Determination of transfer coefficients of a tunnel type screenhouse for thermal modelling

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Abstract. Screenhouses could help the reduction of pesticide usage for sustainable agriculture production in the tropics. A screenhouse is inherently naturally ventilated by the air flowing through the screen that covers the structure. However, overheating is still a problem that often occurs inside screenhouses in the tropics. Therefore, it is important to develop a thermal model as design tool for tropical screenhouses. The objective of this study was to determine the screenhouse transmissivity and the overall heat transfer coefficient of a tunnel type screenhouse for thermal modelling. A thermal model has been developed to consider these transfer coefficients. The model was modified from thermal model proposed by Desmarais et al. Validation of the thermal model was done by comparing predicted air temperature inside the screenhouse to that of measured values. The average transmissivity of the screenhouse obtained was 0.42, while the heat transfer coefficient of the screenhouse averaged from measurement results was 51.6 W/m² °C. The validation showed that predicted air temperature inside the screenhouse agreed well to that of the measured values. It was concluded that the thermal model could be used as a good design tool for tunnel type tropical screenhouses.

1. Introduction

Greenhouses have long been used in subtropical regions to protect crops from low temperatures during winter by utilizing the heat incorporated with solar radiation trapped inside the structure through greenhouse effect. Greenhouses have been also used in tropical regions to protect crops from insect and rain. In tropical regions, focusing on the prevention of insect entering the structure, thus reducing the pesticide usage, led to a widely use of insect-proof screen rather than plastic films to cover the similar structure. The structures, then known as screenhouses, have been developed from virus research in tropical areas [1]. The thermal characteristics of screenhouse in tropical climate have been evaluated [2]. Screenhouses have been used to prevent the invasion of insect that are damaging to crops in the tropics. Protected cultivations under greenhouses and screenhouses in the tropics offer advantages in reducing the usages of pesticide and water, while providing better microclimate variables to grow crop. Moreover, one of the main advantages of using screenhouse is the construction cost of screenhouse is relatively cheaper, as compared to greenhouse.

In tropical regions, air temperature inside the screenhouse tend to be very high as compared to outside air temperatures. On the other hand, screenhouse is inherently naturally ventilated. Therefore, the microclimate inside the screenhouse depends on wind speed and direction and the temperature difference between inside and outside air. Screenhouses have the possibility of preventing overheating without cooling energy cost. A heat transfer model has been developed for screenhouses having one or more than one layer of cover [3]. Furthermore, the effect of insect-proof screen on mass, momentum, and energy exchange has been evaluated comprehensively [4]. It is well known that heat and mass transfer balances of a screenhouse are very complicated. In addition, it is important to
understand the heat and mass transfer characteristics of screenhouses and to identify the most
essential design factors that affect thermal environment inside the screenhouses.

In Indonesia, tunnel type screenhouse has gained attention because of low construction cost and
the effectiveness in preventing the entry of insect. In designing screenhouses, it is important to use
thermal model of screenhouses developed by using reliable transfer coefficients. Therefore, it is
important to determine the transfer coefficients of a tunnel type tropical screenhouse for heat transfer
modelling. This will be valuable for designers in predicting temperature of air inside the screenhouse
under consideration.

2. Materials and Methods

2.1. Site and Greenhouse Description
The experiment was conducted at Agribusiness and Technology Park, Bogor Agricultural University
(IPB University), Indonesia. The station is located at a latitude of 6.50 south of the equator and a
longitude of 106.70 east of the Greenwich meridian. Experiments were conducted in a tunnel type
screenhouse with six rows of cabbage crops inside. The screenhouse was built with steel frames and
covered with an insect-proof screen with 50 mesh size. The screenhouse was built on bared soil on
which the crops were cultivated.

