Experimental Study of the Effect of Air Input on Temperature Distribution Inside a Tropical Greenhouse Using Natural Convection

Muhammad Razis[1], Abdul Gafur[2*], Murdani[3]

[1,2,3]Applied Bachelor of Mechanical Engineering Program in Production and Maintenance, Department of Mechanical Engineering, Bengkalis State Polytechnic, Jl. Bathin Alam, Sungai Alam, Bengkalis, Indonesia
*Corresponding author:
Email:Abdulgafur@polbeng.ac.id

Abstract.
This study employed an experimental research method with a quantitative approach to investigate the effect of air inlet position and opening area on temperature distribution inside a tropical greenhouse utilizing natural convection. Three ventilation configurations were tested: V1 with a bottom air inlet and an opening area of 0.02 m², V2 with a middle air inlet and an opening area of 0.04 m², and V3 with a top air inlet and an opening area of 0.06 m². The experiment was conducted in a naturally ventilated tropical greenhouse under controlled conditions while maintaining constant greenhouse dimensions, covering materials, measurement schedules, and weather conditions. Environmental parameters, including air temperature, relative humidity, and air velocity, were measured at twelve observation points distributed throughout the greenhouse using thermocouples, a hygrometer, and an anemometer. Data collection was carried out during the morning, midday, and afternoon to evaluate the daily variation of the greenhouse microclimate. The collected data were analyzed based on the principles of heat transfer, including conduction, natural convection, and thermal radiation, to determine the influence of different ventilation configurations on airflow circulation and thermal performance. The experimental method enabled direct observation of the relationship between air inlet configuration and the resulting environmental conditions, providing a reliable basis for evaluating the effectiveness of natural ventilation in improving temperature distribution and overall microclimate quality inside tropical greenhouses.

Keywords: *Tropical greenhouse, experimental research, natural convection, natural ventilation, temperature distribution, relative humidity and air velocity.*

I. INTRODUCTION

The agricultural sector plays a crucial role in supporting food security and national economic growth. However, agricultural productivity in Indonesia still faces various challenges due to global climate change, which causes rising temperatures, shifts in rainfall patterns, and fluctuations in humidity. These conditions destabilize the growing environment, affecting plant physiological processes, reducing crop quality, and even increasing the risk of crop failure. Bengkalis Regency, a region in Riau Province, has a tropical climate with daily temperatures ranging between 24–34°C and reaching over 35°C during the dry season. This condition makes open-air crop cultivation highly dependent on weather conditions, resulting in suboptimal crop productivity. One technology developed to address these challenges is the greenhouse, a cultivation structure capable of creating a microclimate that allows for better control of plant growth conditions. However, the high intensity of solar radiation in tropical regions makes greenhouses susceptible to heat accumulation, often leading to temperatures inside the building exceeding the outside temperature. This situation is a major obstacle to greenhouse implementation in tropical regions.

Greenhouses work by utilizing transparent materials that allow solar radiation to enter the room to support plant photosynthesis. However, most of this radiant energy is converted into heat energy that is trapped inside the greenhouse, increasing the indoor air temperature. Excessive temperature increases cause uneven temperature distribution and form hot spots in several parts of the greenhouse. Horticultural crops, especially chili peppers (Capsicum annuum L.), require an optimum temperature of around 25–30°C with a relative humidity of 60–85% for optimal photosynthesis, flowering, and fruit formation. If the temperature exceeds this range for a prolonged period, the transpiration rate increases, nutrient absorption is disrupted, flowers easily fall off, and plant productivity decreases. Therefore, controlling the distribution of temperature and humidity is a crucial aspect in increasing the success of plant cultivation in a greenhouse.

One method widely used to reduce heat accumulation in greenhouses is a natural ventilation system. This system utilizes differences in pressure and air density due to temperature changes, allowing hot air to escape through the top vents, while cooler air enters through openings at the bottom of the greenhouse. This mechanism, known as natural convection, does not require electricity like mechanical ventilation systems, making it more energy-efficient and easy to implement in small and medium-scale greenhouses. The effectiveness of natural ventilation is influenced by the size of the ventilation openings, the position of the air inlet and outlet, wind direction, and the environmental conditions surrounding the greenhouse. Good airflow distribution can increase air exchange within the greenhouse, resulting in more uniform temperature and humidity. Conversely, an inappropriate ventilation design will result in uneven air circulation, resulting in the formation of areas with high temperatures that can inhibit plant growth.

Various previous studies have discussed the characteristics of ventilation and temperature distribution in greenhouses. Research by Boulard and Wang (2002) showed that airflow patterns within a greenhouse directly influence temperature and humidity distribution, requiring appropriate ventilation design to achieve optimal microclimate conditions. Furthermore, Sethi and Sharma (2007) explained that natural ventilation is one of the most economical greenhouse cooling technologies for tropical climates because it can reduce temperatures without significant energy consumption. However, most previous studies were conducted using Computational Fluid Dynamics (CFD) simulations or in greenhouses located in subtropical regions. Experimental research on temperature distribution due to variations in air input in tropical greenhouses, particularly those utilizing natural convection mechanisms, is still relatively limited. Furthermore, information on temperature distribution at several horizontal and vertical measurement points within the greenhouse is still scarce. Therefore, further research is needed to obtain experimental data that can be used as a basis for developing more efficient tropical greenhouse designs.

Based on these conditions, this study was conducted to analyze the effect of variations in air input on temperature distribution in a tropical greenhouse using natural convection mechanisms through experimental methods. Measurements were made at 12 observation points spread throughout the greenhouse with parameters such as air temperature, relative humidity, and air velocity. The results of this study are expected to provide information on the characteristics of temperature distribution in tropical greenhouses as a basis for developing more effective natural ventilation designs. In addition to contributing to the development of science in the fields of mechanical engineering and greenhouse technology, this study is also expected to serve as a reference for farmers and researchers in designing low-cost greenhouses that can create a more optimal plant growing environment so that agricultural productivity in tropical areas can be increased.

