Thermal characteristics of a naturally ventilated greenhouse under tropical climatic condition

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Abstract. The thermal characteristics of a naturally ventilated greenhouse that is covered with transparent plastic roofing and insect-proof net screen sidewall was studied. An experiment was carried out by measuring the daytime indoor temperature of a prototype greenhouse under the tropical climatic condition. Result showed that both the ground floor surface as well as the space near the greenhouse roofing attained higher temperature compared to the middle space of the greenhouse. Further, the middle space of the greenhouse exhibit lower air temperature than the upper and lower near corner spaces. The probability that the indoor temperature of the greenhouse will exceed 30°C was observed to be almost 50%. Based on the result, there is a need to enhance the thermal performance of the present configuration of the prototype greenhouse in order to attain a uniform and reduced temperature suitable to most tropical greenhouse plants during the relatively dry season of the year.

1. Introduction

Protected cultivation has been widely adopted to sustain crop production especially in regions of adverse climatic condition. In tropical climates, greenhouses are used to provide a favorable microclimate environment to protect the plants from extreme heat, heavy rain and insect pests. However, a high indoor air temperature of the conventional tropical greenhouses than the outside ambient air has been a major issue in providing a suitable growing condition for crop [1]. Thus, cooling techniques such as ventilation (natural and forced), shading/reflection, evaporative cooling (fan-pad system, mist/fog and roof cooling) have been employed in order to reduce the interior temperature of the greenhouse [2]. Employing a cooling system in order to remove the heat added inside a greenhouse requires energy and thus would entail additional cost. Due to this, natural ventilation has been used as an attractive method for controlling greenhouse microclimate because of its economic advantage as it requires less energy and equipment and is the cheapest method of cooling [3,4]. In tropical countries such as the Philippines, naturally ventilated greenhouses might differ in both geometric configurations and materials used as those in temperate or arid regions. In order to enhance the thermal performance of the naturally ventilated greenhouse in the tropics, it is necessary to perform an actual experiment to evaluate and describe the thermal characteristics of a specific greenhouse configuration.

Several experimental and theoretical studies analyzed the microclimate characteristics of a naturally ventilated greenhouse. Soni et al. [5] studied the effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouses. They were able to describe the
average vertical diurnal variation of greenhouse air temperature as well as the peak highest values of temperature obtained at various vertical locations inside the greenhouse. Through an experiment, Li et al. [6] described the variations as well as the average indoor temperatures of a naturally ventilated single-sloped greenhouses which were covered with 0.1 mm transparent plastic polyethylene film equipped with straw mat. The average hourly daytime temperature of the indoor air, ground, and greenhouse envelopes was described, as well as the indoor temperature variations at different height from the ground and distance from the south wall.

Ganguly and Bauri [7] used a thermal model to analyze the thermal variations of a naturally ventilated floriculture greenhouse. Variations of the air temperature, leaf temperature, and air water vapour pressure as well as the hourly variations of indoor air temperature, ambient air temperature and plant leaf temperature were described. Numerical simulation of thermal behavior of a ventilated arc greenhouse during a solar day was conducted by Fidaros et al. [8] to generate indoor air temperature contours for hours 10 and 14 as well as daily variations of temperatures at different points inside the greenhouse at variable ambient temperature.

Despite several studies that describe among others the temperature distribution and average temperature variations inside a naturally ventilated greenhouse, the probability density function and contour of the daytime indoor temperature has not been studied at length. In this study, an experiment was conducted to describe the daytime indoor air temperature distribution of a naturally ventilated greenhouse under tropical climatic condition through the application of the probability density function and temperature contour analysis. Analysis of heat distribution in greenhouses is of great importance because it serve as basis for designing either ventilation, cooling or heating systems [5]. As widely reported, temperature distribution in greenhouses is one of the factors that influence the uniformity of crop growth [3].

2. Materials and Methods

2.1 Experimental Site and Greenhouse Specification

The experimental site is located at the University of San Carlos-Talamban Campus, Cebu City, Philippines (10°21’06.34”N, 123°54’48.48”E). The site is 8.0 km from the nearest government’s weather station, the PAGASA-Mactan (10°19’22”N, 123°58’49”E) which is the primary source of climatic data of Cebu City.

