African Journal of Biotechnology Vol. 10(25), pp. 5001-5014, 8 June, 2011
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB10.2668
ISSN 1684–5315 © 2011 Academic Journals

Full Length Research Paper

Simple model to study the effect of temperature on the greenhouse with shading nets

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Accepted 16 February, 2011

Due to high solar intensity, the internal temperature of greenhouses in subtropical regions is so high that it is difficult for crops to survive. There are two types of shading nets that are applied to reduce the solar intensity entering the greenhouse. The purpose of this research is to develop a simple greenhouse model to describe the effect of these shading nets on the inside temperatures of a greenhouse. The thermal condition was assumed as the steady state. The detailed microclimate data of an experimental greenhouse with internal and external shading nets were collected during various weather conditions. The model was validated using experimental data collected from various conditions. The prediction accuracy of the model for air temperature was about 1.5°C. It is concluded that this model could be applied to evaluate the performance of shading nets and serve as a tool for the design of a subtropical greenhouse.

Key words: Subtropical, greenhouse climate model, shading nets.

INTRODUCTION

The application of greenhouse for crop production is very important in the world (Omer, 2009). In order to maintain an adequate microclimate for growth of crops and protection against rain and storms, the greenhouse has become popular in subtropical regions. However, high solar energy leads to heat accumulation in greenhouses especially in summer. The cooling strategy has become a useful technology for environmental control of a subtropical greenhouse.

There are four ways to solve the heat accumulation problem in greenhouses. These are: 1) ventilation, 2) shading, 3) evaporative cooling and 4) composite systems (Sethi and Sharma, 2007). With shading screens, the solar energy is retarded when entering the greenhouse. Thus, excessively high temperatures are reduced. Ventilation and evaporative cooling is also an effective way to remove the hot air from greenhouses (Chen, 2003; Oz et al., 2009). Negative pressure fans are the typical equipment to remove greenhouse heat. However, the walls of a greenhouse need to be kept closed at all times in order to apply these devices. The structure of a greenhouse should be strong enough to resist the side pressure that is induced by the mechanical fans. This may cause the construction cost of a greenhouse to increase.

Recently, a simple and inexpensive greenhouse has been introduced (Critten and Bailey, 2002; Impron et al., 2007), where by, the sidewall of the greenhouse is composed of insect screens and the roof is covered with transparent materials. This kind of greenhouse is referred to as a high tunnel in some literatures (USAID, 2008; van Heum and ven der Post, 2004). Two kinds of shading nets: internal shading and the external shading nets are utilized in these greenhouses. Internal shading nets are installed beneath the roof of the greenhouse and guard against bad weather conditions. External shading nets are installed at the position above the roofs. They can be used to reduce the total solar energy entering the greenhouse and to provide more space for plant growth

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and development. However, these screens are susceptible to damage by the extreme weather conditions.

The structural analysis and the study of the functional characteristics of the greenhouse are prerequisite for greenhouse application (Emekli et al., 2010). A greenhouse climate model is a very useful tool to describe the relationship between the microclimates and the influencing factors. Several types of greenhouse models were reviewed by Kano and Saddle (1985). Froehlich et al. (1979) classified the greenhouse model as steady state, steady-periodic and time-dependant. Boulard and Baille (1993) incorporated the performance of evaporative cooling equipment into these models. Jolliet (1994) proposed an integrated model to consider the transpiration function of crops. Recently, more greenhouse models were proposed and validated. Roy et al. (2002) assumed the greenhouse as a perfectly stirred tank and studied the convective function and ventilation in a greenhouse. Fatnassi et al. (2003) investigated the effect of insect-proof screens on the microclimate of greenhouses. The leaf boundary-layer model was proposed and incorporated into the microclimate model by Boulard et al. (2004). The interactions between the banana crop and the surrounding microclimate were studied by Demrati et al. (2007). A detailed thermal model was developed and validated to evaluate the arch shape greenhouse by Sengar and Kotharl (2008).

However, despite the many greenhouse models developed and validated, in the opinion of the authors, a greenhouse model that considered the effect of positions of shading nets is not yet available. The application of internal and external shading nets was so popular to reduce the solar radiation into the greenhouse and high tunnel. A greenhouse model that incorporates the shading effect needs to be developed and validated. This model could serve as a tool to evaluate the performance of these nets.

The objective of this study was to develop a simple model to describe the effect of the shading nets on the microclimate of a greenhouse. The microclimate data of the experimental greenhouse were collected to validate the model.

Model development

The development of a greenhouse model for the utilization of shading nets was to divide the greenhouse into two layers. The schematic diagram of the thermal fluxes in a typical greenhouse is presented in Figure 1. The assumptions of this model are as follows.

1. No temperature gradient existed in each layer.
2. The heat transfer coefficients of cover materials were constant.
3. The temperatures of the internal air, crops and cover materials were in a steady state.
4. Crops were planted in medium containers, the ground was covered with weeds-inhibiting nets and the soil thermal energy was not considered because crops covered most parts of the floor.
5. Only the transmittance of shading nets was considered.
6. The air exchange rate between the upper parts and lower parts of internal shading nets was assumed as constant.

Thermal transfer model of the upper layer

The thermal systems of upper and lower layer are denoted as “1” and “2”, respectively.

The input energy

$$Q_{S1} = (1-\tau_1)\,\tau_0\, I_S \quad (1)$$

where Q_{S1} is the solar energy in the upper layer in Wm^{-2}; τ_1 is the transmittance of internal shading nets; τ_0 is the transmittance of external shading nets; and I_S is the entrance energy of shortwave radiation from the sun in Wm^{-2}.

The output energy

a. Q_{1a}: energy flow in/out to ambient atmosphere by heat transfer

$$Q_{1a} = A_1\, U_{w1}\, (T_1-T_a) \quad (2)$$

where Q_{1a} is the energy flow to ambient atmosphere by heat transfer in W; A_1 is the surface area of upper layer including the roof and partial wall in m^2, U_{w1} is the heat transfer coefficient of greenhouse cover materials in $Wm^{-2}°K^{-1}$; T_1 is the upper layer temperature in °C; and T_a is the ambient temperature in °C.

b. Q_{12}: energy exchange between upper and layer

$$Q_{12} = A_s\, U_{12}\, (T_1 - T_2) \quad (3)$$

where A_s is the area of internal shading nets in m^2; U_{12} is the heat transfer coefficient of internal shading nets in $Wm^{-2}°K^{-1}$; and T_2 is the lower layer temperature in °C.

c. Q_{m1}: energy exchange by mechanical ventilation

$$Q_{m1} = M_1\, \rho\, C_p\, (T_1-T_a) \quad (4)$$

where M_1 is ventilation rate of mechanical devices in upper part is m^3s^{-1}; ρ is the air density in kgm^{-3} ; and C_p is the air specific heat in J kg-1°C^{-1}

