International Journal of Emerging Technology and Advanced Engineering
Volume 3, Special Issue 3: ICERTSD 2013, Feb 2013, pages 337-343
An ISO 9001:2008 certified Int. Journal, ISSN 2250-2459, available online at www.ijetae.com

EFFECT OF CROP TRANSPIRATION ON THE MICROCILMATE OF A NATURALLY VENTILATED GREENHOUSE

Biplab Bauri and A. Ganguly[1]

Department of Mechanical Engineering,
Bengal Engineering & Science University, Shibpur,
Howrah – 711103, West Bengal

[1]Corresponding author email: aritra78@gmail.com

ABSTRACT

Greenhouse technology is an important method of cultivation of crops, flowers and medicinal plants under a controlled environment. Cultivation of flora in greenhouses is increasing worldwide from high altitude and temperate regions to the warmer regions of tropics and subtropics. Natural ventilation is an important cost effective method of maintenance of suitable temperature and humidity in a greenhouse especially during those months of a year when the ambient climatic conditions are moderate. The present paper discusses a thermal model of a floriculture greenhouse under natural ventilation considering the crop aspects like leaf area index, phenomenon of transpiration, etc. The model considers ambient temperature, air water vapour pressure and wind velocity as input parameters and predicts the greenhouse air temperature, air water vapour pressure and the plant temperature for a given degree of shading.

Keywords- Greenhouse, Natural Ventilation, Thermal Model, Transpiartion, Leaf Area Index.

1. INTRODUCTION

Every plant needs a favorable microclimate in terms of temperature, humidity, light and carbon dioxide level for its optimum growth. These climatic conditions can be artificially nurtured in a greenhouse which is not possible in open field cultivation. Thus, greenhouses are artificial structures covered with transparent material inside which the climatic conditions are artificially regulated for the optimum growth of flora.

Natural ventilation is a passive method of maintenance of a suitable micro-climate in a greenhouse which results from the pressure difference created due to the effect of wind velocity and the thermal buoyancy. The use of natural ventilation in greenhouse cultivation is increasing worldwide primarily due to involvement of lower cost compared to that of fan-pad or fogging systems which require electricity.

In the present work, a thermal model of a greenhouse under natural ventilation has been developed similar to that available in literature [1] and the same has been implemented for predicting the micro-climate of a greenhouse located in the plains of Gangetic Bengal which represents a mixed climate of coastal and plain regions. The model considers the crop aspects like leaf area index, characteristic length of leaf, phenomenon of plant transpiration, etc and predicts the greenhouse air temperature, air water vapour pressure and the plant temperature for a given degree of shading considering ambient climatic data as input.

2.Literature Review

Many researchers have studied the phenomenon of natural ventilation in greenhouses in last three decades by developing analytical models, conducting experiments either in small or full scale greenhouses equipped with or without insect proof screens and using computational fluid dynamics (CFD). In this section literature dealing with natural ventilation performance of greenhouse have been reviewed and presented in brief. Shu-zhen *et al.* [2] developed and experimentally validated a model to predict the variation of air temperature in a naturally ventilated greenhouse equipped with insect proof screen. Roof ventilation and combined roof and sidewall ventilation were considered in the model. Comparison between the two types of ventilation showed that there existed a necessary ventilation rate, which results in decrease in air temperature in natural ventilation under special climatic conditions. Roy et al. [3] reviewed the characterization and modeling of the most relevant convective transfers contributing to the greenhouse microclimate Dayan *et al.* [4] presented a model based on mass and energy balance to calculate the rate of ventilation in a greenhouse used for commercial cultivation of rose. Kumar et al. [1] developed a thermal model to predict the microclimate of a greenhouse for floriculture production considering a number of parameters like greenhouse geometry, external climate and leaf area index of the crop. The model predicted results were validated through experiments.

Boulard and Wang [5] developed a thermal model considering heat and water vapour balance to predict the air temperature and humidity in a greenhouse. The model also estimated the total crop transpiration. The model was validated against the experimental data obtained from a soil-less tomato crop cultivation.

Thus, from this brief review it is evident that almost no work has been reported that deals with the development of a thermal model of a greenhouse under natural ventilation for the climatic conditions of Gangetic Bengal considering the different crop aspects. This was the motivation behind the present work.

