planes, aligned with the X- and Z-axes, were designated for sensor placement, as illustrated in Fig 3. Each sensor was assigned a data-tracking code (refer to Table 1). Thermocouple sensors were used to calibrate and record data more accurately at 5-minute intervals.

Environmental data, including radiation, illuminance, air temperature, wind speed, and wind direction, were recorded using a TYD-ZS2 environmental data logger—the logger's calibration adhered to manufacturer standards. One dataset, corresponding to noon conditions with two-layer shading nets, was selected for CFD model boundary conditions.

The external environmental data was recorded using an environmental data recorder called a TYD-ZS2. The recorder was located in the outdoor open space. The recorder measured radiation, illuminance, air temperature, wind speed, and wind direction during the experiment and recorded 1 time every 1 minute. A FLUKE infrared temperature sensor was utilized to measure the covering materials. One set of indoor and outdoor environmental data at noon was selected for building CFD model simulation. The greenhouse was under two-layer shading nets at the selected moment.

The ZDR-3W1S and the Fluke infrared contact point thermometer were calibrated using higher measurement accuracy thermocouple sensors. The calibration of the TYD-ZS2 environmental data logger was by the manufacturer's calibration; it was calibrated by the manufacturer regularly. Nine sets of data were measured in each of the three parts of the experiment, which was a timing series. The precise measurement procedure is displayed in Table 2, and the number of measurement times was noted.

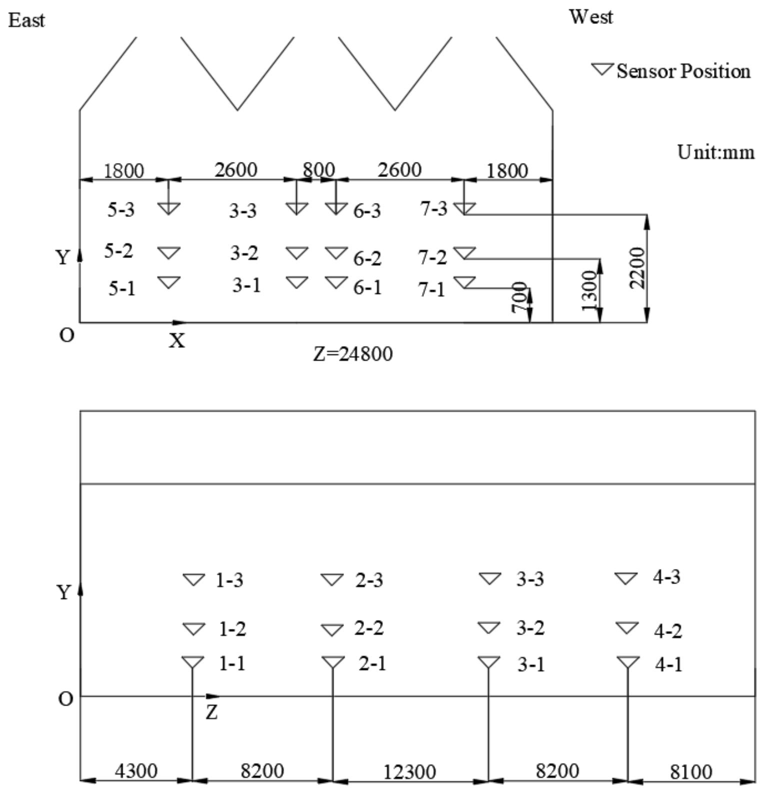


Fig 3. Schematic diagram of temperature sensor arrangement

Table 1. Sensor Positions and Sensor Code

Sensor Positions	1-1	2-1	3-1	4-1	5-1	6-1	7-1
Sensor Code i	P1	P2	P3	P4	P5	P6	P7
Sensor Positions	1-2	2-2	3-2	4-2	5-2	6-2	7-2
Sensor Code i	P8	P9	P10	P11	P12	P13	P14
Sensor Positions	1-3	2-3	3-3	4-3	5-3	6-3	7-3
Sensor Code i	P15	P16	P17	P18	P19	P20	P21

Table 2. Experiment data measurement

Measurement conditions	Two layers of shading net	One layer of shading net	Zero layers of shading net
Time	14:44-15:14	15:24-16:04	16:14-16:54
n	1-9	10-18	19-27

3.3 Meshing

A CFD model was constructed based on the greenhouse's geometric features, with computational domains set at 10 times the greenhouse dimensions. The model employed 3.43 million grid cells, including 0.92 million within the greenhouse (see Fig 4). The meshing was independently verified.