2.2. Thermal Model

Desmarais et al. [3] has developed a thermal model that can be used to explain heat transfer
phenomenon inside various type of screenhouses. However, in their model the temperature of the
ground was set higher than the temperature of the inside air. Therefore, in this study, the thermal
model was designed so that the condition of lower temperature of the ground can be accepted. The
thermal model in this study was based on Desmarais et al. [3] with minor modifications.

Energy balance equation in a screenhouse can be expressed by equation (1), where

\[ q_{teff} + q_{teff} \pm q_g - q_{Nv} - q_{cd} = m_a C_p \frac{dT_i}{dt} \]  

\[ m_a = \rho V \]  

(1)  

(2)

The effective heating coefficient of solar radiation is considered as floor reflectivity in this model.
Effective heat due to solar radiation in the screenhouse can be expressed by using equation (3),

\[ q_{teff} = \eta q_I \]  

(3)

where \( \eta \) is the reflectivity of the screenhouse floor and \( q_I \) is the solar radiation measured inside
the screenhouse. The heat received due to solar radiation at the screenhouse can be explained with the
same equation as the heat received due to solar radiation at the greenhouse. In equation (4), \( \tau \) is the
transmissivity of the cover for shortwave solar radiation, \( I \) is solar radiation, and \( A_f \) is floor area of the
screenhouse.

\[ q_I = \tau I A_f \]  

(4)

Effective heat gain from inside air (\( q_{teff} \)) is considered as a part of the long wave radiation left in
the screenhouse, assuming the energy absorbed by the cover is ignored. Effective thermal heating
\( q_{teff} \) is an input to the heat balance of inside air and accounts for a portion of the thermal radiation
that is not transmitted by the screenhouse cover as described in equation (5),
\[ q_{\text{teff}} = (1 - \tau_t)q_{lw} \]  
\[ q_{lw} = A_f \sigma (\varepsilon_g (T_g + 273)^4 - \varepsilon_a (T_o + 273)^4) \]  

where \( \tau_t \) is the transmissivity of longwave thermal radiation and \( q_{lw} \) is the heat transfer of longwave radiation whose value can be estimated by using equation (6),

\[
q_{lw} = A_f \sigma (\varepsilon_g (T_g + 273)^4 - \varepsilon_a (T_o + 273)^4)
\]

where \( A_f \) is the floor area (m\(^2\)), \( \sigma \) is Stefan-Boltzman constant with a value is 5.67 x 10\(^{-8}\) W/m\(^2\) K\(^4\), \( \varepsilon_g \) is floor emissivity (%), \( T_g \) is floor temperature (°C), \( \varepsilon_a \) is emissivity of atmosphere (%), and \( T_o \) is the air temperature outside the screenhouse.

Convective heat transfer from or to the ground can be obtained by using equation (7),

\[ q_g = h_g A_f (T_g - T_i) \]

where \( h_g \) is the convective heat transfer coefficient on the ground floor and \( T_i \) is the air temperature inside the screenhouse (°C). The \( q_g \) variable acts as the heat gain for air inside the screenhouse when \( T_i > T_o \).

In the screenhouse, ventilation is only caused by natural ventilation because there is no mechanical ventilation. Heat transfer due to natural ventilation can be determined by using equation (8),

\[ q_{Nv} = N_v \rho C_p (T_i - T_o) \]

where \( N_v \) is the natural ventilation rate (air changes/minute). According to ASHRAE [5], \( N_v \) values can be obtained by using equation (9).

\[ N_v = \frac{C_q v A_c}{V} \]

Heat transfer due to convection-conduction from the screenhouse can be obtained using equation (10),

\[ q_{cd} = UA_c (T_i - T_o) \]

where \( U \) is the overall heat transfer coefficient (W/m\(^2\) K) and \( A_c \) is the area of the screenhouse cover (m\(^2\)). The \( q_{cd} \) value in equation (10) is positive when \( T_i > T_o \) and always occurs in screenhouses in warm climates.