3. Model development

The following assumptions have been made for the development of the thermal model:

i. The variation of soil heat flux in the greenhouse is negligible for a day.
ii. The heat storage capacity of the cover and shade net is considered to be small when compared to existing fluxes in the greenhouse.
iii. The long-wavelength radiative heat conductance between plant and sky is considered to be negligible [6].
iv. Transmissivity of the greenhouse cover has been considered as constant for all the spectral (UVR, PAR, NIR) regions which is 0.8 for this model [7].

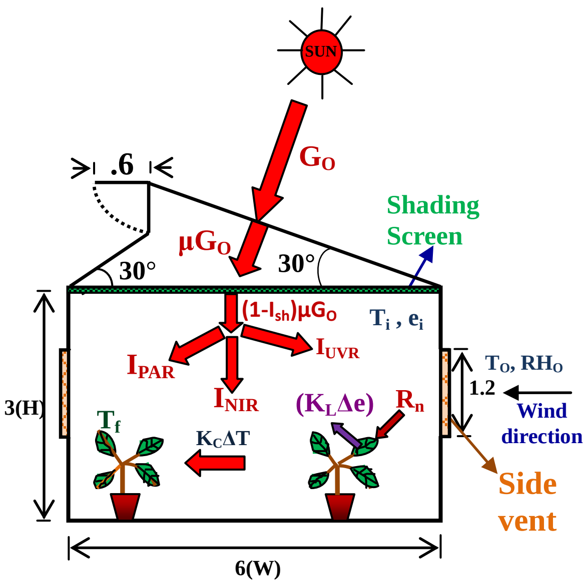

Fig. 1: Energy distribution of greenhouse showing the details of different heat transfer

The overall energy balance for the greenhouse can be given by [8]:

$$(1 - I_{sh})\mu G_O = K_S \Delta T + K_C \Delta T + K_L \Delta e \quad (1)$$

Where, G_o is the outside global radiation (W m^{-2}), I_{sh} is the shading factor of inside shade net of greenhouse, ΔT is the temperature difference between interior and exterior air of greenhouse (K), Δe is the water vapour pressure difference between the inside and outside air (Pa) and K denotes the heat transfer coefficient. Transmissivity of the greenhouse covering material (μ) denotes the part of solar radiation which reaches the plantation zone. In the present work its value has been considered to be 0.8 [7].

The sensible heat transfer coefficient between inside and outside the greenhouse (k_s) is proportional to the ventilation flux and can be given by the following expression [5]:

$$K_S = \frac{\rho C_p Q}{A_g} \quad (2)$$

In Eq. (2), Q denotes the ventilation rate which can be expressed as [3]:

$$Q = C_d \left(2g\frac{\Delta T}{T_O} \left(\frac{(A_R A_S)^2}{{A_R}^2 + {A_S}^2} \right) + \left(\frac{A_R + A_S}{2} \right)^2 C_W {U_O}^2 \right)^{0.5} \quad (3)$$

The values of the parameters C_d (Coefficient of discharge through the vents) and C_w (wind pressure coefficient) depend upon the geometry of a particular greenhouse and the vent configuration. The average value of C_d is considered to be 0.4224 and C_w to be 0.1042 respectively for the development of this thermal model [7]. The values of A_R (area of roof opening) and A_S (area of side opening) are considered to be 3.84 m^2 and 11.52 m^2 [7] respectively.

In Eq. (2), ρ is the air density (1.25 Kg m^{-3}), C_p is specific heat of air at constant pressure and A_g (area of greenhouse floor) is considered to be 90 m^2 [7].

The overall heat transfer coefficient depends upon external wind speed (U_o) and can be estimated by the following relation [9]:

$$K_C = A + BU_O \quad (4)$$

The value of A and B depends upon greenhouse aspect ratio and cover characteristics. In the present work the average values of A and B have been considered to be 6.5 and 0.4, respectively [1].