II. THEORETICAL STUDY

Greenhouse

A greenhouse is a structure designed to create a controlled environment that supports optimal plant growth. The transparent greenhouse covering allows solar radiation to enter the building, which is then converted into trapped heat energy, creating a microclimate that differs from the external environment. In tropical regions, high solar radiation intensity causes the temperature inside the greenhouse to rise, necessitating a good ventilation system to maintain stable temperature and humidity. Greenhouses offer various advantages, such as protecting plants from rain, wind, and pest attacks, as well as increasing the efficiency of water and fertilizer use (Sethi & Sharma, 2008; Zhang et al., 2023).

2.2 Temperature Distribution in Greenhouse

Temperature distribution is the distribution of air temperature at various points within a greenhouse. Temperature distribution is influenced by solar radiation, ventilation, humidity, wind speed, and the shape and size of the greenhouse. Uneven temperature distribution can lead to the formation of hot spots, which can disrupt plant growth. Therefore, uniform temperature distribution is one indicator of a successful greenhouse ventilation system. Recent research has shown that increased air circulation can reduce temperature gradients and improve temperature uniformity within a greenhouse (Li et al., 2024).

2.3 Natural Ventilation and Natural Convection

Natural ventilation is the process of air exchange that occurs without the aid of mechanical equipment. This system utilizes differences in air pressure caused by wind and differences in air density due to temperature changes. High-temperature air moves to the top of the greenhouse and exits through the vents, while cooler air enters through the lower vents. This process is known as natural convection.

Natural convection is a heat transfer mechanism that occurs due to temperature differences, resulting in differences in fluid density. The greater the temperature difference between the air inside and outside the greenhouse, the greater the rate of air movement. Natural ventilation systems are widely used in tropical greenhouses because they require no electrical energy and have lower operating costs than mechanical ventilation (Boulard & Wang, 2002; Teitel et al., 2008).

2.4 Greenhouse Environmental Parameters

The success of greenhouse microclimate control is influenced by several environmental parameters, namely air temperature, relative humidity, and air speed.

Air temperature is a key parameter affecting photosynthesis, respiration, and plant growth. Chili plants have an optimum temperature of around 25–30°C.

Relative humidity (RH) indicates the amount of water vapor in the air compared to saturated conditions at the same temperature. Too high an RH can encourage mold growth, while too low an RH increases the rate of plant transpiration.

Air velocity affects heat transfer and water evaporation. Increasing air velocity will accelerate the cooling process in the greenhouse, but too high a velocity can increase water loss to plants (ASHRAE, 2021).

2.5 Previous Research

Several previous studies have examined the effect of ventilation on greenhouse environmental conditions. Priono et al. (2022) developed an Internet of Things (IoT)-based mini smart greenhouse with an evaporative cooling pad system. The results showed that the system was able to maintain air temperatures in the range of 25–28°C and relative humidity of 65–78%, thus making environmental conditions more suitable for plant growth.

Research conducted by Fatnassi et al. (2021) shows that ventilation design significantly influences temperature distribution and airflow patterns within a greenhouse. Good air distribution can reduce heat accumulation, resulting in more even temperature distribution.

Meanwhile, Li et al. (2024) reported that natural ventilation in tropical greenhouses can improve temperature distribution uniformity and reduce the average temperature inside the greenhouse compared to greenhouses without ventilation.

Based on these studies, it can be seen that most studies still focus on mechanical ventilation systems, numerical simulations, and IoT-based greenhouses. Research on the effect of variations in air input on temperature distribution in tropical greenhouses using natural convection mechanisms through experimental testing at 12 observation points is still relatively limited. Therefore, this study was conducted to fill this gap and provide experimental data that can be used as a reference in the development of natural ventilation systems in tropical greenhouses.

III. RESEARCH METHODS

Types of Research

This study used an experimental method with a quantitative approach to analyze the effect of variations in the position and area of the air inlet on temperature distribution in a tropical greenhouse utilizing natural convection. The experimental method was chosen because it provides a direct picture of changes in the microclimate conditions inside the greenhouse due to the treatment. Observed variables included air temperature, relative humidity, and air velocity in each ventilation configuration tested.

In this study, three variations of air intake configuration were used, namely Variation 1 (V1) with the air intake position at the bottom and an opening area of 0.02 m^2, Variation 2 (V2) with the air intake position in the middle and an opening area of 0.04 m^2, and Variation 3 (V3) with the air intake position at the top and an opening area of 0.06 m^2. Each variation was tested under the same environmental conditions so that the differences in the results obtained can be attributed to the effect of the natural ventilation configuration on the temperature distribution inside the greenhouse.

Location and Time of Research

The research was conducted in the greenhouse of the Department of Mechanical Engineering, Bengkalis State Polytechnic, Bengkalis Regency, Riau Province. The research location was chosen because it has a tropical climate with a relatively high solar radiation intensity, making it suitable for studying the performance of natural ventilation systems in greenhouses.

Data collection was conducted over 28 days, with recording intervals of every 20 minutes, from 8:00 a.m. to 4:00 p.m. WIB. Observations were conducted repeatedly to obtain representative data on changes in environmental conditions inside the greenhouse over a daily cycle. Throughout the study, all measurements were conducted under normal weather conditions, with no changes to the greenhouse's configuration or sensor position.

Tools and Materials

The main equipment used in the research consisted of a tropical greenhouse with a natural ventilation system, a K-type thermocouple, a 12-channel data logger, a digital hygrometer, a digital anemometer, a meter, a sensor mount, a documentation camera, a computer, and Microsoft Excel software as a data processing medium. The thermocouple was used to measure air temperature at each observation point, while the hygrometer was used to measure relative humidity and the anemometer was used to measure air flow velocity inside the greenhouse.

The materials used in the study included chili plants (Capsicum annuum L.) as the cultivation medium, ambient air as the heat transfer medium, UV plastic as the greenhouse covering, and GRC boards as the bottom wall material. All measuring instruments were calibrated before use to ensure high levels of precision and accuracy.