3.4 Turbulence Model

The Reynolds number of air movement inside the continuous glass temperature chamber was large. The Equation (1) gives the Rayleigh number:

$$Ra = \frac{g\beta(T_S - T_\infty)L^3}{v\alpha} \quad (1)$$

For Equation (1), g denotes the acceleration of gravity, β thermal expansion coefficient, T_s denotes the surface temperature, T_∞ denotes the quiescent temperature, L denotes the characteristic length and υ of the kinematic viscosity, α of the thermal diffusivity (Turcotte & Schubert, 2002). For the experiment greenhouse, using Equation (1) and g=9.8m/s, β=0.0035$/K$, T_s=316.65K, T_∞=312.15K, L=5.3m, υ=1.5 × 10^{-5} m^2/s, α=2.2 × 10^{-5} m^2/s.

After calculation, Rayleigh's numbers were more significant than 3× 10^{10}, determining that the airflow of the greenhouse was turbulent. To simulate the turbulence(Zhang et al., 2016) (ANSYS, 2010), the $k-\varepsilon$ Standard Turbulence Model and Standard Wall Function were selected based on literatures (Kavga et al., 2023) (Kim et al., 2021). The Discrete Ordinate (DO) radiation model simulated shading net effects by adjusting Radiation Source terms in the Energy Equation.

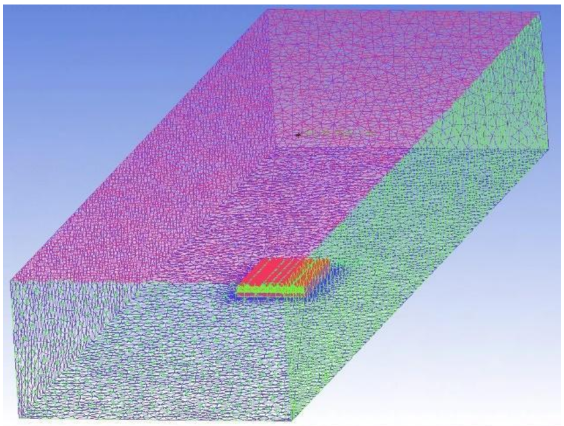


Fig 4. Grid division

3.5 Boundary Conditions

The optical properties of the glass were treated as semi-transparent for simulation purposes. Boundary conditions for noon high-heat scenarios are in Table 4, while material properties are listed in Table 5.

Based on the existing research literature on shading nets (Abdel-Ghany et al., 2015) (Abdel-Ghany & Al-Helal, 2011) (Ahemd et al., 2016), in combination with the physical parameters of specific materials of shading nets used in the experiment roof fully-open greenhouse, the greenhouse shading was simulated by ways of radiation discounting. Analyzed the material and installation status of shading nets at the experimental site, the value of outdoor solar radiation was reduced from 800 W/m² to 304 W/m² under two-layer shading nets.

Table 4. Boundary Conditions

Parameter	Solar radiation	Wind speed	Wind direction	East wall	South wall
value	800 W/m²	0.9 m/s	150°	42°C	43°C
Parameter	West wall	North wall	Roof	Inner ground	Outer ground
value	43°C	41°C	43°C	43°C	51°C

Table 5. Related parameters of materials of the CFD model

Material type	Density (kg.m^{-3})	Specific heat capacity (Jkg^{-1}.K^{-1})	Thermal conductivity (Wm.K^{-1})
Air Glass Concrete	1.165 2 500.0 2 100.0	1 025.5 700.0 880.0	0.026 79 0.71 1.4
Material type	Absorption coefficient (m^{-1})	Rate of refraction	
Air Glass Concrete	0 0.1 0.6	1.000 28 1.7 1.6	

Additionally, the model treated the greenhouse's dry wet curtain as porous media. Based on Burghardt's Wind-Pressure Relationship and the Basic Seepage Law (Kong & Xiangyan, 1999) (Chen et al., 2005), the infiltration rate α of the dry wet curtains was determined to be 2.4×10^{-6} m², ignoring the nonlinear inertial losses amount of fluid. The calculations did not consider the effects of heat pressure inside and outside the greenhouse.

