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Thermal Analysis of Greenhouse Environment Using Computational Fluid Dynamics (CFD), Case Study in ITERA

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ABSTRACT

Greenhouse is a modern agricultural technology that allows for increased agricultural yields. The purpose of this study was to analyze the thermal distribution in the greenhouse of the Sumatra Institute of Technology (ITERA) in 3-time conditions, namely in the morning, afternoon and evening. The method used is CFD modeling using Solidwork. The dimensions of the greenhouse are 12.5 x 25 x 4.26 m³. The greenhouse is divided into a grid into 20 thermal measurement points separated by 2.5 m. The greenhouse has 2 cooling pads and 2 exhaust fans separated by 12.5 m. Model validation using MAPE and R2. The results of the analysis show that 3 models have valid results with MAPE <10% and R2> 0.75 and can continue in the review of thermal distribution. of the 3-time condition models that provide a thermal distribution of 28 - 37 °C. Morning conditions are hotter than afternoon and evening. Cold air from the cooling pad sucked by the exhaust fan is only able to control an area <50%. So, the thermal distribution of the greenhouse needs improvement.

Keywords: *CFD, Greenhouse, ITERA, thermal*

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ABSTRACT

Greenhouse merupakan teknologi pertanian modern yang memungkinkan untuk peningkatan hasil pertanian. tujuan penelitian ini adalah menganalisis persebaran termal pada greenhouse Institut Teknologi Sumatera (ITERA) pada 3 kondisi waktu yaitu pada pagi hari, siang hari dan sore hari. Metode yang digunakan adalah pemodelan CFD menggunakan Solidwork. Dimensi greenhouse berukuran 12.5 x 25 x 4.26 m³. Greenhouse dibagi grid menjadi 20 titik pengukuran termal yang dipisahkan 2.5 m. greenhouse memiliki 2 cooling pad dan 2 exhaust fan yang dipisahkan 12,5 m. validasi model menggunakan MAPE dan R^2. Hasil analisis menunjukkan bahwa 3 model memiliki hasil yang valid dengan MAPE < 10% dan R^2 > 0.75 dan bisa lanjut dalam tinjauan persebaran termal. dari 3 model kondisi waktu yang memberikan persebaran termal 28 - 37 ℃. Kondisi pagi lebih panas daripada siang dan sore hari. Udara dingin dari cooling pad yang dihisap oleh exhaust fan hanya mampu mengendalikan area < 50%. Maka persebaran termal greenhouse perlu adanya perbaikan.

Keywords: *CFD , Greenhouse, ITERA, thermal*

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INTRODUCTION

Greenhouses play a crucial role in the development of agriculture in Indonesia, particularly due to the tropical climate conditions that are not always conducive to the growth of certain crops. By using greenhouses, farmers can control environmental conditions such as temperature, humidity, and light intensity, which help increase the productivity and quality of crops[1]. In addition, greenhouses allow for year-round cultivation, independent of seasonal changes, leading to more stable and sustainable food production[2]. This technology not only benefits farmers by improving crop yields but also encourages the adoption of more modern and efficient farming methods, thereby contributing to the overall advancement of Indonesia's agricultural sector.

The application of precision agriculture in the greenhouse that serves as the research object for this final project, specifically the ITERA Botanical Garden greenhouse, faces several challenges, including high temperatures, especially during midday, when temperatures can rise to 30°C to 35°C, with humidity levels ranging from 42% to 60%. Based on this problem, it is necessary to have a picture of the thermal distribution in the greenhouse in order to improve the greenhouse system.

Computational Fluid Dynamics (CFD) is an appropriate method for understanding heat distribution in greenhouse systems because it allows accurate simulation of airflow and heat transfer within the structure. Using CFD, a 3D model of the greenhouse can be used to visualize and analyze how heat and air move throughout the structure, helping identify areas that need improvement to maintain optimal temperatures for plant growth[3]. CFD also provides crucial information about the efficiency of ventilation and cooling systems in the greenhouse, which is essential for maximizing crop productivity. The purpose of this study is to analyze the thermal distribution of the ITERA greenhouse at 3-time conditions, namely in the morning, midday and afternoon. It is hoped that this analysis can provide recommendations for improving the agricultural greenhouse system.

