Studies in Engineering and Exact Sciences
ISSN: 2764-0981

A computational fluid dynamics (CFD) modeling in a new design of closed greenhouse

Modelagem de dinâmica de fluidos computacional (CFD) em um novo projeto de estufa fechada

DOI: 10.54021/seesv5n1-037

Recebimento dos originais: 19/02/2024
Aceitação para publicação: 08/03/2024

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ABSTRACT
Closed greenhouses are crucial buildings for agriculture in controlled environments because they offer the best growing conditions for crops and shield them from outside influences. Researchers can now better optimize design parameters for increased crop output and energy efficiency by simulating airflow and temperature distribution inside closed greenhouses with the use of computational fluid dynamics (CFD) modeling. We examine the temperature distribution and airflow patterns inside the greenhouse under various environmental conditions using CFD simulations. Our findings show that, in comparison to traditional greenhouse constructions, the novel design greatly improves temperature uniformity and lowers energy use. Moreover, the greenhouse's thermal insulation design minimizes heat loss during the colder months, enhancing energy efficiency overall. We offer important insights into how design changes affect airflow dynamics and thermal performance in enclosed greenhouses by utilizing CFD modeling. Our research highlights how effective CFD modeling can be in maximizing crop yields and achieving sustainable agricultural practices through greenhouse design optimization. The integration of novel design components for improved energy efficiency and crop yield is a feasible outcome of this research, which advances the field of closed greenhouse technology overall. The research highlights the value of using CFD modeling to inform the design of next-generation closed greenhouse systems and has important ramifications for sustainable agriculture methods and greenhouse management techniques. The goals were to assess how well various heating/cooling systems maintained the ideal environmental conditions for plant growth. A verified CFD model was used to run the simulations, which took into account a number of variables including the shape of the greenhouse, the outside environment, and the interior heat sources. Important discoveries include understanding temperature gradients, airflow patterns, and possible areas for environmental management enhancement are presented in this paper. Results showed that the species mass transfer of vapor (H2o) will vary over time.

Keywords: greenhouse, CFD modeling, humidity, mass transfer and heat transfer.

RESUMO
As estufas fechadas são edifícios essenciais para a agricultura em ambientes controlados, pois oferecem as melhores condições de cultivo para as plantações e as protegem de influências externas. Agora, os pesquisadores podem otimizar melhor os parâmetros de projeto para aumentar a produção das culturas e a eficiência energética, simulando o fluxo de ar e a distribuição de temperatura dentro das estufas fechadas com o uso da modelagem de dinâmica de fluidos computacional (CFD). Examinamos a distribuição de temperatura e os padrões de fluxo de ar dentro da estufa sob várias condições ambientais usando simulações de CFD. Nossos resultados mostram que, em comparação com as construções tradicionais de estufas, o novo projeto melhora muito a uniformidade da temperatura e reduz o uso de energia. Além disso, o projeto de isolamento térmico da estufa minimiza a perda de calor durante os meses mais frios, aumentando a eficiência energética em geral. Oferecemos percepções importantes sobre como as alterações no projeto afetam a dinâmica do fluxo de ar e o desempenho térmico em estufas fechadas, utilizando a modelagem CFD. Nossa pesquisa destaca como a modelagem CFD pode ser eficaz para maximizar o rendimento das colheitas e alcançar práticas agrícolas sustentáveis por meio da otimização do

projeto da estufa. A integração de novos componentes de projeto para melhorar a eficiência energética e o rendimento da colheita é um resultado viável desta pesquisa, que avança o campo da tecnologia de estufas fechadas em geral. A pesquisa destaca o valor do uso da modelagem CFD para informar o projeto de sistemas de estufas fechadas de última geração.

Palavras-chave: estufa, modelagem CFD, umidade, transferência de massa e transferência de calor.

1 INTRODUCTION

In recent decades, the idea of using closed greenhouses was developed to save water and energy [1]. The main applications for which greenhouses are used are flower and vegetable production, product drying and solar energy capture for heating a passive building [2]. Greenhouses can be categorized according to different characteristics, either by their construction features, the mode of operation, or by the temperatures maintained in them [2-3]. A number of research projects have been carried out on closed greenhouses with the dual aim of saving energy and improving crop production [4]. Greenhouse systems were developed to protect crops from adverse environmental conditions, thus, extending the growing season. Improved growing conditions have considerably increased product quality and production [5-6]. Researches that predict environmental factors has been steadily conducted in order to better control greenhouse environments [7-8-9-10-11]. The introduction of closed greenhouse technology raised the question of what combination of climatic conditions should be considered optimal for crop growth and maximum possible production [12].