3.6 Model Validation

Simulated data was compared against experimental measurements at sensor locations P1–P21 to validate CFD model. The results in Fig 5 indicate strong agreement, with the maximum and minimum temperature deviations of 2.9°C and -0.2°C, respectively. Relative errors ranged from -0.5% to 7.1%, averaging 3.9%. Mean absolute error (MAE) was 1.7 and root mean square error (RMSE) was 1.8, respectively, confirmed the model's reliability for simulating varying greenhouse environmental conditions.

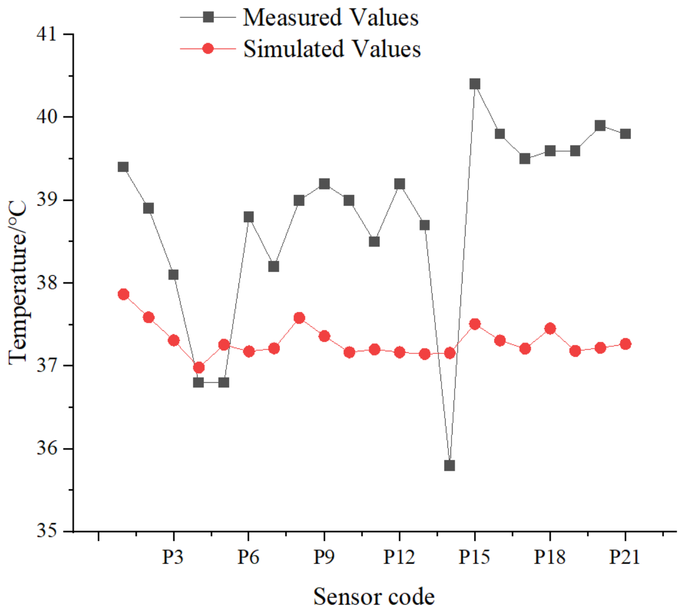


Fig 5. Comparison of simulated and measured values

3.7 Simulation Experiment

After validation, CFD model is used to perform optimization simulations. The experimental condition of the greenhouse was recorded as Case A.

Case B: Ventilation optimization. Raise the fan and wet curtain of the greenhouse, add medium opening (45°) side windows on the four walls, and the skylight angle was set to 60°.

Case C: Ventilation optimization. Raise the fan and wet curtain of the greenhouse, and add larger opening (90°) side windows on the four walls; the skylight was the same as in Case B.

Case D: Multi-Layer Shading. Maintain the ventilation structure and change the incident radiation of the greenhouse to simulate the greenhouse using three layers of shading nets.

