Simulation Study of Greenhouse Crop Layer Environment Based on Heat and Mass Transfer

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Abstract. Greenhouse environmental control is one of the key technologies in modern facility agriculture, and accurate prediction of its environmental parameters is crucial for crop growth. This paper investigates the characteristics of heat transfer and fluid flow in greenhouse environments through numerical simulation, analyzing greenhouse conditions with and without crops. The study establishes a mathematical model based on the Navier-Stokes equations, solving temperature and velocity fields for a single-fan greenhouse using the finite difference method, and introduces the crop layer as a porous medium for comprehensive analysis incorporating Darcy's law. The results indicate that under the current fan parameter settings, the environmental parameters at both 0.5m and 0.1m heights within the crop layer fail to meet optimal growth requirements, with temperature distribution unable to maintain within the ideal range of 23-26℃ and wind velocity failing to achieve the recommended range of 0.3-1m/s. These findings provide a theoretical basis for optimizing greenhouse ventilation system design and improving crop growth conditions.

Keywords: Greenhouse environment, Heat and mass transfer, porous media, Numerical simulation.

1. Introduction

With the rapid development of modern agriculture, greenhouse cultivation has become an essential approach to ensure stable crop production [1-3]. The regulation of the greenhouse internal environment directly affects crop growth conditions, where temperature distribution and airflow organization are key factors determining greenhouse environmental quality [4, 5]. However, due to the complexity of heat transfer and mass transport within greenhouses, especially in the crop layer characterized as a porous medium environment, accurate prediction and optimization of environmental parameters still face significant challenges [6, 7]. Traditional greenhouse environment studies often oversimplify the crop layer, making it difficult to truly reflect the interaction between crops and their environment. This severely constrains the accuracy and effectiveness of greenhouse environmental control [8, 9].

Based on heat and mass transfer theory, this study models the crop layer as a porous medium and conducts numerical simulations of the greenhouse environment using computational fluid dynamics methods. The research comprehensively considers multiple factors including convective heat exchange, thermal conduction, and physiological activities of the crop layer, establishing a mathematical model incorporating the Navier-Stokes equations and Darcy's law. This study not only helps to deeply understand the environmental characteristics of the greenhouse crop layer but also provides a theoretical foundation for optimizing greenhouse environmental control strategies, holding significant theoretical and practical implications for improving the efficiency of facility agriculture production.

2. Numerical Simulation and CFD Analysis of Greenhouse Environment

The data in this paper originates from http://www.apmcm.org. In establishing the greenhouse model under no-crop conditions, the structure essentially functions as a closed regular container. Several key factors require consideration in this initial phase. The greenhouse environment simultaneously experiences both convection and conduction for temperature and heat transfer distribution, wherein heat conduction equations are employed to simulate the impact of fan-generated airflow. Regarding fluid dynamics, the model incorporates the fundamental Navier-Stokes Equations to characterize various fluid movements within the space. For boundary conditions, the greenhouse's glass shell and the lower crop area are designated as boundaries, where heat exchange occurs through both convection and conduction processes.

With the fan established as the velocity vector inlet and considering the aforementioned aspects, the heat transfer model is simulated accordingly.

$$\nabla \bullet (D\nabla T) + \rho C_P (\mathrm{u} \bullet \nabla) T = Q \tag{1}$$

In the model, temperature (T), thermal conductivity (D), specific heat capacity (Cp), and material density (P) represent the primary thermal parameters. The aerodynamic model is established based on these fundamental parameters.

$$\rho(\mathrm{u} \bullet \nabla)\mathrm{u} = -\nabla \mathrm{p} + \mu \nabla^2 \mathrm{u} \tag{2}$$

In the model, the velocity of the fluid (U) and dynamic viscosity of the fluid (μ) serve as key parameters. The boundary conditions specify a fan velocity of 2 m/s and an internal temperature of 40 degrees Celsius. The analysis requires the calculation of wind velocity and temperature distributions at 0.5 m altitude within these established models.