The complex mechanisms involving heat and mass transfer processes that take place inside the greenhouse as well as actions that occur between the inside of the greenhouse and its surroundings combine to create the microclimate inside. These processes are intricately linked and very non-linear. It is necessary to create equations for the mass and heat balances of the air inside the greenhouse in order to create a mathematical model of these processes [13-14].

Cooling the interior climate is a major problem for greenhouse production and development. High summertime temperatures have a direct effect on the productivity of greenhouse crops grown all year round. When designing a greenhouse, greenhouse designers must to take into account the financial feasibility of implementing a cooling system that effectively regulates the greenhouse's microclimate concerning the weather outside [15-16-17].

When choosing the greenhouse design parameters and making management decisions in practical production, it is crucial to comprehend the effects of various parameters that influence cooling/heating demand to obtain optimal greenhouse operating conditions. This can be done through greenhouse modeling [18].

According to [19] all of the theoretical models created to forecast indoor air temperatures make the assumption that the greenhouse's temperature is constant. These methods provide a precise image of the temperature profiles and airflow field in the greenhouse, but they do not clearly map the physical values. These models do not adequately capture the extremely dynamic mechanisms in time and place that underlie the temperature fluctuations in every section of the greenhouse. Conversely, CFD modeling is thought to be an effective method for simulating the greenhouse's space- and time-dependent microclimate [20].

There are several disciplines in which computational fluid dynamics, or CFD, has been used. Air flows in rooms, towers, greenhouses, and other structures are predicted using it [21].

With the use of simulation, CFD assesses the behavior of various fluid flow patterns, heat and mass transfer, chemical processes [22-23-24-25].
CFD is used in the plant design process to create the ideal climate [26].

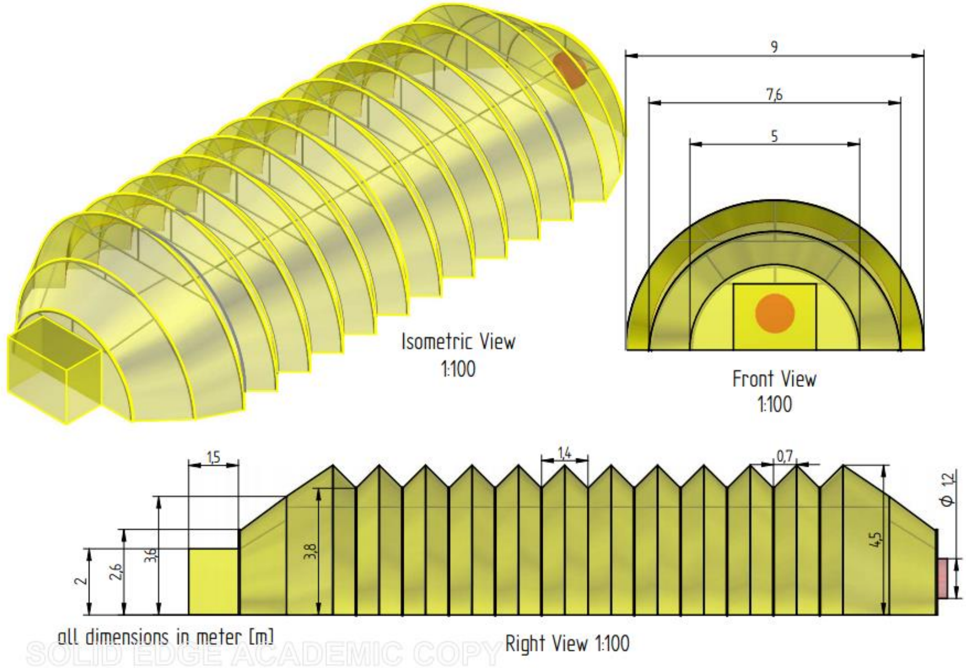
Three basic components are present in all CFD codes: (1) A pre-processor, which defines the flow parameter and the boundary conditions to the code, inputs the problem geometry and creates the grid. (2) A flow solver, which applies the specified conditions to solve the flow's governing equations. The finite difference method, the finite element method, the finite volume method, and the spectral method are the four approaches that are utilized as flow solvers. (3) A post-processor, which modifies the data and presents the findings in a readable, graphical style [27]. In [27,28] the primary variables controlling air flows within the greenhouse, concentrating on findings from field tests, lab-scale models, and CFD simulations were examined.

Assess the energy efficiency of the greenhouse design by studying factors such as heat loss through walls, roof, and ventilation openings. CFD simulations can help identify opportunities for improving insulation or optimizing heating and cooling systems to reduce energy consumption. Therefore, in this work a numerical study was carried out to simulate the performance of a new greenhouse design and optimize heating and cooling systems in details.

