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The Role of Fan Speed and Misting for Computational Fluid Dynamics (CFD) Analysis of Temperature and Humidity Regulation in Greenhouses

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ABSTRACT

Maintaining an optimal climate is essential for plant growth, and greenhouses though controlled often face challenges such as excessive heat. To address this, fan and misting systems are commonly used. This study investigates the role of fan speed and misting in regulating temperature and relative humidity (RH) in a smart greenhouse using Computational Fluid Dynamics (CFD) simulations. In this research, CFD simulations were performed using actual temperature and RH measurements as input data. The scenarios included varying fan speeds (3.4 m/s, 4.5 m/s) and a control condition without a fan, combined with 15-minute misting sessions. The results show that a fan speed of 4.5 m/s with misting is more effective at lowering temperature compared to 3.4 m/s under the same misting conditions. The simulation errors were below 10% across all treatments, indicating the model's reliability. These findings offer valuable insights for optimizing climate control in greenhouses, supporting more efficient and sustainable crop production.

1. INTRODUCTION

Open-field agriculture remains the predominant cultivation method among Indonesian farmers. However, climate change has introduced increasing unpredictability in weather patterns, which significantly affects crop productivity. Unstable weather conditions such as excessive heat or unexpected rainfall can disrupt plant growth cycles and reduce yields. As a solution, the adoption of controlled environment agriculture—particularly greenhouses—has gained traction to mitigate such challenges and enhance crop productivity (Bonde *et al*., 2021). A greenhouse is a structure designed to create an optimal environment for plant growth by controlling factors such as temperature, humidity, light, and air movement. Cultivation in greenhouses offers several advantages, including improved yield quality, year-round production, reduced dependence on external climatic conditions, and more efficient pesticide usage (Tando, 2019). Even under suboptimal external conditions, plants inside greenhouses can thrive due to the regulated internal environment. Among the environmental parameters, temperature and relative humidity (RH) play a crucial role in influencing plant growth and development.

Greenhouses tend to accumulate heat due to limited air exchange and the greenhouse effect caused by trapped solar radiation. This results in higher internal temperatures compared to the outside environment (Alahudin, 2013). Temperature affects plant phenology, morphology, and overall physiology. Different crops require specific temperature ranges to reach optimal growth, and fluctuations beyond these ranges can lead to growth stress or reduced productivity (Servina, 2019). Moreover, temperature changes influence the air capacity to retain moisture, which in turn affects RH. RH is defined as the ratio of actual water vapor pressure to the maximum water vapor pressure at a given temperature.

To maintain suitable temperature and RH levels within greenhouses, technologies such as fans and misting systems are commonly used. Fans promote air circulation and reduce heat buildup, while misting introduces fine water droplets that absorb heat as they evaporate, thereby reducing temperature and increasing humidity. Monitoring temperature distribution manually is challenging without specialized tools like thermal cameras (Ukiwe *et al*., 2023). Hence, computational modeling offers a practical alternative for analyzing internal microclimates. Computational Fluid Dynamics (CFD) is a simulation-based approach that models fluid flow behavior within defined spaces. CFD applies numerical analysis—specifically the finite volume method—to solve mass, momentum, and energy conservation equations across two- or three-dimensional spaces (Versteeg & Malalasekera, 2007).

CFD has become a valuable tool in agricultural research, allowing detailed visualization and optimization of greenhouse environments without the need for repeated physical trials. Several studies have demonstrated its usefulness in simulating air and heat flow, energy efficiency, ventilation dynamics, and other greenhouse processes (Bartzanas *et al*., 2013; Chen *et al*., 2015; Malekjani & Jafari, 2018; Villagran *et al*., 2019; Chapman & Doom, 2021; Bournet & Rojano, 2022; Szpicer *et al*., 2023; Fu *et al*., 2023). CFD simulations allow researchers to assess spatial temperature and RH distribution patterns that support uniform crop development. Software such as ANSYS provides integrated solutions for meshing, joint-physics simulations, and compatibility with various CAD platforms (Alawadhi, 2009).

Romdhonah *et al*. (2014) have used CFD to simulate the impact of humidification and ventilation systems on greenhouse environments. Jalaluddin *et al*. (2019) further demonstrated the capability of CFD in visualizing temperature and RH distribution by dividing the greenhouse space into computational cells through a process known as meshing. These simulations are critical for designing efficient climate control systems. The present study focuses on evaluating the effects of different fan speeds combined with misting durations on greenhouse microclimate using CFD simulations. This approach aims to support the optimization of temperature and humidity regulation for improved crop productivity in smart greenhouses. The outcomes of this study are expected to guide the development of efficient climate control strategies in greenhouses, enabling growers to maintain optimal microclimate conditions while minimizing energy and water consumption, thus supporting sustainable agriculture.

2. MATERIALS AND METHODS

Greenhouse system analyzed for this research was depicted in Figure 1. Environmental parameters, including air temperature and relative humidity (RH), were directly measured inside the greenhouse, while surrounding climate data were also recorded. These measurements were used as input for the CFD simulations. The treatments consisted of three fan conditions: 3.4 m/s, 4.5 m/s, and a control without a fan. The fan employed was a stand fan (WH-1881 M type, 18 inches, 220 V–50 Hz, 50 W), with rotational speeds of 4733 and 5283 rpm for 3.4 and 4.5 m/s, respectively. A misting system was also operated for 15 minutes to support temperature regulation; however, its effect was represented as part of the greenhouse air temperature rather than as an inlet boundary in the simulation. All treatments were conducted under identical boundary conditions, with data collected at 08:00, 13:00, and 16:00 WIB (Table 1).