LITERATURE REVIEW

Computational Fluid Dynamics (CFD)

A ventilation system generates an airflow that creates a variable capable of controlling the climate by producing a dynamic and non-linear transient behavior, which can be represented by a second-order differential equation that is complex and lacks an analytical solution. To solve this problem, a numerical method known as Computational Fluid Dynamics (CFD) is used, which involves applying the Navier-Stokes equations. A fluid flow field is characterized by three properties: mass conservation, momentum, and total energy. These three properties are described using continuity equations, which will be explained below[4].

law of conservation of mass:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \qquad \text{….. (1)}$$

Where P = pressure (Pa), t= time (s), ρ = density of mass (kg/m^3) and u = fluid velocity (m/s). The conservation of mass equation uses the time derivative which is the accumulation or loss of mass in a system.

The momentum equation is as follows:

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla \rho + \nabla \cdot \tau + \boldsymbol{F} \qquad \text{…..(2)}$$

Where P = pressure (Pa), t= time (s), ρ = density of mass (kg/m^3) and u = fluid velocity (m/s), τ = tensor force , F =external force. The momentum equation describes the rate of change in time of some physical quantity of an element that depends on space and time.

Energy equations:

$$\frac{\partial}{\partial x}\left[\rho\left(e+\frac{1}{2}u^2\right)\right]+\nabla\cdot\left[\rho\boldsymbol{u}\left(e+\frac{1}{2}u^2\right)\right] = \nabla\cdot(k\nabla T)+\nabla\cdot(-\rho\boldsymbol{u}+\tau\cdot\boldsymbol{u})+\boldsymbol{u}\cdot\boldsymbol{F}+\boldsymbol{Q} \quad ...(3)$$

Where P = pressure (Pa), t= time (s), ρ = density of mass (kg/m3) and u = fluid velocity (m/s), τ = tensor force, F =external force (N), k = thermal conductivity (W/m^2°C), T= temperature (°C) , Q = heat (J), e = energy (J). The law of conservation of energy states that the total energy of a system is equal to the sum of the work and heat added to the system.

Finite element method (FEM)

The Finite Element Method (FEM) is a numerical approach used to solve differential equations in two or three dimensions [5]. FEM works by dividing a larger structure into smaller parts, called finite elements. This is achieved by discretizing a specific space within its spatial dimensions, implemented through the construction of a mesh of the object: a numerical domain for the solution, which has a limited number of points. There are several types of FEM solutions, including triangular elements and quadrilateral elements, each used differently to achieve the best accuracy. Quadrilateral elements are well-suited for beam-like structures because their sides become "bilinear" during deformation, meaning they do not stay straight. On the other hand, triangular elements are well-suited for irregular shapes, as their sides remain "linear" or straight during deformation.

METHOD

Greenhouse

The ITERA greenhouse is located in South Lampung, with dimensions of 12.5 x 25 x 4.26 m^3. It has two cooling pads with dimensions of 1.52 x 0.52 m^2 and two exhaust fans with dimensions of 1.4 x 1.4 m^2. The positions of the cooling pads and exhaust fans are arranged 12.5 m apart, as shown in Figure 1. Measurements were taken at 20 points, each spaced 2.5 m apart, and both cooling pads and exhaust fans are positioned 0.74 m above the ground. The greenhouse type is an arch type, and the entire greenhouse structure is covered with a UV polyethylene cover.

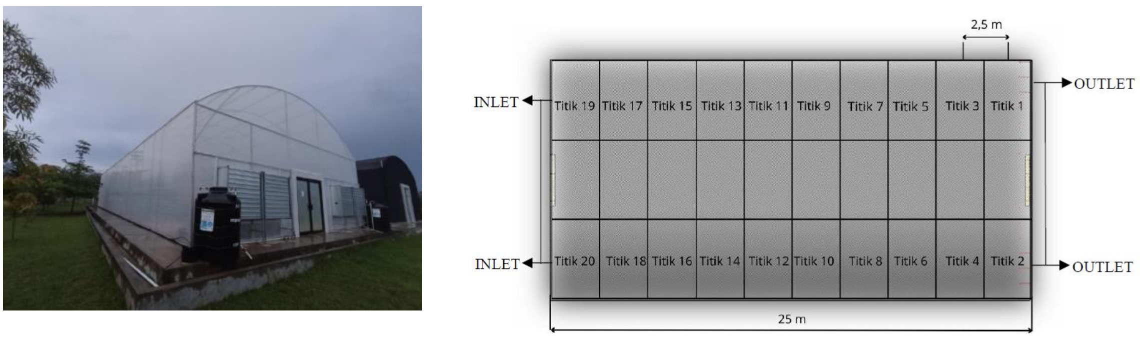


Figure 1. a. ITERA's Greenhouse, b. 20 points of measurement.

The parameters measured were room temperature and relative humidity. Measurements were taken at three different times: in the morning (at 09:00 AM WIB), at midday (at 1:30 PM WIB), and in the afternoon (at 4:30 PM WIB). Room temperature and relative humidity were measured using a humidifier meter.