Solar radiation has an important role in the heat balance of the screenhouse. Researchers have tried to find parameters that explain the effective heating of solar radiation in the greenhouse [6, 7, 8]. A coefficient has been introduced to describe the conversion of solar energy into sensible heat, namely the absorbance of solar radiation in a greenhouse [6]. The idea of the heating efficiency of solar radiation has been put forward for a greenhouse and has been defined in proportion to the transmissivity of the greenhouse cover and the absorptivity of the greenhouse floor [8].

To apply the concept of effective heating of solar radiation to the screenhouse, the heat reflected from the floor is considered. Radiation energy that falls on the surface of the material is divided to reflected, absorbed, and transmitted fractions, as determined by the reflectivity, absorptivity, and transmissivity, respectively. Reflectivity (\( \eta \)) can be defined as the reflected fraction, absorptivity (\( \alpha \)) as the fraction absorbed by the material, and transmissivity (\( \tau \)) as the fraction transmitted by the material. The relationship between these three variables is presented as follows.

\[ \eta + \alpha + \tau = 1 \]

Ground transmissivity can be assumed to be zero. Therefore, the relationship between reflectivity and absorptivity can be explained by using equation (12).
Equations (3) through (12) are equations that make up Equation (1). Heat balance for the tunnel type tropical screenhouse studied in this research can be expressed by equation (13) which was a modification from equation proposed by Desmarais et al. [3].

\[
(1 - \alpha)\tau I_A f + (1 - \tau)q_{tw} \pm h_g A_f (T_g - T_i) - \left[ N_o V \rho C_p + U A_c \right] (T_i - T_o) = m_a C_p \frac{dT_i}{dt} \tag{13}
\]

2.3. Transfer Coefficients

In this study, there are two important coefficients that need to be determined namely screenhouse transmissivity \((\tau)\) and overall coefficient of heat transmission \((U)\) of the screenhouse.

2.3.1. Transmissivity

The transmissivity of the screenhouse \((\tau)\) can be obtained from the ratio of radiation measured inside the screenhouse \((I_i)\) and external radiation \((I_o)\) [9]. In this study, Equation (14) was used to calculate the transmissivity by using solar radiation measured inside and outside the screenhouse.

\[
\tau = \frac{I_i}{I_o} \tag{14}
\]

2.3.2. Overall Coefficient of Heat Transmission

Desmarais [3] used data on indoor and outdoor temperatures at night to determine the overall coefficient of heat transmission \((U)\). In general, the temperature outside and inside the screenhouse at night is almost constant. This means that at night, the assumption of \(\frac{dT_i}{dt} = 0\) can be used and the following equation could be used to determine the value of \(U\).

\[
U = \frac{q_{teff} + q_g - q_{Ne}}{A_c (T_i - T_o)} \tag{15}
\]

2.4. Measurements

Measurements were performed from June to July 2019 for a full day. Measurements were sampled at 5 minutes intervals. Inside the screenhouse, the indoor air temperature and relative humidity were measured by sensors that were included inside the Vantage Pro2 console receiver. The ground temperature was measured by using type T thermocouple that were connected to Graphtec GL-240 type hybrid recorder. Inside solar radiation was measured by MS-401 pyranometer. The pyranometer was also connected to the same hybrid recorder. The outside air temperature, air relative humidity, and outside solar radiation data were measured by using Vantage Pro2 weather station.

2.5. Inside Air Temperature Simulations

A simulation program was made to predict air temperature inside the screenhouse. This simulation program was created using the QB64 application in BASIC programming language based on the simulation program that Desmarais et al. [3] has developed. Air temperature outside the screenhouse and solar radiation are two input variables that change with time. Various other input variables were obtained from calculations and literature. The heat transfer equation that has been arranged was solved by using the Fourth-Order Runge-Kutta numerical analysis method.