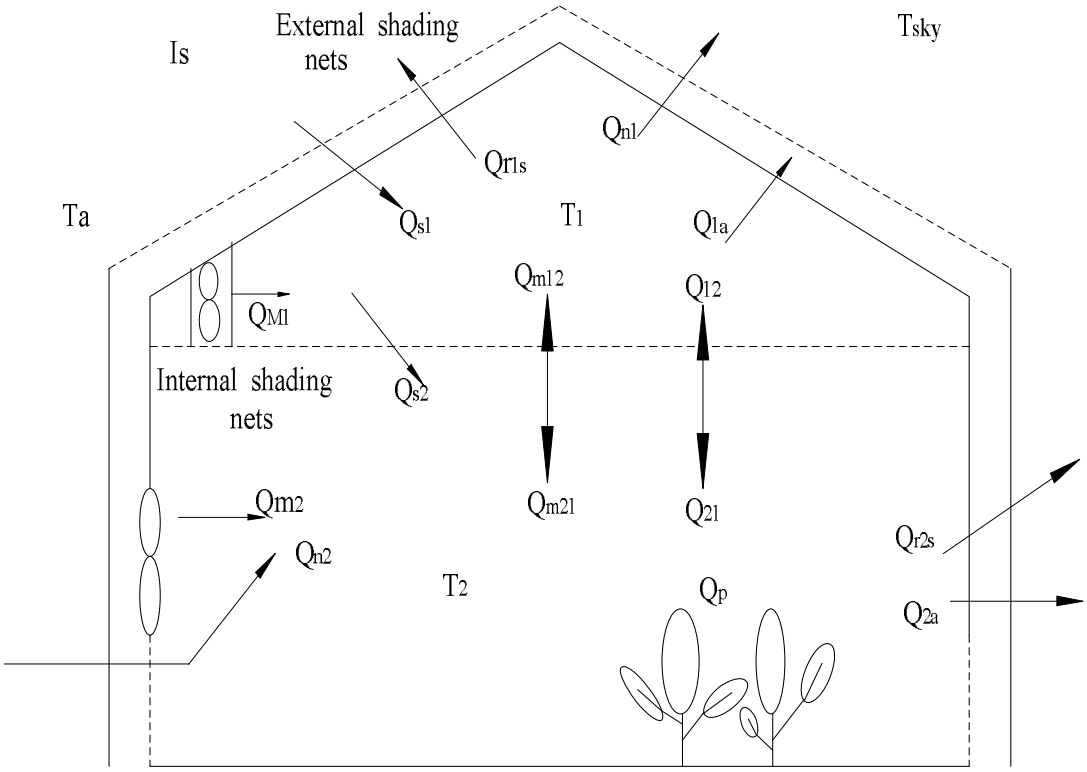

Figure 1. Schematic diagram of the thermal transfer model for a greenhouse with shading nets; I_s, entrance energy of shortwave radiation from the sun ; T_{sky}, sky temperature ; T_a, ambient temperature; T_1, upper layer temperature ; T_2, lower layer temperature ; Q_{S1}, the solar energy in the upper layer; $Q_{1a:}$, energy flow in/out to ambient atmosphere by heat transfer; Q_{12}, energy exchange between upper and layer; Q_{m1}, energy exchange by mechanical ventilation; Q_{n1}, energy exchange by natural ventilation; Q_{m12}, energy exchange rate due to the air from the lower layer; Q_{r1s}, energy exchange by the radiation heat exchange; Q_{S2}, the solar energy in the lower layer; Q_{2a}, energy flow to ambient atmosphere by heat transfer; Q_{21}, energy exchange between lower and upper layer; Q_{m2} ,energy exchange by mechanical fans; Q_{n2}, energy exchange due to natural ventilation; Q_{m21}, energy exchange from upper layer due to the mechanical ventilation of lower layer; Q_{r2s}, energy exchange by the radioactive heat exchange; Q_p, transpiration energy by crops.

d. Q_{n1}: energy exchange by natural ventilation

$$Q_{n1} = AR\,\rho\,C_p\,(T_1-T_a) \quad (5)$$

where AR is the natural air exchange rate of greenhouse in m^3s^{-1}. AR was calculated following the equation of Roy et al. (2002):

$$AR = 0.5A_{op}\,C_d\,(g\,(T_{ave}-T_a)H/2T_a)^{0.5} \quad (6)$$

$$Tave = (T_1V_1+T_2V_2)/(V_1+V_2) \quad (7)$$

where A_{op} is the area of opening in m^2; C_d is discharge coefficient; g is gravitational acceleration in ms^{-2}; T_{ave} is the average temperature of greenhouse in ℃; H is the opening height in m; V_1 is the volume of the upper layer in m^3; and V_2 is the volume of the lower layer in m^3.

e. Q_{m12}: energy exchange rate due to the air from the lower layer

$$Q_{m12} = M_{12}\,\rho\,C_P\,(T_1-T_2) \quad (8)$$

where M_{12} is the ventilation rate between the upper and lower layer due to the mechanical ventilation of upper layer in m^3s^{-1}.

f. Q_{r1s}: heat transfer due to long-wave radiation

$$Q_{r1s}= \varepsilon\,F_{1s}\,\sigma\,As\,(T_{1k}^4-T_{sky}^4) \quad (9)$$

$$T_{sky} = 0.0552(T_{ak})^{1.5} \quad (10)$$

where ε is the long ware thermal transmittance of cover materials; F_{1s} is the shape factors for the sky as seen from the upper layer; σ is the Stephan-Boltzman constant; T_{1k} is the absolute temperature of upper layer air in K; T_{sky} is the sky temperature in K; and T_{ak} is ambient air temperature in K. The energy balance

equation for the upper layer is:

$$Q_{S1} = Q_{10} + Q_{12} + Q_{m1} + Q_{n1} + Q_{m12} + Q_{r1s} \quad (11)$$

The thermal transfer model of the lower layer

The input energy

A. Q_{S2}: input energy

$$Q_{S2} = \tau_1 \tau_0 I_s \quad (12)$$

The output energy

B. Output energy
a. Q_{2a}: energy flow to ambient atmosphere by heat transfer

$$Q_{2a} = A_2 U_{k2} (T_2 - T_a) \quad (13)$$

where A_2 is the wall area of lower part in m^2; and U_{k2} is the heat transfer coefficient of cover materials in $Wm^{-2}°K^{-1}$.

b. Q_{21}: energy exchange between lower and upper layer

$$Q_{21} = A_s U_{12} (T_2 - T_1) \quad (14)$$

c. Q_{m2}: energy exchange by mechanical fans

$$Q_{m2} = M_2 \rho C_p (T_2 - T_a) \quad (15)$$

where M_2 is the air exchange rate due to the mechanical fans in lower part in m^3s^{-1}.

d. Q_{n2}: energy exchange due to natural ventilation

$$Q_{m2} = AR\rho Cp(T_2 - T_a) \quad (16)$$

where AR is the natural air exchange rate of greenhouse in m^3s^{-1}.

e. Q_{m21}: energy exchange from upper layer due to the mechanical ventilation of lower layer

$$Q_{m21} = M_{21} \rho C_p (T_a - T_2) \quad (17)$$

where M_{21} is the ventilation rate between the upper and lower part due to the mechanical ventilation of lower layer in m^3s^{-1}.

f. Q_{r2s}: heat transfer due to long-wave radiation

$$Q_{r2s} = \varepsilon F_{2s} \sigma A_f (T_{2k}^4 - T_{sky}^4) \quad (18)$$

where F_{2s} is the shape factors for the sky as seen from the lower layer; A_f is the floor area in m^2; and T_{2k} is the absolute air temperature of lower part in K.

g. Qab: absorption of thermal energy of nets

$$Qab = \alpha(1-\tau_1) \tau_0 I_S \quad (19)$$

where α is the absorptance of internal nets

h. Q_p: crop transpiration

$$Q_p = \lambda Tr Pf Af \quad (20)$$

where λ is latent heat of vaporization in $kJkg^{-1}$; Tr is transpiration rate of tomatoes in kgm^{-2}; and Pf is the canopy area index. The transpiration model of tomatoes is adopted from the HORTITRANS model (Jolliet, 1994):

$$Tr = aI_s / \lambda + h_t (1-RH) P_{ws} / (\lambda \gamma) \quad (21)$$

$$a = 0.154 \ln(1+1.1LAI^{1.13}) \quad (22)$$

$$k_t = 1.65 LAI (1-0.56\exp(-I_s/13.0)) \quad (23)$$

$$\gamma = 0.066 kPa K^{-1} \quad (24)$$

P_{ws} was calculated following Weiss (1977):

$$P_{ws} = 0.61078 \exp(17.2694*T_a)/(T_a+237.3) \quad (25)$$

where RH is relative humidity in decimal; and LAI is leaf area index.

The energy balance equation for the lower layer is:

$$Q_{s2} = Q_{20}+Q_{21}+Q_{m2}+Qm_{21}+Qr_{2s}+Q_{ab}+Qp \quad (26)$$

EXPERIMENTAL DETAILS

Greenhouses

A 12.8 × 32 × 3.5 m high, polycarbonate glazed steel framed structure greenhouse located at Wufeng, in Taichung was selected to validate the thermal transfer model. The transmittance was 50% for external and internal shading nets. The roof vents and side windows were operated with motors. The mechanical ventilation system consisted of 4 units of 40 cm fans with a capacity of 180 m^3min^{-1} at the upper layer and 4 units of 135 cm fans with a capacity of 550 m^3min^{-1} at the lower layer. The height of internal shading net was 3.0 m. The schematic of the experimental greenhouse is presented in Figure 2.

Tomatoes were planted in medium bags placed on the ground and crop spacing was 1.35 m. The ratio for the tomatoes to the floor was nearly 70%.

Measuring devices

T-type thermocouples (Omega Engineering, USA) were applied to measure the upper, lower and ambient air temperature. The thermocouples junctions were placed in a radiation-shielded box

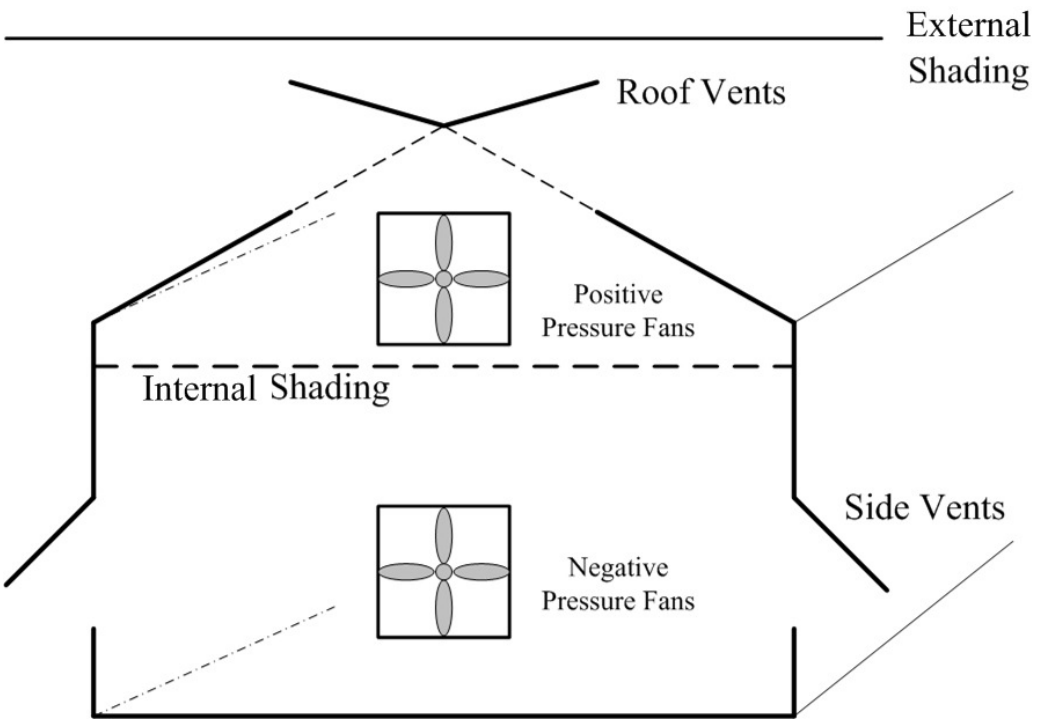

Figure 2. Schematic diagram of experiment greenhouse.