Based on the initial conditions, this study first constructs a schematic diagram as shown in Figure 1:

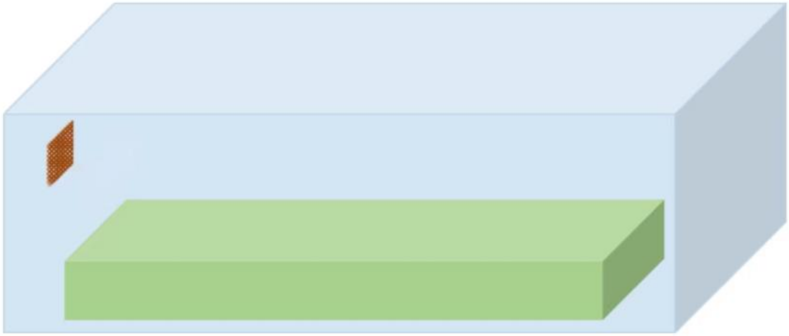

Figure 1. Layout simulation diagram of single-fan greenhouse

The analytical process proceeds as follows: Initially, greenhouse dimensions (length, width, and height) are established through variable initialization. The fan parameters are defined within two dimensions of the model framework to calculate grid point intervals and total count. For greenhouse climate CFD simulation, arrays are constructed to store temperature and velocity data. Initial conditions are set at 20 degrees Celsius for temperature and zero for velocity, with a designated fan influence zone established at the left interface.

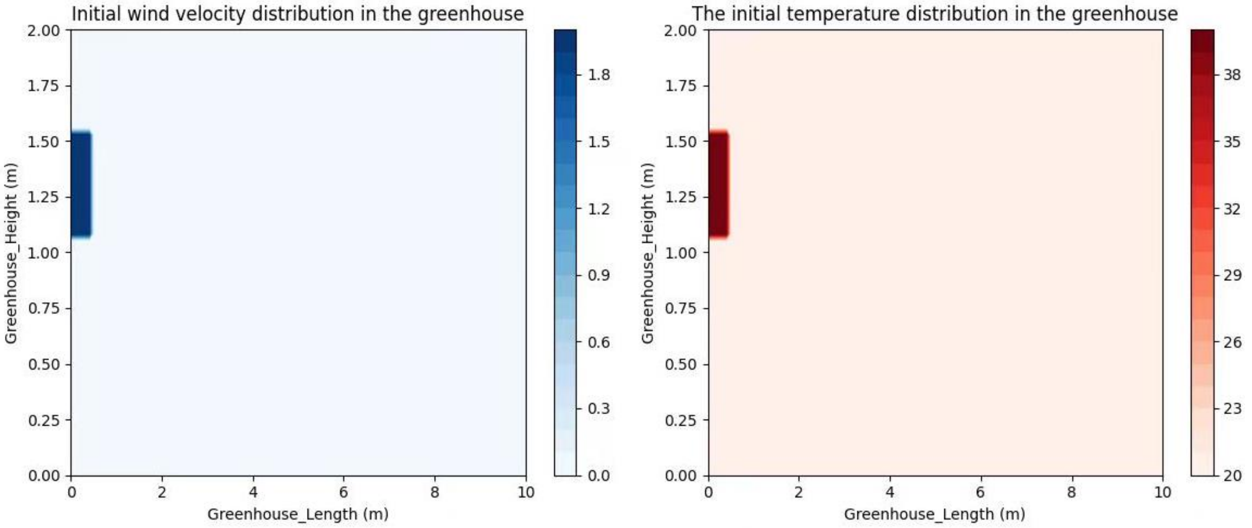

Figure 2. Initial wind velocity and temperature distribution in the greenhouse

The initial results before the iterative solution are shown in Figure 2. The temperature and wind velocity distributions at the fan are observed to be 40 degrees with a wind speed of 2 m/s, establishing the baseline for the subsequent iterative solution process.

