Modeling Climatic Parameters affecting a Greenhouse Irrigation System

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ABSTRACT

Enclosed greenhouses are essential for controlled-environment agriculture, as they provide optimal growing conditions while shielding crops from external influences. Computational Fluid Dynamics (CFD) modeling enables the precise simulation of air circulation, temperature, and humidity distribution,

allowing for improved greenhouse climate management. This study employed CFD simulations to analyze the distribution of climatic parameters under various environmental conditions, offering insights into airflow dynamics and thermal performance. The findings demonstrate that the proposed greenhouse design improves the uniformity of temperature, humidity, and air speed, optimizing environmental conditions for crop growth. This study quantified the temperature and humidity gradients, airflow velocity, and pressure variations to provide actionable data for enhanced climate control. The experimental validation confirmed the reliability of the CFD model, aligning well with literature and real-world measurements. This research advances CFD modeling in greenhouse environments by integrating novel design elements that enhance sustainability and efficiency. It also underscores the role of CFD in developing next-generation greenhouse systems with direct implications for sustainable farming and precision climate management.

Keywords-enclosed greenhouse; CFD modeling; climate control; airflow dynamics; sustainability

I. INTRODUCTION

The use of closed greenhouses for energy and water conservation has gained significant attention in recent decades [1]. Greenhouses serve multiple functions, including the cultivation of flowers and vegetables, drying food, and utilizing solar energy for passive heating [2]. They can be categorized by their structural design, operational mechanisms, and temperature-control strategies [2, 3]. Extensive research has been conducted to improve greenhouse efficiency to increase agricultural productivity while minimizing energy consumption [4]. Greenhouse systems are designed to protect crops from adverse environmental conditions and extend the growing season, resulting in significant improvements in both yield and product quality [5, 6]. Given the importance of optimizing greenhouse environments, research has focused on accurately predicting the key environmental parameters [7-11]. However, despite these advancements, a crucial research gap remains. Existing greenhouse models often lack precision in predicting microclimate conditions, particularly in dynamically controlled closed greenhouses. Traditional experimental methods, though valuable, are time-consuming and resource-intensive, limiting their practicality for large-scale optimization. This gap underscores the need for advanced computational modeling techniques, such as CFD, to enhance the accuracy of greenhouse climate predictions and improve the overall system efficiency.

The greenhouse microclimate is governed by complex interactions involving mass and heat transfer between the internal and external environments. These interactions are highly nonlinear and interdependent, necessitating the development of robust mathematical models based on heat and mass balance equations [12, 13]. CFD modeling has emerged as a powerful tool for simulating greenhouse environments, offering insights into airflow patterns, temperature distributions, and humidity variations. Unlike traditional empirical approaches, CFD enables a detailed analysis of greenhouse conditions under diverse operational scenarios, making it a valuable tool for optimization. CFD simulations consist of three primary components: (1) a pre-processor that defines the problem geometry, grid generation, and boundary conditions; (2) a flow solver that applies numerical methods, such as the spectral method, finite difference method, finite element method, or finite volume method—to solve governing equations; and (3) a post-processor that processes and visualizes results for interpretation [14]. Previous studies explored the key factors influencing greenhouse airflow using experimental, laboratory-scale, and CFD simulation approaches [15]. However, further research is needed to refine CFD models for enhanced predictive accuracy and validation against real-world greenhouse conditions.

This study aims to address this research gap by utilizing CFD modeling to optimize closed greenhouse microclimates. The specific objectives include:

- Developing a validated CFD model for predicting temperature, humidity, and airflow patterns in a controlled greenhouse environment.
- Analyzing the impact of various design and operational parameters on greenhouse performance.
- Proposing optimization strategies to enhance energy efficiency and crop productivity based on CFD insights.

By integrating CFD-based methodologies with experimental validation, this research seeks to contribute to the development of more efficient and sustainable greenhouse systems.