Table 1. Model input parameter for the greenhouse model.

Symbols	Description	Numeric values	Units
U_{w1}	Thermal transfer coefficient of roofs	6.1	$Wm^{-2}C^{-1}$
U_{w2}	Thermal transfer coefficient of walls	6.3	$Wm^{-2}C^{-1}$
τ_0	Transmittance of the cover materials	0.8	
τ_i	Transmittance of the inner shading nets	0.5	
A_S	Area of the internal shading nets	390	m^2
U_{12}	Heat transfer coefficient of the inner shading nets	0.2	$Wm^{-2}C^{-1}$
C_d	Discharge coefficient	0.35	
M_{12}	Ventilation rate of between upper and lower nets	0.1	m^3s^{-1}
F_{1S}	Shape factor for the sky as seen from the upper layer	0.85	
F_{2S}	Shape factor for the as seen from the lower layer	0.39	
V_1	Volume of the upper layer	512	m^3
V_2	Volume of the lower layer	1229	m^3
α	absorptance of internal nets	0.04	

including an aspirated fan. All thermocouples were connected to a Delta-T 2e data logger (Delta-T Co., UK). The accuracy of these temperature sensors was maintained within 0.15℃ after calibration with the temperature calibrator (TC-2000, Instrutek, AS Norway).

The air relative humidity was measured by the Shinyei THT-B121 resistive-type transmitter (Shinyri Kaisha Co., Tokyo, Japan). The accuracy of these sensors was kept within 0.7% after calibration with saturated salt solutions.

The solar radiation was detected by three E8-48 Pyranometers (Eppley Co., USA). The solar radiation at upper layer, lower layer and ambient atmosphere condition were recorded by the same data logger. The air velocity was measured by TSI 8450 air velocity transducer (TSI Co., St. Paul, MN USA). The measuring range was from 0 to 20 ms^{-1} and the accuracy was within 1.5% of reading. The leaf area index (LAI) was measured by LAI-200 Plant Canopy Analyzer (Li-COR, NL USA). The experimental design of this study included cases of no ventilation, natural ventilation and mechanical ventilation.

Parameters for the thermal transfer model

The physical parameters for this study are listed in Table 1. Most of the parameters were obtained from the manufacture's specification. Only the air ventilation rates were measured in the study. Five air velocity transducers were placed below the internal net. The

ventilation rate between the upper and lower layer was calculated by the average air velocity and the area of internal net.

Simulation

In this study, two unknown temperatures, T_1 and T_2 were calculated from two equations, Equations 11 and 26. As the temperature involved the fourth power term T_{ik}^4, the T_1 and T_2 values could not be directly calculated by algebraic method. The calculation of AR values also involved the T_1 and T_2 value. A Q-BASIC program (NETS.BAS) was written by the authors to do the computing work. The iterative method was applied and two temperatures were determined using the following procedures:

1. Input the ambient conditions including air temperature, relative humidity and solar radiation.
2. Input the air exchange rate of mechanical ventilation if necessary.
3. Input two initial values (T_{10} and T_{20}).
4. Calculate the natural air exchange rate by Equations 6 and 7.
5. Calculate the first iterative value of T_{11} by Equation 11.
6. T_{11} and T_{20} were the initial condition to calculated the first iterative value of T_{21} by Equation 26.
7. Calculate the T_{12} values with the T_{11} and T_{21} values.
8. Calculate the T_{22} value with the T_{12} and T_{21} values.
9. Compare the absolute temperature difference of all deviations that are less than 0.05°C as the final step of the calculation. Otherwise, repeat the computing from step 4.

Evaluation of prediction performance

The criteria of the model evaluation were defined as follows:

1. Predictive errors

$$P_i = Y_i - X_i \quad (27)$$

where Y_i is the measurement temperature in °C and X_i is the predicted temperature by thermal model in °C.

2. Predictive performance

$$P_{ave} = \Sigma \left| Pi \right| / n \quad (28)$$

where $\left| Pi \right|$ is the absolute value of P_i and n is the number of data.

RESULTS AND DISCUSSION

Predictive ability of model

A typical microclimate of the greenhouse for July 1, 2007 is presented in Figure 3a. Partly cloudy skies were found. The maximum solar radiation was nearly 850 Wm^{-2}. The maximum temperature was found at 14:30 pm. The external and internal shading nets were applied on this day. Roof vent and side vent were kept partially open and the air exchange rate by natural ventilation was nearly 0.15 h^{-1}.

As the solar radiation increased, the ambient temperature T_a is increased. The T_1 values, air temperature of upper layer was significant higher than that of T_2 values, air temperature of lower layer. The maximum difference between T_1 and T_a was 10°C. The maximum difference between T_2 and T_a was 6°C. The transmittance of internal shading nets was 50%. As solar energy passed external shading nets and cover materials, 50% of the energy was entering the lower layer of the greenhouses. However, 50% of the energy was kept in the space that was enclosed by the cover materials and internal shading nets. The internal shading nets limited the air flow rate from the bottom of the greenhouse to the upper parts due to the natural ventilation effect. The heat accumulation was enhanced on increase of T_1 value. Heat accumulation was also found in the lower layer. Some of the heat energy was transmitted to the upper layer due to the wind suction of natural ventilation. So the T_2 value was lower than the T_1 values.

The predictive values of T_1 and T_2 are shown in Figure 3b. The maximum difference between predicted values and T_1 was 2.8°C. The P_{ave} value for T_1 was 1.3°C. The maximum difference between predicted values and T_2 was 1.9°C. The P_{ave} value for T_2 was 1.3°C. Larger deviations between the predicted value and actual measured values were found in the early stage. The reason for this may be that the heat transfer of the ground was negligible. As the radiation energy entering was low, the amount of heat transfer into the greenhouse ground could be significant.

In the second observation, only the internal shading nets were utilized. The roof vent and side vent were kept in a fully open condition. The boundary of the air temperature and solar radiation is presented in Figure 4a. The temperature distribution and predicted values are indicated in Figure 4b. The T_1 values were 6°C higher than the ambient temperatures. The T_2 values were higher than T_a by 2.7°C. The maximum difference between two predictive temperatures was 1.9°C for T_1, and 1.8°C for T_2. The P_{ave} values for T_1 and T_2 were 1.1 and 0.7°C. Compared with Figure 3b, the predictive ability of the model was improved. This may be due to the fact that the increase of air exchange capacity by natural ventilation enhanced the predictive ability of the model.

In the third investigation, external and internal shading nets were applied. The boundary of the air temperature and solar radiation is presented in Figure 5a. Only the exhaust fans of the upper layer were operated. The temperature distribution and predictive values are shown in Figure 5b. The maximum temperature difference was 4.2°C for T_2 and T_a, and 2.1°C for T_1 and T_a. The P_{ave} values for two predictive temperatures were 0.7°C for T_1 and 0.5°C for T_2. The operation of exhaust fans could draw in the ambient air into the upper layer to expel the heat accumulation. The release of heat accumulation could help the greenhouse air temperature to remain at a lower level.