The iterative solution process for steady-state temperature and velocity distributions employs finite difference methods. For both grid point sets, the simulation values and associated visualizations are derived through code implementation using similar Laplacian second derivatives. Given the potentially extensive number of iterations required, the execution continues until either convergence between two consecutive iterations is achieved or the maximum iteration limit is reached. The simulation ultimately converges after 5,527 iterations, with the resultant data presented in the figure 3.

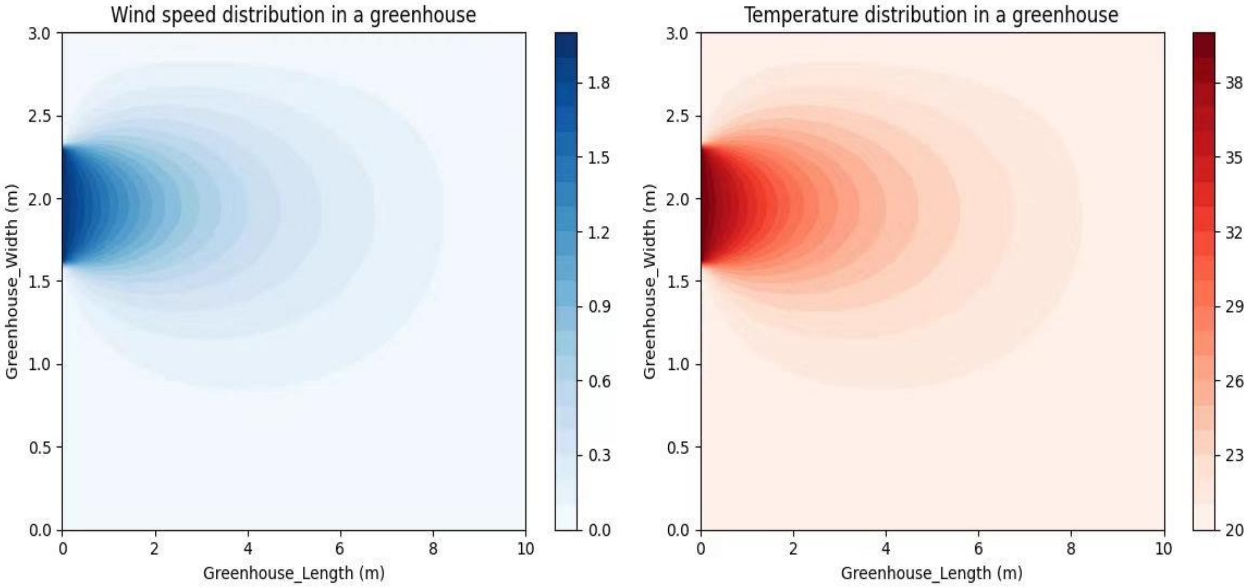

Figure 3. Wind speed and temperature distribution in the greenhouse

Through analysis of the simulation results, a comprehensive visualization map has been generated, displaying both wind velocity and temperature distributions at 0.5 m height within the greenhouse. These final distribution patterns are subsequently rendered in three-dimensional visualization to provide a more intuitive representation of the spatial variations. As shown in figure 4.