2 MATERIALS AND METHODS

2.1 GREENHOUSE DESIGN

Figure 1: A schematic representation of a Greenhouse



Source: Authors.

Greenhouses come in various shapes, including rectangular, square, quonset (arched), and even geodesic domes. Figure 1 depicts the physical problem under consideration schematically of the greenhouse. The greenhouse model was created in ANSYS Fluent 16 for CFD Simulation, with dimensions of 21.1 m x 9 m x 4.5 m, under of the PRIMA project funded by DGRSDT.

A humid-air occupied in two-dimensional enclosure with wall heat flux subjected to the top wall. The vertical walls are considered impermeable and adiabatic.

2.2 GOVERNING EQUATIONS GREENHOUSE

According to [29], 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:

Continuity equation:

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

Momentum equation:

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

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

Energy equation:

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

Concentration equation:

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

Where P is the fluid pressure, α is the thermal expansion coefficient, D is the mass diffusivity, and u is the kinematic viscosity.

Using a 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 calculations were simulated to reach a convergence point at 10^{-7} of the remaining root mean square values.

2.3 MODEL OF TURBULENCE

Based on the turbulent kinetic energy equations $\boldsymbol{k}$ and the rate of dissipation of turbulent kinetic energy $\boldsymbol{\varepsilon}$, [30] established a typical basic model of turbulence called $\boldsymbol{k-\varepsilon}$. Because of its reliability and steady accuracy, it is used to examine flow and heat transfer computations.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x}(\rho k u) = \frac{\partial}{\partial y}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (6)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x}(\rho \varepsilon u) = \frac{\partial}{\partial y}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}(G_k + C_{\varepsilon 3}G_b) - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad (7)$$

Where σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively, and μ_t is the eddy viscosity.

User-defined source words are S_k and S_ε. Y_M denotes the contribution of the expansion of fluctuations, $C_{\varepsilon 1}$=1.44, $C_{\varepsilon 2}$=1.92, $C_{\varepsilon 3}$=0.09, σ_k=1, σ_ε=1.3, and G_k and G_b indicate the kinetic energy generation of turbulence due to velocity gradients and buoyancy, respectively.

2.4 LIMITATIONS

The problem's boundary conditions are as follows:

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

$U = V = 0, C = 0, dt/dy = 0$

$0 < X < L, Y = 0$

$U = V = 0, dC/dx = 0, T = T_0$

$0 < X < L, Y = H$

$U = V = 0, dC/dx = 0, T = T_{OUT}$

Dimensionless variables are assigned to the following:

$$T^* = (T - T_C)/(T_H - T_C), X^* = x/L, Y^* = y/L \quad (8)$$

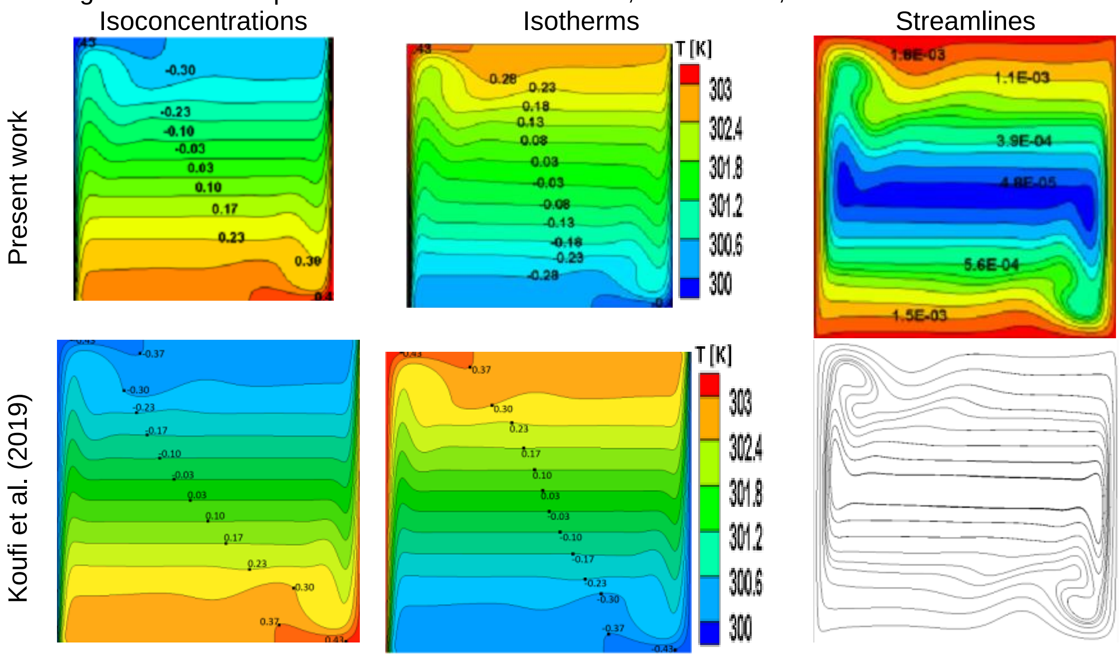
The density of a variable parameter is expressed by the Probability Density Function PDF (%), which provides its potential value at a given place as a function of the sum of the probabilities in a specific medium or cavity.