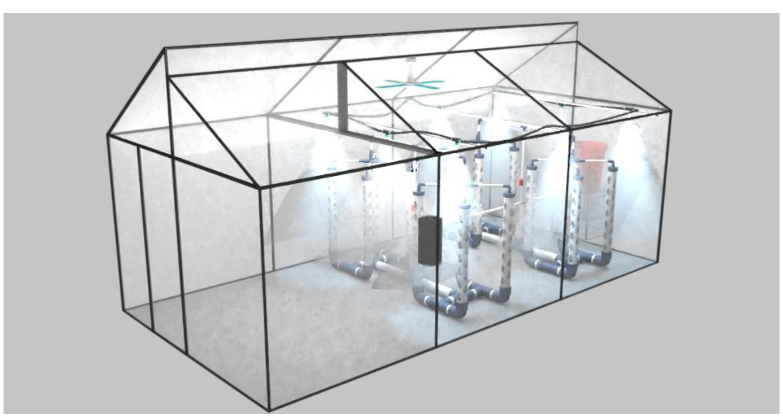

Figure 1. Overview of system in greenhouse

Table 1. Treatment in this research

Treatment	Condition
1	Without fans and misting
2	Fan speed 3.4 m/s and misting 15 min
3	Fan speed 4.5 m/s and misting 15 min

2.1. Temperature Measurement

Temperature measurements were conducted at multiple points within the smart greenhouse using a thermo-hygrometer. Measurements were taken at three locations—front, middle, and back. The average value from these points was used to represent the greenhouse temperature, ensuring higher measurement accuracy. Data were recorded at three time intervals: 08:00, 13:00, and 16:00 WIB.

2.2. RH measurement

Relative humidity is measured using a thermos-hygrometer. This RH measurement is carried out at several points in the smart greenhouse. RH measurements were carried out at 08.00 WIB, 13.00 WIB and 16.00 WIB. Retrieval of RH data is carried out at locations such as measuring temperature in a greenhouse.

2.3. CFD simulation

Creating a CFD simulation using Ansys software consists of three main stages, namely Pre-Processing, Processing, and Post-Processing. Steps to Simulate CFD:

2.3.1. Pre-processing

In the simulation process with CFD, the first step is pre-processing. The procedures performed at this stage include creating the geometry of the model to be simulated. Next is the meshing process which functions to divide the geometry into elements with smaller sizes to obtain more convergent results in the analysis (Yudhatama *et al*., 2018). At this stage, the geometric boundary fields are determined.

2.3.2. Processing

This stage is a fluid simulation process in CFD or is called the solution stage. The boundary conditions that have been set during pre-processing will be calculated by the software automatically using the equations involved in the CFD simulation until convergent conditions are obtained (Rumanto *et al*., 2021). The solver process is based on mathematical equations that express laws in physics. There are 3 fluid flow equations which state the law of conservation of physics (Versteeg & Malalasekera, 2007). The accuracy level of the solver is affected by the boundary conditions or assumptions used (boundary conditions), the mesh size used, and numerical errors that can occur due to software limitations or processing errors (Rumanto *et al*., 2021).

2.3.3. Post-Processing

This stage is the last in the CFD simulation. At this stage, the results of the simulation will be displayed. The result can be a color, vector, or contour graph that will be displayed (Rumanto *et al*., 2021).

2.4. Model Validation

Model validation was analyzed by comparing the temperature of the simulation results with the temperature measurements in the field. The percentage error is calculated to get the accuracy of the simulation results (He *et al*. 2018). If the error value is <10% then the CFD simulation results can be said to be valid (Anwar & Panggabean, 2019). Error was expressed by the Equation (1) for temperature, and Equation (2) for RH:

$$\text{Error: } \left|\frac{(T_{sim}-T_{mea})}{T_{mea}}\right| \times 100\% \tag{1}$$

$$\text{Error: } \left|\frac{(RH_{sim}-RH_{mea})}{RH_{mea}}\right| \times 100\% \qquad (2)$$

where T_{sim} is simulated temperature (℃),T_{mea} is measured temperature (℃), RH_{sim} is simulated RH (%), and RH_{mea} is measured RH (%).

3. RESULTS AND DISCUSSION

3.1. Results of Greenhouse Temperature and RH Measurements

Based on direct measurements that have been carried out in the field, temperature, and RH data were obtained for the treatment without fan and misting, the fan speed of 3.4 m/s and misting for 15 minutes, and the fan speed of 4.5 m/s, and misting for 15 minutes and also the ambient temperature as follows.

Table 2. Results of temperature and RH measurements

Treatment	Time	Greenhouse Temperature (℃)	RH (%)	Environment Temperature (℃)	RH (%)
Without fans and misting	08.00	27.76	83.24	27.93	82.45
	13.00	37.35	56.84	36.93	56.07
	16.00	34.14	61.69	33.33	63.27
Fan speed 3.4 m/s and misting 15 min	08.00	28.35	87.02	28.40	81.07
	13.00	35.11	62.44	36.03	57.73
	16.00	32.47	71.80	32.50	65.20
Fan speed 4.5 m/s and misting 15 min	08.00	27.74	88.82	28.30	79.97
	13.00	33.83	69.85	35.13	58.87
	16.00	32.84	74,37	33.13	66.60

The boundary condition is used to provide certain conditions at the inlet and outlet as well as the wall. The value entered in the boundary condition is obtained from measurements in the field. In the velocity inlet, the value represented is greenhouse room data, while the pressure outlet is represented by environmental data. The value entered into the boundary condition is shown in the following table.

3.2. CFD Simulation Results of Temperature Distribution and RH in Greenhouses

CFD simulation was carried out to determine the distribution of air temperature and RH in the greenhouse. The simulation was carried out in 3 conditions, namely without a fan and misting, using a fan speed of 3.4 m/s and misting for 15 min and using a fan speed of 4.5 m/s and misting for 15 min.