The prototype greenhouse used in this experiment is a combination of a plastic roofing and an insect-proof net screen sidewall covering materials (Figs. 1a & 1b). The insect-proof net screen provided ventilation through natural convection of the surrounding air to the interior of the greenhouse. The greenhouse has a gable (double-sloped) roof shape which is a typical roofing shape of most of the greenhouses constructed in the Philippines because of its simple construction allowing easy use of non-metal frames such as wooden structural frames or the use of bamboo poles as frames. The roofing is sloped at 45° while the eave height is 1.55 m from the ground with the roof overhang of 0.28 m from the wall. The greenhouse prototype is fully covered and do not have any other ventilation openings except the mesh openings of the insect-proof net screen. The door which has a dimension of 1.8m x 0.6m is made of 6.4 mm thick plywood and is located at the eastern side of the south wall. The ground flooring which is made out of 6.4 mm thick plywood has a space dimension of 1.83 m by 1.83 m. All the support frames were made of metal angular bars and pipes. The greenhouse roof ridge was positioned in a north to south orientation to reduce interior shading from the structure itself on the plants. During the experiment, the greenhouse is empty and do not have any plants being raised inside.
The experiment was conducted during the warm and dry days of February 2017 with no observed rain as monitored by the nearest weather station (Table 1). This climatic condition represents the relatively dry season of the year that occurs from November to April in the locality (central and southern parts of Cebu, Philippines).

Fig. 1. (a) Actual picture the experimental site showing the southern side of the prototype greenhouse (ISO, automatic; exposure value, 0; resolution, 16:9), (b) Schematic diagram of the greenhouse showing its orientation, and the location of temperature sensors (numbered 1-16), (c) Detailed sketch of the temperature sensors locations at different points (numbered 1-16) and heights (H₀, H₁, H₂, and H₃) above the greenhouse floor, (d) Sample temperature contour showing the location of the temperature sensors (numbered 1-16)
Table 1. Climatic conditions recorded by the nearest weather station PAGASA-Mactan during the experiment

<table>
<thead>
<tr>
<th>Date</th>
<th>$T_{\text{max}}$ [$^\circ$C]</th>
<th>$T_{\text{min}}$ [$^\circ$C]</th>
<th>$T_{\text{ave}}$ [$^\circ$C]</th>
<th>RH$_{\text{ave}}$ [%]</th>
<th>Rainfall [mm]</th>
<th>$V_{\text{wind}}$ [m/s]</th>
<th>Prevailing wind direction [deg]</th>
<th>Sunshine duration [min.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 12, 2017</td>
<td>30</td>
<td>23</td>
<td>26.5</td>
<td>68</td>
<td>0</td>
<td>6</td>
<td>20</td>
<td>4.9</td>
</tr>
<tr>
<td>Feb. 13, 2017</td>
<td>29.4</td>
<td>23.2</td>
<td>26.3</td>
<td>60</td>
<td>0</td>
<td>8</td>
<td>10</td>
<td>10.2</td>
</tr>
</tbody>
</table>

2.2 Temperature Data Acquisition

Temperature measurement was carried out with an Applent AT4516 model 16-channel data recorder. This instrument can be adjusted to a sampling frequency of 1 s/channel (low speed) to 100 ms/channel (fast speed). The probe being used was a home-made type-K thermocouple having a wire diameter of 300 μm. The diameter of the spark-welded bead was approximately 980 μm. Prior to the actual experiment, the temperature probes were calibrated using a standard glass thermometer inside the laboratory under the temperature range of $2^\circ$C – $96^\circ$C.

During the experiment, the 16 probes were equally spaced inside the east-west mid-section of the greenhouse (Figs. 1b & 1c). Nylon strings were used to support the temperature probes fastened at different locations using a double adhesive tape. Measurements were carried out from 6:00AM to 6:00PM local time. The data recorder was set at 5 seconds sampling rate so that about 8,572 data in each temperature probe was generated each day. Data generated were automatically saved in a 14.4 GB capacity flash disk mounted in the USB interface of the temperature meter.

The temperature data recorded in the flash disk was downloaded to a personal computer for analysis. In this study, only the recorded daytime (6:00AM-6:00PM) temperature was selected for analysis to describe the daytime thermal characteristics of the greenhouse as primarily influenced by solar radiation.

2.3 Thermal Analysis

To describe the general temperature pattern inside the greenhouse at different heights from the flooring ($H_0=0$ m, $H_1 = 0.61$ m, $H_2 = 1.22$ m, and $H_3 = 1.83$ m), the average temperature at every 15 minutes time interval was calculated. As shown in Figure 1c, the temperatures at the ground floor surface of the greenhouse ($H_0=0$ m) were being measured by sensors (1, 2, 3 & 4). Temperatures at $H_1$, $H_2$, and $H_3$ were measured by sensors (5, 6, 7, & 8), (9, 10, 11, & 12), and (13, 14, 15, & 16), respectively.