4.0 Findings

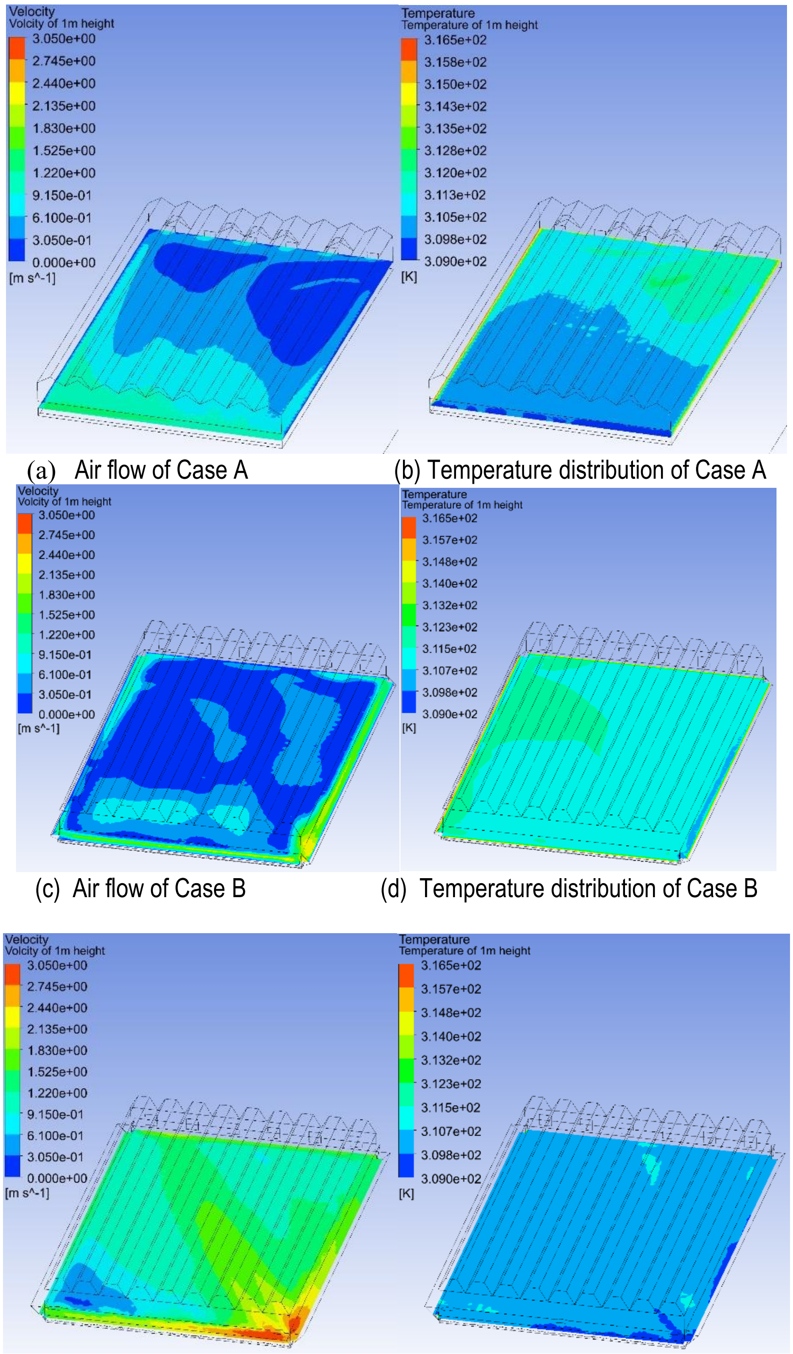
4.1 Ventilation Optimization

In a greenhouse, airflow and temperature distribution are both critical. Reasonable airflow distribution can ensure the fluidity of planting air and maintain appropriate transpiration rates and gas exchange to provide favorable conditions for healthy plant growth. Reasonable temperature distribution can promote the consistency of plant growth and avoid plant diseases and insect pests.

The ventilation performance was analyzed at the 1 m height cross-section, corresponding to the crop-growing area. The airflow distribution under experimental conditions (Case A) is shown in Fig 6 (a). The prevailing southeast wind entered the greenhouse through wet curtain, advancing northward. The air velocity was higher in the southern section and decreased towards the north. Similarly, airflow was stronger in the east than in the west, creating a slow-flow zone in the northeast due to the absence of side windows on the east and west walls.

The corresponding temperature distribution at the same cross-section was illustrated in Fig 6(b), where temperatures were lower in the south and higher in the north. A high-temperature zone was observed in the northeast quadrant, consistent with the airflow stagnation region.

To enhance ventilation, the side window configuration was modified. When 45° side windows were added (Case B), airflow and temperature distribution improved slightly but not significantly (Figs 6(c) and 6(d)).



(a) Air flow of Case A (b) Temperature distribution of Case A

(c) Air flow of Case B (d) Temperature distribution of Case B

(e) Air flow of Case C (f) Temperature distribution of Case C

Fig. 6 (a)-(f): The comparison of airflow and temperature distribution

Conversely, 90° side windows (Case C), coupled with a skylight adjustment to 60°, produced substantial improvements (Figs 6(e) and 6(f)). Airflow conditions became more uniform, and high-temperature zones were largely eliminated. These findings indicate that larger opening (90°) side windows can optimize greenhouse ventilation during weak wind conditions.

The wind rose chart for the experimental period (Fig 7) confirmed that the prevailing wind direction was southeast, aligning with the observed airflow and temperature patterns. This suggests that the findings broadly represent summer greenhouse conditions in the Yangtze River Delta.