II. METHODOLOGY

Greenhouses are designed in various shapes to accommodate different environmental and structural requirements. Common shapes include rectangular, square, quonset (arched), and geodesic domes. In this study, a greenhouse model was developed to simulate environmental conditions. Figure 1 presents a schematic of the physical problem and illustrates the dimensions and structure of the greenhouse. The model was created using the ANSYS Fluent 16 CFD software to simulate the airflow, temperature distribution, and humidity levels inside the greenhouse. The dimensions of the greenhouse were 21.1 m in length, 9 m in width, and 4.5 m in height, providing a realistic representation of a typical greenhouse structure for the simulation. Humid air occupied a two-dimensional enclosure with a wall heat flux that was subjected to the top wall. The vertical walls were considered impermeable and adiabatic, meaning that no mass transfer occurred through these walls, confining the humid air within the enclosure, while the walls did not conduct heat, effectively insulating the system from external thermal influences on the sides. This configuration allows focusing on the internal heat transfer processes and fluid movements resulting from the applied heat flux at the top wall, without the complicating factors of side wall heat exchange or air leakage.

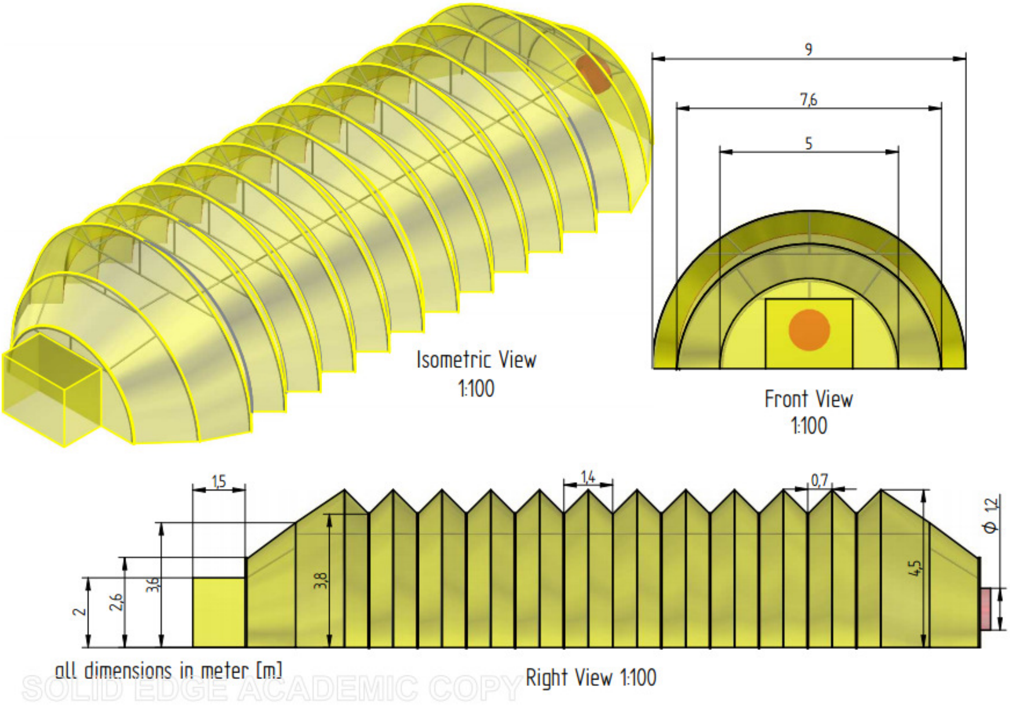


Fig. 1. Schematic representation of the greenhouse.

III. GOVERNING EQUATIONS INSIDE THE GREENHOUSE

According to [16], the continuity, momentum, energy, and concentration of the humid-air liquid equation for natural convection are the governing equations for heat and mass movement inside the greenhouse:

The continuity equation is expressed as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

The momentum equation is:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left(\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial x^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+v\left(\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial x^2}\right)+g\beta(T-T_0) \tag{3}$$

The energy equation is given by:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

The concentration equation is given by:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right) \tag{5}$$

Where P is the fluid pressure, α is the thermal expansion coefficient, D is the mass diffusivity, and u is the kinematic viscosity. Using the CFD code, the proposed open cavity's governing equations for mass and heat transfer were all solved in the turbulent domain. It was decided to solve the concentration and momentum equations using a second-order upwind technique.

The airflow in the greenhouse is a low-speed flow field at room temperature and can be regarded as an incompressible fluid [17].