The latent heat transfer coefficient can be given by [5]:

$$K_L = \frac{\lambda \zeta \rho Q}{A_g} \quad (5)$$

In Eq. (5), ζ is the conversion factor between air water content at standard temperature and air water vapour pressure. The value of ζ is assumed to be 6.25×10^{-6} kg_w kg_a^{-1} Pa^{-1} [5], while λ is the latent heat of vapourization whose value is considered to be 2.45 MJ Kg^{-1}[10].

In Eq. (1), the term $K_L\Delta e$ denotes the latent heat transfer by the greenhouse vegetation through plant transpiration. The greenhouse crop transpiration λE can be given by [5]:

$$\lambda E = K_L \Delta e \tag{6}$$

Where, λ is the latent heat of vapourization in J Kg^{-1}, E is the amount of canopy transpiration in Kg $m^{-2}s^{-1}$ and Δe is water vapour pressure difference between the interior and exterior air.

Greenhouse crop transpiration λE can also be represented as [9]:

$$\lambda\, E = \frac{\rho Cp\, I_{LA}}{\gamma}\left(\frac{e_f^* - e_i}{r_s + r_a}\right) \tag{7}$$

Where, I_{LA} is the leaf area index (LAI) expressed as leaf area per unit ground area. The value of LAI is considered to be 3.5 for the present model [1].

γ denotes the psychrometric constant in Pa K^{-1} and can be given by [10]:

$$\gamma = \frac{C_p P}{\epsilon \lambda} \tag{8}$$

In Eq. (8), P is atmospheric pressure, ϵ is the ratio of molecular weight of water vapour to dry air (considered to be 0.622) and λ is the latent heat of vapourization. The value of λ is considered to be 2.45×10^6 J Kg^{-1} in the present work [10].

In Eq. (7), e_f^* is the saturated water vapour pressure of the air at the vegetation temperature (in Pa) and e_i is the water vapour pressure of the greenhouse inside air (in Pa).

In Eq. (7) e_f^*- e_i can be expressed as [9]:

$$e_f^* - e_i = \delta(T_i)\Delta T_f + D_i \tag{9}$$

Where, δ (T_i) is the slope of the water vapour saturation curve at greenhouse temperature Ti (Pa K^{-1}).Generally slope of the water vapour saturation curve $\delta(T)$ for certain temperature T can be given by [6]:

$$\delta(T) = \left(\frac{5385}{T^2}\right) 2.229 \times 10^{11} \exp\left(-\frac{5385}{T}\right) \tag{10}$$

ΔT_f is the temperature difference between inside air and vegetation (K) and represented as:

$$\Delta T_f = T_f - T_i = (T_f - T_o) - (T_i - T_o) = \Delta T_{fo} - \Delta T \tag{11}$$

ΔT_{fo} is the temperature difference between vegetation and ambient air.

The internal air water vapour pressure deficit (D_i) in Eq. (9) can be expressed as:

$$D_i = e^*(T_i) - e_i \tag{12}$$

Where, e_i is the water vapour pressure of the greenhouse inside air in Pa and $e^*(T_i)$ is the saturated water vapour pressure of the air at the greenhouse temperature (T_i) which can be given by the expression [11]:

$$e^*(T) = \exp\left(25.317 - \frac{5144}{T + 273.15}\right) \tag{13}$$

Eq. (12) can also be written as [1]:

$$D_i = e^*(T_i) - e_i + e^*(T_o) - e^*(T_o) + e_o - e_o \tag{14}$$

$e^*(T_o)$ is the saturated water vapour pressure of the air at the ambient temperature T_o and e_o is the water vapour pressure of the exterior air and both are expressed in Pa.

D_i can also be approximated as [9]:

$$D_i = [e^*(T_i) - e^*(T_o)] - (e_i - e_o) + [e^*(T_o) - e_o] \tag{15}$$

Finally D_i can be represented as [5]:

$$D_i = \delta(T_o)\Delta T - \Delta e + D_o \tag{16}$$

D_o is the outside air water vapour pressure deficit and it can be written as

$$D_o = [e^*(T_o) - e_o] \tag{17}$$

δ (T_o) is the slope of the water vapour saturation curve at T_o and can be expressed as :

$$\delta(T_o) = \frac{e^*(T_i) - e^*(T_o)}{\Delta T} \tag{18}$$

e*(T) is the saturated water vapour pressure of air at the temperature T (Pa)

