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Enhancing Crop Cooling of Greenhouse in the 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 the 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 decreases with each additional shade net layer. 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

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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). 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 the Yangtze River Delta conditions. 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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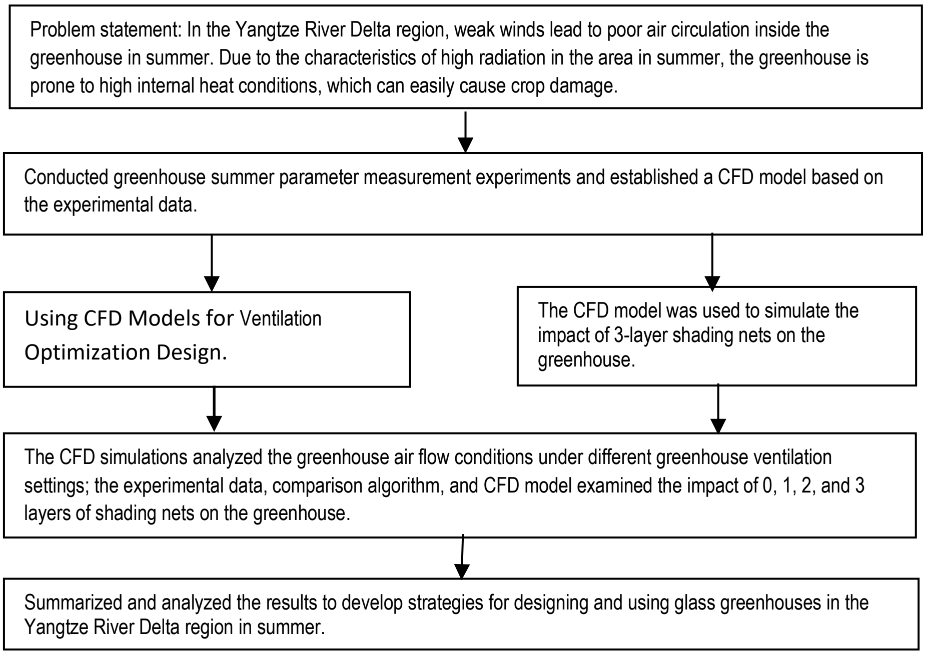


Fig. 1: Research process

This study investigates the impact of ventilation and shading nets on the cooling capacity of greenhouses through natural ventilation in the Yangtze River Delta. The objective is to evaluate how these factors affect temperature regulation within greenhouse environments.

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). These studies provide a reference for greenhouse window design.

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). In a study on multi-span greenhouses, Santorini showed that low-permeability screens optimized the temperature distribution (Santolini et al., 2022).

In a study for the Botanical Garden in Shanghai, Shi 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). These studies provide a reference for the research on greenhouse shading nets.

Many scholars have studied greenhouse cooling measures and ventilation optimization (Mao & Li, 2025; Fatnassi & Poncet, 2025); however, the existing literature lacks research on the low wind and high radiation conditions in the Yangtze River Delta, resulting in a lack of theoretical guidance for the use of summer greenhouses in the region. The main gap between this study and the existing literature is in the research area and the regional climate.

3.0 Methodology

3.1 Site

The study was conducted in a commercial greenhouse in the Jinshan District of Shanghai, China. The greenhouse consists of three spans, oriented north to south, and measures 41.1 meters in length and 28.8 meters in width. The height of the ridges is 5.3 meters, while the eaves are 4.3 meters high. Additionally, the skylight has an opening angle of 52°, as illustrated in Fig. 2.