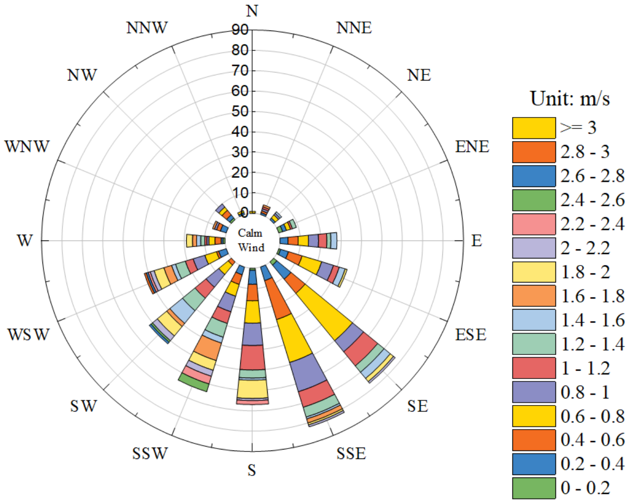


Fig 7. Flow field analysis under operating condition

This research provides a design theoretical reference for a specific climate compared to previous studies. Greenhouse users in the Yangtze River Delta region can consider designing a greenhouse with larger opening (90°) side windows, which is suitable for the weak wind climate in the summer in the area. It significantly improved ventilation conditions and will be more conducive to natural ventilation in summer.

4.2 Multi-layer Shading Nets simulation

Greenhouse ventilation optimization is more suitable for new greenhouse design references; changing the ventilation device is usually a significant cost for the old greenhouse. To be a mathematical description of the time-series data analysis and the comparison process, the following definitions were made in Table 6.

Shading nets offer a cost-effective approach to improving greenhouse environments, particularly for existing structures where ventilation modifications may be impractical. Through the analysis of the literature(Abdel-Ghany et al., 2015) (Abdel-Ghany & Al-Helal, 2011) (Ahemd et al., 2016), discounting the radiation method in the CFD model was used to simulate the greenhouse environment under a three-layer shading net (Case D). Analyzed the material and installation status of shading nets at the experimental site, the original outdoor radiation value 800W/m² was discounted to 187W/m². The value met the requirements of many plants' light levels.

5.0 Discussion

5.1 *Cooling Capacity*

To facilitate the experimental analysis, the following equations were used:

$$T_i = \frac{\sum_{n0}^{n1} t_{in}}{n1 - n0 + 1} \tag{2}$$

$$\Delta T_i = T_i - T_{o(n0-n1)} \tag{3}$$

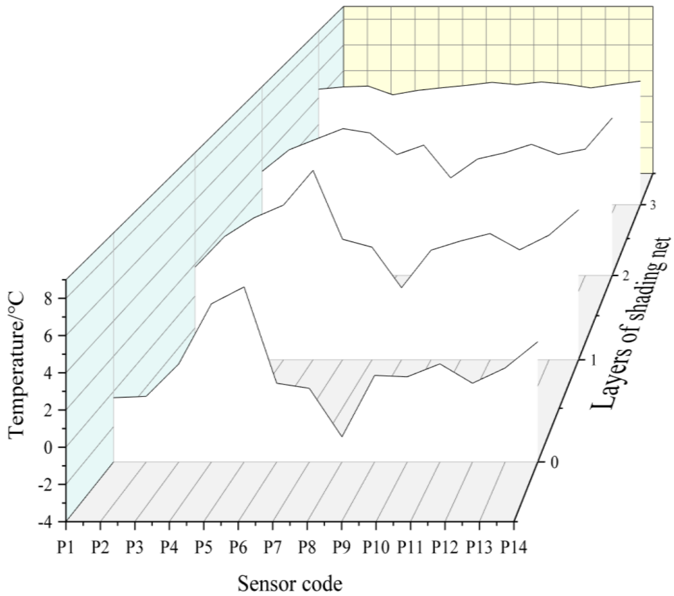
$$T_s = \frac{\sum_{i0}^{i1} \Delta T_i}{i1 - i0 + 1} \tag{4}$$

Table 6: Algorithm Parameter List

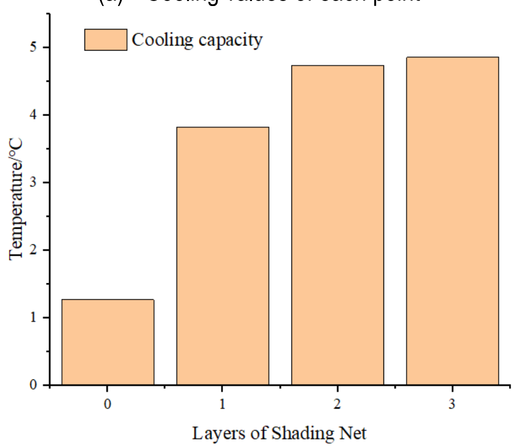
Parameters	T_i	
Meaning	The average temperature value is measured by a specific sensor multiple time.	
Parameters	ΔT_i	t_{in}
Meaning	The difference between the average temperature measured by a specific sensor multiple times and the outdoor temperature	The value of a sensor in a measurement
Parameters	t_o	$i0$