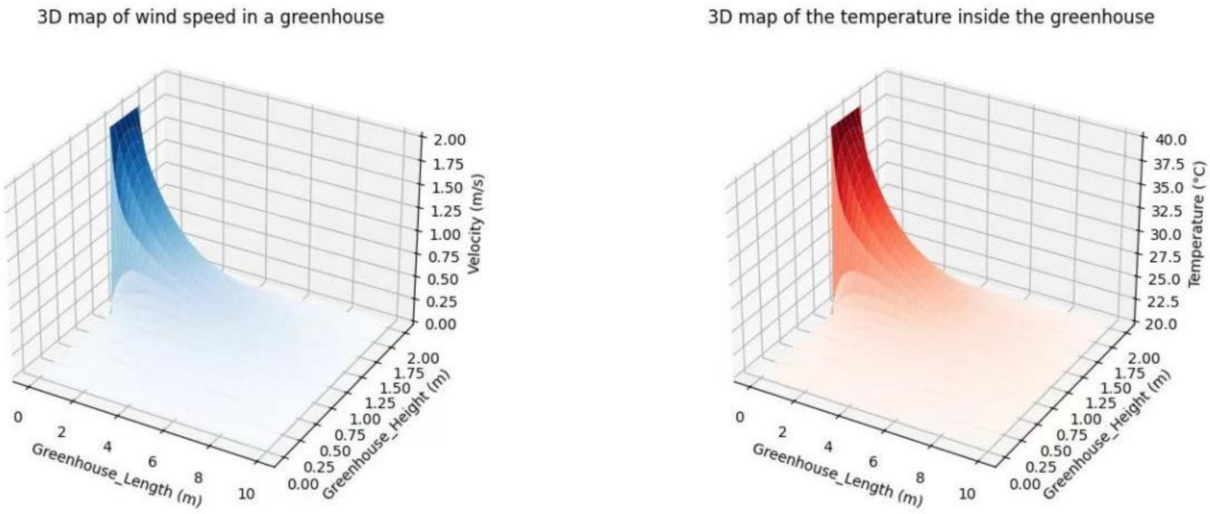

Figure 4. 3D map of wind speed and temperature in the greenhouse

3. Numerical Simulation of Greenhouse Environment Under Porous Media Conditions

The model is further refined by incorporating crops as porous media, enabling the analysis of temperature and wind velocity distributions under these new conditions. The introduction of porous media necessitates modifications to the previous hydrodynamic characteristics and heat transfer patterns, with Darcy's law implemented to characterize these effects. The modifications encompass a revision of the heat conduction model to accommodate the altered distribution patterns resulting from crop introduction, and the establishment of a new interior distribution framework where the space is partitioned into two distinct regions: an open upper section and a media-occupied lower section. The influence of crops on fluid flow and heat exchange mechanisms is characterized through mathematical equations, beginning with the heat conduction equation.

$$\nabla \bullet \left(D\nabla T\right) + \rho C_{\mathrm{p}} \mathrm{u} \bullet \nabla T = Q_{\mathrm{m}} \tag{3}$$

Temperature is denoted as T, thermal conductivity as D, and velocity as U, while Qm represents the energy generated through physiological activities within the crop layer. The fluid flow through the porous media is characterized by Darcy's Law [10].

$$\mu \frac{\mathrm{u}}{L_{\mathrm{m}}} + \nabla \mathrm{p} = \rho g \tag{4}$$

The gravitational acceleration is denoted as g, medium permeability as Lm, and the velocity of fluid flowing through the medium as μ. In practical computations, these equations are applied across varying heights of the medium layer to simulate the spatial distributions of wind velocity and temperature.

After incorporating additional initial parameters and modifying the previous heat transfer model and boundary interface configurations, the iterative process yielded new temperature and wind velocity distribution results, as illustrated in figure 5.