IV. LIMITATIONS

The boundary conditions of the problem are:

$$X=0;0<Y<H \text{ and } X=L;0<Y<H$$

$$\mathrm{U}=\mathrm{V}=0,\mathrm{C}=0,\mathrm{dt/dy}=0$$

$$0<X<L,Y=0$$

$$\mathrm{U}=\mathrm{V}=0,\mathrm{dC/dx}=0,\mathrm{T}=\mathrm{T}_0$$

$$0<X<L,Y=H$$

$$\mathrm{U}=\mathrm{V}=0,\mathrm{dC/dx}=0,\mathrm{T}=\mathrm{T}_{\mathrm{OUT}}$$

Dimensionless variables are assigned to the following:

$$\mathrm{T}^*=(\mathrm{T}-\mathrm{T}_\mathrm{C})/(\mathrm{T}_\mathrm{H}-\mathrm{T}_\mathrm{C}),\mathrm{X}^*=\mathrm{x/L},\mathrm{Y}^*=\mathrm{y/L} \tag{8}$$

The density of a variable parameter is expressed by the Probability Density Function (PDF) (%), which provides its potential value at a given location as a function of the sum of the probabilities in a specific medium or cavity. The boundary conditions are listed in Table I.

TABLE I. BOUNDARY CONDITIONS

	Temperature (K)	**Roughness constant (m)**
Bottom wall	308.4	0.5
Top wall	298.5	0.5

V. RESULTS AND DISCUSSION

A. Validation

To verify the effectiveness of CFD, an analysis was conducted for the case of heat and mass transfer in turbulence (Ra = 107 with different buoyancy ratios) of the closed square cavity. The computational results were compared with those obtained in [18] with respect to the flow visualization for isotherms, streamlines, and iso-concentrations, as can be seen in Figure 2 [19].

- The mesh optimization was checked until it was found that it did not significantly affect the results.
- The results were then compared with the data for all elements.

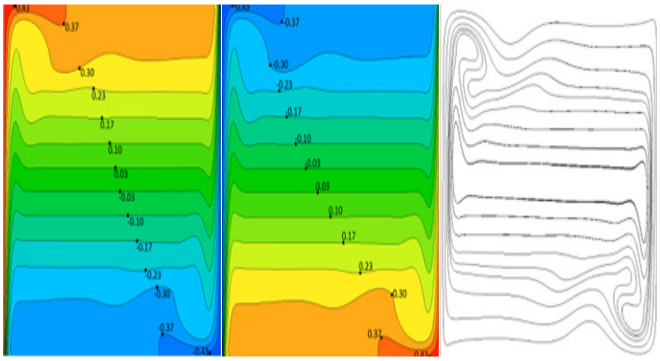


Fig. 2. Computational results of isotherms, streamlines, and iso-concentrations.

B. Computational Fluid Dynamics Solver and Assumptions

- The use of ANSYS Fluent 16 suggests a reliance on the Finite Volume Method (FVM) for discretization.
- A second-order upwind scheme was used for better accuracy in solving the transport equations.
- The convergence criterion of 10^{-7} RMS residuals indicated a high-accuracy solution.

C. Simulation Results

It can be observed that temperature exhibits a general upward or downward trend, whereas humidity follows an inverse trend relative to temperature, as demonstrated in Figures 3-5.

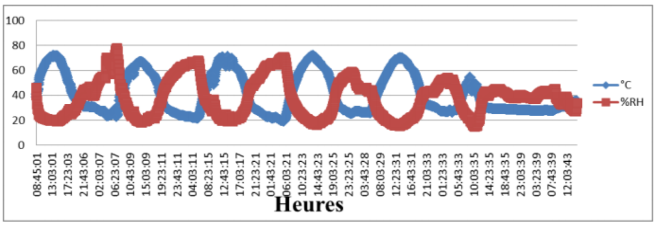


Fig. 3. Experimental results of the temperature and relative humidity of sensor 01 (h=0.25 m).

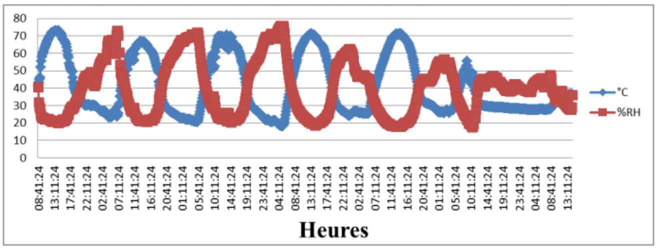


Fig. 4. Experimental results of temperature and relative humidity of sensor 02 (h=2.4 m).