Thus, combining Eqs. (9), (11) and (16) yields [9]:

$$e_f^* - e_i = \delta(T_i)\Delta T_{fo} - [\delta(T_i) - \delta(T_o)]\Delta T - \Delta e + D_o \tag{19}$$

In Eq. (7) r_s is the stomatal resistance (s m^{-1}) and can be written as [5]:

$$r_s = 200\left(1 + \frac{1}{\exp\left(0.05(\mu G_o - 50)\right)}\right) \tag{20}$$

Where, μ is the transmissivity of the greenhouse cover and G_o is the global solar radiation intensity. In Eq. (7) r_a is the aerodynamic resistance (s m^{-1}) and can be expressed as [12]:

$$r_a = 305\left(\frac{d_v}{U_i}\right)^{0.5} \tag{21}$$

Where, d_v is the characteristic length of the leaf (in m) and can be given by the expression [13]:

$$d_v = \sqrt{\overline{LA}} \tag{22}$$

$\overline{LA}$ is the average area of one leaf (m^2).

The characteristic length of gerbera plant has been calculated to 0.025m [14].

U_i is the mean internal air speed in ms^{-1} and it can be expressed as [9]:

$$U_i = \frac{Q}{A_{sa}} \tag{23}$$

Q is the ventilation rate in $m^3\ s^{-1}$ and A_{sa} is the total area of the vent openings (both side and roof).

From Eqs. (6), (7) and (19), the following relationship can be deduced [9]:

$$\frac{\rho C_p\ I_{LA}}{\gamma}\left(\frac{e_f^* - e_i}{r_s + r_a}\right) = K_L \Delta e$$

$$e_f^* - e_i = \frac{\gamma(r_s + r_a)}{\rho C_p\ I_{LA}} K_L \Delta e$$

$$\frac{\gamma(r_s+r_a)}{\rho C_p\ I_{LA}} K_L \Delta e = \delta(T_i)\Delta T_{fo} - [\delta(T_i) - \delta(T_o)]\Delta T - \Delta e + D_o$$

$$\left[\frac{\gamma(r_s+r_a)}{\rho C_p\ I_{LA}} K_L + 1\right]\Delta e = \delta(T_i)\Delta T_{fo} - [\delta(T_i) - \delta(T_o)]\Delta T + D_o \tag{24}$$

If (T_i -T_f) is equal to ΔT_{fo} - ΔT, the sensible heat balance of the crop is written as [9]:

$$\Delta T_{fo} - \Delta T = \frac{r_a}{\rho C_p\ I_{LA}}(R_n - K_L \Delta e) \tag{25}$$

Where, R_n is the net radiation at plant or canopy in W m^{-2}.

R_n can be expressed as [6]:

$$R_n = P_f - H_{f-sky,LWR} \tag{26}$$

P_f is the absorption of solar radiation by the canopy or plant, $H_{f\text{-}sky}$ is the heat exchange between canopy and sky by long-wave radiation which has been considered as negligible for this model [6].

P_f can be expressed as [6]:

$$P_f = P_{f,PAR} + P_{f,NIR} \tag{27}$$

$P_{f,PAR}$ and $P_{f,NIR}$ are the absorption of PAR (Photo-synthetically Active Radiation) and NIR (Near Infrared Radiation) by the plant or canopy, respectively.

Absorption of PAR and NIR of solar radiation by the canopy or plant [6] is

$$P_{f,PAR} = (1 - 0.057)\{1 - \exp(-0.715 I_{LA})\} I_{PAR} \tag{28}$$

$$P_{f,NIR} = (1 - .389)\{1 - \exp(-0.358 I_{LA})\} I_{NIR} \tag{29}$$

I_{PAR} (W m^{-2}) is the photo-synthetically active radiation transmitted to the greenhouse and I_{NIR} (W m^{-2}) is the near infrared radiation transmitted to the greenhouse and both can be expressed as [6]:

$$I_{PAR} = 0.434(1 - I_{sh})(\mu * G_o) \tag{30}$$
$$I_{NIR} = 0.52(1 - I_{sh})(\mu * G_o) \tag{31}$$