In the fourth experiment, two shading nets and the exhaust fans installed at upper and lower layer were all

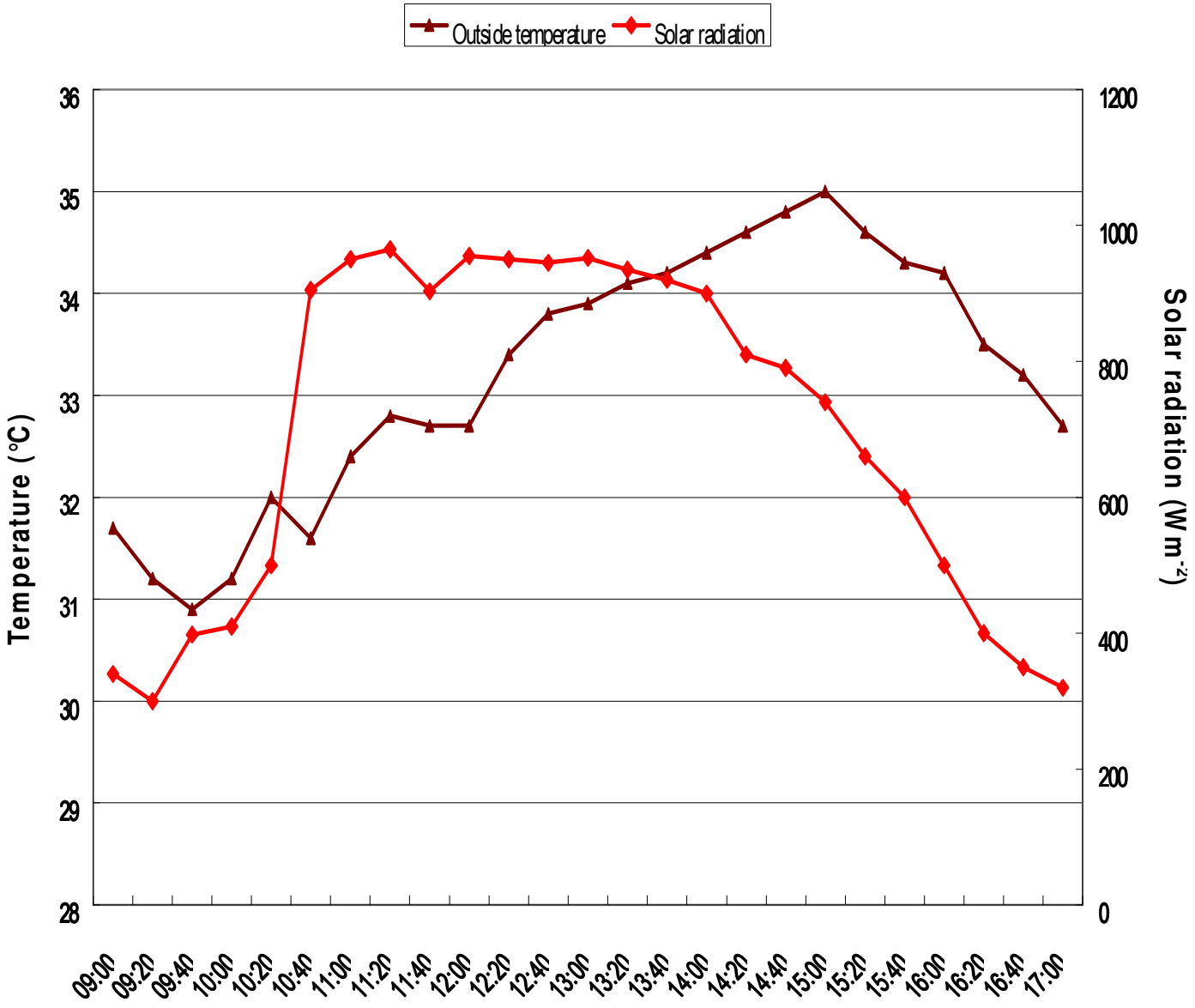

Figure 3a. The boundary of the air temperature and solar radiation for the first observation: ▲, outside temperature; ●, solar radiation; the roof and side vents were partially opened.

utilized. The boundary of the air temperature and solar radiation is presented in Figure 6a. The temperature distribution and predicted values from the model are shown in Figure 6b. The maximum difference between the T_1 and T_a were 2.0℃. The difference between the temperature distribution curves of T_2 and T_a were only 0.5℃. The operation of exhaust fans could draw in enough external air to surpass most of the heat accumulation in the lower layer. The T_2 values were almost the same as the T_a values. The heat accumulation in the upper layer made the 2℃ difference between T_2 and T_a. The P_{ave} value was 0.6℃ for T_1 and 0.7℃ for T_2. Comparing the results with other operating conditions, the model had a good predictive performance at the higher ventilation rates.

Sensitivity analysis of model

Typical weather conditions in the summer were used to simulate the temperature distribution in a greenhouse. The distribution of temperature and solar radiation is shown in Figure 7.

Three conditions were simulated; no ventilation, natural ventilation and mechanical ventilation. Under the first simulation conditions, no ventilation of greenhouse induced

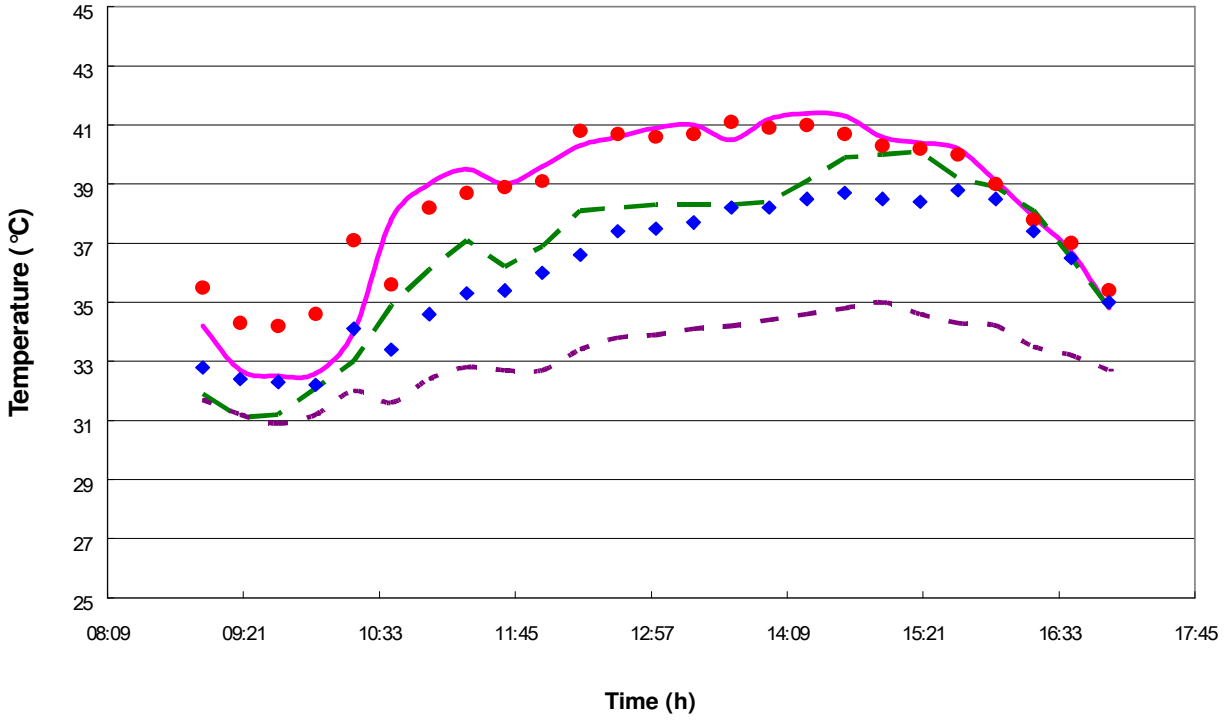

Figure 3b. The distribution of measured temperature and predictive temperature of model, the roof and side vents were partially opened: ●, measured temperature of upper layer; ——, predicted temperature of upper layer; □, measured temperature of lower layer; __ __ __, predicted temperature of lower layer; ------- , measured temperature of ambient air.