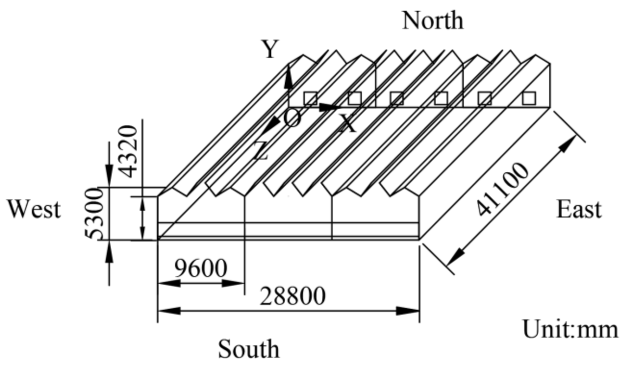


Fig. 2. Greenhouse geometric model

The experiment was conducted in early August, during a period characterized by high radiation and weak winds typical of summer in the Yangtze River Delta. Humidity and temperature measurements were taken in the middle span of the greenhouse. Sensors (ZDR-3WIS automatic temperature recorders) were placed at three different heights: 0.7 m, 1.3 m, and 2.2 m, corresponding to the levels of crops and higher zones, respectively. The crop area was defined as being within 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 given a unique data-tracking code (refer to Table 1). To ensure more accurate data collection, thermocouple sensors were used for calibration and recorded data at 5-minute intervals.

3.2 Equipment

Environmental data, including radiation, illuminance, air temperature, wind speed, and wind direction, were recorded using a TYD-ZS2 environmental data logger, calibrated per the manufacturer's standards. The TYD-ZS2 recorder was positioned in an open outdoor space, measuring these environmental parameters at one-minute intervals. Additionally, a FLUKE infrared temperature sensor was employed to assess the temperature of the covering materials.

A specific set of indoor and outdoor environmental data collected at noon was chosen for constructing a CFD model simulation. At this time, the greenhouse was covered with two layers of shading nets. The ZDR-3W1S and the FLUKE infrared contact point thermometer were calibrated utilizing high-accuracy thermocouple sensors. The TYD-ZS2 environmental data logger underwent regular calibration by the manufacturer to ensure precise measurements.

3.3 Data Collection

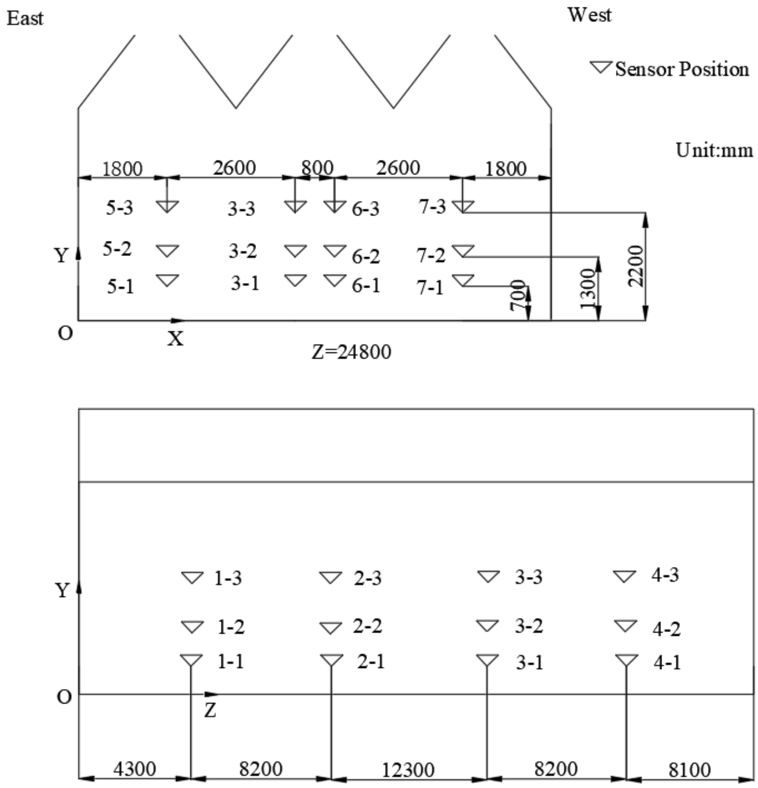


Fig. 3. Schematic diagram of temperature sensor arrangement

Nine data sets were measured in each part of the experiment, comprising a timing series. The detailed measurement procedure and recorded measurement times are presented in Table 2.