3.2.1. Greenhouse temperature distribution

3.2.1.1. Temperature at 08.00

The results of the simulations performed represent the temperature distribution that occurs in the greenhouse room. The simulation results in the greenhouse at 08.00 for various treatments are shown in Figure 2. In the figure, it can be seen that the temperature in the greenhouse is not uniform at all points. This is due to the movement of fluid in the form of air which affects the temperature conditions. The shape of the temperature distribution in the greenhouse at 08.00 in the control treatment (without fan and misting), fan speed of 3.4 m/s 15 min of misting and fan speed of 4.5 m/s and 15 min of misting can be seen in Figure 2a, 2b, and 2c. The color gradation in the image represents the magnitude of the temperature value. More red indicates a temperature with a higher value. Meanwhile, the darker the blue color displayed in the simulation results, the lower the temperature at that location.

From Figure 2a it can be seen that the lowest temperature distribution dominates the greenhouse floor. Getting closer to the roof of the greenhouse, the temperature seems to have increased. The temperature on the floor is 26.42 ℃ and the roof temperature is 27.89 ℃. The natural convection process will affect the increase in temperature which is accompanied by a decrease in density. This will cause hot, dry air to be at the top of the room while cool, moist air to

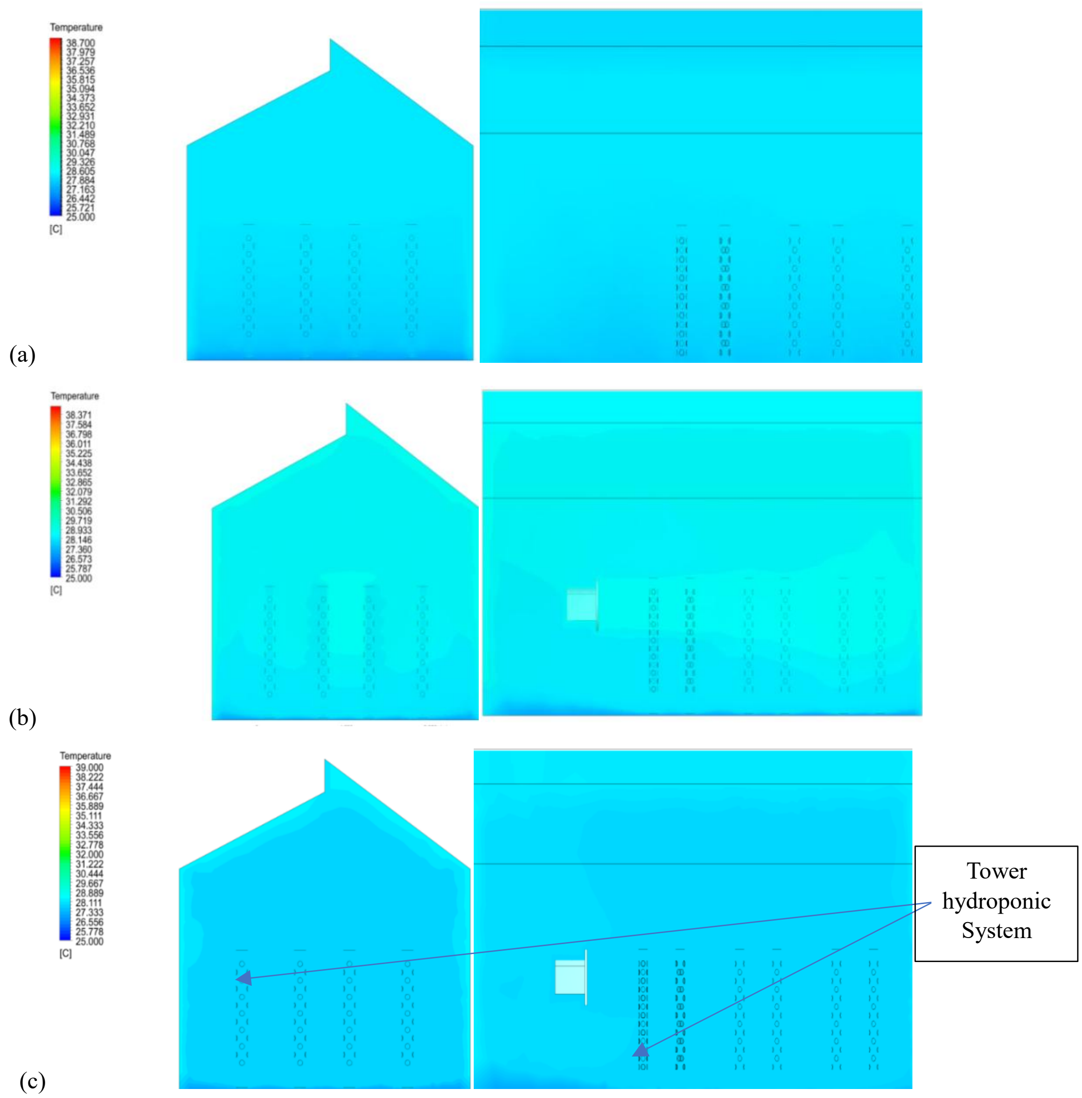

Figure 2. Temperature distribution of the greenhouse at 08.00: (a) No fan no misting, (b) with fan at speed of 3.4 m/s and misting for 15 min, (c) with fan at speed of 4.5 m/s and misting for 15 min

be at the bottom of the room (Putro *et al*., 2015). In the hydroponic tower system, the resulting temperature is low, marked with a deep blue color in the figure.