CFD Simulation

The 3D greenhouse model was designed at a 1:1 scale based on the actual dimensions using AutoCAD. The CFD simulation was conducted using SolidWorks, following the steps shown in Figure 2. Next, the geometry was defined, and material characteristics were assigned to the model. The fluid in the greenhouse was considered to be air (gas), and a laminar flow was used. To simulate the model, initial boundary conditions were set, as shown in Table 1.

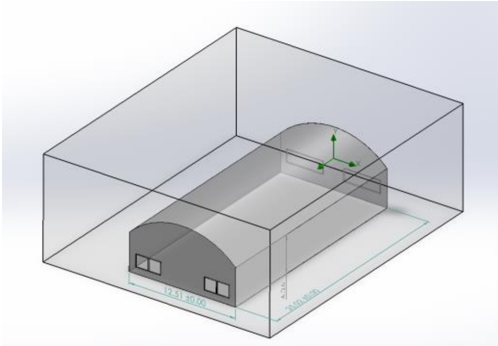


Figure 2. 3D Model ITERA's Greenhouse

Tabel 1. Initial conditions of greenhouse.

No	Parameter	Value
1	UV Plastic Conductivity	6,2 W/m^2°C
2	Air Exchange (/hour)	4,2 ACH
3	Motor Rotation	1.400 rpm
4	Fan Rotation	610 rpm
5	Cooling Pad Height from Ground	135 cm
6	Exhaust Fan Height from Ground	74 cm

Analysis

Simulation results, the model will be evaluated before being studied related to thermal distribution in the greenhouse. The evaluation used uses 2 equations, namely:

$$MAPE = \frac{\sum \frac{x-y}{x}}{n} \times 100\% \qquad \text{……(4)}$$

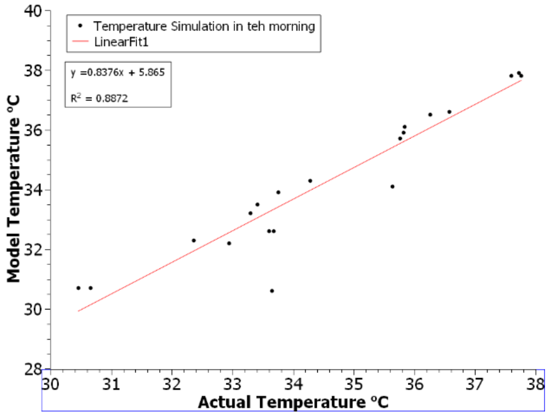
$$R^2 = \frac{\sum xy}{\sum x^2 \sum y^2} \qquad \text{……(5)}$$

Where x = actual temperature (℃) , y = simulation temperature (℃) and n = data amount, MAPE is Mean Average Percentage error and R is correlation coefficient.

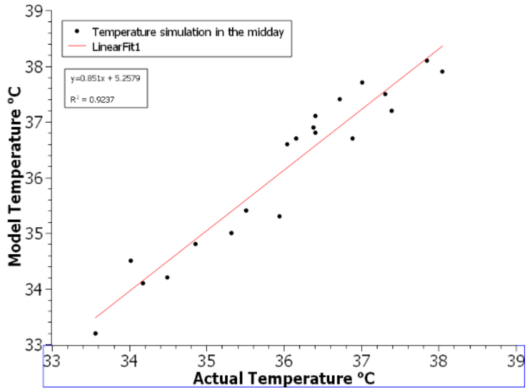
Decision maker which states the evaluation results are acceptable if MAPE <20% and R^2 approach to 1 or ≥ value 0.75. The next study is to analyze the thermal distribution in the area inside the greenhouse.

RESULT AND DISCUSSION

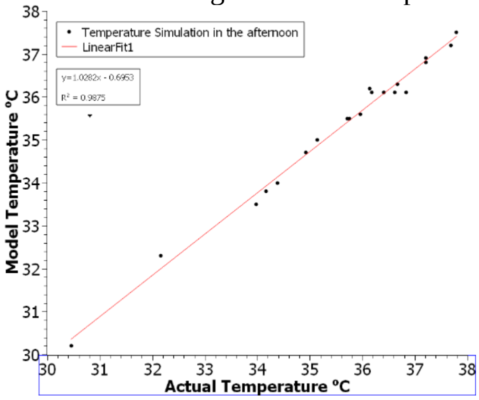
The initial assessment is to validate the model by comparing the results between the model temperature and the actual temperature using MAPE and the correlation coefficient R. Figure 3 shows the descriptive correlation values at three-time conditions.



a. Temperature simulation in the morning



b. Temperature simulation in the midday



c. Temperature simulation in the afternoon

Figure 3. Validation analysis using correlation coefficient

The correlation coefficient value in the morning is 0.88, which is considered acceptable for this model case. This may be due to the fact that, at that time, the sunrise in the South Lampung region occurs earlier, resulting in more heat being received by the greenhouse. The correlation values during midday and in the afternoon are greater than 0.90, providing a strong data comparison. The correlation coefficient between the model temperature and the actual temperature is greater than 0.75, indicating that the model is acceptable.