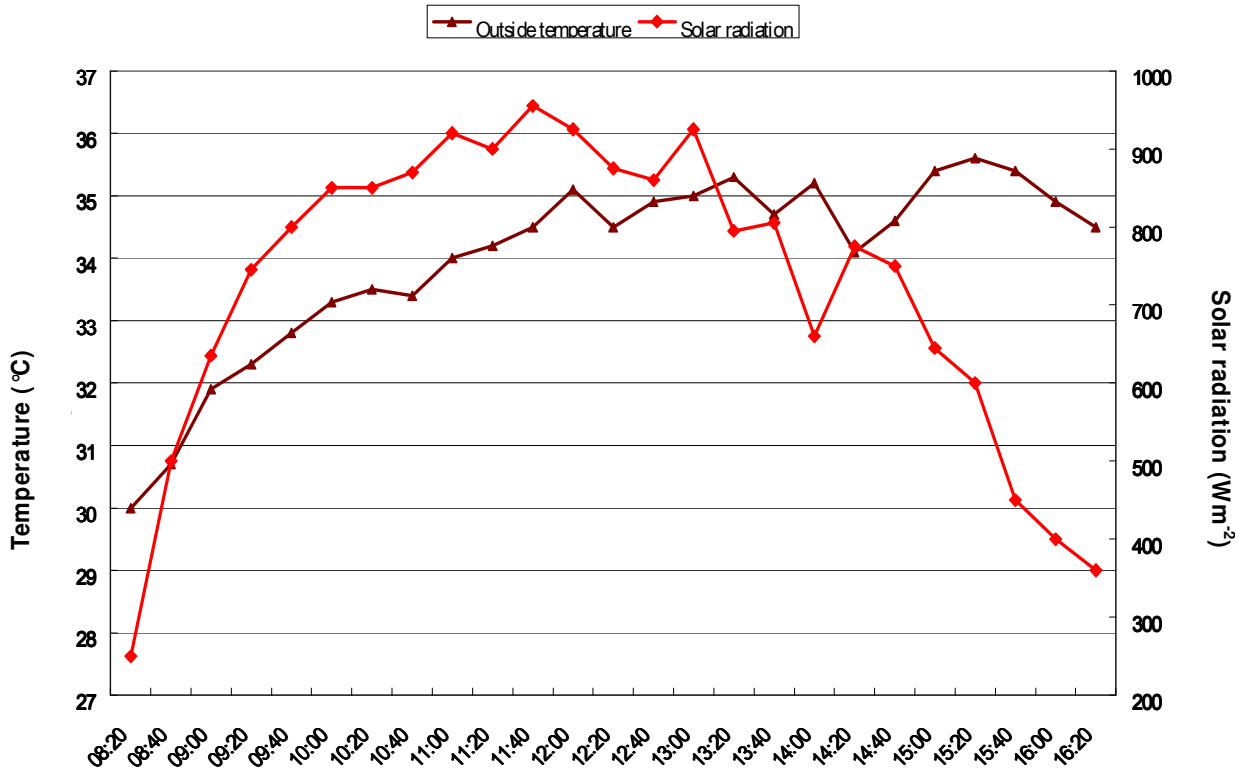

Figure 4a. The boundary of the air temperature and solar radiation for the second observation, ▲, outside temperature; ●, solar radiation; the roof and side vents were full opened.

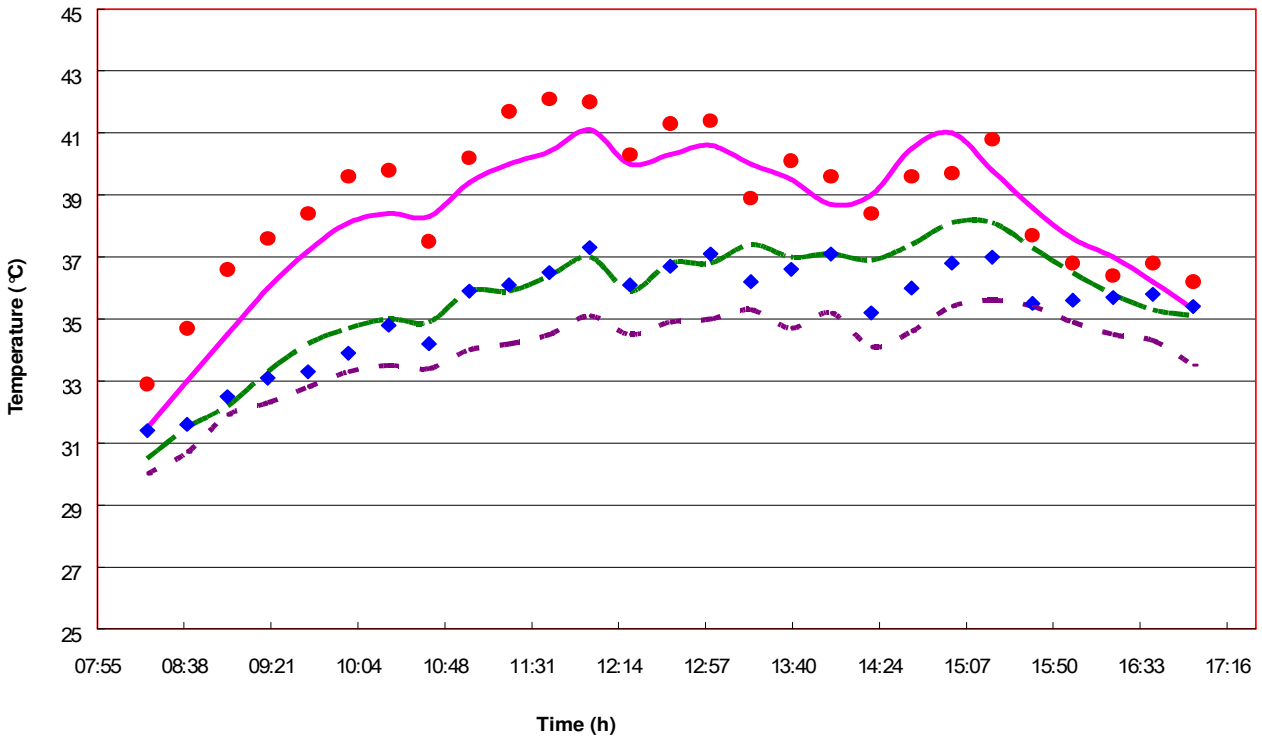

Figure 4b. The distribution of measured temperature and predictive temperature of model, the roof and side vents were fully opened: ●, measured temperature of upper layer; ——, predicted temperature of upper layer; □, measured temperature of lower layer; __ __ __, predicted temperature of lower layer; -------, measured temperature of ambient air.

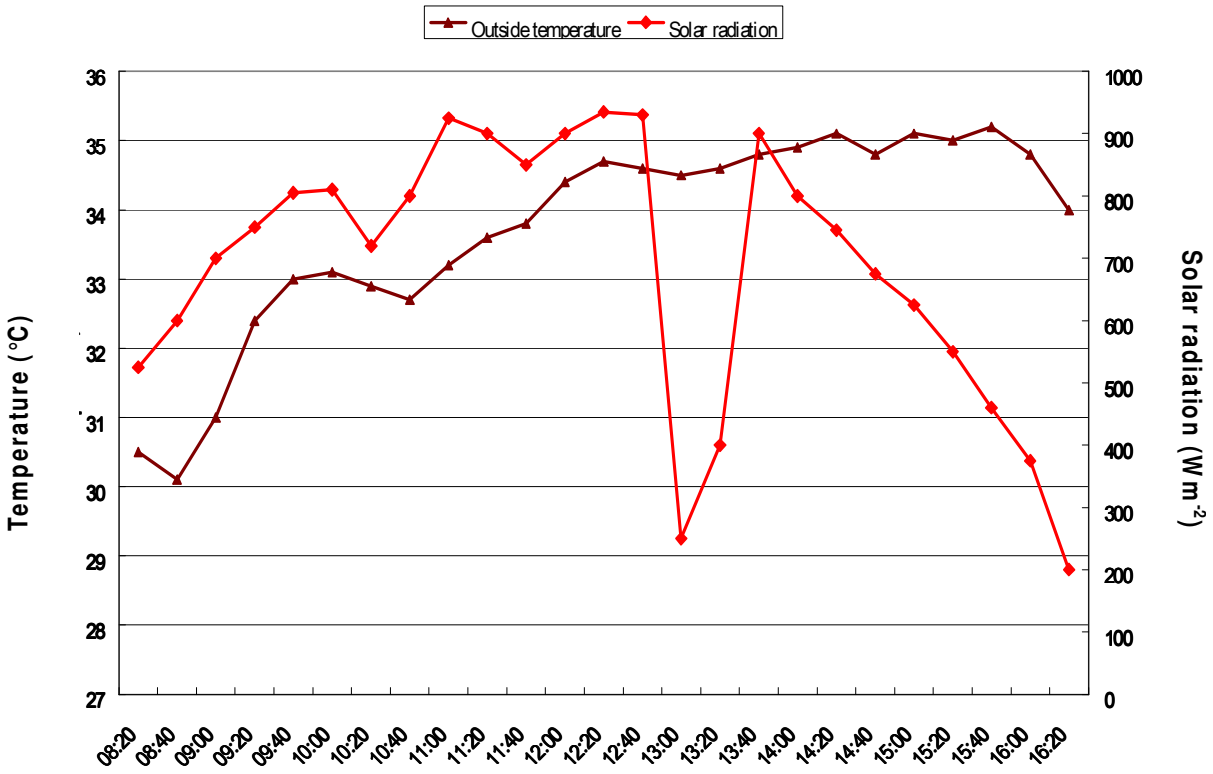

Figure 5a. The boundary of the air temperature and solar radiation for the third investigation, ▲, outside temperature; ●, solar radiation; the exhausted fans of upper layer were operated.