3 RESULTS AND DISCUSSION

3.1 VALIDATION

To verify the effectiveness of CFD, the analysis is conducted for the case of heat and mass transfer in turbulent (Ra = 10^7 with different buoyancy ratio) of closed square cavity. The computational results are compared with those obtained by [31] with respect to a flow visualization for isotherms, streamlines, and iso-concentrations (Figure 2).

Figure 2: The computational results of isotherms, streamlines, and iso-concentrations



Source: Authors, Koufi et al. (2019).

3.2 PRESSURE DISTRIBUTION INSIDE THE GREENHOUSE

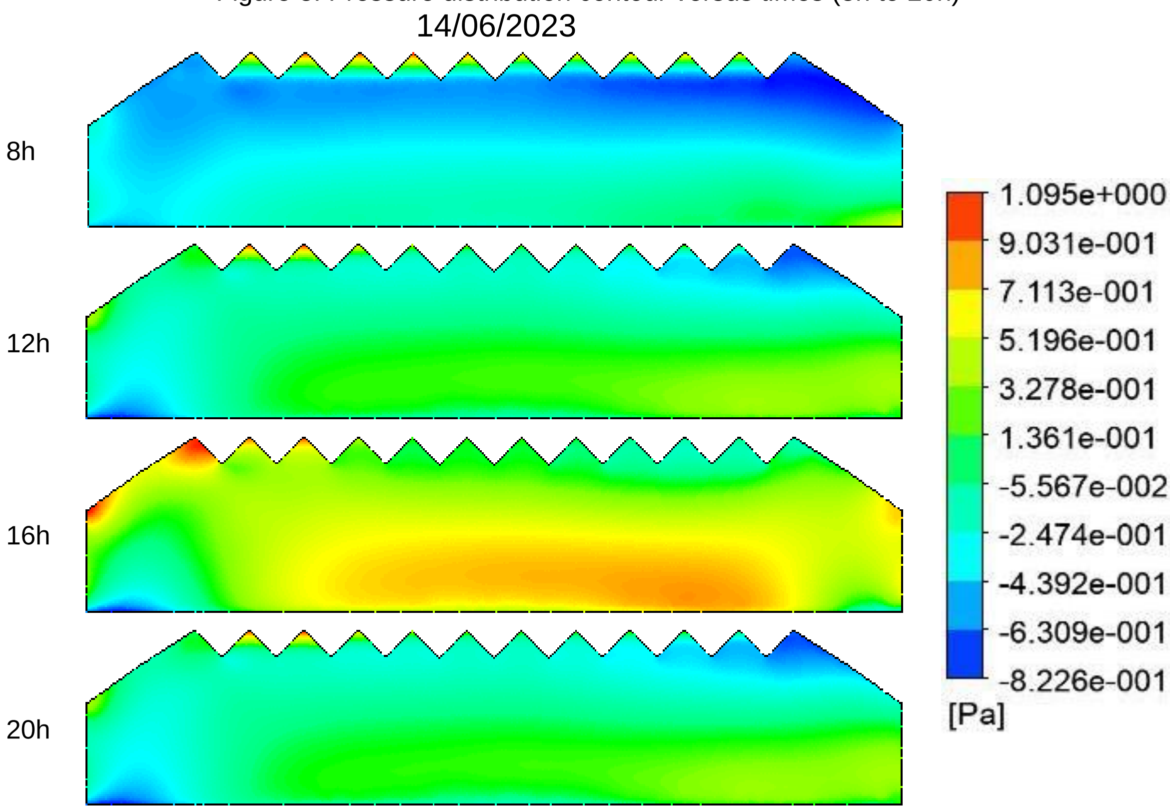
The pressure contour versus time in a closed greenhouse without cultivation and ventilation is dependent on a number of variables, such as the starting conditions, the structure of the greenhouse, and the external environmental conditions. A broad idea of how the pressure contour would change over time in this kind of situation will describe as follow:

The pressure within the greenhouse will initially be about equal to the outside pressure when it is closed. Nevertheless, as figure 3 illustrates, a closed greenhouse without ventilation will eventually undergo specific pressure variations.