2.6. Model Validation

The validation process aims to measure the performance of simulation results against the measurement results. It was done by calculating the Standard Error of Prediction \((SEP)\), bias \((\bar{d})\), Coefficient of Variation \((CV)\), and Average Percentage of Deviation \((APD)\). Regression analysis is formed on the linear relationship between the predicted air temperature \((y)\) and the measured air temperature \((x)\) where the value of \(b\) represents the intercept and the value of \(a\) indicates the slope or gradient of the regression line. The prediction will be more accurate if the linear line approaches the
$y = \frac{x - \alpha}{\beta}$ line or the gradient of the regression equation approaches one while the intercept approaches zero. The coefficient of determination ($R^2$) produced can be used to indicate the level of closeness of the correlation between the calculation results with the measurement results.

3. Results and Discussion

3.1. Transmissivity

The transmissivity of the screenhouse was determined by using equation (14), with input from radiation measurements inside and outside the screenhouse. The transmissivity value is obtained by dividing the radiation value inside with the radiation value outside the screenhouse measured at the same time. Transmissivity measurement was done from 7 a.m. until 5 p.m.

Figure 1 shows the typical changes in solar radiation that occur outside the screenhouse and solar radiation that has passed through the screen inside the screenhouse on July 1, 2019. Because the sunlight was partially blocked by the screenhouse cover, the solar radiation measured inside the screenhouse is always lower than that of measured outside the screenhouse.

![Figure 1. Screenhouse transmissivity ( ), typical changes in solar radiation inside the screenhouse ( ), and those measured outside the screenhouse ( ) on July 1, 2019](image)

3.2. Overall Coefficient of Heat Transmission

Night time data, from 0 a.m. to 6 a.m., for 14 nights of observation was used to obtain the $U$ value by using equation (15). The average $U$ value for each night was calculated by using data on outside air temperature, internal air temperature, and soil temperature as changing variables recorded every 5 minutes. These $U$ values are shown in table 1.

Air temperature inside the screenhouse is always higher than outside. This means that $q_{Nv}$ will always act as an energy output. The soil temperature is always higher than the air temperature in the screenhouse at night so the $q_g$ variable will always be an energy input at night.
Table 1. The U values of the screenhouse, calculated from night-time data

| Date      | U Values (W/m² °C) |
|-----------|-------------------|
| June 23   | 11.4              |
| June 24   | 34.4              |
| June 25   | 25.9              |
| June 26   | 22.5              |
| June 27   | 25.3              |
| June 28   | 24.0              |
| June 29   | 53.4              |
| June 30   | 26.3              |
| July 1    | 117.4             |
| July 2    | 99.5              |
| July 3    | 74.3              |
| July 4    | 108.9             |
| July 5    | 42.8              |
| July 6    | 56.3              |

Based on observations and calculations, the average of U values each day was in the range of 11.4 W/m² °C to 117.4 W/m² °C with an overall average value of 51.6 W/m² °C. This value is greatly influenced by air temperatures outside and inside the screenhouse and the temperature of the soil inside the screenhouse. A greater difference between air temperature outside and inside the screenhouse triggers a greater exchange of air. This could produce smaller U values, and vice versa.

3.3. Air Temperature Inside the Screenhouse

The computer program to simulate temperature of air inside the screenhouse was written based on the heat transfer model that has been developed earlier. Equation (13) was used in the simulation program and solved by using the fourth order Runge-Kutta numerical analysis method. The simulation was carried out by using heat transfer characteristics data such as τ and U that have been obtained from the experiments. The values of other parameters required in the simulation were obtained from the literature or from measurements. In the simulation, air temperature and solar radiation data for outside the screenhouse were obtained from measurements for the relevant day.

The simulation program was designed to be able to call files containing data on temperature and solar radiation when the program is run. The program was designed to take data from these files as input that changes with time, namely the temperature of the air outside the screenhouse, the initial temperature of air inside the screenhouse, the temperature of soil inside the screenhouse, and solar radiation. Constant input values that were not change with time are presented in table 2. Air temperatures as the output of the simulation were stored in the calculation result files. These files were then transferred to a spreadsheet for further processing.