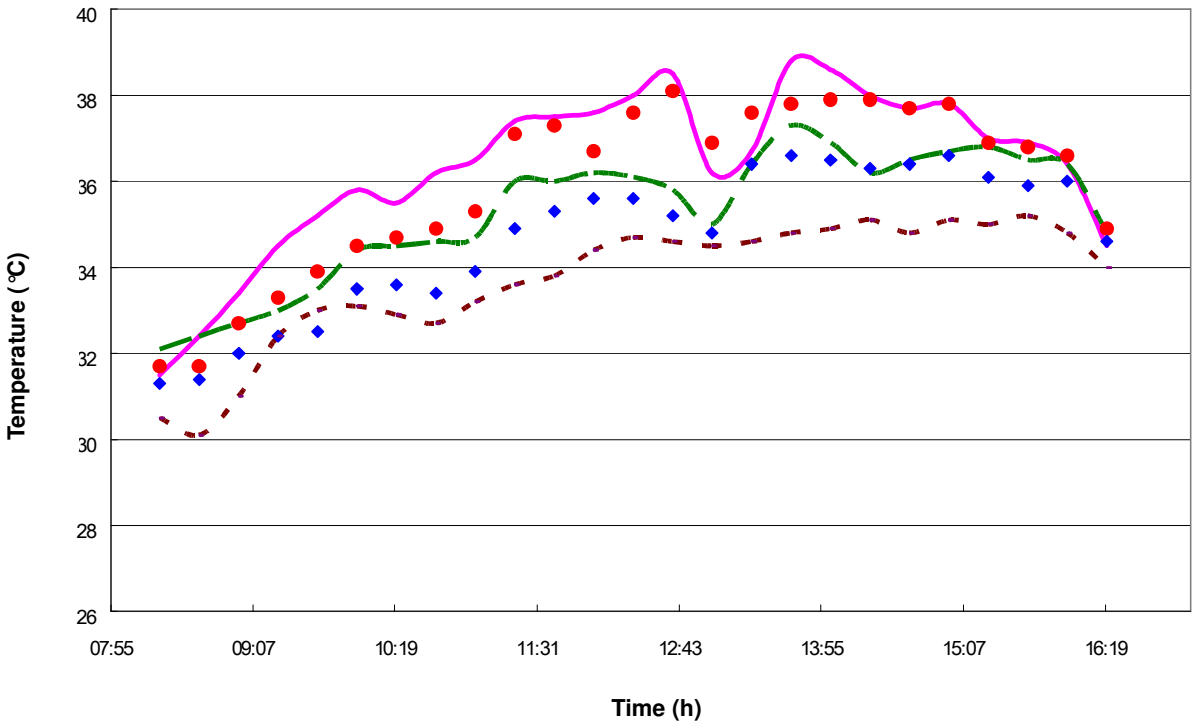

Figure 5b. The distribution of measured temperature and predictive temperature of model, the exhausted fans of upper layer were operated: ●, measured temperature of upper layer; ——, predicted temperature of upper layer; □, measured temperature of lower layer; __ __ __, predicted temperature of lower layer; -------, measured temperature of ambient air.

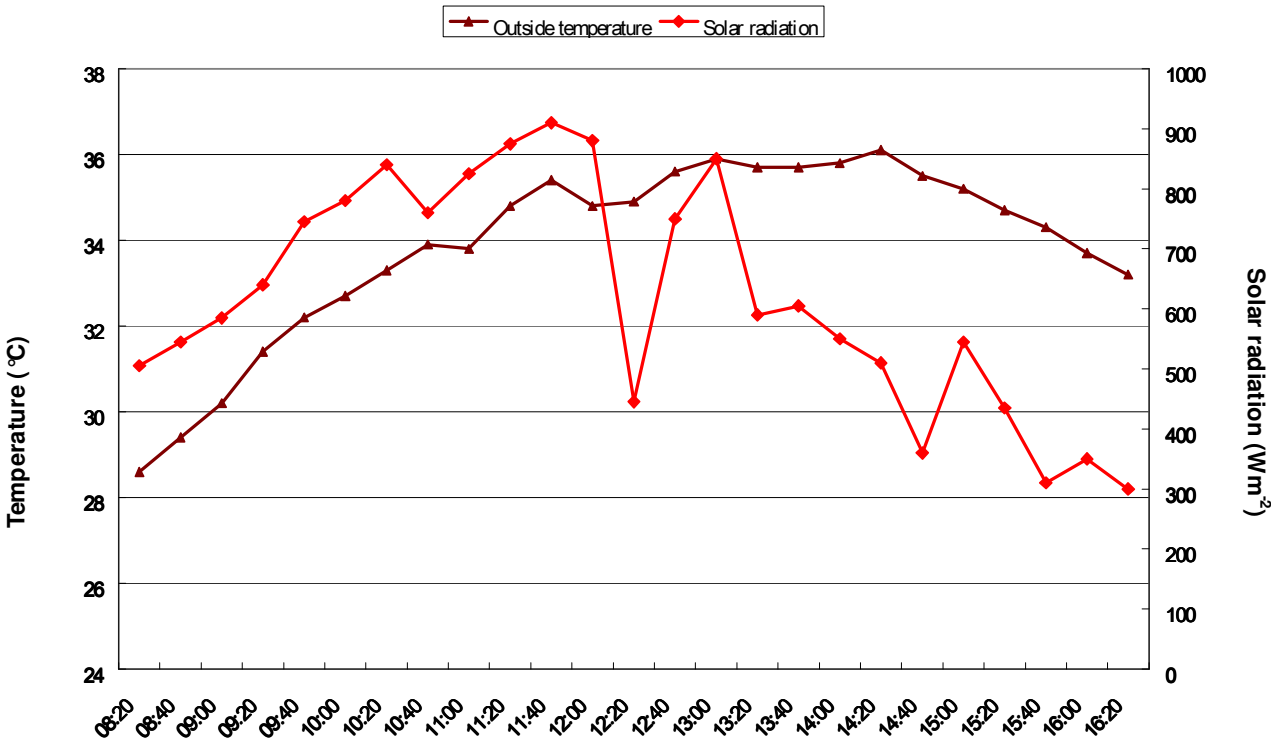

Figure 6a. The boundary of the air temperature and solar radiation for the fourth experiment, ▲, outside temperature; ●, solar radiation; the exhausted fans of upper and lower layer were operated.

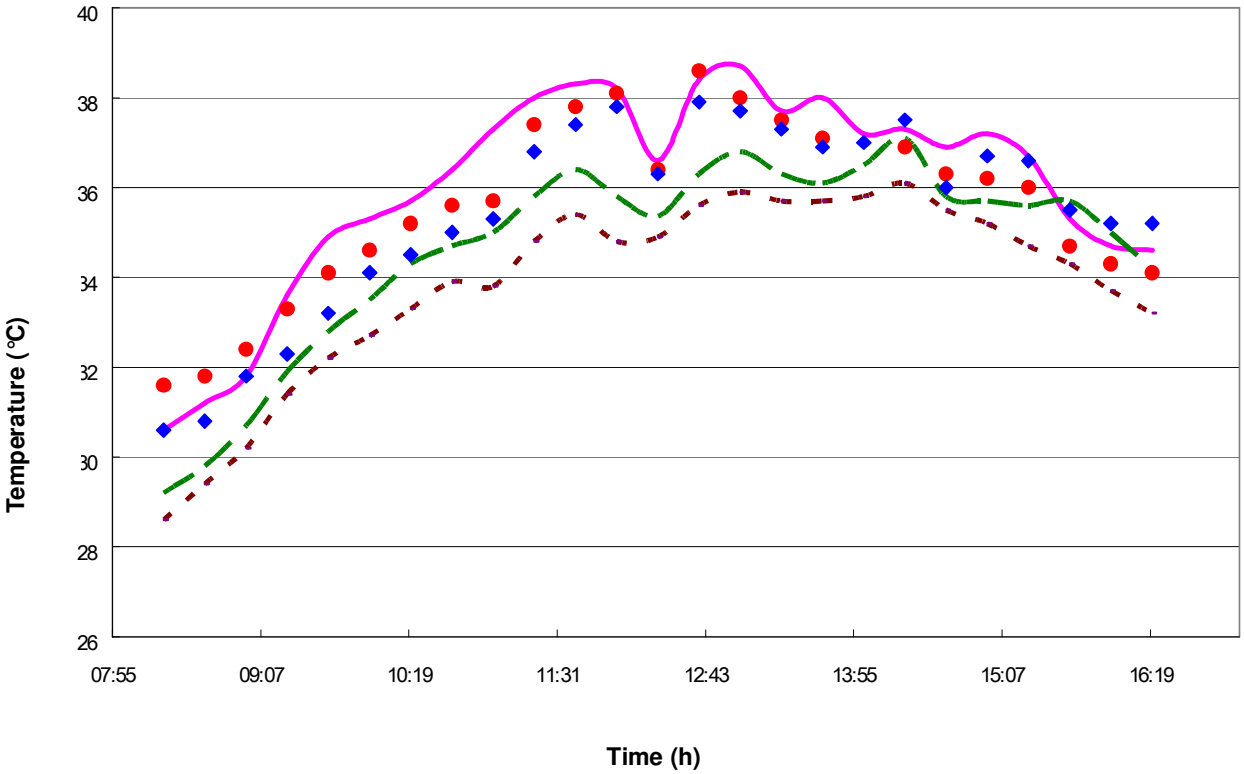

Figure 6b. The distribution of measured temperature and predictive temperature of model, the exhausted fans of upper and lower layer were operated: ●, measured temperature of upper layer; ——, predicted temperature of upper layer; □, measured temperature of lower layer; __ __ __, predicted temperature of lower layer; -------, measured temperature of ambient air.