When the sun is shining during the day, solar radiation may cause the temperature inside the greenhouse to start rising. The air within the greenhouse will expand as the temperature rises, increasing pressure as a result. Since there is nowhere for the expanding air to escape in a closed greenhouse without ventilation, this pressure increase may be more noticeable.

On the other hand, the temperature within the greenhouse may begin to drop at night or during the absence of direct sunlight. The greenhouse's internal pressure will drop as the air cools and contracts. Again, because there is no opening for fresh air to enter and balance the pressure, this drop in pressure may be more noticeable in a closed greenhouse without ventilation.

Figure 3: Pressure distribution contour versus times (8h to 20h)



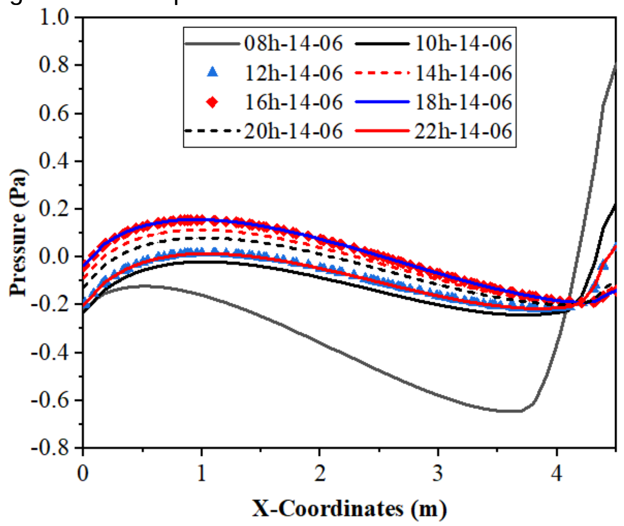
Source: Authors.

On the other hand, the temperature within the greenhouse may begin to drop at night or during the absence of direct sunlight. The greenhouse's internal pressure will drop as the air cools and contracts. Again, because there is no opening for fresh air to enter and balance the pressure, this drop in pressure may be more noticeable in a closed greenhouse without ventilation.

In a closed greenhouse, the pressure contour versus time is likely to show swings depending on temperature changes inside the greenhouse without any cultivation or ventilation. Since there won't be as many possibilities for pressure equalization with the external environment, these oscillations can be more noticeable in the absence of ventilation.

It's crucial to remember that this is an oversimplified explanation and that, as figure 4 illustrates, the real pressure variations will rely on the particular circumstances and features of the greenhouse.

Figure 4: Static pressure as a function of the middle line



Source: Authors.

3.3 VELOCITY DISTRIBUTION INSIDE THE GREENHOUSE

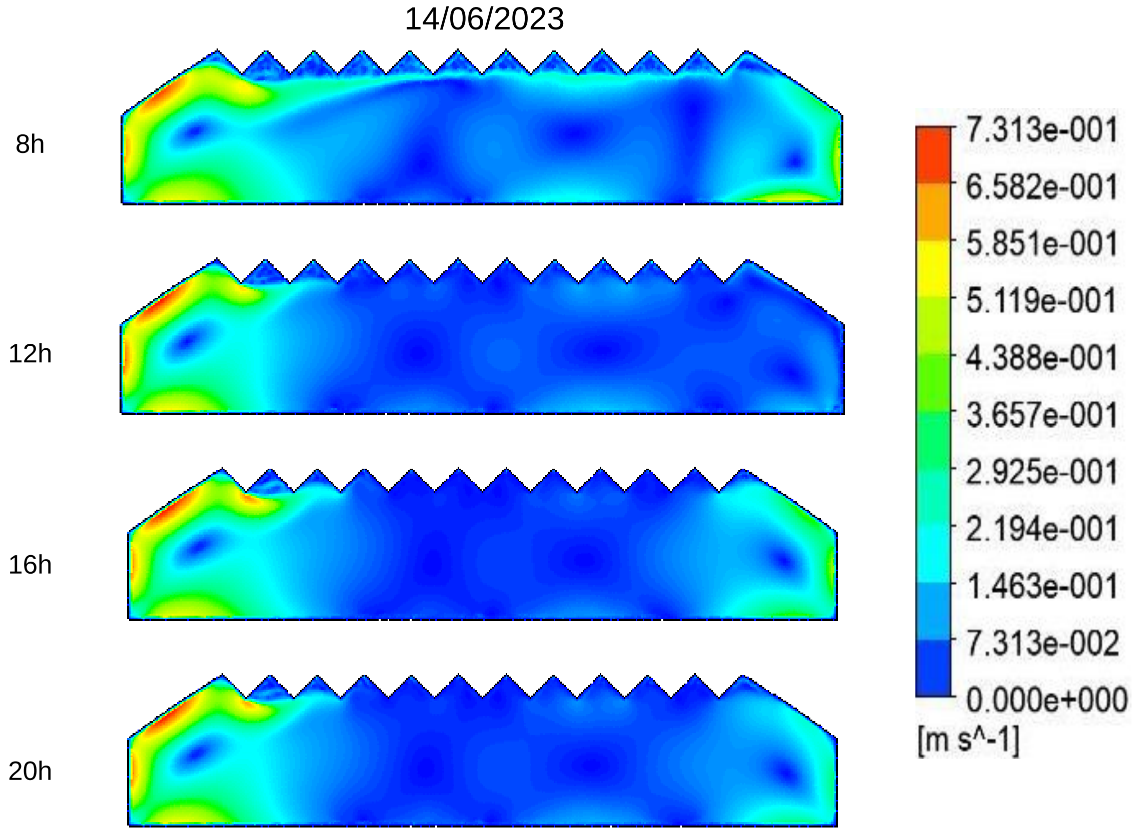
The velocity contour versus time in a closed greenhouse devoid of cultivation and ventilation would be influenced by a number of variables, including temperature variations, air pressure gradients, and the features of the greenhouse construction, as shown in figure 5. It's crucial to remember that the air movement and velocity inside the greenhouse would change greatly from a normal greenhouse environment in the absence of ventilation and cultivation.