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

3.4 CFD Setup

A CFD (Computational Fluid Dynamics) model was created based on the geometric features of the greenhouse, with the computational domains set to be ten times larger than the greenhouse dimensions. The model utilized 3.43 million grid cells, of which 0.92 million were located within the greenhouse (see Fig. 4). The meshing process was independently verified. The Reynolds number for air movement inside the continuous glass temperature chamber was significant. Equation (1) provides 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 denotes the thermal expansion coefficient, T_s denotes the surface temperature, T_∞ denotes the quiescent temperature, L denotes the characteristic length, and v denotes the kinematic viscosity, α denotes 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, v=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 the literature (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. In greenhouse CFD calculations, the $k - \varepsilon$ model offers stability, versatility, and suitability advantages for simulating considerable, low-velocity turbulence. In contrast, the DO model accurately handles solar radiation and heat transfer through transparent covering materials. Therefore, choosing these two models balances accuracy, computational cost, and physical applicability.

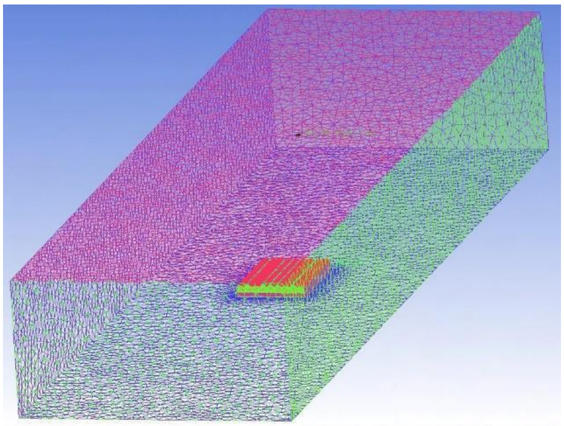


Fig. 4. Grid division

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, a 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 the 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 of fluid. The calculations did not consider the effects of heat pressure inside and outside the greenhouse.

3.5 Validation

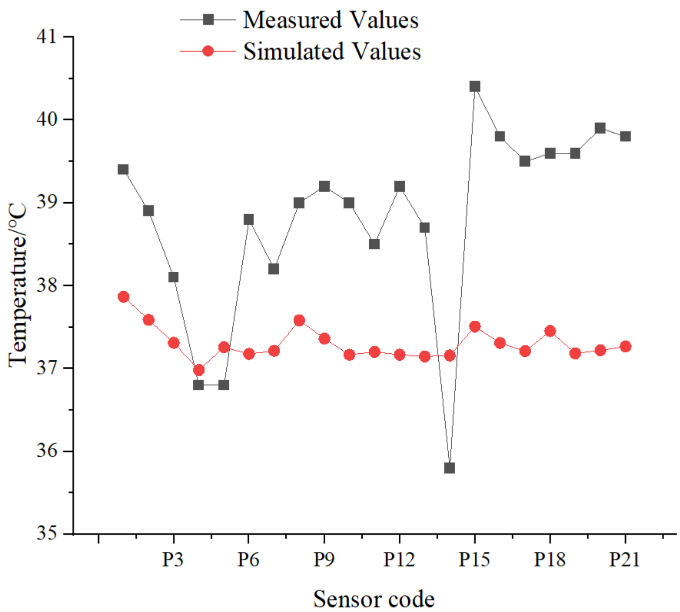


Fig. 5. Comparison of simulated and measured values

3.6 Simulation Experiment

After validation, the 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

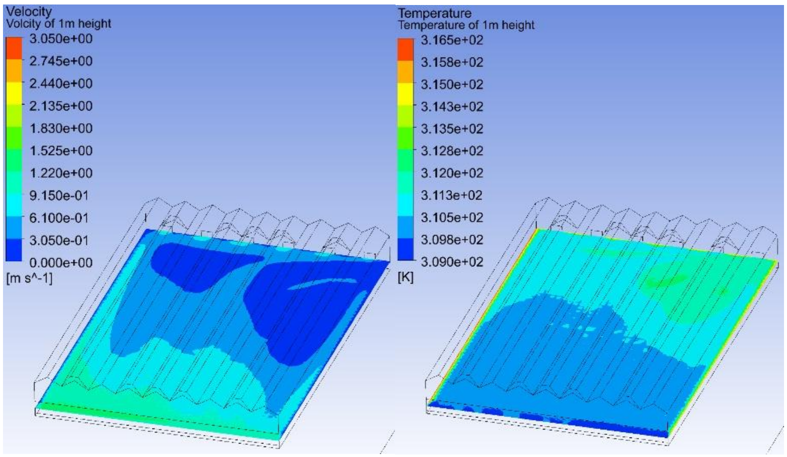
4.1 Ventilation Optimization

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.