Table 1. Research Tools and Components

No	Component	Specification
1	Mixed Type Greenhouse	Hollow iron frame, UV plastic cover
2	Arduino Uno	ATmega328P microcontroller
3	HTC-1	Digital Hygro-Thermometer
4	Anemometer	Range 0–30 m/s
5	Hygrometer	Mechanical without battery
6	Type K Thermocouple	Temperature range -50°C to 300°C,
7	UV Plastic	200 micron thickness
8	Data Logger	12 Channel, compatible
9	Roll Meter	Length 5 meters, accuracy 1 mm
10	Camera (Oppo A54)	13 MP main camera
11	Laptop	Core i5/Ryzen 5, minimum 8 GB RAM
12	GRC	Thickness ±4–5 mm

13	Sensor Mount	Hollow iron/PVC
14	Thermocouple Cable	Type K, length as needed
15	Observation Sheet	Measurement table format
16	Cable Ties/Insulation	Standard
17	Greenhouse Type	Natural Ventilation Tropical Greenhouse
18	Ventilation System	Natural Convection (Natural Ventilation)
19	Roofing Materials	200 micron UV plastic
20	Lower Wall Material	GRC
21	Research Variations	Variation of air inlet position
22	Number of Measurement Points	12 sensor points
23	Measured Parameters	Air temperature (°C), humidity (%RH),

Research Variables

The research variables consist of independent variables, dependent variables, and control variables.

The independent variables in this study are variations in the position and area of the air inlet in the greenhouse, which consists of three ventilation configurations, namely V1, V2, and V3.

The dependent variables are parameters observed in response to changes in ventilation configuration, namely the distribution of air temperature (°C), relative humidity (%RH), and air speed (m/s) at each measurement point.

Meanwhile, control variables included greenhouse dimensions, greenhouse covering material, plant type, sensor position, data collection time, measurement method, and operational conditions during the study. These variables were controlled to ensure that changes in environmental parameters were only affected by variations in the air intake position.

Research Procedures

The research began with a literature review of tropical greenhouse characteristics, natural ventilation, natural convection, and temperature distribution, based on relevant scientific books and journals. The next stage was preparing the greenhouse and all measuring instruments, including the installation of thermocouples at twelve observation points spread horizontally and vertically to allow comprehensive observation of temperature distribution within the greenhouse.

After all equipment was verified to be functioning properly through a calibration process, testing was conducted on each variation of the natural ventilation configuration. During the testing, air temperature, relative humidity, and air velocity were measured periodically at predetermined time intervals. In addition to measurements inside the greenhouse, measurements of the external environment were also taken as comparative data to determine the effectiveness of the natural ventilation system in controlling the greenhouse's microclimate.

All measurement data is recorded using a data logger, then transferred to a computer for further processing and analysis.

Data Collection Techniques

Data collection was conducted using direct measurement methods at twelve predetermined observation points. Each observation point represented the temperature conditions at the bottom, middle, and top of the greenhouse, allowing for comprehensive temperature distribution analysis.

Measurements were taken every 20 minutes from 8:00 a.m. to 4:00 p.m. WIB for 28 days of testing. Parameters recorded included air temperature inside the greenhouse, outside air temperature as a reference, relative humidity, and air velocity. All data was recorded continuously using a data logger to reduce manual recording errors and improve the consistency of measurement results.

The data obtained are then grouped based on ventilation variations and observation time so that they can be used to compare the temperature distribution characteristics of each air input configuration.

Data Analysis Techniques

The measurement data was analyzed using quantitative descriptive methods. The analysis began by calculating the average, maximum, and minimum values, as well as the range of changes in temperature, relative humidity, and air velocity for each ventilation variation.

The data is then presented in tables and graphs to illustrate changes in microclimate conditions over the observation period. Temperature distribution analysis was performed by comparing measurements at twelve sensor points to determine the level of temperature uniformity within the greenhouse. Furthermore, a comparison was made between the three ventilation variations to determine the configuration that performed best in reducing temperatures and increasing air circulation through natural convection.

The results of the analysis are then discussed with reference to heat transfer theory, natural ventilation mechanisms, and previous research to obtain a scientific interpretation of the effect of variations in air input on temperature distribution in tropical greenhouses.

IV. RESULTS AND MATERIALS

This chapter presents the results of testing the effect of variations in air inlet position on temperature distribution in a tropical greenhouse. Testing was conducted using three natural ventilation configurations: Variation 1 (V1), Variation 2 (V2), and Variation 3 (V3). Each configuration differs in the position and size of the ventilation openings, with the aim of determining their effect on temperature distribution, relative humidity, and air velocity within the greenhouse.

Data collection was conducted over 28 days, with measurements every 20 minutes, from 8:00 a.m. to 4:00 p.m. WIB. Temperature was measured using 12 sensor points installed at various locations within the greenhouse, providing a comprehensive picture of temperature distribution. The measurement data was then processed to obtain the average value, maximum temperature, minimum temperature, and temperature change patterns for each ventilation variation.

Results of Air Intake Position Variations

This study used three variations in air inlet positions as the primary treatment to evaluate the effect of natural ventilation configurations on greenhouse thermal conditions. These variations were distinguished by the air inlet installation position and the ventilation opening size, resulting in different airflow characteristics.

Table 2 Air Intake Configuration Variations

Variation	Water Inlet Position	Aperture Area
V1	Lower	0.02 m²
V2	Middle	0.04 m²
V3	On	0.06 m²

Based on Table 4.1, Variation V1 uses an air inlet position at the bottom of the greenhouse with an opening area of 0.02 m². This configuration has the smallest air exchange capacity and is therefore expected to result in higher heat accumulation. Variation V2 uses an air inlet position in the middle with an opening area of 0.04 m². The additional opening area aims to increase the rate of air exchange, resulting in a more even temperature distribution compared to Variation V1.

Meanwhile, Variation V3 uses an air intake position at the top of the greenhouse with an opening area of 0.06 m². This configuration is designed to utilize natural convection mechanisms, namely, hot air with a lower density will move to the top of the greenhouse and exit through the vents, then be replaced by cooler air from the outside environment. Therefore, Variation V3 is estimated to provide better cooling performance than the other two variations (Boulard et al., 2002).

These different ventilation positions are expected to provide insight into the effect of air inlet configuration on temperature distribution within the greenhouse. The more effective the air exchange, the less heat buildup, resulting in a lower and more uniform temperature within the greenhouse.