The global solar radiation comprises of ultra-violet, photo-synthetically active part and near infra red components. The transmission of the global solar radiation by the greenhouse is I_G and mathematically we can write it as [6]:

$$I_G = I_{UVR} + I_{PAR} + I_{NIR} \tag{32}$$

Finally, from Eqs. (1), (24) and (25) three unknowns (ΔT, ΔT_{fo} and Δe) have been formulated which can be represented by the following [9]:

$$(K_S + K_C)\Delta T + K_L \Delta e = (1 - I_{sh})\mu G_O - Q_m \tag{33}$$

$$[\delta(T_i) - \delta(T_o)]\Delta T + \left[\frac{\Upsilon(r_s + r_a)}{\rho C_p\ I_{LA}} K_L + 1\right]\Delta e - \delta(T_i)\Delta T_{fo} = D_O \tag{34}$$

$$\frac{\rho C_p\ I_{LA}}{r_a}\Delta T - K_L \Delta e - \frac{\rho C_p\ I_{LA}}{r_a}\Delta T_{fo} = -R_n \tag{35}$$

Knowing the characteristics parameters for the greenhouse (K_c and μ), the crop (I_{LA}, d_v, r_a and r_s) and the measured boundary conditions for the outside climate (G_o, T_o and e_o), the unknown variablesΔT, ΔT_{fo} and Δe can be deduced analytically using Gauss-seidel iteration technique.

Boundary condition e_o is the water vapour pressure of the exterior air (Pa) and it can be written in terms of RH_o (Relative humidity outside the greenhouse in %) from the expression [10]

$$RH_o = \frac{e_o}{e_o^*} \times 100 \tag{36}$$

$$e_o = \frac{RH_o \times e_o^*}{100} \tag{37}$$

In Eq. (37) value of e_o^* can be easily calculated by the Eq. (13) where T is the ambient temperature T_o.