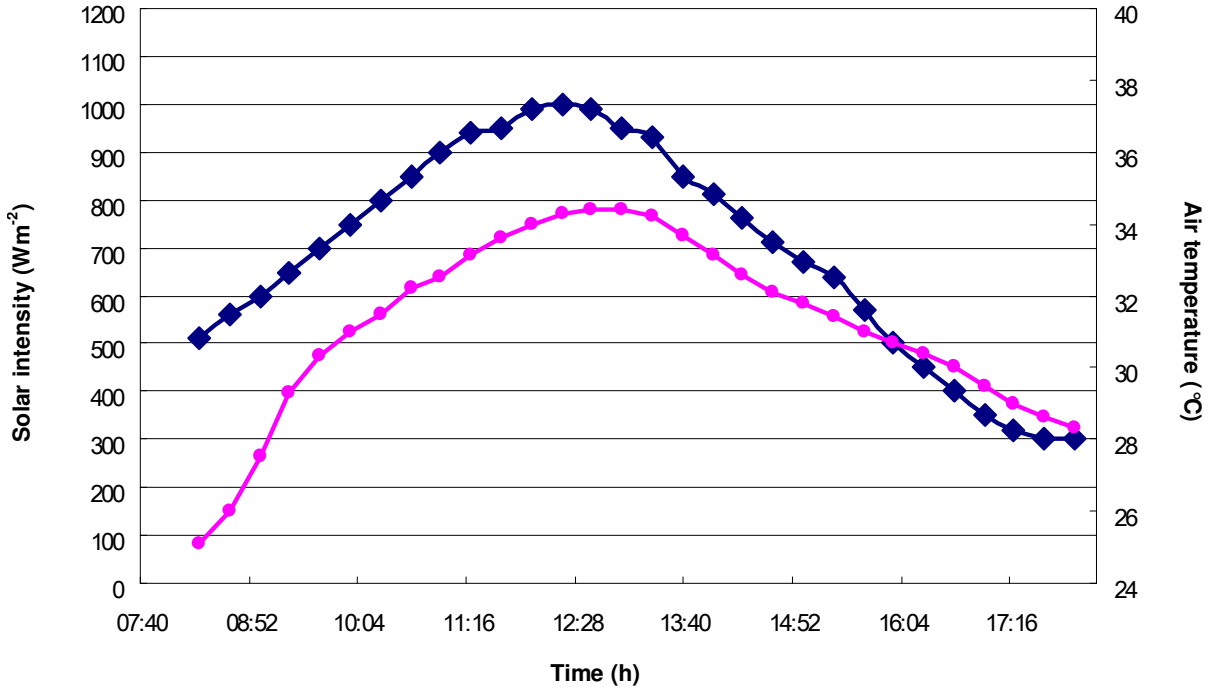

Figure 7. The distribution of temperature and solar intensity of ambient air for sensitive analysis: □, solar radiation; ■, ambient temperature.

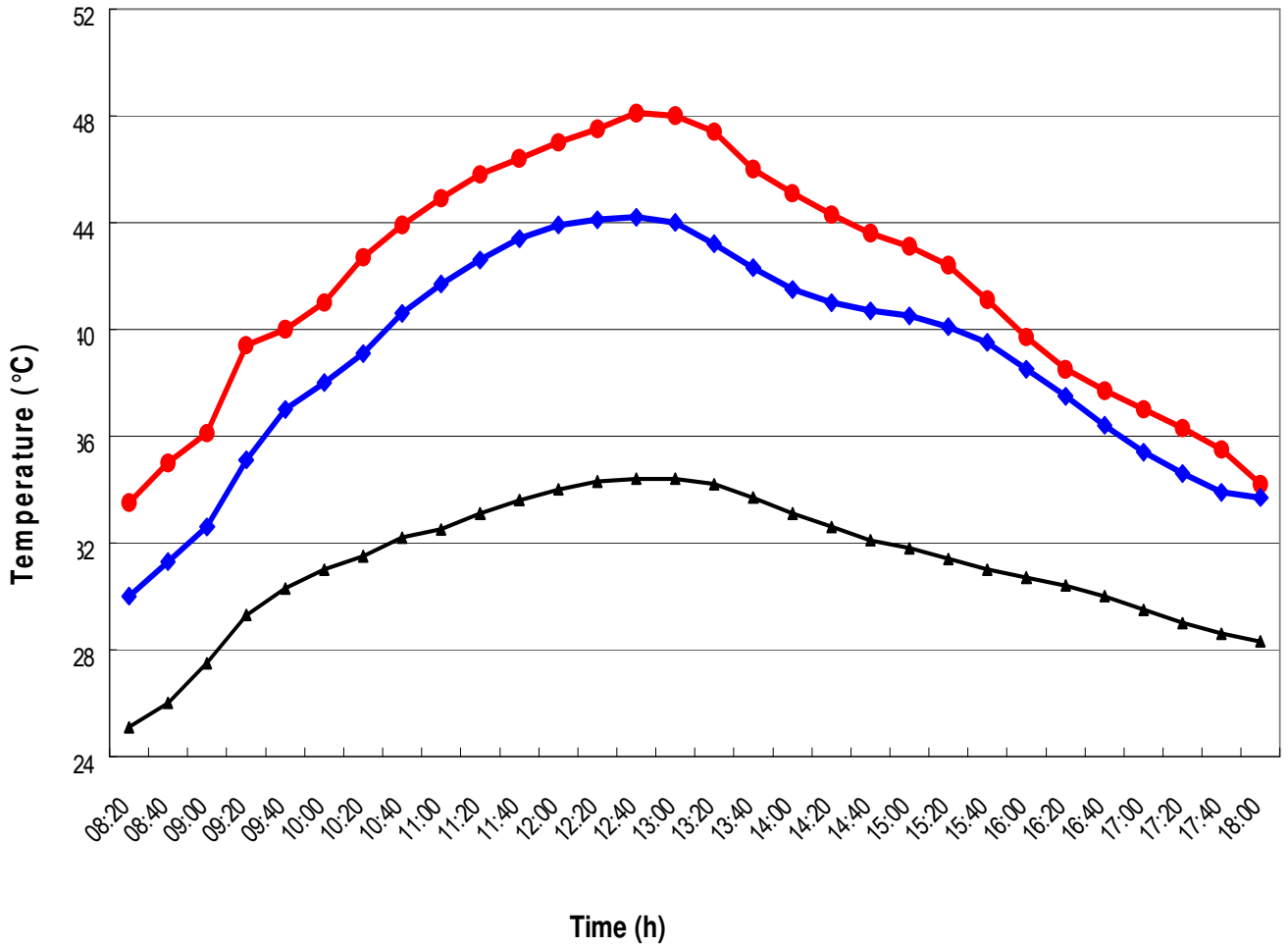

Figure 8. The distribution of the predictive temperature of model for sensitive analysis at the closed state of greenhouse: ●, upper temperature; □, lower temperature; ▲, ambient temperature.

a serious heat accumulation. The simulation result is presented in Figure 8. The shading nets only retarded the heat accumulation. However, only a small portion of the heat entering greenhouse could be transmitted to ambient environment by heat transfer. The temperature difference was larger than 20°C for T_1 and T_a, and 16°C for T_2 and T_a. As the air temperature was higher than 40°C, no commercial plant could survive under this serious heat stress.

In the second condition, the ambient air was induced into the greenhouse by natural ventilation. The effect of control technique is presented in Figure 9. The maximum difference between internal and external temperatures was 15°C for T_2 and 10°C for T_1. The internal shading nets could decrease the amount of solar radiation entering. However, the nets retarded the air flow from the bottom to the roof. The function of natural ventilation could not release the heat accumulation effectively.

In the third condition, the amount of ambient air was sucked into the greenhouse by fans. The effect of control technique is presented in Figure 10. The T_1 values were 1.0°C higher than that of ambient air. The T_2 values were almost the same as the ambient air temperature.

The purpose of application of greenhouse conditions in the summer was to grow the high value crops. From the simulation results of this model, a higher ventilation rate and reduction of solar radiation by shading nets was significant in reducing the air temperature in a greenhouse. Utilization of shading nets only, did not help the heat release in the greenhouse. The cooling performance with the shading nets and mechanical ventilation reduced the interior temperature of the greenhouse to a level similar to ambient atmosphere temperature.