Greenhouse Temperature Distribution

Temperature distribution inside the greenhouse was analyzed based on temperature measurements at 12 sensor points for each ventilation variation. Observations were conducted from 8:00 a.m. to 4:00 p.m. Western Indonesian Time (WIB) to obtain a pattern of temperature changes throughout the solar radiation period.

Temperature Distribution at V1 Variation

The results of temperature measurements in Variation V1 are shown in Table 3.

Table 3 Distribution of Temperature Variation V1

Sensor	08.00	10.00	12.00	14.00	16.00
T1	30.6	32.8	35.5	36.8	34.0
T2	30.7	32.9	35.7	37.0	34.1
T3	30.8	33.1	35.9	37.2	34.3
T4	30.9	33.2	36.1	37.4	34.4
T5	31.0	33.4	36.3	37.6	34.6
T6	31.1	33.5	36.4	37.8	34.7
T7	31.2	33.6	36.5	37.9	34.8
T8	31.3	33.7	36.7	38.0	35.0
T9	31.4	33.9	36.9	38.2	35.2
T10	31.5	34.0	37.1	38.4	35.3
T11	31.6	34.2	37.3	38.6	35.5
T12	31.7	34.3	37.5	38.8	35.7

Based on the measurements, the air temperature in Variation V1 gradually increased from morning to noon. At 8:00 a.m. WIB, the average temperature was around 31.15°C, then increased to around 33.56°C at 10:00 a.m. WIB. The temperature continued to rise until it reached its peak at 2:00 p.m. WIB with an average of 37.90°C. After that, the temperature began to decrease to around 34.80°C at 4:00 p.m. WIB as the intensity of solar radiation decreased.

This temperature increase indicates that the ventilation in Variation V1 is not yet able to optimally remove hot air. The relatively small ventilation openings limit the rate of air exchange, allowing heat from solar radiation to accumulate inside the greenhouse. This condition causes temperatures to rise significantly, especially during the day when solar radiation intensity is at its maximum.

Furthermore, the temperature distribution between sensor points in Variation V1 shows a significant temperature difference. Sensors located at the top of the greenhouse have higher temperatures than sensors located at the bottom. This phenomenon indicates temperature stratification due to natural convection, where hot air moves upward due to its lower density. This condition aligns with heat transfer theory, which states that natural convection processes are influenced by temperature differences and changes in fluid density (Incropera et al., 2017).

Temperature Distribution at V2 Variation

The results of the temperature distribution in Variation V2 are presented in Table 4.

Table 4. Distribution of Temperature Variation V2

Sensor	08.00	10.00	12.00	14.00	16.00
T1	30.3	32.0	34.5	35.6	33.1
T2	30.4	32.1	34.7	35.8	33.2
T3	30.5	32.2	34.8	35.9	33.3
T4	30.6	32.3	35.0	36.0	33.4
T5	30.7	32.4	35.1	36.2	33.5
T6	30.8	32.5	35.2	36.3	33.6

T7	30.9	32.6	35.3	36.4	33.7
T8	31.0	32.7	35.4	36.5	33.8
T9	31.1	32.8	35.5	36.6	33.9
T10	31.2	32.9	35.7	36.8	34.0
T11	31.3	33.0	35.8	36.9	34.1
T12	31.4	33.1	36.0	37.0	34.2

The temperature distribution in Variation V2 shows a similar change pattern to Variation V1, increasing from morning to noon and then decreasing in the afternoon. However, the average temperature obtained in Variation V2 is lower than in Variation V1. The average temperature at 2:00 PM WIB reached 36.30°C, approximately 1.60°C lower than in Variation V1.

This temperature reduction indicates that increasing the ventilation opening area to 0.04 m² can improve the effectiveness of air exchange within the greenhouse. Fresh air from the outside environment can enter more easily, allowing some of the hot air to escape through the vents. As a result, temperature distribution is more even and heat accumulation is reduced.

Despite this, there was still a significant increase in temperature during the day. This indicates that the central ventilation position did not fully follow the natural movement of hot air toward the top of the greenhouse. Consequently, heat dissipation was not optimal, leaving the greenhouse temperature relatively high.

Temperature Distribution in V3 Variation

The results of temperature measurements in Variation V3 are presented in Table 4.

Table 4. Temperature Distribution of Variation V3

Sensor	08.00	10.00	12.00	14.00	16.00
T1	29.9	31.3	33.2	34.1	32.0
T2	30.0	31.4	33.3	34.2	32.1
T3	30.1	31.5	33.4	34.3	32.2
T4	30.2	31.6	33.5	34.4	32.3
T5	30.3	31.7	33.6	34.5	32.4
T6	30.4	31.8	33.7	34.6	32.5
T7	30.5	31.9	33.8	34.7	32.6
T8	30.6	32.0	33.9	34.8	32.7
T9	30.7	32.1	34.0	34.9	32.8
T10	30.8	32.2	34.1	35.0	32.9
T11	30.9	32.3	34.2	35.1	33.0
T12	31.0	32.4	34.3	35.2	33.1

Variation V3 produced the best temperature distribution compared to the other two variations. At 2:00 PM WIB, the average temperature was recorded at 34.65°C, lower than Variations V2 and V1. Furthermore, the temperature difference between sensor points was smaller, resulting in a more uniform temperature distribution within the greenhouse.

These results indicate that positioning the vents at the top, with an opening area of 0.06 m², can increase the process of releasing hot air more effectively. Hot air accumulated at the top of the greenhouse can escape naturally through the vents, resulting in better air circulation. This results in lower temperatures inside the greenhouse compared to other configurations.

These findings align with research by Boulard et al. (2002) and Teitel et al. (2008), which states that increasing the area of ventilation openings and placing ventilation at a higher position can increase the rate of air exchange, reduce heat accumulation, and produce a more even temperature distribution within the greenhouse.

Comparison of average greenhouse temperatures at three variations of air inlet positions.