3.1 Flowchart of the Model:

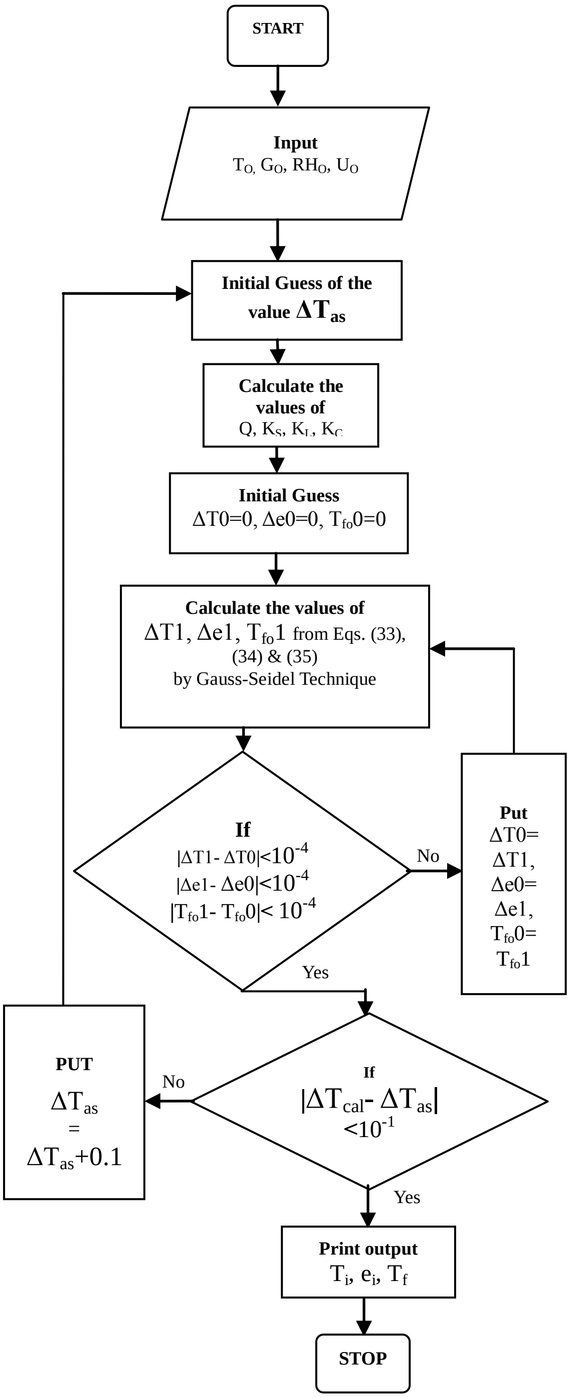

Fig. 2: Flowchart of the developed Thermal Model

3.2 Results and Discussion

A computer code in 'C' has been developed to predict the greenhouse temperature considering monthly average values of solar radiation intensity (W/m^2), ambient relative humidity and ambient temperature for Kolkata as obtained from Regional Meteorological Centre (RMC), Kolkata, 2009 [7] along with crop data as inputs [14].

Figure 3 shows the hourly variation of ambient, greenhouse and plant temperature with the time of the day for the month of December. It is observed from the figure that the greenhouse plant temperature is lower than that of greenhouse air temperature throughout the day. However, the temperature difference between the greenhouse air and plant temperature decreases with the decrease in intensity of solar radiation. Thus, in the early morning and at night, the difference becomes minimal.

Figure 4 shows the hourly variation of greenhouse air temperature with the time of the day for various leaf area indices (leaf area per plant to the land area per plant) for the month of December. A shading of 50% was applied in the canopy to restrict the entry of solar radiation. It is found that with the increase in leaf area index from 3 to 4, the peak greenhouse temperature reduced by about 1^{0}C. This is due to the fact that with the increase in leaf area index, the transpiration loss from the plant increases, reducing the greenhouse air temperature.

Figure 5 shows the variation of greenhouse temperature with the time of the day for the month of February under different conditions of shading. When 50% shading was applied, the greenhouse temperature exceeded the maximum permissible limit (present case 30^{0}C) during the peak sunshine hours. It is found that with 75% shading, the maximum greenhouse temperature can be restricted around 28^{0}C even during the peak sunshine hours of the day when the corresponding ambient temperature exceeds 30^{0}C.

Figure 6 shows the variation of temperature difference (between greenhouse and ambient) with the time of the day for the months of June, August and December 2009 for a given degree of shading (50% in the present case). It is found that for most of the time of the day, the temperature difference is lower for the month of December as compared to that in June and August owing to lower values of solar radiation intensity and ambient relative humidity. It is also observed that from 8AM to 10AM in the month of December, the temperature difference is higher compared to that in June and August which may be attributed to lower values of the ambient wind speed in that period resulting in reduced heat transfer through convection from plant leaf to the surroundings. This results in reduced rate of transpiration which results in lower greenhouse temperature.