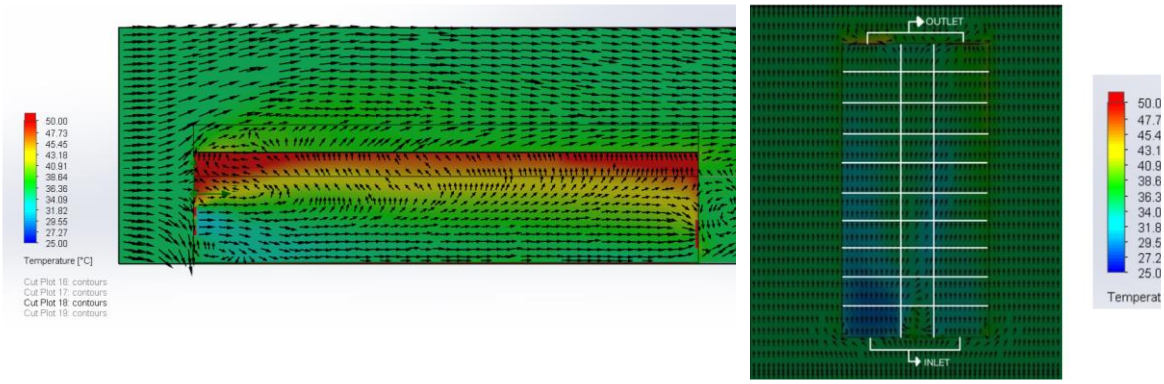
The MAPE values shows in Table 2 for the three-time conditions are 1.412% in the morning, 0.353% in the midday, and 0.624% in the afternoon. Since the MAPE value is less than 20% for the simulation case, the greenhouse model is considered acceptable.

Table 2. MAPE in three-time conditions

Point	Morning (%)	Midday (%)	Afternoon (%)
1	4.516	0.254	0.448
2	0.058	0.598	1.268
3	0.223	0.265	0.453
4	0.658	0.289	0.537
5	0.529	0.401	0.028
6	0.475	0.507	0.583
7	0.106	1.114	0.637
8	0.055	0.080	0.303
9	0.720	0.554	1.163
10	0.168	0.566	0.746
11	0.269	0.109	0.796
12	0.413	0.109	0.366
13	2.298	0.397	1.341

Point	Morning (%)	Midday (%)	Afternoon (%)
14	0.301	0.141	1.349
15	3.313	0.143	0.418
16	0.186	0.172	0.180
17	3.067	0.171	0.734
18	0.130	0.028	0.433
19	9.967	0.058	0.603
20	0.782	1.111	0.096
mean	1.412	0.353	0.624

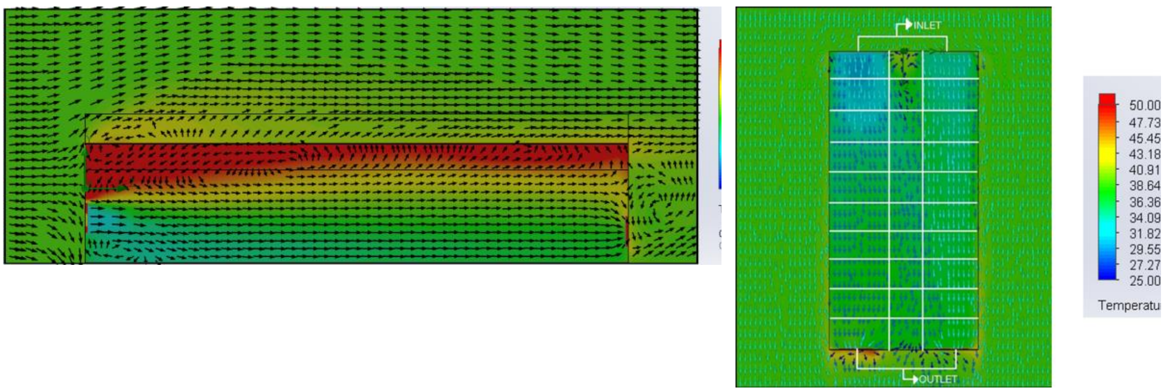
The simulation of the ITERA greenhouse was conducted using the Computational Fluid Dynamics (CFD) method with the SolidWorks application. Measurements were taken between the cooling pad and the exhaust fan to observe the temperature distribution and airflow inside the greenhouse.