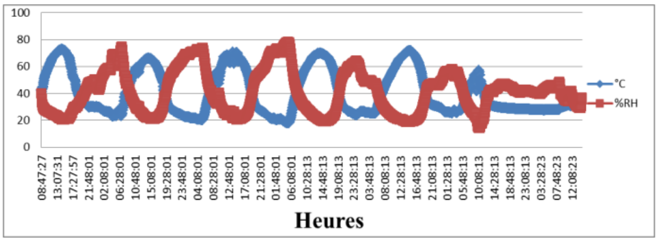


Fig. 5. Experimental results of temperature and relative humidity of sensor 03 (h=3.75 m).

TABLE II. CORRELATION ANALYSIS OF SENSORS AND EL OUTAYA WEATHER STATION

	Sensor 01		**Sensor 02**		**Sensor 03**		**St. météo**	
	T(°C)	**HR (%)**	**T (°C)**	**HR (%)**	**T (°C)**	**HR (%)**	**T (°C)**	**HR (%)**
T (°C)	1		1		1		1	
HR (%)	-0.8748	1	-0.8734	1	-0.8769	1	-0.6761	1

It is evident that temperature generally shows an upward or downward trend, whereas humidity exhibits the opposite pattern, as depicted in Table II. The temperature rises during the day and falls at night, whereas the humidity increases at night owing to condensation. The measurements showed regular peaks in humidity in the evening.

The correlation coefficient is negative ($r < 0$), indicating an inverse relationship between the two variables (temperature and relative humidity). In other words, an increase in one variable is accompanied by a decrease in the other, and vice versa.

D. Temperature Curves as a Function of x and y Coordinates

To examine air temperature fluctuations within the greenhouse and near its walls more explicitly, Figure 6 presents the temperature variation along the X dimension (at y = 21 m) and Figure 7 the temperature curves at the center of the greenhouse (x = 4.5 m), varying the Y dimension. This approach allowed studying the behavior of the air near both the floor and roof.

The temperature distribution in an enclosed greenhouse can be influenced by various factors, including solar radiation, air circulation, and the thermal properties of the materials.

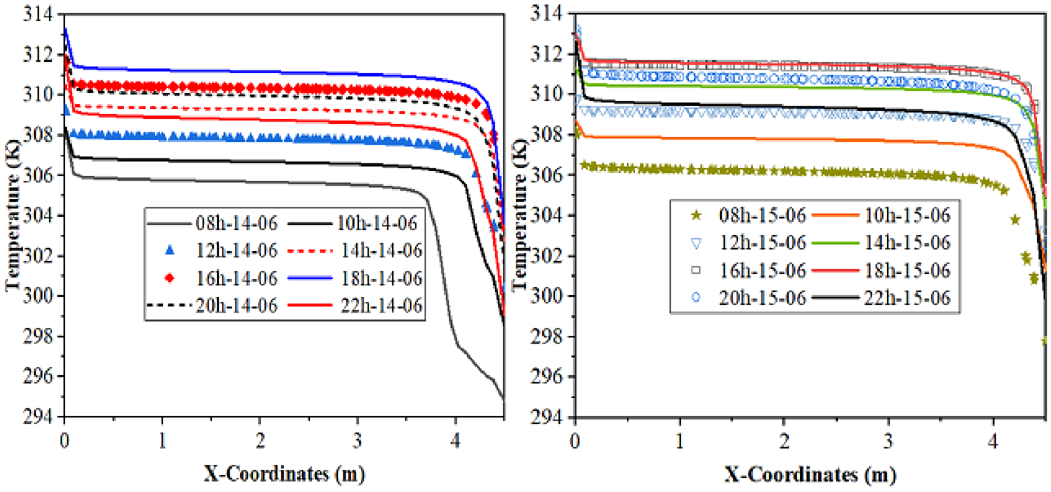


Fig. 6. Temperature as a function of the x-coordinate (m).