Meaning	The outdoor temperature value in a particular measurement time	The initial values of multiple consecutive calculated sensor numbers
Parameters	$i1$	$n0$
Meaning	The final value of multiple consecutive calculated sensor numbers	The initial value of the number of consecutive calculated measurement times
Parameters	$n1$	T_s
Meaning	The final value of the number of consecutive calculated measurement times	The average outdoor temperature value of T_n within $i0$-$i1$
Parameters	$T_{o(n0-n1)}$	
Meaning	The average outdoor temperature value during the consecutive calculated measurement times $n0$-$n1$	

Using Equation (2), (3), $n0$=19, $n1$=27; $n0$=10, $n1$=18; $n0$=1, $n1$=9; i=1, 2, 3...14 and using simulation data. The cooling values of each point comparison of zero-layer, one-layer, two-layer, and three-layer shading nets are shown in Fig 8(a). Using Equation (4), the cooling capacity comparison is shown in Fig 8(b).



(a) Cooling values of each point

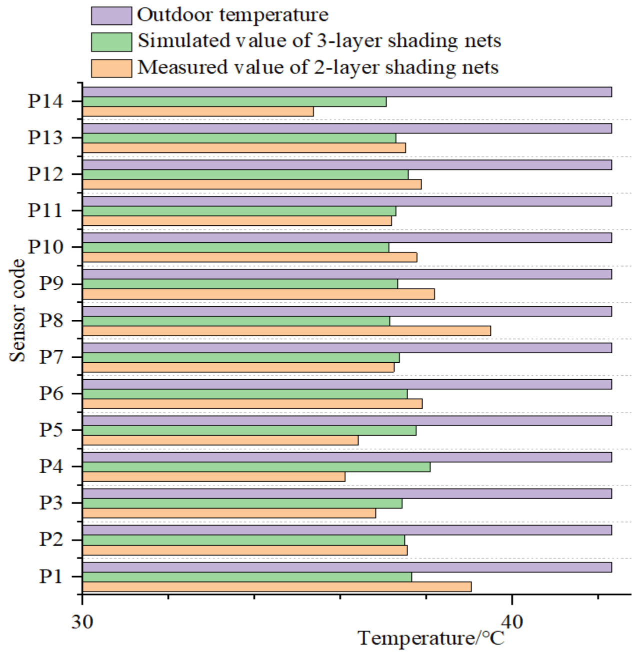


(b) Cooling capacity comparison

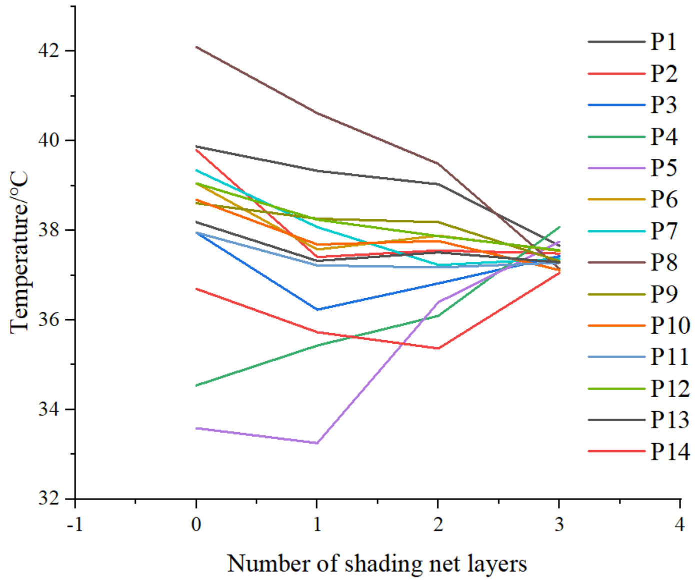
Fig 8. Cooling Capacity of layers of shading net

The cooling capacity values of zero-layer, one-layer, two-layer, and three-layer shading nets were 1.27℃, 3.83℃, 4.74℃, 4.86℃. As can be seen, adding layers improved cooling performance at all measurement points, the more layers of shading net, the better the cooling effect. However, as the number of shading net layers increases, the degree of change in cooling capacity with each additional layer net decreases.