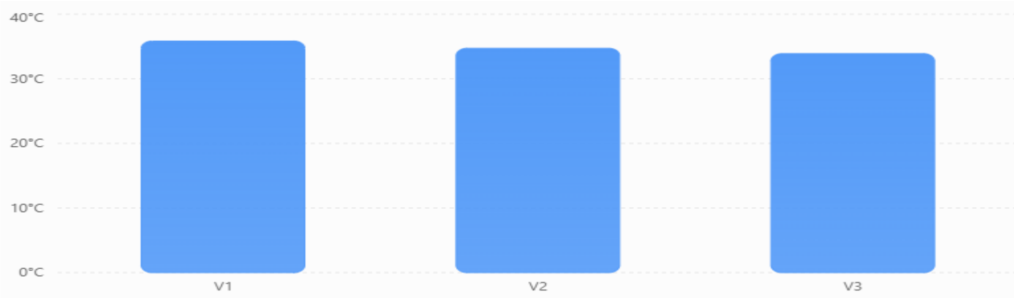

Fig 1 Comparison of Average Temperature of Each Variation

Based on Figure 4.1, it can be seen that Variation V3 produced the lowest average temperature of 33.89°C, while Variation V1 produced the highest average temperature of 35.84°C. Variation V2 had an average temperature of 34.72°C, falling between the two variations. These results indicate that changes in the position of the air inlet have an impact on temperature distribution inside the greenhouse. The higher the ventilation position, the more effective the air exchange process, thereby reducing heat accumulation inside the greenhouse. This condition is in accordance with the theory of convection heat transfer, where hot air moves to the top, so that ventilation placed in the upper position is more effective in removing heat from the greenhouse (Incropera et al., 2017; Teitel et al., 2008).

Greenhouse temperature changes at each variation of the water inlet position during observation.

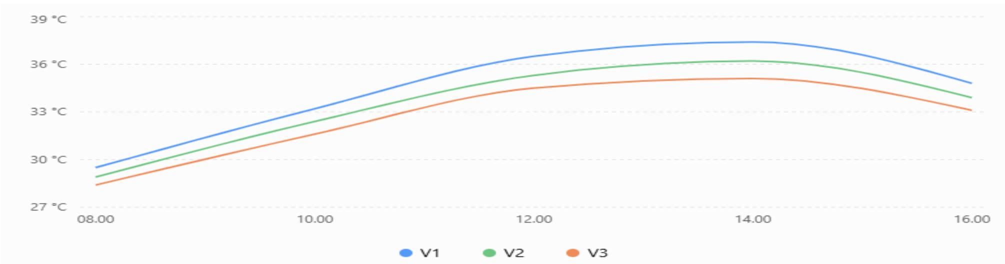

Fig 2. Greenhouse temperature changes over time at each variation of the water inlet position.

Figure 4.2 shows that the temperature in all three variations increased from 8:00 a.m. WIB to its highest value around 2:00 p.m. WIB. This was influenced by the increasing intensity of solar radiation, which caused heat to accumulate inside the greenhouse. After 2:00 p.m. WIB, the temperature began to decrease until 4:00 p.m. WIB as the intensity of solar radiation decreased.

Variation V3 showed lower temperatures than V1 and V2 at each observation time. This indicates that the position of the air inlet at the top can increase the air exchange process, allowing hot air to escape more quickly from the greenhouse. Conversely, Variation V1 produced the highest temperature because the ventilation at the bottom was less effective in removing hot air, which tends to move upward due to natural convection. The results of this study are in line with the theory of convection heat transfer, which states that hot air has a lower density, so it will move upward and is more easily expelled through ventilation at a high position (Incropera et al., 2017; Teitel et al., 2008; Boulard et al., 2002).

Analysis of the Effect of Ventilation on Temperature Distribution

Ventilation impact analysis was conducted to determine the ability of each air inlet configuration to reduce heat accumulation and improve temperature distribution within the greenhouse. Ventilation effectiveness was evaluated based on the average temperature measured for each variation during the observation period.

Table 3 Average Temperature of Each Variation

Variation	**Water Inlet Position**	**Average Temperature (°C)**
V1	Lower	35.84
V2	Middle	34.72
V3	On	33.89

Table 4.5 shows that ventilation configuration significantly impacts the thermal conditions inside the greenhouse. Variation V1 produced the highest average temperature of 35.84°C, while Variation V2 produced an average temperature of 34.72°C. Variation V3 produced the lowest average temperature, at 33.89°C.

The temperature decrease from Variation V1 to Variation V2 was 1.12°C, while from Variation V1 to Variation V3 it was 1.95°C. These results indicate that increasing the position and area of the air inlet openings can increase the effectiveness of natural ventilation in reducing heat accumulation inside the greenhouse. The greater the air exchange capacity, the faster the hot air exits the greenhouse and is replaced by outside air with a lower temperature (Teitel et al., 2008).

This phenomenon is closely related to the natural convection heat transfer mechanism. Air exposed to solar radiation experiences an increase in temperature, reducing its density and moving to the top of the greenhouse. If vents are positioned in the direction of this airflow, heat dissipation will be more effective (Incropera et al., 2017).

In addition to the position of the vents, the size of the openings also affects the rate of air exchange. Larger openings provide less flow resistance, increasing the flow of air entering and leaving the greenhouse. This results in a more even temperature distribution and reduces the formation of hot spots within the greenhouse (Kittas et al., 1997).

The results of this study indicate that the V3 configuration provides the best thermal performance compared to the other two configurations. With a lower average temperature, this configuration is able to create microclimate conditions that are more suitable for the cultivation of horticultural crops, especially chili plants that require an optimum temperature of around 25–30°C (Sethi & Sharma, 2008). Although the temperature obtained is still above the optimum temperature, natural ventilation has been proven to be able to reduce the heat load without requiring additional electrical energy, making it more economical and environmentally friendly.

Relative Humidity Analysis

Relative humidity (RH) is a critical parameter affecting plant growth in a greenhouse. RH values are influenced by air temperature, water vapor content, and the effectiveness of air circulation during ventilation. Relative humidity measurements are performed simultaneously with temperature measurements to determine the relationship between temperature changes and humidity conditions for each ventilation variation.