Conclusions

A simple greenhouse climate model was developed in this study that considered the effect of shading nets. The model was used to consider the effect of ventilation rate

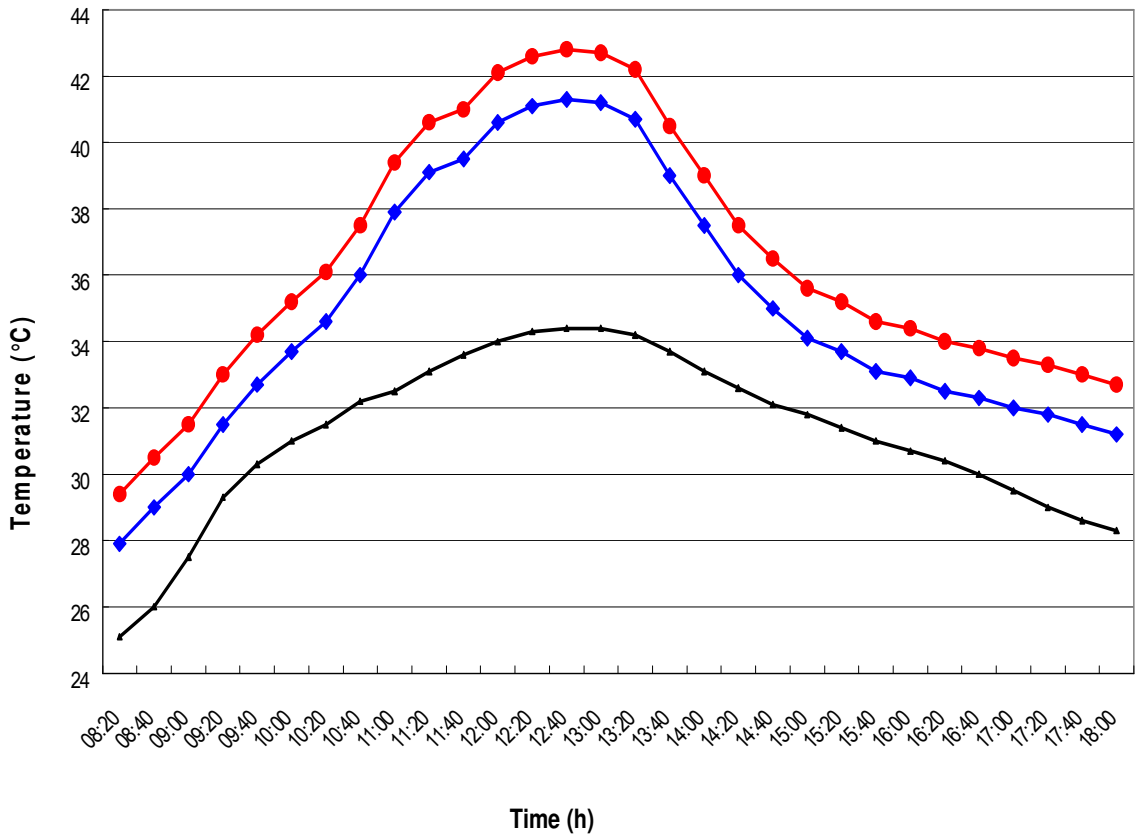

Figure 9. The distribution of the predictive temperature of model for sensitive analysis by natural ventilation: ●, upper temperature; □, lower temperature; ▲, ambient temperature.

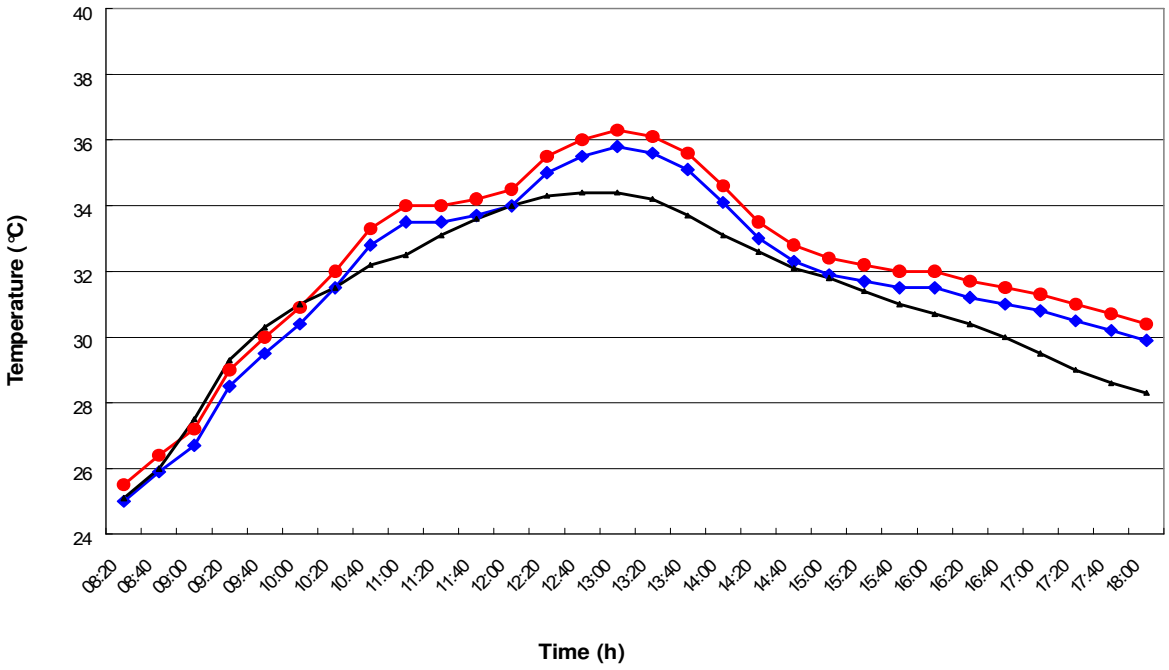

Figure 10. The distribution of the predictive temperature of model for sensitive analysis by forced ventilation: ●, upper temperature; □, lower temperature; ▲, ambient temperature.

and shading function. This model was validated by data measured in a greenhouse with tomatoes. A close agreement was found between the predictive values and measured values. The application of the model by sensitivity analysis revealed that the combination of shading application and higher ventilation rates was the best way to reduce the internal temperature of a greenhouse during the summer months.

Notation

a, constant; $\mathbf{A_1}$, surface area of the upper layer included the roof and partial wall, m^2; $\mathbf{A_2}$, wall area of the lower part, m^2; $\mathbf{A_f}$, floor area, m^2; $\mathbf{A_{op}}$, area of opening, m^2; $\mathbf{A_s}$, area of internal shading nets, m^2; **AR,** natural air exchange rate of the greenhouse, m^3s^{-1}; $\mathbf{C_d}$, discharge coefficient value; $\mathbf{C_p}$; air specific heat, J $kg^{-1}℃^{-1}$; $\mathbf{F_{1s}}$, shape factors for the sky as seen from the upper layer; $\mathbf{F_{2s}}$, shape factors for the sky as seen from the lower layer; **g,** gravitational acceleration, ms^{-2}; **H,** opening height, m; $\mathbf{h_t}$, constant; $\mathbf{I_S}$, Incoming shortwave radiation, Wm^{-2}; **LAI,** leaf area index; $\mathbf{M_1}$, ventilation rate of mechanical devices in the upper part, m^3s^{-1}; $\mathbf{M_2}$, ventilation rate of mechanical devices in the lower part, m^3s^{-1}; $\mathbf{M_{12}}$, ventilation rate between the upper and lower layer due to the mechanical ventilation of the upper layer, m^3s^{-1}; $\mathbf{M_{21}}$, ventilation rate between the upper and lower part due to the mechanical ventilation of the lower layer, m^3s^{-1}; **n,** number of data; $\mathbf{P_{ave}}$, predictive performance, ℃; **Pf,** Canopy area index; $\mathbf{P_i}$, predictive error, ℃; $\mathbf{P_{ws}}$, air saturated vapor pressure, kPa; **RH,** relative humidity, %; $\mathbf{T_1}$, upper layer temperature, ℃; $\mathbf{T_{1k}}$, absolute air temperature of the upper layer air, K; $\mathbf{T_2}$, lower layer temperature, ℃; $\mathbf{T_{2k}}$, absolute air temperature of lower part, K; $\mathbf{T_a}$, ambient temperature, ℃; $\mathbf{T_{ak}}$, ambient air temperature, K ; $\mathbf{T_{ave}}$, average temperature of greenhouse, ℃; **Tr,** transpiration rate of tomatoes, $kgm^{-2}s^{-1}$; $\mathbf{T_{sky}}$, sky temperature, K; $\mathbf{U_{12}}$, heat transfer coefficient of internal shading nets, $Wm^{-2}℃K^{-1}$; $\mathbf{U_{k2}}$, heat transfer coefficient of cover materials, $Wm^{-2}℃K^{-1}$; $\mathbf{U_{w1}}$, heat transfer coefficient of greenhouse cover materials, $Wm^{-2}K^{-1}$; $\mathbf{V_1}$, volume of the upper layer, m^3; $\mathbf{V_2}$, volume of the lower layer, m^3; $\mathbf{X_i}$, predicted temperature by thermal model, ℃; $\mathbf{Y_i}$, measurement temperature, ℃; $|Pi|$, absolute values of predictive error; **α,** absorptance of internal nets; **ρ,** air density, kgm^{-3}; **σ,** Stephan-Boltzman constant; **ε,** long ware thermal transmittance of cover materials; $\boldsymbol{\tau_0}$, transmittance of external shading nets; $\boldsymbol{\tau_1}$, transmittance of internal shading nets; **λ,** latent heat of vaporization, $kJkg^{-1}$; **γ,** thermodynamic psychrometric constant, kPa K^{-1}.

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