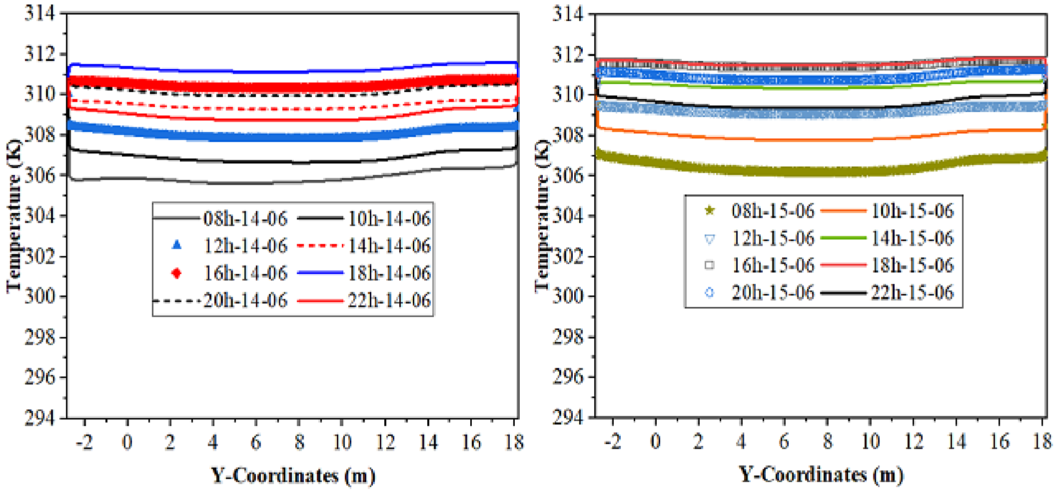


Fig. 7. Temperature as a function of the y-coordinate (m).

Figures 6 and 7 show that the temperatures were generally higher near the walls exposed to the sun, reaching up to 313 K. As one moves away from the walls, the temperature can drop to approximately 298 K, particularly at the center of the greenhouse. Temperatures began to rise gradually in the morning, peaking between 2 and 4 p.m., and then started to decline, reaching their lowest values after 10 p.m. and lasting until 8 a.m., repeating this cycle daily. The heating inside the greenhouse is primarily due to the increasing intensity of the solar flux, which is absorbed by the greenhouse walls. Cooling occurs due to the evaporation of the liquid layer formed by condensation overnight and the effect of the sun's declination.

Natural convection can create temperature variations with warmer zones near the ceiling and cooler zones near the floor. Polyethylene allows light to penetrate while providing insulation, which can lead to thermal gradients depending on sunlight. The temperature curves revealed significant gradients within the greenhouse, which were influenced by sunlight, air circulation, and material properties. Understanding these variations is essential for optimizing the internal conditions.

E. Relative Humidity Curves as a Function of x and y Coordinates

Water vapor is released by the greenhouse through evaporation. The evaporation rate depends on factors, such as temperature and humidity. These processes contribute to the spatial distribution of water vapor. While rising air temperatures tend to worsen the saturation deficit, the confinement and airtightness of the greenhouse increase humidity.

As portrayed in Figures 8 and 9, the relative humidity ranged from 30% to 40% in most of the greenhouses, and from 50% to 60% at the roof level from morning to midday. The temperature decreases at night and the greenhouse roof frequently experiences condensation. In the afternoon, the increase in air temperature can cause a significant drop in the relative humidity, which can range from 20% to 30% at the roof level, from 10% to 20% in the rest of the greenhouse, and eventually drop to zero at the extremes. This cycle is repeated daily.