On the fan with a speed of 3.4 m/s and misting for 15 min, the lowest temperature value is on the floor of the greenhouse. Blowing air from the fan flows at a higher temperature than the surrounding temperature as seen from a lighter blue color (Figure 2b). The higher temperature is on the roof of the greenhouse with a value of 28.15 ℃ and the temperature on the floor is 26.57 ℃. The tower temperature in the hydroponic system is lower when compared to the temperature that dominates the room.

In the temperature distribution on the fan with a speed of 4.5 m/s and 15 min of misting in Figure 2c it can be seen that the distribution of air in the greenhouse is more even. The tower temperature in the hydroponic system is uniform with the greenhouse room temperature. High temperatures are on the walls of the greenhouse and also the roof of the greenhouse. The temperature on the greenhouse floor is 26.55 ℃ and the roof temperature is 28.11 ℃. Based on the three conditions in the greenhouse, it can be seen that fan treatment with a speed of 4.5 m/s and misting for 15 min can create a more even distribution of temperature conditions compared to the other 2 conditions.

3.2.1.2. Temperature at 13.00

The greenhouse temperature simulation results at 13.00 are shown in Figure 3. The temperature distribution at 13.00 for each treatment is shown in Figure 3a (treatment 1), Figure 3b (treatment 2), and Figure 3c (treatment 3). The condition of the greenhouse without fans and misting is shown in Figure 3a. It can be seen that the high temperatures around the greenhouse roof enter the hydroponic tower system. This causes the tower temperature in the hydroponic system to be higher than room temperature. In the hydroponic tower system, it is 37.72 ℃, the lowest temperature on the floor is 35 ℃ and in the celling temperature is 39 ℃.

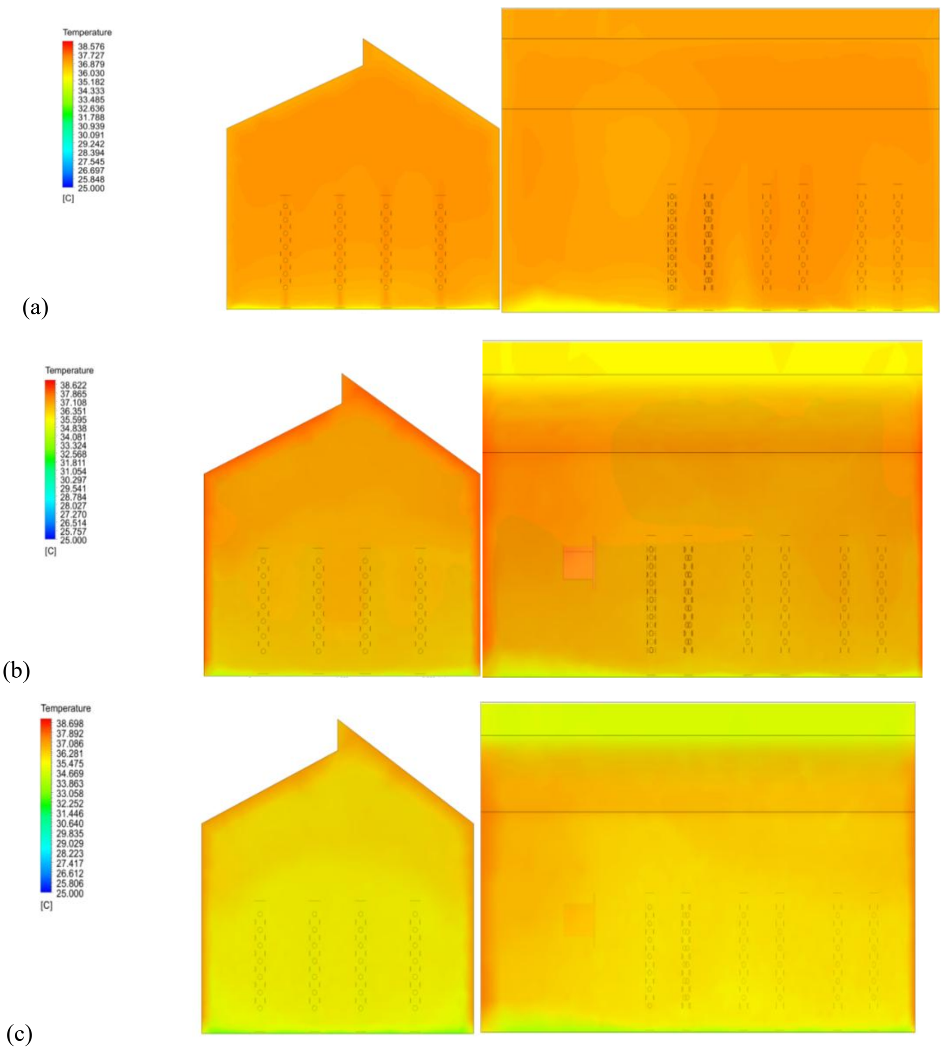

Figure 3. Temperature distribution of the greenhouse at 13.00: (a) No fan no misting, (b) with fan at speed of 3.4 m/s and misting for 15 min, (c) with fan at speed of 4.5 m/s and misting for 15 min

At the fan speed variation of 3.4 m/s and 15 minutes of misting at 13.00 in Figure 3b, it can be seen that high temperatures cover the walls and around the greenhouse roof. In the hydroponic tower system, the temperature looks lower than the temperature that dominates the greenhouse room. The closer to the floor the lower the temperature is indicated by a lighter yellow color.

The temperature distribution on the fan with a speed of 4.5 m/s and misting for 15 minutes at 13.00 is shown in Figure 3c. The highest temperature is on the roof and sides of the greenhouse wall at 35.47 ℃ and the temperature decreases down to the floor of the greenhouse with the lowest temperature around 32.25 °C. Furthermore, in the hydroponic tower system, the flowing temperature is lower than the overall temperature that dominates the room because the yellow color shown is getting younger. Trapped hot air and high solar radiation hitting the greenhouse roof cause high air temperature at the top of the greenhouse.