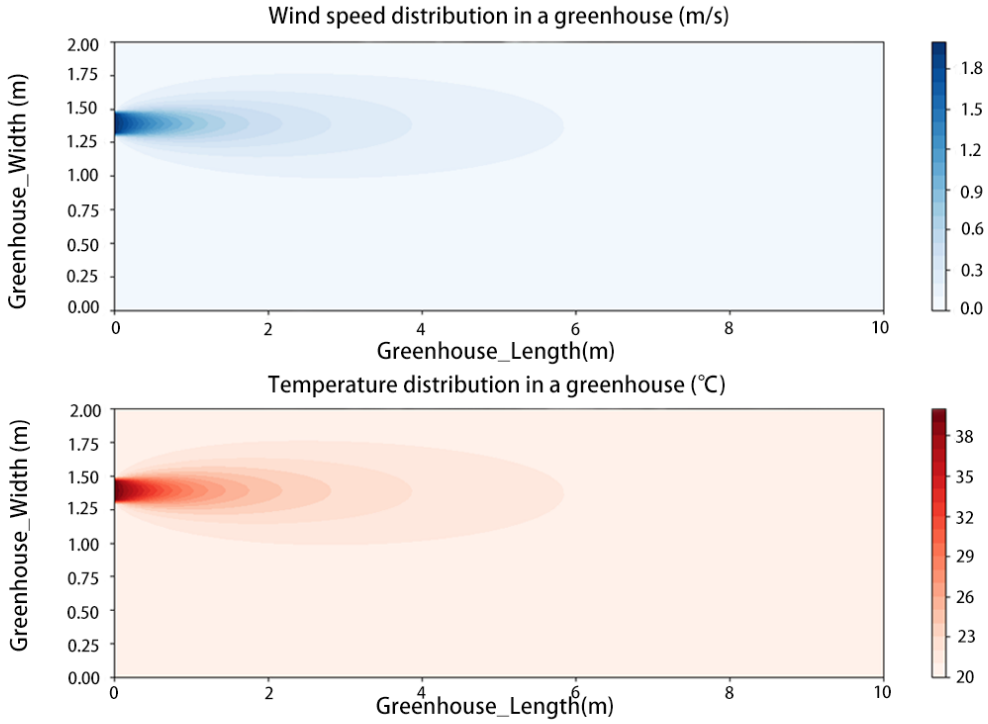

Figure 5. Wind speed and temperature in the greenhouse

At a height of 0.5 m, designated as the first critical point, the analysis aims to synthesize findings by correlating data from this location with the second critical point. As shown in figure 6.

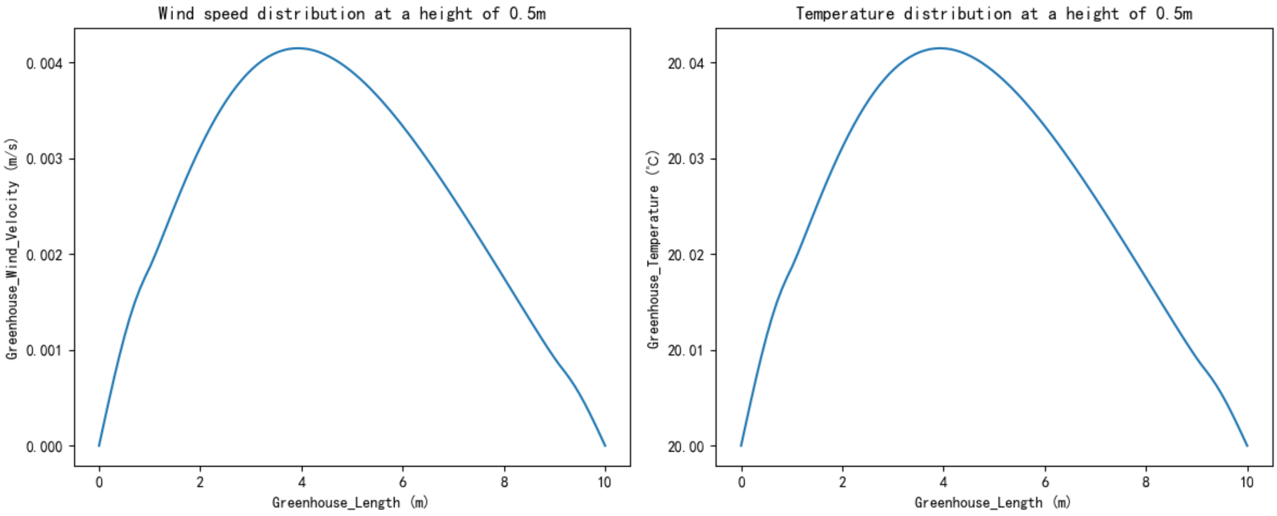

Figure 6. Wind speed and temperature distribution at a height of 0.5m

Analysis of the data reveals that at 0.5 m height, both temperature and wind velocity parameters fall outside optimal ranges. The temperature distribution fails to maintain within the desired 23-26 degrees range, while the wind velocity does not achieve the recommended 0.3-1 m/s range. Further investigation indicates that this deviation stems from rapid parameter degradation with decreasing height, making it particularly challenging to achieve suitable conditions at lower elevations.