Natural convection, the process of heat transfer through the movement of air due to temperature variations, would be the main source of air movement within the closed greenhouse in the absence of ventilation. Air currents will arise in reaction to temperature differences when the greenhouse's temperature fluctuates.

The air would first warm up more quickly after the greenhouse is closed because of heat exchange with the outside environment and sun radiation. An upward flow is produced as the air around the glazing warms up and becomes less dense. Warm air that was rising would be replaced at the same time by colder air from the greenhouse's lower sections, creating a downward movement. As long as the temperature differential is present, convection will continue.

The arrangement and strength of the air velocities inside the greenhouse are depicted by the velocity contour, which is impacted by the size, shape, and direction of the greenhouse in addition to the particular temperature gradients that exist. The contours would normally show lower velocities in the lower sections of the greenhouse and higher velocities close to the glass, where the temperature disparity is most noticeable.

Figure 5: Velocity distribution contour versus times (8h to 20h)



Source: Authors.

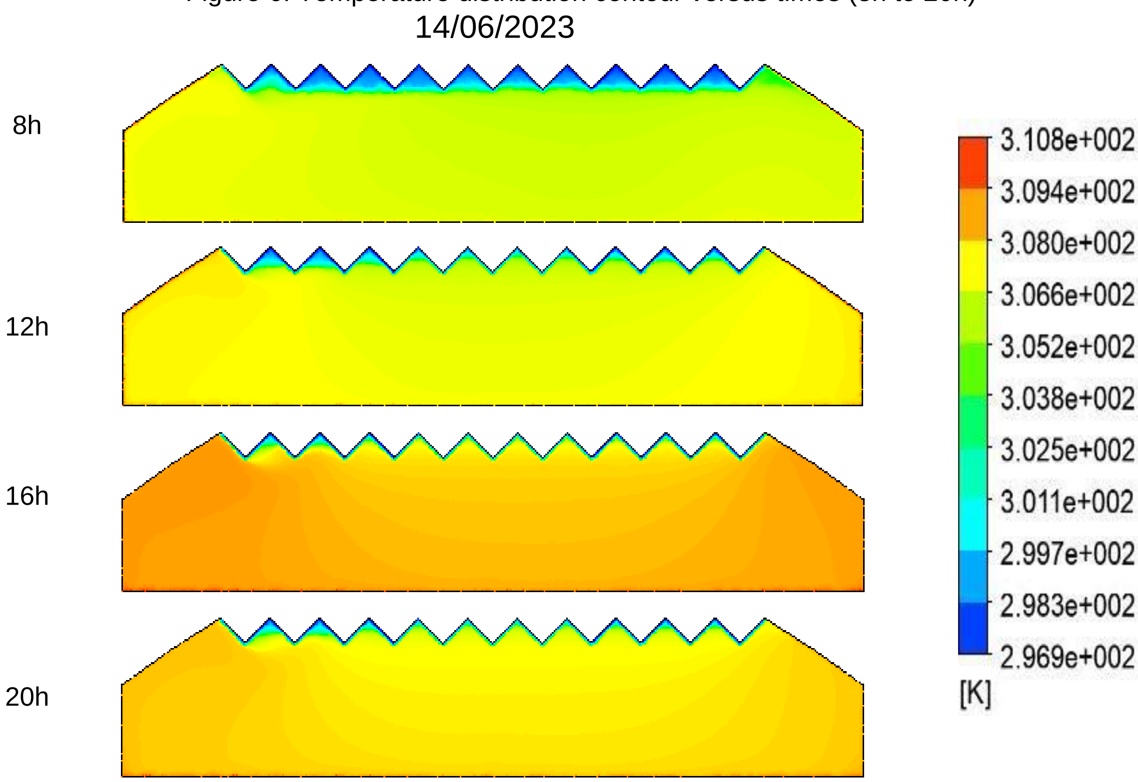
The velocity contour would alter over time in response to variations in the greenhouse's temperature distribution. In contrast to a vented greenhouse, the temperature variations may not be as noticeable in the absence of cultivation or any interior heat sources, which would lead to comparatively weaker air movement and slower velocities.