3.2.1.3. Temperature at 16.00

The greenhouse temperature simulation results at 16.00 for each treatment are shown in Figure 4. The simulation results at 16.00 for the treatment without fan and misting, fan speed of 3.4 m/s and misting of 15 min, and fan speed of 4.5 m/s and misting of 15 min are presented in Figure 4a, Figure 4b, and Figure 4c. At 16.00 the air temperature simulation results showed a decrease in temperature compared to 13.00. This is due to a decrease in solar radiation. The condition of the temperature distribution in the greenhouse without any additional treatment at 16.00 showed that the floor temperature was lower. The highest temperature is at the bottom of the pipe flowing towards the top of the tower system in hydroponics. The highest temperature reaches 35.11 °C and the lowest temperature is on the floor with values ranging from 30.44 °C.

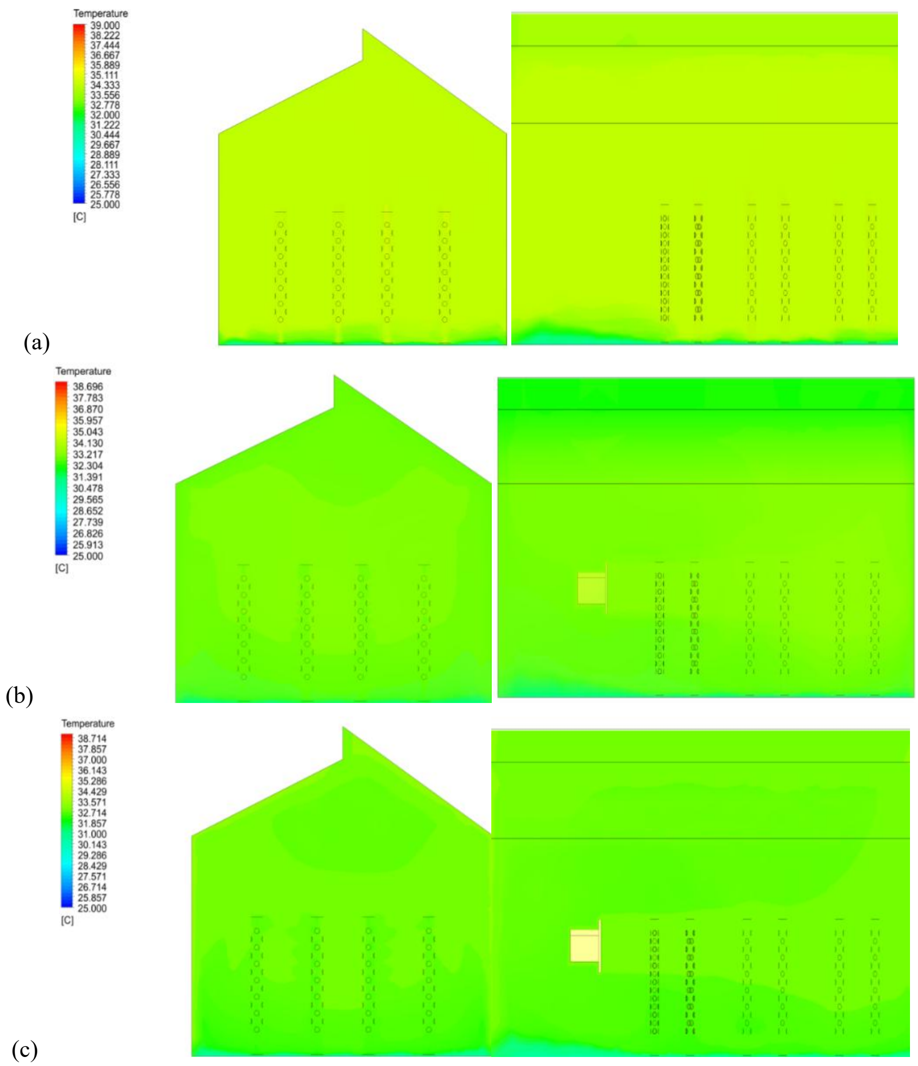

Figure 4. Temperature distribution of the greenhouse at 16.00: (a) No fan no misting, (b) with fan at speed of 3.4 m/s and misting for 15 min, (c) with fan at speed of 4.5 m/s and misting for 15 min

Variations in fan speed of 3.4 m/s and 15 minutes of misting can be seen in Figure 4b, which shows that the airflow from the fan produces hot air that spreads throughout the greenhouse. The air temperature generated from the inlet in the form of a fan is 33.21 ℃, getting closer to the bottom of the floor the temperature decreases as seen from the simulation results which have a bluish color with values ranging from 30.47–31.39 ℃. Gusts of wind from fans that flow higher air do not affect the temperature conditions of the tower in the hydroponic system because the temperature is still lower than the surrounding temperature.

At a fan speed of 4.5 m/s and 15 minutes of misting, the high temperature is shown in the gusts of wind from the fan with a lighter green color (Figure 4c). The lowest temperature is on the floor with values ranging from 30.14 ℃ and the highest temperature is 33.57 ℃. The temperature on the surface of the tower system in hydroponics is lower than the indoor temperature marked by an increasingly dense green color.