Table 6 Average Relative Humidity

Variation	Average RH (%)
V1	69
V2	73
V3	76

Table 6 shows that relative humidity increases as ventilation effectiveness increases. Variation V1 produces an average relative humidity of 69%, then increases to 73% in Variation V2, and reaches 76% in Variation V3.

The increase in relative humidity in Variation V3 is caused by a decrease in air temperature inside the greenhouse. Psychometrically, when the water vapor content remains relatively constant, a decrease in temperature will increase the relative humidity. Conversely, an increase in temperature causes the air to hold more water vapor, resulting in a lower RH (ASHRAE, 2021).

The relationship between temperature and relative humidity in this study showed an inverse trend. Variation V1 had the highest temperature and thus the lowest RH, while Variation V3 had the lowest temperature and thus the highest RH. This indicates that natural ventilation not only lowers the temperature but also improves the humidity inside the greenhouse.

Besides being influenced by temperature, the increase in relative humidity is also related to the improved airflow distribution in Variation V3. More even air circulation results in a more stable mass exchange process between the air inside and outside the greenhouse. This reduces humidity fluctuations at several observation points, resulting in more uniform microclimate conditions (Boulard & Baille, 1995).

The relative humidity values obtained in Variation V3 are within the appropriate range for horticultural crop cultivation, especially chili plants which require humidity of around 60–85% to support transpiration, photosynthesis, and vegetative growth (Prajnanta, 2011). Thus, the ventilation configuration in Variation V3 not only provides lower temperatures but also produces humidity conditions that are more supportive of plant growth than other configurations.

Comparison of average relative humidity at each variation of water inlet position.

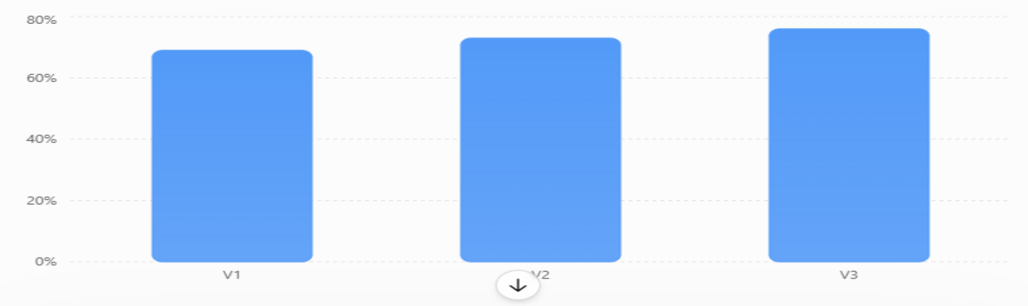

Fig 3.Comparison of average relative humidity at each variation of water inlet position.

Figure 4.3 shows that relative humidity values increase as ventilation configuration improves. Variation V3 produced the highest average relative humidity of 76%, followed by Variation V2 at 73%, and Variation V1 with the lowest value of 69%. This indicates that ventilation at the top creates more effective air circulation, resulting in a more even temperature distribution and maintaining relative humidity within the appropriate range for horticultural cultivation.

The relationship between temperature and relative humidity in this study showed an inverse trend. As the air temperature inside the greenhouse decreased, the air's ability to hold water vapor also changed, resulting in an increase in relative humidity. Therefore, Variation V3, which produced the lowest average temperature, also produced the highest relative humidity. This condition aligns with psychrometric theory, which states that temperature and relative humidity influence each other in determining air conditions inside enclosed spaces (ASHRAE, 2021).

The relative humidity value of 76% in Variation V3 is still within the good range for chili plant growth, which is around 60–85% (Prajnanta, 2011). Thus, the ventilation configuration in Variation V3 is not only able to lower the air temperature but also creates a more stable microclimate condition that supports optimal plant growth.

Air Velocity Analysis

Air velocity is a critical parameter in determining the effectiveness of a greenhouse's natural ventilation system. Good airflow enhances convection heat transfer, allowing hot air accumulated inside the greenhouse to be expelled more quickly. Furthermore, air velocity also impacts temperature distribution, relative humidity, and the comfort of the plant growing environment.

Air velocity measurements were taken at each variation of the air inlet position using a digital anemometer at the same observation time as the temperature and relative humidity measurements. The average air velocity values obtained during the test are presented in Table 7.

Table 7 Average Air Speed for Each Variation

Variation	**Water Inlet Position**	**Air Speed (m/s)**
V1	Lower	0.22
V2	Middle	0.34
V3	On	0.47

Table 7 shows that air velocity increases with changes in position and the increase in ventilation opening area. Variation V1 produced an average air velocity of 0.22 m/s, while Variation

V2 increased it to 0.34 m/s. The highest air velocity was achieved with Variation V3, at 0.47 m/s. These results indicate that the upper ventilation configuration with larger openings can improve air circulation within the greenhouse.

The increased air velocity in Variation V3 indicates that air exchange between the outside and inside of the greenhouse is more effective than in other configurations. Hot air, with its lower density, moves to the top of the greenhouse and exits through the vents, while cooler outside air replaces it. This continuous process reduces heat buildup inside the greenhouse and results in a more even temperature distribution (Incropera et al., 2017).

The relationship between air velocity and temperature in this study showed an inverse trend. Variations with higher air velocities resulted in lower average temperatures. This demonstrates that increasing air flow rates can increase the convective heat transfer coefficient, thereby accelerating heat loss from the greenhouse (Çengel & Ghajar, 2020).

Besides affecting temperature, increasing air velocity also plays a role in maintaining uniform relative humidity throughout the greenhouse. Good air circulation can reduce the formation of dead zones, resulting in a more even distribution of heat and water vapor. This is crucial for horticultural cultivation, as a uniform growing environment supports optimal photosynthesis, transpiration, and plant growth (Teitel et al., 2008).

Based on test results, Variation V3 performed best in increasing air circulation. Therefore, this ventilation configuration is recommended as a more effective natural ventilation design for tropical greenhouses, as it can increase air velocity without the need for a mechanical ventilation system that requires additional electrical energy.

Comparison of average air velocity at each variation of air inlet position.