It's important to remember that improper ventilation and cultivation in a closed greenhouse can negatively impact the health and growth of plants. Plants may not receive enough resources for photosynthesis and may be more vulnerable to disease and pest infestations in the absence of adequate airflow and gas exchange, such as that between carbon dioxide and oxygen. Proper cultivation techniques and ventilation are essential for preserving a healthy greenhouse atmosphere and encouraging ideal plant growth.

3.4 TEMPERATURE DISTRIBUTION INSIDE THE GREENHOUSE

The temperature distribution contour vs times (8h to 20h) is shown in Figure 6. A number of variables, including as the insulating qualities, the external environmental conditions, and the design of the greenhouse, will affect the temperature distribution or contour inside the greenhouse. However, it is challenging to generate an exact temperature contour vs time without knowing specifics about the greenhouse's construction or environmental circumstances.

Figure 6: Temperature distribution contour versus times (8h to 20h)



Source: Authors.

When a greenhouse is exposed to sunshine, the air and greenhouse structure are heated by solar radiation, which causes the temperature to rise steadily over time. The places closest to the sun will have the highest temperature.

Through convection and conduction, heat will eventually move from the warmer to the colder regions. As a result, temperature gradients may occur inside the greenhouse, with warmer regions in the middle and colder regions close to the walls.

The thermal characteristics of the materials used in the greenhouse will also affect the temperature contour. When comparing a greenhouse with good insulation to one with poor insulation, the temperature inside the former may rise more slowly and ultimately reach a lower degree.

It's crucial to remember that the greenhouse can get very hot without ventilation, especially in the summertime. Excessive temperatures may result from this, which might not be good for plant development or possibly damaging to the greenhouse's structure.

It is typically required to include ventilation systems, shading devices, or other temperature management techniques in order to maintain a more optimal temperature range inside a closed greenhouse. With the use of these systems, surplus heat may be dispersed and a steadier, ideal temperature for plant growth can be maintained.

3.5 SPECIES (MASS FRACTION OF H_2O) DISTRIBUTION INSIDE THE GREENHOUSE

The species mass fraction of water vapor (H_2o) will change over time in a closed greenhouse without cultivation and ventilation because of variables including temperature, humidity, and the greenhouse's beginning conditions, as figure 7 illustrates. However, a realistic contour representation of the mass fraction of water vapor over time cannot be provided without precise values or limits.

When water evaporates off surfaces and plants and the air's moisture content rises, the mass fraction of water vapor in the greenhouse will typically grow with time. There will eventually be a reasonably steady mass fraction of water vapor when the rate of evaporation and the rate of condensation approach an equilibrium.