The simulation results in Table 3 indicate that fan speed significantly influences the temperature distribution within the greenhouse. At 08:00, temperatures across all treatments remain relatively similar, with values ranging from 26.42–28.11 °C, showing minimal effect of fan operation in the cooler morning hours. However, at 13:00, when external conditions are hottest, the difference becomes more pronounced: without fan operation, temperatures reach as high as 37.72 °C, whereas using fans at speeds of 3.5 m/s and 4.5 m/s reduces maximum temperatures to 35.47 °C. By 16:00, the no-fan condition still records a relatively high maximum temperature of 35.11 °C, while the use of a fan at 4.5 m/s lowers it to 33.57 °C. Based on the overall simulation results of the temperature distribution in the greenhouse for each treatment, it can be seen that the highest temperature is generally located on the roof of the greenhouse. This is due to the natural convection process in the greenhouse room. The tower system area in hydroponics when misting is used shows a lower temperature than the temperature that dominates the environment. This is because the misting used is located at the top of the tower system in hydroponics, causing a decrease in temperature at that location.

Table 3. Minimum and maximum temperatures resulted from simulation

Time	Speed 0 (No fan)		Speed 3.5 m/s		Speed 4.5 m/s	
	Min	Max	Min	Max	Min	Max
08:00	26.42	27.89	26.57	28.15	26.55	28.11
13:00	35.00	37.72	32.25	35.47	32.25	35.47
16:00	30.44	35.11	33.21	33.21	30.14	33.57

3.2.2. Distribution of RH greenhouses

3.2.2.1. RH at 08.00

Distribution of RH in each treatment at 08.00 is shown in Figure 5. In a greenhouse without fans and misting, it can be seen that the lowest RH is dominated by the outlet portion up to half of the greenhouse. then at a fan speed of 3.4 m/s and misting for 15 min the lowest RH comes from the inlet which blows the wind so that the air condition becomes dry and hits the surface of the tower system in hydroponics so that it spreads throughout the room. Distribution of RH tends to be the same in all parts of the greenhouse using fan at speed of 4.5 m/s and 15 min of misting.

3.2.2.2. RH at 13.00

The simulation results of the RH distribution at 13.00 are shown in Figure 6. The condition of the distribution of RH when there is no fan and misting in the greenhouse shows that the lowest RH is in the hydroponic tower system which spreads to the greenhouse. Furthermore, the RH condition at a fan speed of 3.4 m/s and 15 min misting and a fan speed of 4.5 m/s and 15 min misting showed almost uniform results, namely the distribution of RH generated and the inlet which approached the RH of the room.

3.2.2.3. RH at 16.00

The RH simulation results in the three conditions at 16.00 are shown in Figure 7. Distribution of RH at 16.00 from conditions without fan and misting, given a fan speed of 3.4 m/s and 15 min of misting and a fan speed of 4.5 and 15

(a)
(b)
(c)

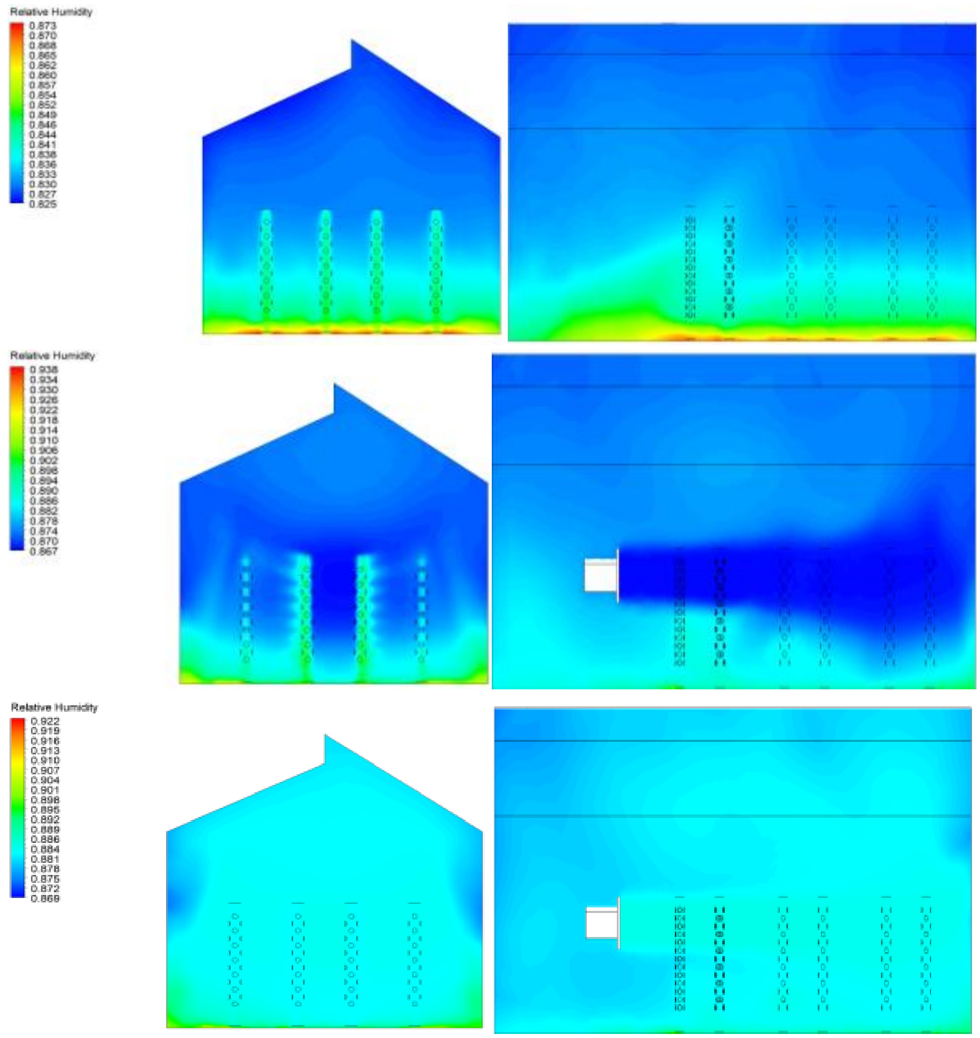

Figure 5. Distribution of RH in the greenhouse at 08.00: (a) No fan no misting, (b) with fan at speed of 3.4 m/s and misting for 15 min, (c) with fan at speed of 4.5 m/s and misting for 15 min