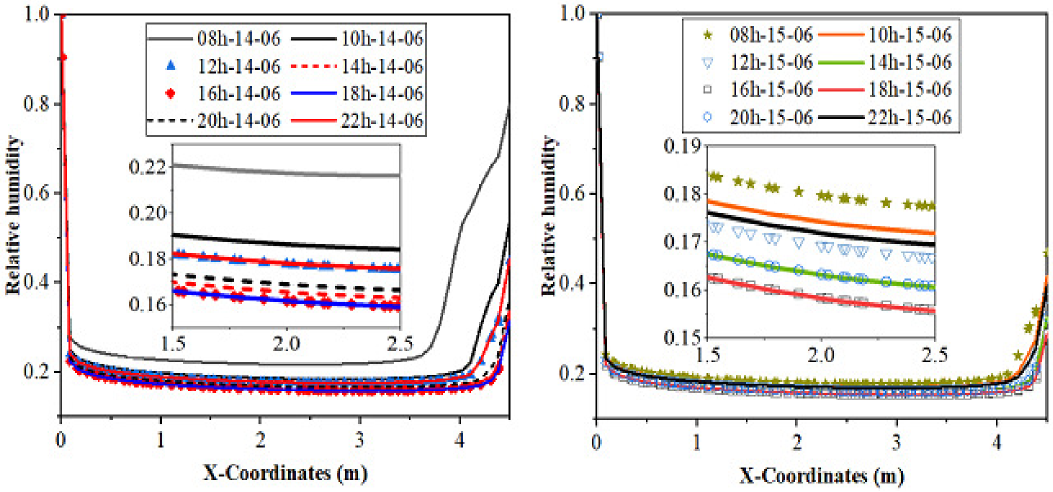


Fig. 8. Relative humidity as a function of the x-coordinate (m).

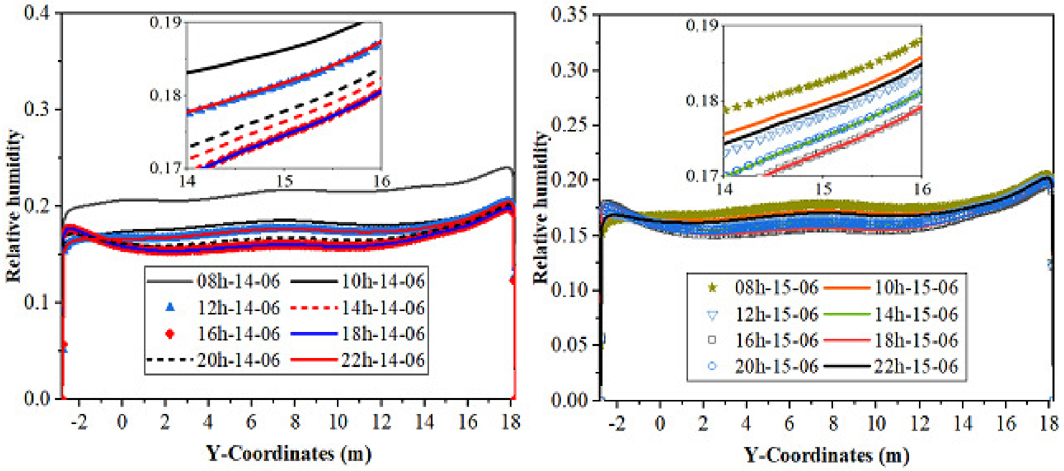


Fig. 9. Relative humidity as a function of the y-coordinate (m).

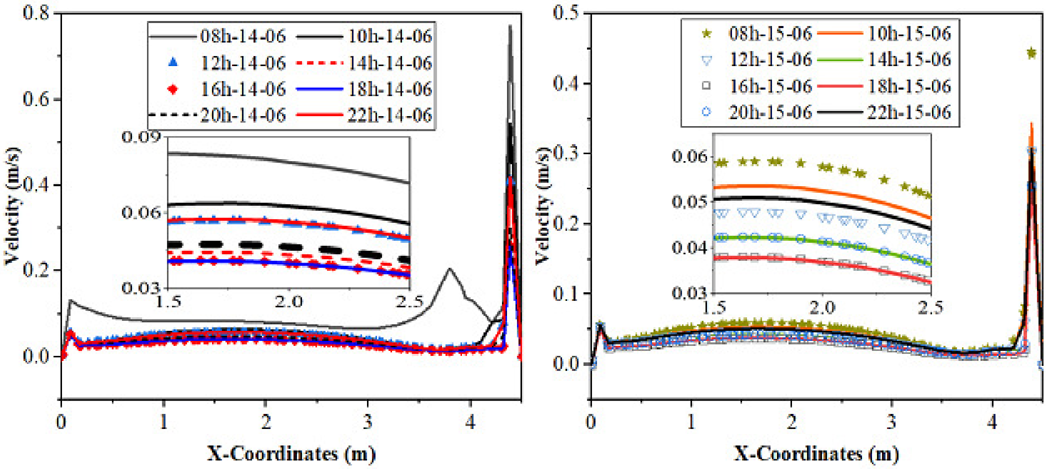
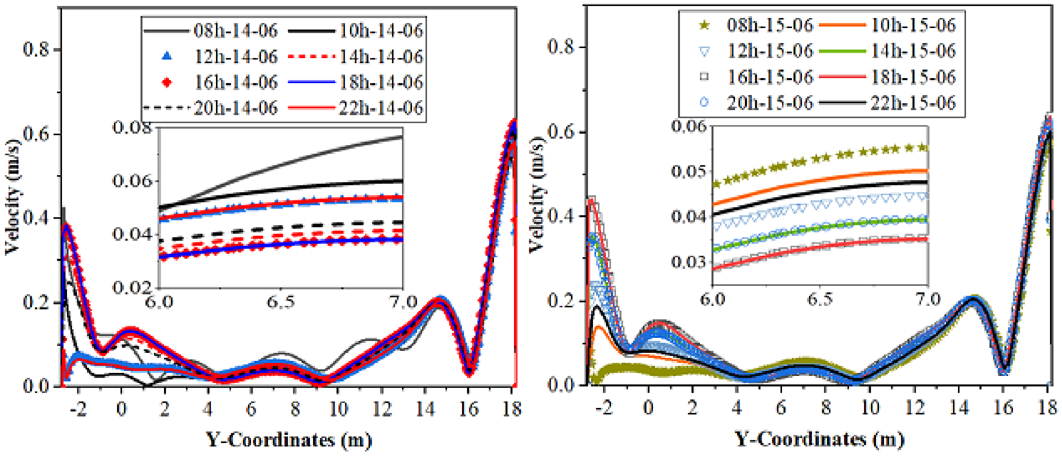