Probability Density Function (PDF) was used to describe probabilities associated with the random temperature variable. For continuous variables such as temperature, the PDF is the curve that approximates the shape when its values are displayed on a bar chart or histogram. The PDF of the daytime temperature inside the greenhouse at $H_0$, $H_1$, $H_2$, and $H_3$ were estimated to observe thermal variations at different regions. The interval size of $1^\circ$C was chosen in the analysis. Calculations were carried out using Microsoft Excel while plots of the PDF were generated using Tecplot Version 10.0-2-24. To visualize thermal variations inside the cross-section of the greenhouse, temperature contours at hourly interval starting from 7:00 AM until 6:00 PM were generated using Tecplot Version 10.0-2-24. The actual observed temperatures of the 16 sensors in each particular time was used in the analysis in order to come up with the temperature contour as illustrated in Figure 1d.
3. Results and Discussion

3.1 Greenhouse Temperature Pattern

Figure 2 shows the daytime temperature at different heights inside the greenhouse. On day 1 of the experiment (February 12, 2017), the daytime temperature inside the greenhouse ranged from 19.6°C to 41.5°C with an average ($T_{\text{mean}}$) of 28.6°C which is about 2°C higher that the average ambient air temperature ($T_{\text{ave}} = 26.5°C$) recorded by the nearest weather station. On day 2 (February 13, 2017), the daytime temperature ranged from 18.3°C to 44.8°C with $T_{\text{mean}} = 29.4°C$ which is about 3°C higher than the average temperature ($T_{\text{ave}} = 26.3°C$) of the nearest weather station. The greenhouse temperature at different height from the ground floor can be observed as almost uniform during the early hours of the day and also about an hour before sunset. Temperature higher than $T_{\text{mean}}$ occurred between 9:00AM to 4:00PM local time. It can be observed that during this period of time, variations of the average temperature at different heights is very much obvious. The temperature at $H_0$ and $H_3$ can be observed to be relatively higher than the temperature at $H_1$ and $H_2$ which suggest that the air temperature near the roof as well as at the floor surface is higher than the air temperature at the middle space of the greenhouse. The result is in agreement with Al-Helal et al. [9] in their study on naturally ventilated greenhouse which revealed that the floor surface temperature is higher for greenhouse without canopy under a sunny weather and that the air temperature near the roof is also high as affected by the solar radiation absorbed by the roof cover.

Fluctuations in temperature can also observed between 8:00AM to 4:00PM, the time courses when the solar radiation is expected to be high and that the inside greenhouse temperature is higher than the outside air temperature. Drops in temperature during this course of time might be due to shading effect of the clouds as well as the convective heat transfer by wind that may occur at any time of the day.

![Graph showing temperature at different heights](image)

Fig. 2. Temperature at different height ($H_0 = 0$ m, $H_1 = 0.61$ m, $H_2 = 1.22$ m, and $H_3 = 1.83$ m) from the flooring of the greenhouse. The climatic condition reported by the nearest weather station (PAGASA-Mactan) during the experiment where: (a) February 12, 2017, $T_{\text{max}} = 30.0°C$, $T_{\text{min}} = 23.0°C$, $T_{\text{ave}} = 26.5°C$, $R\text{H}_{\text{ave}} = 68\%$, Rainfall = 0.0 mm, $V_{\text{wind}} = 6.0$ m/s and (b) February 13, 2017, $T_{\text{max}} = 29.4°C$, $T_{\text{min}} = 23.2°C$, $T_{\text{ave}} = 26.3°C$, $R\text{H}_{\text{ave}} = 60\%$, Rainfall = 0.0 mm, $V_{\text{wind}} = 8.0$ m/s
3.2 Greenhouse Temperature Distribution