Figures 2, 3, and 4 show the comparison on air temperatures between the simulation results and the measurement results on different days. The simulations were conducted on the days that represent the lowest U value, closest to the average U value, and the highest U value, which were June 23 with U value of 11.4 W/m² °C, June 29 with U value of 53.4 W/m² °C, and date July 1 with U value of 117.4 W/m² °C. As can be seen in these figures, air temperature from simulation results agreed well with the measurement results. Air temperatures resulted from simulation tend to follow that of from measurement. The largest difference between the simulated and measured air temperature was 2.16 °C. It can be said that the U value and the transmissivity value used as constants in the heat transfer modelling applied in this study were very good in providing estimates of air temperature inside the tunnel type tropical screenhouse.
Table 2. Values used in the simulation

| Symbol | Value |
|--------|-------|
| \( \tau \) | 0.42 |
| \( U \) | 51.6 W/m\(^2\)\( ^\circ\)C |
| \( \eta \) | 0.4 |
| \( N_v \) (day) | 0.5 air change/min (Desmarais [2]) |
| \( N_v \) (night) | 0.1 air change/min (Desmarais [2]) |
| \( h_g \) | 1.9 W/m\(^2\)\( ^\circ\)C (Granados [10]) |
| \( A_f \) | 360 m\(^2\) |
| \( A_c \) | 476 m\(^2\) |
| \( V \) | 848.2 m\(^3\) |
| \( \tau_i \) | 0.55 (Desmarais [2]) |
| \( \rho \) | 1.15 kg/m\(^3\) |
| \( C_p \) | 1 kJ/m\(^3\)\( ^\circ\)C |

Figure 2. Typical changes in air temperatures inside the screenhouse obtained from measurement (□) and simulation (○) for June 23, 2019 that represent the lowest \( U \) value

Figure 3. Typical changes in air temperatures inside the screenhouse obtained from measurement (□) and simulation (○) for June 29, 2019 that represent the closest to the average \( U \) value
3.4. Validation of the Thermal Model

In figure 5, temperatures of air inside the screenhouse simulated by using the thermal model are plotted versus the measured air temperatures inside the screenhouse. A good correlation was found between the simulated air temperature and those of measured values. The regression equation shown in figure 5 shows that the resulting gradient is 1.0127 and the resulting intercept is 0.0652. Although the results show that the simulated values of air temperature inside the screenhouse were slightly higher than those measured inside the screenhouse, the estimation using this simulation is quite good because the regression equation has a gradient close to one and intercept close to zero. The coefficient of determination ($R^2$) obtained is 0.9906 which indicates that the magnitude of the variation in the temperature of the simulation results can be explained by the measurement of temperature. The SEP calculation resulted the SEP value is 0.0004508 which means that the simulation met the criteria of good validation. The resulting bias value is 0.4094, the CV value obtained is $1.6362 \times 10^{-5}$, and the APD value obtained is 0.0919%. It was concluded that the thermal model for the tunnel type screenhouse was fitted to experimental data of air temperature inside the screenhouse.

Figure 4. Typical changes in air temperatures inside the screenhouse obtained from measurement (■) and simulation (○) for July 1, 2019 that represent the highest $U$ value

Figure 5. Simulated air temperature inside the screenhouse versus measured air temperature inside the screenhouse
4. Conclusions

A lumped parameter approach was used to model the screenhouses. The overall heat transfer coefficient ($U$) obtained was in the range of 11.4 W/m$^2$ °C to 117.4 W/m$^2$ °C with an overall average value of 51.6 W/m$^2$ °C. The transmissivity to solar radiation of insect-proof screen of the tunnel type screenhouse was relatively stable at the value of 0.42. Comparison between experimental and simulation results were in good accord, showing that this thermal model can be used to predict air temperature inside tunnel type tropical screenhouse within a 2 °C difference. The developed thermal model would be valuable in designing tunnel type tropical screenhouse.

5. References

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