Fig. 10. Air speed as a function of x-coordinates (m).



Air speed as a function of y-coordinates (m).

F. *Air Speed Curves as a Function of x and y Coordinates*

The air speed is summarized in Figures 10 and 11 as follows: during the day and night, the maximum air speed distribution near the ground was approximately 0.73 m/s, while the minimum air speed decreased to zero and was influenced by factors such as greenhouse design (as in our greenhouse). The presence of obstructions and temperature variations inside the greenhouse can induce natural convection currents that can affect the speed distribution [20]. Temperature variations due to solar radiation can lead to differences in air density and induce natural convection currents, thereby influencing air speed in the greenhouse.

The air speed inside the greenhouse was almost always the same at all times, from day to night. However, as you move towards the center of the greenhouse, the air speed almost cancels out.

VI. CONCLUSIONS

Modeling and simulating the climatic parameters of an enclosed greenhouse using Computational Fluid Dynamics (CFD) represents a significant advance in modern agriculture. This study explored the complex interactions between different climatic parameters, such as temperature, humidity, pressure, and air velocity in a greenhouse. The ability to simulate these interactions in a controlled environment paves the way for more precise and sustainable agriculture capable of meeting the challenges posed by the climate change and a growing world population.

One of the major contributions of this study lies in the development of a robust CFD model that integrates thermal, hydric, and lighting aspects. Using advanced simulations, the current work was able to visualize air flows, analyze thermal exchanges, and optimize the humidity within the greenhouse. These results enable improving the greenhouse management practices and anticipate crop needs in relation to external climatic variations.

Furthermore, this study highlights the importance of a multidisciplinary approach. By combining agronomy, engineering, and computer science, a holistic understanding of the greenhouse cropping systems has been developed. This synergy between disciplines is essential for addressing the complex challenges agriculture faces. It also paves the way for future research that could explore even more innovative solutions, such as the integration of intelligent sensors for the real-time monitoring of climatic conditions.

However, it is crucial to recognize the limitations of the present study. Although the proposed CFD model has been validated in specific scenarios, it still requires further adjustments and testing to be adapted to a variety of crops and environmental conditions. In addition, the practical implementation of these models in real agricultural systems could encounter challenges related to the initial costs and training required for farmers.

This study revealed significant temperature gradients within the greenhouse, influenced by sunlight, air circulation, and material properties, demonstrating their relevance in improving greenhouse applications. These findings provide valuable insights into the temperature, humidity, and air velocity inside closed greenhouses, which could enhance efficiency, sustainability, and productivity in controlled agricultural environments.

However, certain limitations exist, including experimental constraints, data limitations, and modeling challenges. Addressing these issues in future research could lead to more robust conclusions and broader applications. Further investigations should focus on additional variables to consider, advanced methodologies, such as AI, and practical field applications.

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