5.2 Uniformity



(a) Temperature distributions under two and three-layer shading nets



(b) Sensor values of each point

Fig 9. Cooling Capacity of layers of shading net (Poorly uniform temperature distribution often leads to plant diseases, pests, and uneven growth)

Using Equation (2), $n0$=1, $n1$=9, i=1, 2, 3...14 and using simulation data. Temperature distributions under two and three-layer shading nets were compared in Fig 9. The three-layer configuration achieved lower temperatures and more excellent uniformity. The maximum temperature under two-layer shading nets was 39.5°C under one-layer shading, was 40.6℃and the zero-layer was 42.1℃, all exceeding the tolerance level for most heat-tolerant crops. In comparison, the three-layer configuration reduced maximum temperatures to 38.0°C, meeting the requirements for some heat-resistant crops, such as pumpkins, under typical summer conditions.

Using Equation (2), $n0$=19, $n1$=27; $n0$=10, $n1$=18; $n0$=1, $n1$=9; i=1, 2, 3...14 and using simulation data. Fig 9 (b) shows each point's sensor values. Adding layers improved the uniformity of temperature distribution, and the three-layer configuration achieved the highest uniformity of temperature distribution.

Variance in mean temperature values across measurement points decreased from 4.67 for zero-layer shading nets to 0.08 for three-layer shading nets (Table 7), highlighting the effectiveness of multi-layer shading nets in stabilizing greenhouse environments.

Table 7. Variance of sensor values under zero to three layers of shading nets

Layers of shading net	Zero-layer	One-layer	Two-Layers	Three-layers
The variance of mean values of measuring points P1-P14 (℃)	4.67	3.18	1.19	0.08

6.0 Conclusion& Recommendations

After adding 45° side windows, the airflow condition was not significantly improved in the greenhouse, but the airflow condition was considerably enhanced when adding 90° side windows. The cooling efficacy of shading nets increases with the number of layers; however, as the number of shading net layers increases, the degree of change in cooling capacity with each additional layer net decreases. The cooling capacity values of zero-layer, one-layer, two-layer, and three-layer shading nets were 1.27℃, 3.83℃, 4.74℃, 4.86℃. The three-layer shading nets reduced the maximum temperatures of the crop area to below 38 °C under the typical summer weather of the Yangtze River Delta.

The multi-layer shading nets enhance the uniformity of temperature distribution, reducing the variance from 4.67 °C (zero layer) to 0.08 °C (three layers).

Further, strategies for summer greenhouse design are proposed.

To cope with the weak wind weather in summer, greenhouses in the Yangtze River Delta region can be considered when designing side windows on the four walls, and the larger openings (90°) of side windows can achieve significant ventilation effects.

In high radiation weather, greenhouses in the Yangtze River Delta region can use three-layer shading nets to reduce the high temperature inside while meeting the plant growth illumination. Using multi-layer shading nets not only reduces greenhouse air temperature but also improves the uniformity of the distribution of greenhouse temperatures.

Future studies should evaluate the long-term performance of different shading materials and window configurations under dynamic weather patterns, ensuring scalability across diverse agricultural regions. This study underscores the potential of passive cooling strategies, such as optimized ventilation and multi-layer shading nets, to reduce greenhouse energy consumption. Policymakers can integrate these findings into guidelines promoting sustainable agricultural practices, aligning with national and regional climate action plans.

This study has some limitations. First, the main conclusions of this study were based on simulation experiments. Although verified, there must be a particular gap between the simulation results and the actual situation. In addition, this study was mainly carried out on greenhouses in the Yangtze River Delta region, and its conclusions and application scenarios have regional limitations. In subsequent research, reality experiments can be carried out for these simulation conditions, and multi-regional results comparison analysis can be carried out.

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Paper Contribution to Related Field of Study

For greenhouse users in the Yangtze River Delta region, adding side windows is helpful to enhance ventilation, and the ventilation effect of 90° side window opening is stronger than 45°. The use of multi-layer sunshades not only reduces the temperature, but also improves the uniformity of indoor temperature distribution.

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