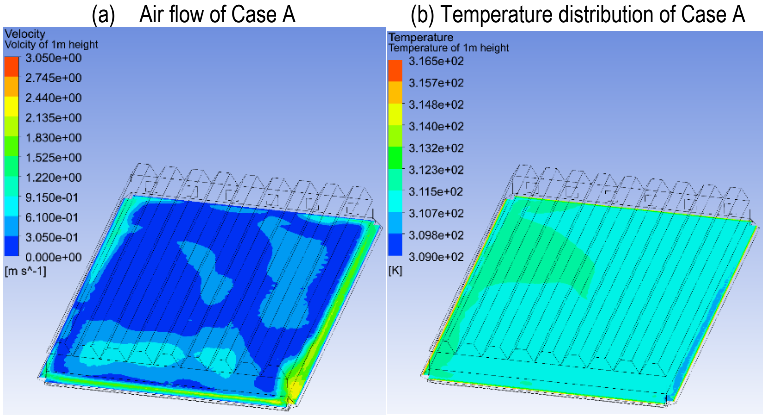
The ventilation performance was analyzed at the 1 m height cross-section, corresponding to the crop-growing area. The airflow distribution under experimental conditions (Case A) is shown in Fig. 6 (a). The prevailing southeast wind entered the greenhouse through the wet curtain, advancing northward. 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.

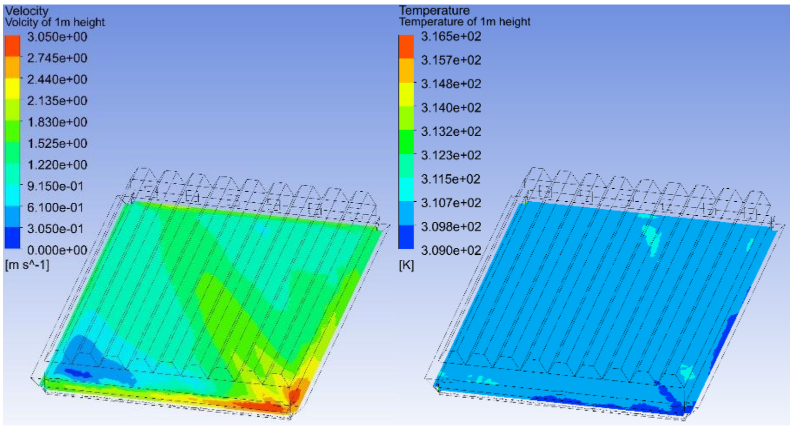
To enhance ventilation, the side window configuration was modified. When 45° side windows were added (Case B), airflow and temperature distribution improved slightly but not significantly (Figs 6(c) and 6(d)).



(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.