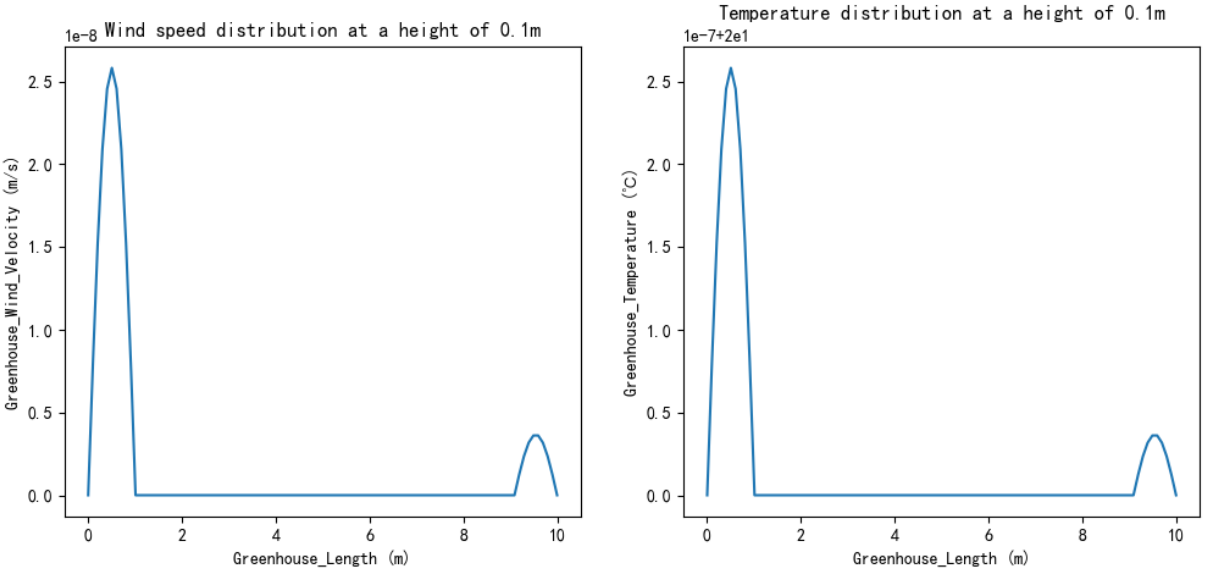

Figure 7. Wind speed and temperature distribution at a height of 0. 1m

As shown in figure 7. Evidently, at 0.1 m height, suitable environmental conditions remain unattainable. Analysis through both calculations demonstrates that the initial fan parameter settings are insufficient to sustain proper crop growth conditions.

4. Conclusion

The numerical simulation analysis in this study reveals that under conditions where the crop layer is treated as a porous medium, the greenhouse internal environment exhibits distinct vertical stratification characteristics. The simulation results uncover a significant phenomenon: greenhouse environmental parameters demonstrate a marked height-dependent attenuation effect, posing severe challenges for environmental control in critical crop growth zones. Specifically, even with fan inlet velocities reaching 2m/s, temperature, and wind velocity distributions at 0.5m height deviate from optimal crop growth ranges, with these deviations becoming more pronounced at 0.1m height. In-depth analysis indicates that this phenomenon primarily stems from the crop layer's flow resistance and heat transfer attenuation effects, making it difficult for conventional single-fan ventilation systems to maintain uniform environmental parameter distribution in the vertical direction. This finding challenges traditional greenhouse ventilation system design concepts, suggesting that when designing greenhouse environmental control systems, special attention should be paid to environmental parameter variations at different crop layer heights, considering layered or composite ventilation schemes to improve environmental uniformity.

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