a. CFD Grid is seen from the side b. CFD Grid is seen from above

Figure 4. CFD grid diagram distribution in morning conditions

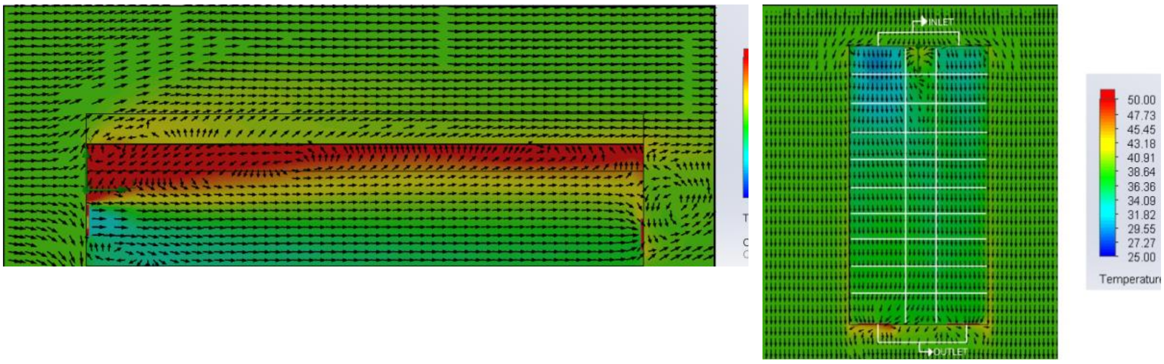
Figure 4 shows the simulation results of the greenhouse in the morning, displaying airflow from the left side to the right side (from the cooling pad towards the exhaust fan) and the internal temperature of the greenhouse. It can be observed that the temperature within the greenhouse ranges from 29°C to 50°C. However, since the melon plants only reach a height of three meters, the temperature around the plants is between 33°C and 38°C. The airflow within the greenhouse in the morning ranges from 0.1 m/s to 1.9 m/s.



a. CFD Grid is seen from the side b. CFD Grid is seen from above

Figure 5. CFD grid diagram distribution in midday conditions

Figure 5 shows the simulation results of the greenhouse during midday, illustrating the airflow moving from the left side to the right side (from the cooling pad to the exhaust fan) and the internal temperature of the greenhouse. It can be observed that the temperature within the greenhouse ranges from 28°C to 54°C. However, since the melon plants only grow up to three meters in height, the temperature around the plants is between 33.5°C and 44°C. The airflow within the greenhouse during midday ranges from 0.1 m/s to 2.24 m/s.



a. CFD Grid is seen from the side

b. CFD Grid is seen from above

Figure 6. CFD grid diagram distribution in midday conditions

Figure 6 shows the results of the greenhouse simulation in the afternoon, illustrating the airflow from the left side to the right side (from the cooling pad to the exhaust fan) and the temperature inside the greenhouse. The internal temperature of the greenhouse ranges from 28°C to 53°C, but since the melon plants only grow up to three meters in height, the temperature around the plants is between 30°C and 37°C. The airflow within the greenhouse in the afternoon ranges from 0.1 m/s to 2.24 m/s.

Simulation performance in the morning when viewed from above, the humid air taken by the exhaust fan can almost reach 50% of the length of the greenhouse with the smallest temperature of 29°C. humid air performance during the day can only reach 35% of the length of the greenhouse and in the afternoon, it reaches 20% (although the smallest temperature in the afternoon is 28℃). of all CFD performances, the exhaust fan in the right area has a low speed because when the incident occurred there was a fan performance malfunction so that its distribution was not the same as the left area. High temperatures in the greenhouse are trapped in the upper area, which is called the chimney effect [6]. This is due to the buoyancy force, namely the difference in density of hot and cold air.

CONCLUSION

Based on the results of the ITERA greenhouse CFD performance, it provides a fairly warm temperature of 28 ℃ - 37℃ when measured at a height of 1 m from the ground. with conditions that can be considered warm, plants are needed that are in accordance with these conditions. or, there are alternative suggestions that can be considered, namely the reconstruction of the greenhouse dimensions by reducing the length of the greenhouse, increasing the speed of the exhaust fan, changing the position to the long part of the greenhouse and adding exhaust fans and cooling pads.

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