min of misting is shown in Figure 7a to 7c. When the greenhouse is in good condition without fans and misting, it can be seen that the resulting distribution of RH tends to be low with the lowest RH being represented by the tower system area in hydroponics. As for the condition of the RH distribution when given a fan speed of 3.4 m/s and 15 minutes of misting and a fan speed of 4.5 m/s and 15 minutes of misting, the RH distribution results tend to be the same. The inlet flow produces a lower RH than the room RH marked with a more intense blue color. The tower system in hydroponics that gets direct airflow from the fan is seen to produce low RH as well as RH around the fan flow.

The simulation results presented in Table 4 show that fan speed has a significant effect on relative humidity (RH) distribution inside the greenhouse. At 08:00, when environmental conditions are relatively cooler, RH values remain high across all treatments, with the highest RH observed at a fan speed of 4.5 m/s (88–89%) compared to no fan (82.5–83.5%). At 13:00, when temperature typically peaks, RH drops substantially, especially without fan operation (56–57%), whereas the use of fans helps maintain higher RH levels, reaching 69–70% at a speed of 4.5 m/s. By 16:00, RH values begin to recover, with no fan treatment showing 61.5–62.5% and the 4.5 m/s fan speed producing the highest RH at 74–75%. These findings indicate that increasing fan speed, particularly when combined with misting, not only improves temperature regulation but also enhances RH stability, thereby creating a more favorable and consistent microclimate within the greenhouse.

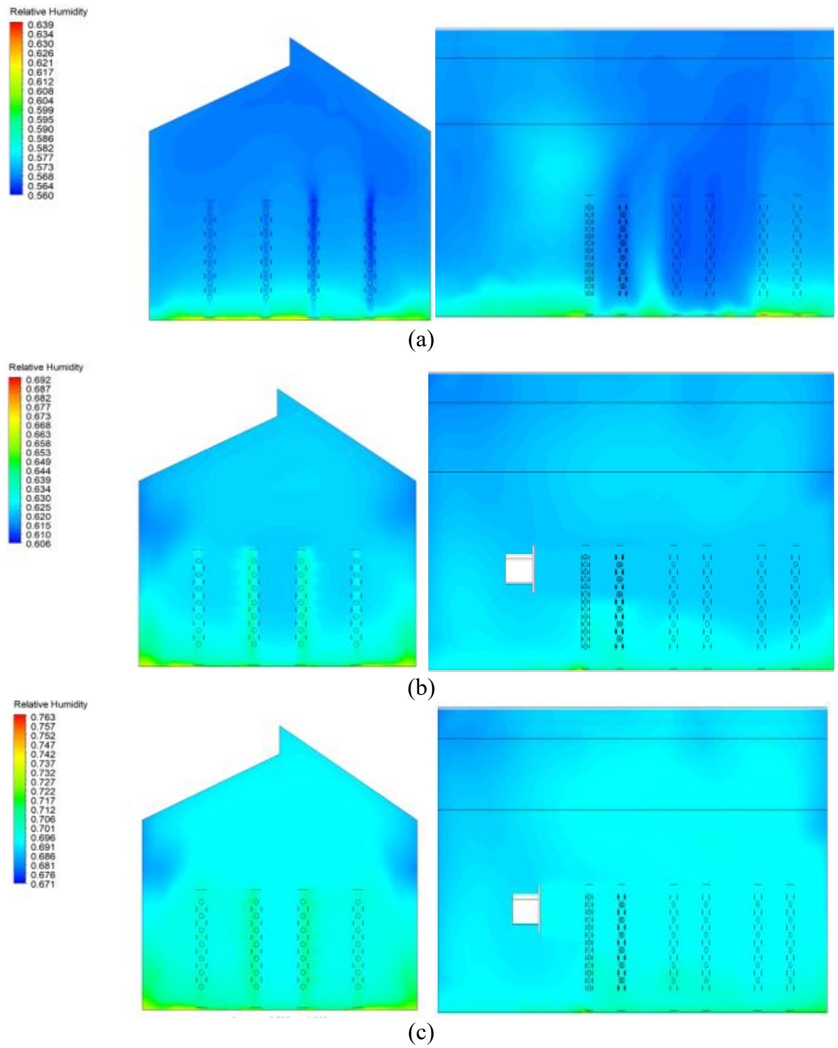

Figure 6. Distribution of RH in the greenhouse at 13.00: (a) No fan no misting, (b) with fan at speed of 3.4 m/s and misting for 15 min, (c) with fan at speed of 4.5 m/s and misting for 15 min