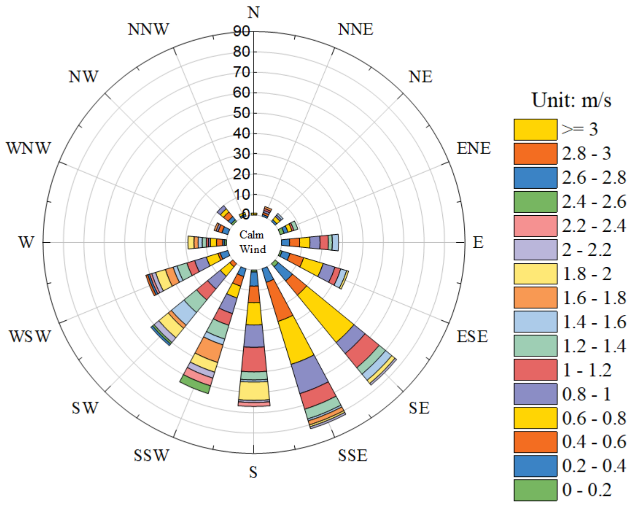


Fig. 7. Flow field analysis under operating conditions

This research provides a design theoretical reference for a specific climate compared to previous studies. Users can consider designing a greenhouse with larger opening (90°) side windows in the Yangtze River Delta region. Larger opening (90°) side windows suit the weak wind climate. The average temperature and airflow speed of Case A was 37.62℃ and 0.5m/s, Case B was 38.08℃and 0.7m/s, Case C was 37.02℃and 1.0m/s. Finally, in comparison, the stable temperature of Case C was 0.6℃ lower than that of Case A's, and the airflow speed was also 0.5m/s faster. 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 (Shi et al., 2023; Shukla & Kumar, 2024; Abdel-Ghany et al., 2015), 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 of 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:

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

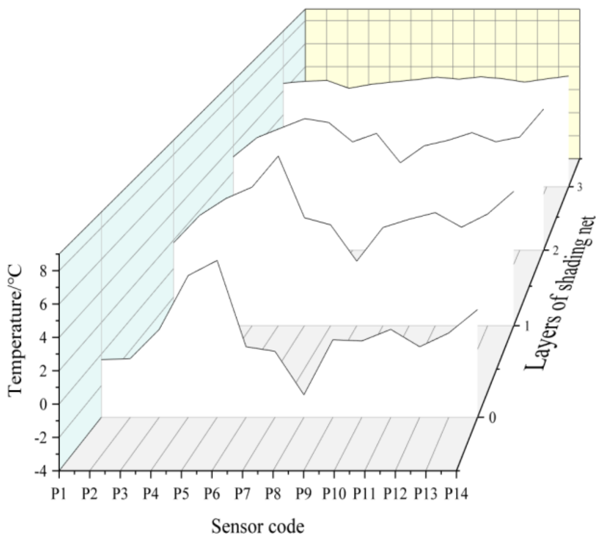
$$\Delta T_i = T_i - T_{o(n0-n1)} \quad (3)$$

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

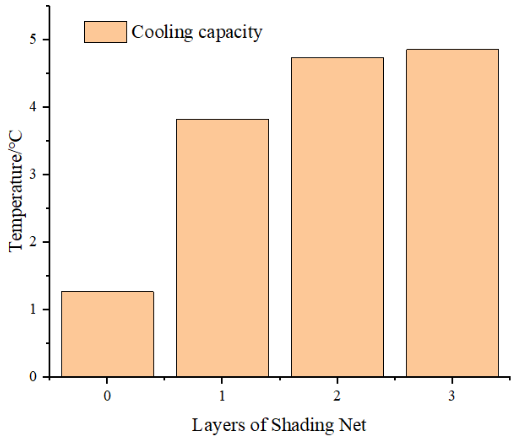
Table 6. Algorithm Parameter List

Parameters	T_i	
Meaning	The average temperature value is measured by a specific sensor multiple times.	
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 at 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

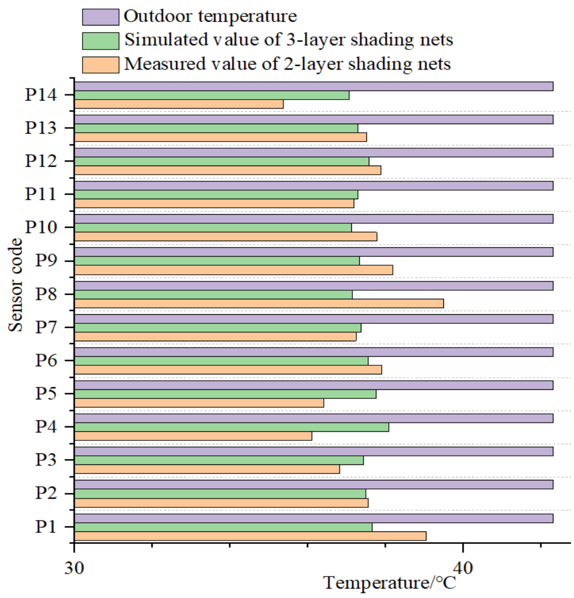


(b) Cooling capacity comparison

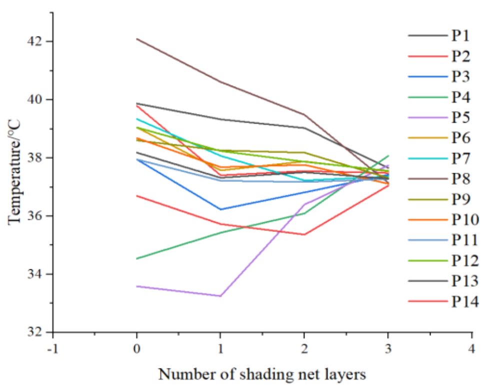
Fig. 8. Cooling Capacity of layers of shading net