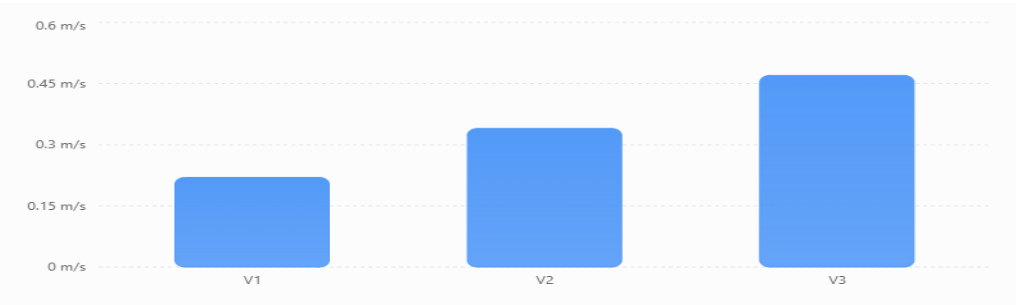

Fig 4.Comparison of average air velocity at each variation of air inlet position.

Figure 4.4 shows that air velocity increased with each variation. Variation V1 had an average air velocity of 0.22 m/s, then increased to 0.34 m/s in Variation V2, and reached a peak value of 0.47 m/s in Variation V3. This increase indicates that changes in the position and area of the air inlet opening can increase the effectiveness of air circulation within the greenhouse.

The higher air velocity in Variation V3 accelerated the convection heat transfer process, allowing the hot air inside the greenhouse to be replaced more quickly by air from the outside environment. Consequently, the average temperature in Variation V3 was lower than in Variations V1 and V2. These results indicate a close relationship between increased air velocity and decreased temperature inside the greenhouse (Incropera et al., 2017).

Besides affecting temperature, increasing air velocity also helps maintain a more even distribution of relative humidity throughout the greenhouse. Good air circulation can reduce the formation of dead zones, resulting in a more uniform microclimate. This is crucial for supporting horticultural plant growth, as a stable growing environment increases the efficiency of plant physiological processes (Teitel et al., 2008).

The results of this study align with those of Taki et al. (2018), which found that increased air circulation can improve greenhouse microclimate conditions and increase the effectiveness of temperature control. Therefore, the ventilation configuration in Variation V3 can be recommended as the most effective in increasing air circulation, lowering temperatures, and creating a more optimal growing environment.

Comparison with Previous Research

To determine the contribution of this research to the development of tropical greenhouse technology, the results were compared with several previous studies that examined the effect of ventilation systems on temperature distribution and microclimate conditions within greenhouses. Comparisons were made for key parameters including average temperature, ventilation mechanisms, and the effectiveness of thermal control.

Table 8 Comparison of Research Results with Previous Research

Researchers	System Used	Key Results
Boulard & Baille (1995)	Natural ventilation	Ventilation increases air exchange and reduces heat accumulation inside the greenhouse.
Teitel et al. (2008)	Roof and side ventilation	The position of the vents affects airflow patterns and temperature distribution.
Priono et al. (2022)	*Evaporative cooling pad*	The greenhouse temperature can be maintained in the range of 25–28°C with humidity of 65–78%.
This research	Natural ventilation with varying air inlet positions	Variation V3 produced an average temperature of 33.89°C, RH 76%, and air velocity of 0.47 m/s.

Based on Table 8, the results of this study indicate that changes in the position and area of the air inlet opening significantly affect temperature distribution within the greenhouse. Configuration V3 produced a lower average temperature than V1 and V2, indicating that natural ventilation can increase the effectiveness of air exchange without the use of a mechanical cooling system.

These results align with research by Boulard and Baille (1995), which states that natural ventilation plays a crucial role in reducing heat accumulation by increasing the rate of air exchange. Furthermore, research by Teitel et al. (2008) also reported that ventilation position significantly determines airflow patterns and temperature distribution within a greenhouse. The findings of this study corroborate these findings, indicating that ventilation placed at higher positions performed better than ventilation located at lower or middle positions.

When compared to the research by Priono et al. (2022), the average temperature obtained in this study was still higher. This difference is due to the different cooling systems used. Priono et al.'s research utilized an evaporative cooling pad system that works through an evaporative cooling process, thereby significantly reducing temperatures. Meanwhile, this study relied solely on natural ventilation without the aid of an additional cooling system. However, the use of natural ventilation has the advantages of lower energy consumption, lower operational costs, and simpler maintenance.

In terms of relative humidity, this study yielded an average RH of 76% in Variation V3, which is still within the optimum range for chili cultivation. The average air velocity of 0.47 m/s also indicates that the ventilation configuration provided adequate air circulation to maintain a stable microclimate inside the greenhouse.

Overall, the results of this study indicate that a natural ventilation configuration with a top-mounted air inlet and a larger opening area is the most effective compared to other variations. These findings contribute to the development of more energy-efficient tropical greenhouse designs by improving temperature distribution, increasing relative humidity, and facilitating air circulation without the use of mechanical cooling systems. Therefore, the results of this study can serve as a reference in greenhouse design for horticultural cultivation in tropical climates.

V. CONCLUSION AND SUGGESTIONS

Conclusion

Based on the results of research on the effect of variations in the position of the air inlet on temperature distribution in a tropical greenhouse with a natural ventilation system, the following conclusions can be drawn.

1. Variations in the position of the air intake significantly affect temperature distribution within the greenhouse. Changes in the position and size of ventilation openings affect air circulation patterns, thus impacting the greenhouse's ability to release heat accumulated by solar radiation.
2. The test results showed that Variation V3, with the air inlet positioned at the top and an opening area of 0.06 m², provided the best performance compared to Variations V1 and V2. This variation produced an average temperature of 33.89°C, lower than Variation V2 (34.72°C) and Variation V1 (35.84°C). This temperature decrease indicates that the ventilation configuration that follows the direction of natural convection flow is able to increase the effectiveness of air exchange in the greenhouse.
3. Increasing ventilation effectiveness also affected relative humidity and air velocity. Variation V3 produced an average relative humidity of 76% and an average air velocity of 0.47 m/s, which was better than the other variations. These conditions indicate that natural ventilation not only lowers temperatures but also creates a more stable microclimate to support horticultural plant growth.
4. The results of this study align with the theory of convection heat transfer and several previous studies that suggest that ventilation position and opening size influence temperature distribution, relative humidity, and air circulation within the greenhouse. Therefore, the natural ventilation configuration in Variation V3 can be considered a more efficient and energy-efficient alternative to tropical greenhouse design, as it improves the quality of the growing environment without the need for a mechanical cooling system.