Figure 7: Mass transfer distribution contour versus times (8h to 20h)
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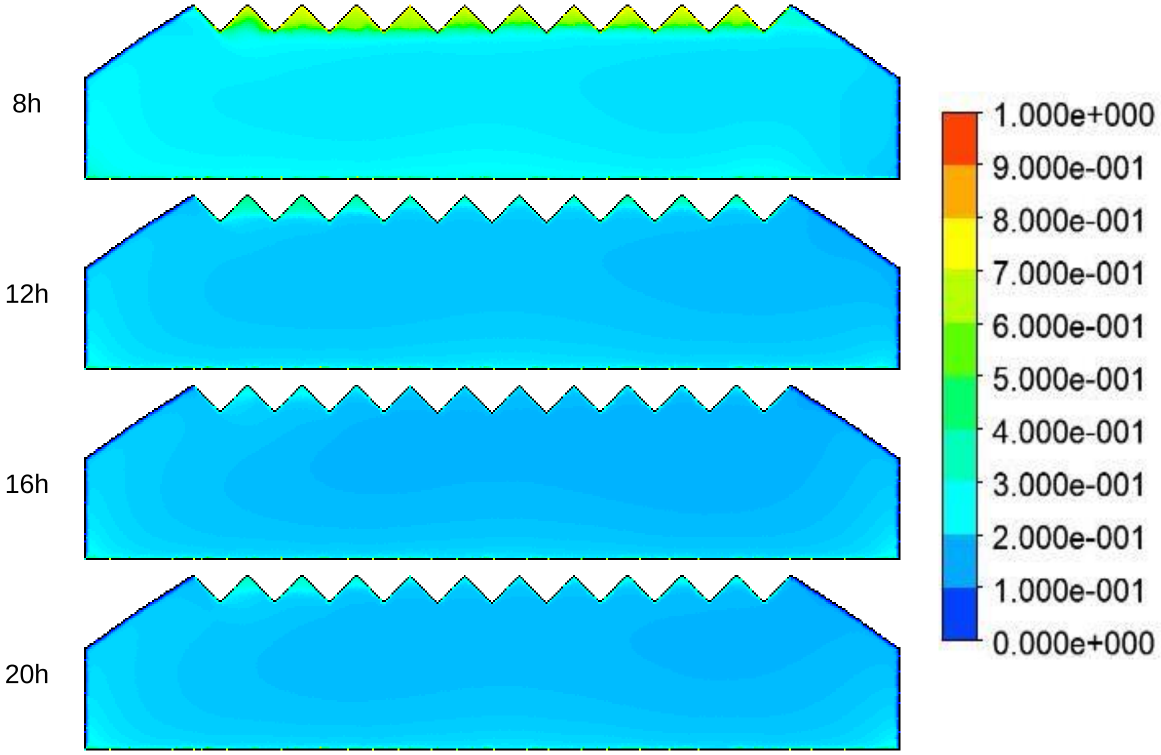
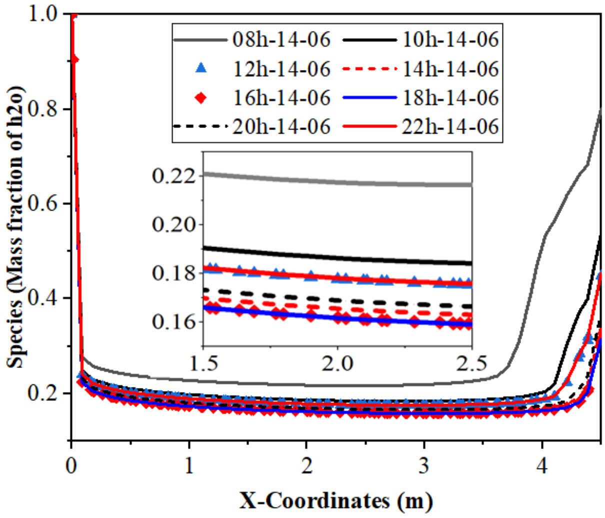


Source: Authors.

Figure 8 illustrates how the rate of evaporation and the water vapor mass fraction are affected by many factors in a greenhouse, including temperature, starting humidity, and the surface area of water sources. The greenhouse environment can also be impacted by outside factors like humidity and general temperature.

Figure 8: Species (mass fraction of H_2O) as a function of x-coordinates



Source: Authors.

4 CONCLUSION

Optimizing the design and functionality of closed greenhouses can be achieved with the help of computational fluid dynamics (CFD) modeling. It enables a thorough examination of the greenhouse's temperature distribution, humidity levels, and airflow patterns, which aids in locating possible areas for enhancement in terms of crop output and energy efficiency. CFD modeling can assist greenhouse operators in making well-informed decisions to establish a better regulated and sustainable plant growth environment by simulating various scenarios and situations. The application of CFD modeling in closed greenhouses can result in more productive and efficient operations, which eventually improve the financial productivity and preserve the environment.

The study's assumptions and simplifications, difficulties with validation and sensitivity to input factors are among its limitations when it comes to CFD modeling in new design closed greenhouses.

Greenhouses play a crucial role in modern agriculture by extending the growing season, enabling cultivation in harsh climates, and providing a controlled environment for high-value crops. By optimizing the design of greenhouses through CFD modeling, society benefits from increased agricultural productivity and a more reliable food supply. This is particularly important in regions with limited arable land or vulnerable to climate change impacts.

Future research in this field is advised to improve validation through experimental investigations, carry out sensitivity analyses, incorporate multi-physics modeling, and optimize greenhouse design sustainability and efficiency using CFD simulations.

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