The cooling capacity values of zero-layer, one-layer, two-layer, and three-layer shading nets were 1.27℃, 3.83℃, 4.74℃, and 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 decreases. Research from northern Italy supports similar conclusions (Santolini et al., 2022).

5.2 Uniformity



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



(b) Sensor values of each point

Fig. 9. Shading net layers are essential for maintaining temperature uniformity, preventing plant diseases, pests, and uneven growth.

Using simulation data, using Equation (2), $n0$=1, $n1$=9, i=1, 2, 3...14. Temperature distributions under two and three-layer shading nets were compared in Fig. 9. The three-layer configuration achieved lower temperatures and better uniformity. The maximum temperature under two-layer shading nets was 39.5°C, under one-layer shading, it was 40.6℃and the zero-layer shading, it was 42.1 ℃ °C, 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 the mean values of measuring points P1-P14 (°C)	4.67	3.18	1.19	0.08

6.0 Conclusion& Recommendations

After incorporating 45° side windows, there was no significant improvement in airflow within the greenhouse. However, the introduction of 90° side windows substantially enhanced airflow. The effectiveness of shading nets in cooling increases with the number of layers; nevertheless, the incremental cooling capacity from each additional layer diminishes as more layers are added. The cooling capacity values for zero-layer, one-layer, two-layer, and three-layer shading nets were measured at 1.27°C, 3.83°C, 4.74°C, and 4.86°C, respectively. The three-layer shading nets kept the maximum temperatures of the crop area below 38°C during the typical summer weather of the Yangtze River Delta.

Moreover, multi-layer shading nets improved the uniformity of temperature distribution, reducing the variance from 4.67°C (with zero layers) to 0.08°C (with three layers). In terms of design strategies for summer greenhouses, it is recommended that greenhouses in the Yangtze River Delta include side windows on all four walls to accommodate weak winds during the summer. Larger openings, at a 90° angle, can provide significant ventilation benefits. In high-radiation weather, utilizing three-layer shading nets can effectively decrease internal temperatures while allowing sufficient light for plant growth. Using multi-layer shading nets lowers the air temperature in greenhouses and improves the uniformity of temperature distribution.

Future research should evaluate the long-term performance of various shading materials and window configurations under changing weather conditions, ensuring these strategies can be scaled to different agricultural regions. This study highlights the potential of passive cooling methods, such as optimized ventilation and multi-layer shading nets, to reduce greenhouse gas energy consumption. Policymakers should consider integrating these findings into guidelines that promote sustainable agricultural practices in alignment with national and regional climate action plans.

This study has several limitations. Firstly, the main conclusions are derived from simulation experiments. While these simulations have been verified, there is likely a gap between the simulation outcomes and real-world conditions. Furthermore, the research primarily focused on greenhouses in the Yangtze River Delta region, which may restrict the applicability of the findings to other areas. Additionally, certain specific environmental factors, such as variations in wind gusts and humidity effects, may have introduced biases into the study.

In future research, conducting real-world experiments to validate these simulation conditions and perform comparative analyses across multiple regions would be beneficial. To enhance the accuracy of results, validating findings with multi-season field experiments, testing alternative shading materials, and utilizing higher-resolution computational fluid dynamics (CFD) models are recommended. Furthermore, exploring adaptive smart-shading systems, integrating CFD with crop growth models, and assessing economic feasibility could broaden the research scope significantly.

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Paper Contribution to the Related Field of Study

In the Yangtze River Delta region, adding side windows to greenhouses improves ventilation, especially when opened at a 90° angle compared to 45°. Using multi-layer sunshades lowers temperatures and creates a more uniform indoor climate. These strategies can be combined for enhanced cooling.

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