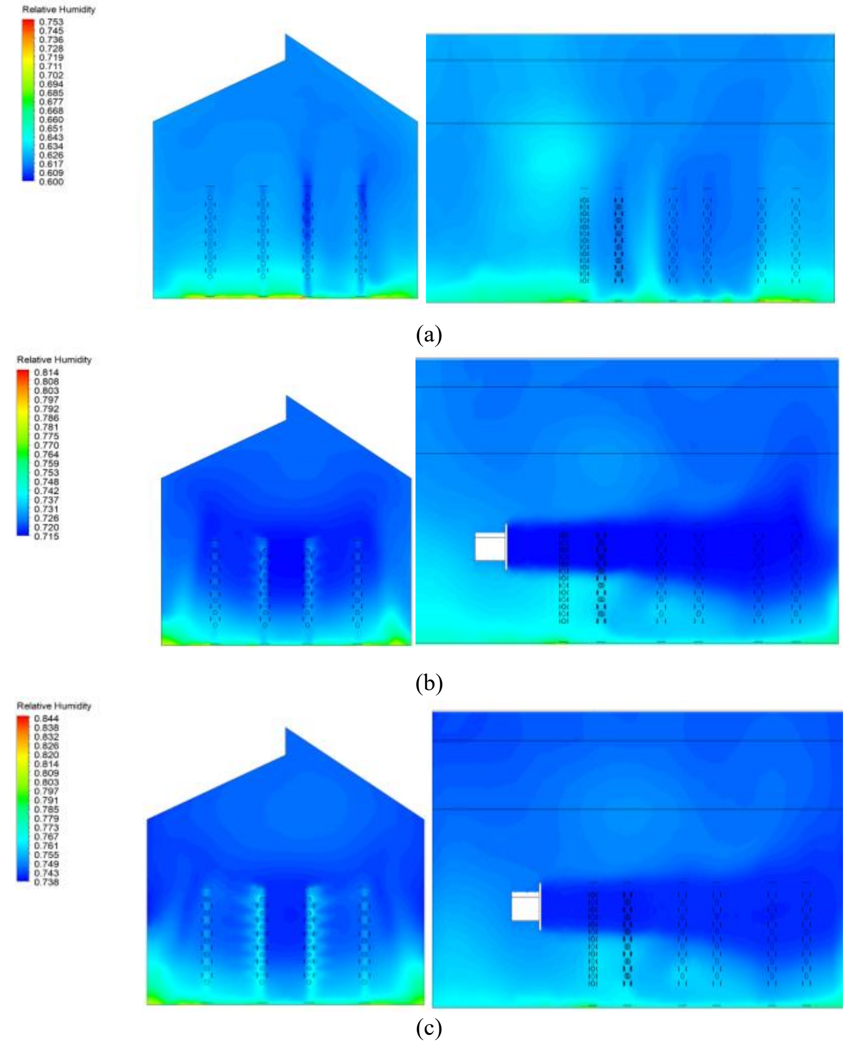

Figure 7. Distribution of RH in the greenhouse at 16.00: (a) No fan no misting, (b) with fan at speed of 3.4 m/s and misting for 15 min, (c) with fan at speed of 4.5 m/s and misting for 15 min

Table 4. Minimum and maximum RH resulted from simulation

Time	Speed 0 (No fan)		Speed 3.5 m/s		Speed 4.5 m/s	
	Min	Max	Min	Max	Min	Max
08.00	82.50.00	83.50.00	86.90	87.50.00	88.00.00	89.00.00
13.00	56.00.00	57.00.00	62.00.00	62.50.00	69.00.00	70.00.00
16.00	61.50.00	62.50.00	71.00.00	72.50.00	74.00.00	75.00.00

3.2.3. Model Validation

After the simulation is carried out, the error value can be compared between the measurement data in the field and the simulation results. The error value in this simulation can be seen in Table 5. Based on the table above, it can be seen that the highest error value was obtained at 1.017%. This shows that the simulation results are in the good range because they do not exceed the simulation error limit value of 10% (Anwar & Panggabean, 2019).

Table 5. Comparison of measurement results and simulation results

Time	Treatment	Temperature (°C)			RH (%)		
		Measurements	Simulation	Error (%)	Measurements	Simulation	Error (%)
08.00	Without fans and misting	27.76	27.71	0.180	83.24	83.17	0.084
	Fan speed 3.4 m/s and misting 15 min	28.35	28.20	0.529	87.02	87.48	0.529
	Fan speed 4.5 m/s and misting 15 min	27.74	27,85	0.397	88.82	88.08	0.833
13.00	Without fans and misting	37.35	37.20	0.402	56.84	56.99	0.264
	Fan speed 3.4 m/s and misting 15 min	35.11	35.14	0.085	62.44	62.20	0.384
	Fan speed 4.5 m/s and misting 15 min	33.83	33.99	0.473	69.85	69.25	0.859
16.00	Without fans and misting	34.14	33.90	0.703	61.69	62.09	0.648
	Fan speed 3.4 m/s and misting 15 min	32.47	32.20	0.832	71.80	72.53	1.017
	Fan speed 4.5 m/s and misting 15 min	32.84	32.71	0.395	74.37	74.73	0.484

4. CONCLUSION

Based on the research conducted, it can be concluded that the distribution of temperature and relative humidity (RH) within the greenhouse is influenced by both internal and external factors. Internally, the use of fans and misting systems plays a crucial role in reducing or regulating temperature to prevent it from becoming excessively high, while external environmental conditions also significantly affect the microclimate inside the greenhouse. A fan operating at a speed of 4.5 m/s combined with misting for 15 minutes is more effective in reducing temperature and achieving a more uniform temperature distribution compared to a fan with a speed of 3.4 m/s and the same misting duration, as observed at all three observation times. The hydroponic tower system located at the center of the greenhouse benefits more from the cooling effect of the fan airflow than those positioned near the greenhouse walls. The low RH flow observed in the overall simulation results with fan treatment originates from the inlet area. Furthermore, the simulation error rate for all treatments is below 10%, indicating that the simulation results are accurate and reliable. The hydroponic system should be positioned in areas that receive optimal airflow from the fan, and continuous monitoring of temperature and humidity is necessary to ensure a stable microclimate that supports plant growth. Future research should explore different misting durations and intervals, as well as variations in fan position and number, to optimize cooling efficiency and temperature uniformity. Additionally, energy consumption analysis and evaluations of microclimate effects on actual plant growth are recommended to ensure both technical and economic effectiveness.

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