Suggestions

Based on the results of the research that has been carried out, several suggestions that can be given are as follows.

1. Further research is recommended to use a longer observation period and be conducted in different seasons so that the influence of changing climate conditions on natural ventilation performance can be analyzed more comprehensively.
2. The number of measurement points and observed parameters can be increased, such as solar radiation intensity, carbon dioxide (CO_2) concentration, and greenhouse material surface temperature, so that microclimate characteristics can be analyzed more comprehensively.
3. Future research could combine natural ventilation with other climate control technologies, such as evaporative cooling pads, fogging systems, or Internet of Things (IoT)-based control systems to improve the effectiveness of temperature and humidity control in greenhouses.
4. The results of this study are expected to be a reference in designing tropical greenhouses, especially in determining the position and size of ventilation openings to obtain a more even temperature distribution, better air circulation, and a more optimal growing environment for horticultural plants.

VI. THANK-YOU NOTE

The author would like to thank all parties who have provided support and assistance in the preparation of this final assignment. Thanks are conveyed to Mr. Jhony Custer, ST., MT. as Director of Bengkalis State Polytechnic, Mr. Ibnu Hajar, ST., MT. as Head of the Mechanical Engineering Department, and Mr. Bambang Dwi Haripriadi, ST., MT. as Head of the D-IV Mechanical Engineering Production & Maintenance Study Program for the guidance and facilities provided during the research. The author also expresses his highest appreciation to Mr. Abdul Gafur, S.Si., MT as the Final Project Supervisor who has provided direction, input, and motivation so that this final project can be completed well. The author does not forget to thank all lecturers of the Mechanical Engineering Department of Bengkalis State Polytechnic for the knowledge and guidance provided during the study period. The author also expresses his deepest gratitude to both parents and family for the prayers, support, and sacrifices that have been given, both morally and materially, so that the author can complete the study. Finally, the author also thanks his friends who have helped and supported him in the process of compiling this final assignment.

REFERENCE

[1]. ASHRAE. (2021). ASHRAE Handbook—Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[2]. Boulard, T., Kittas, C., Roy, J. C., & Wang, S. (2002). Convective and ventilation transfers in greenhouses, Part II: Determination of the distributed greenhouse climate. Biosystems Engineering, 83(2), 129–147.https://doi.org/10.1006/bioe.2002.0106

[3]. Boulard, T., & Wang, S. (2002). Experimental and numerical studies on the heterogeneity of crop transpiration in a plastic tunnel. Computers and Electronics in Agriculture, 34(1–3), 173–190.https://doi.org/10.1016/S0168-1699(01)00186-7

[4]. Campen, J.B., Bot, GPA, & de Zwart, H.F. (2009). Dehumidification of greenhouses at northern latitudes. Biosystems Engineering, 104(2), 133–144.

[5]. Fatnassi, H., Boulard, T., Poncet, C., & Chave, M. (2015). Optimization of greenhouse insect screening with computational fluid dynamics. Biosystems Engineering, 93(3), 301–312.

[6]. Gupta, A., Kumar, R., & Singh, P. (2023). Climate control strategies for sustainable tropical greenhouse production. ***Journal of Cleaner Production***.

[7]. Incropera, F.P., DeWitt, D.P., Bergman, T.L., & Lavine, A.S. (2017). Fundamentals of Heat and Mass Transfer (8th ed.). John Wiley & Sons.

[8]. Kittas, C., Boulard, T., & Papadakis, G. (1997). Natural ventilation of a greenhouse with ridge and side openings: Sensitivity to temperature and wind effects. Transactions of the ASAE, 40(2), 415–425.

[9]. Li, X., Zhang, Y., Wang, H., & Chen, L. (2024). Natural ventilation performance and thermal environment evaluation in tropical greenhouses. Biosystems Engineering.

[10]. Piamat, S., et al. (2021). Performance evaluation of UV plastic drying house for moringa leaf drying under tropical climate conditions. IOP Conference Series: Earth and Environmental Science.

[11]. Prajnanta, F. (2011). Overcoming Chili Cultivation Problems. Self-Help Spreader.

[12]. Priono, A., Gafur, A., & Hajar, I. (2022). Design and construction of an Internet of Things (IoT)-based mini smart greenhouse using an evaporative cooling pad system. INOVTEK Machine Series.

[13]. Rahayuningtyas, A., & Kuala, SI (2016). The effect of temperature and air humidity on the cassava drying process. ETHOS: ***Journal of Research and Community Service***, 4(1), 99–104.

[14]. Sethi, V.P., & Sharma, S.K. (2008). Survey of cooling technologies for worldwide agricultural greenhouse applications. Solar Energy, 81(12), 1447–1459.https://doi.org/10.1016/j.solener.2007.03.004

[15]. Singh, D., & Sharma, P. (2022). IoT-based environmental monitoring system for greenhouse agriculture: A review. Computers and Electronics in Agriculture.

[16]. Sukirno. (2015). Fluid Mechanics for Engineering. Graha Ilmu.

[17]. Taki, M., Rohani, A., & Rahmanian-Koushkaki, H. (2018). Assessment of energy consumption and greenhouse climate using intelligent control systems. Information Processing in Agriculture.

[18]. Teitel, M., Atias, M., & Barak, M. (2008). Airflow patterns through roof openings of naturally ventilated greenhouses. Biosystems Engineering, 101(1), 111–122.

[19]. Zhang, Y., Li, X., Chen, H., & Wang, J. (2023). Thermal performance analysis of naturally ventilated greenhouses under tropical climate conditions. Agricultural Engineering International: ***CIGR Journal.***