Figure 3 shows the PDF of daytime temperature at different height above the ground floor of the greenhouse. In both figures (Figs. 3a and 3b), the PDF of temperature of the ground floor surface \( H_0 \) almost coincide with the PDF of the temperature of space near the roof \( H_3 \) of the greenhouse. Also, the PDF of the temperatures at the middle space \( H_1 \) and \( H_2 \) almost coincide with each other. Based from the PDF, it can be observed that both the ground floor surface as well as the space near the greenhouse roofing attained higher temperature compared to the middle space of the greenhouse. For instance, it is noticeable in both PDF plots that the likelihood to obtain a temperature greater than 30°C is much higher in \( H_0 \) and \( H_3 \) as compared to \( H_1 \) and \( H_2 \), given the climatic conditions during the experiment. Further, by visual inspection of the PDF in Figures 3a and 3b, it can be estimated that the probability to have the greenhouse temperature higher than 30°C which might already cause heat stress to most tropical greenhouse plants is almost 50% of the total daytime. According to Harmanto et al. [10], the screening net can cause a restriction to the airflow which can lead to an increase in air temperature inside the greenhouse. Thus, the result suggest the need to supplement the existing natural ventilation provided by the insect-proof net screen with a cooling system in order brought down the temperature to desirable levels.

The hourly thermal variations at the east-west mid-section of the greenhouse is visualized through temperature contours in Figures 4 and 5. Generally, the temperature of the east-west mid-section under analysis is not uniform. At 7:00 AM local time which is just about an hour after sunrise, a slight variation in temperature of about 1-3°C in both days of the experiment can already be observed. The same temperature variation can be observed during the last hour of the day (6:00PM local time), just after sunset. Between 8:00AM – 5:00PM when solar radiation is expected to be of higher intensity, higher temperature variations (about 4°C to 6°C) can be observed at the east-west mid-section of the indoor of the greenhouse.

It can be observed that the regions with relatively low temperature are usually concentrated at the center space of the mid-section of the greenhouse. Whereas, the regions with highest temperature are usually spread at the corners (upper and lower corners) of the greenhouse’ mid-section. The upper corners (points 13 and 16 in Figures 1b and 1c) are in contact with the plastic roofing as well as the side corner metal framing of the greenhouse. As discussed earlier, the temperature in these regions is greatly influenced by the solar radiation absorbed by the roof cover and the metal framing which could be the reason of its having a usual high temperature compared to other regions. Similarly, the lower corners (points 1 and 4 in Figures 1b and 1c) which are at the ground floor surface and side corner metal framing of the greenhouse has been affected much by the thermal radiation of the greenhouse’ flooring and the metal frame. Further, near corner spaces are considered as stagnant regions [11] where the air exchange rate is restricted compared to that of the center or middle space of the insect-proof net screen walls. Thus, it is expected that near corner spaces will develop higher temperature as heat transfer by convection is restricted. With the present geometric configuration and ventilation of the greenhouse, a cooling system could be designed to attain a lower and uniform temperature in the entire inner space of the greenhouse.
Fig. 3. Probability density functions of the daytime greenhouse temperature measured by the thermocouples at various height ($H_0 = 0$ m, $H_1 = 0.61$ m, $H_2 = 1.22$ m, and $H_3 = 1.83$ m) from the flooring. (a) Average ambient temperature of the day: 27.0°C, and (b) Average ambient temperature of the day: 26.9°C
Fig. 4. Temperature contours of the cross-sectional area (H x W) inside the naturally ventilated greenhouse at different hours of the day. Temperature sensors are located at points numbered 1-16 in the cross-sectional area.

Average ambient temperature of the day: 27.0°C
Fig. 5. Temperature contours of the cross-sectional area (H x W) inside the naturally ventilated greenhouse at different hours of the day. Temperature sensors are located at points numbered 1-16 in the cross-sectional area. Average ambient temperature of the day: 26.9°C
4. Conclusions

Under the tropical climate and relatively dry season of the year, the thermal characteristics of a naturally ventilated greenhouse that is fully enclosed with transparent plastic as roofing and insect-proof net screen sidewall is not uniform. Without any plants inside the structure, the ground floor surface and the uppermost space of the greenhouse exhibited higher temperature than the middle space most of the time of the day. Given the climatic condition of the locality where the ambient air temperature ranges from 23°C to 30°C and an average relative humidity of about 60-68%, the probability that the indoor temperature of the greenhouse will exceed 30°C is almost 50%. Higher indoor temperature variations was observed between 8:00AM to 5:00PM when the solar radiation is high, while the middle space of the greenhouse has lower air temperature than the upper and lower near corner spaces. The result suggest a need to enhance the thermal performance of the present configuration of the prototype greenhouse in order to attain a uniform and reduced temperature suitable to most tropical greenhouse plants during the relatively dry season of the year.

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References