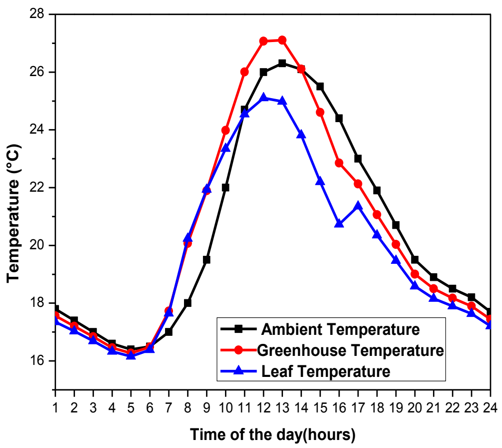

Fig.3: Variation of temperature with time of the day in December

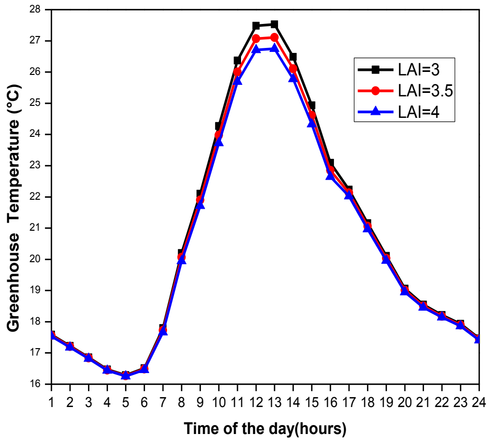

Fig.4: Variation of temperature with time for various LAI

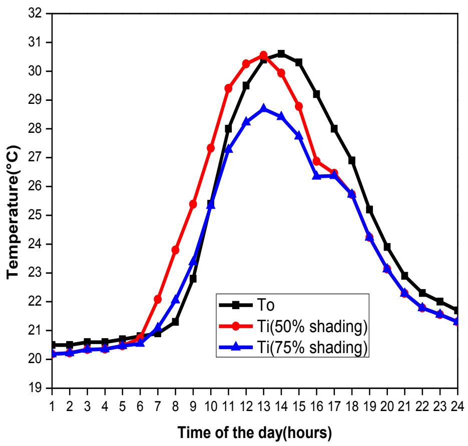

Fig.5: Variation of greenhouse temperature in February

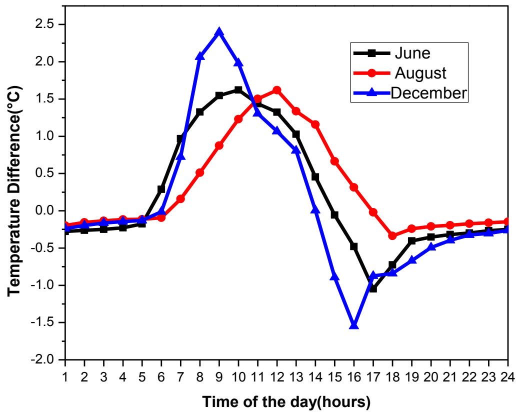

Fig.6: Variation of temperature difference with time for various seasons of a year

4. CONCLUSIONS

In the present work a thermal model of a naturally ventilated greenhouse has been developed considering the crop aspects like leaf area index, characteristic length of the leaf, phenomenon of transpiration, etc. The model considers ambient temperature, air water vapour pressure and wind velocity as input parameters and predicts the greenhouse air temperature, air water vapour pressure and the plant temperature for a given degree of shading. The study reveals that the model performance is highly sensitive to the ambient climatic conditions like temperature, wind speed, etc and also on the crop aspects like leaf area index (LAI), characteristic length of leaf, etc. The study reveals that the natural ventilation can be successfully employed in the greenhouse to maintain a suitable microclimate throughout the day during the months of February, December and August for the cultivation of target flowers in the area under consideration.

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NOMENCLATURE

Symbol

T	Temperature	(K)
A	Area	(m^2)
U	Wind speed	($m\ s^{-1}$)
G	Global solar radiation intensity	($W\ m^{-2}$)
I	Transmitted solar radiation intensity	($W\ m^{-2}$)
RH	Relative Humidity	(%)
K	Heat transfer coefficient	($W\ m^{-2}\ K^{-1}$)
e	Air water vapour pressure	(Pa)
D	Air water vapour pressure deficit	(Pa)
r	Resistance	($s\ m^{-1}$)
C	Coefficient	
Δ	Difference between inside and outside	
E	Plant transpiration	($Kg\ m^{-2}\ s^{-1}$)
λ	Latent heat of vapourization	($J\ Kg^{-1}$)
d	Characteristic length	(m)
Υ	Psychometric constant	($Pa\ K^{-1}$)
Q	Ventilation rate	($m^3\ s^{-1}$)
ρ	Air density	($Kg\ m^{-3}$)
R	Radiation absorbed by the plant	($W\ m^{-2}$)
δ	Slope of the water vapour saturation curve	($Pa\ K^{-1}$)
ζ	conversion factor between air water vapour content at standard temperature and air water vapour pressure	($Kg_w\ Kg_a^{-1}\ Pa^{-1}$)

Subscripts

i	Greenhouse inside
o	Greenhouse outside
f	Plant leaf or canopy
g	Ground or floor of greenhouse
R	Roof opening
S	Side opening
UVR	Ultra Violet Radiation
PAR	Photosynthetically Active Radiation
NIR	Near Infrared Radiation
d	Discharge
w	Wind pressure
n	Net or total
sh	Shading factor
LA	Leaf area
as	Assumed
cal	Calculated

Superscripts

*	Saturation condition

AUTHOR BIOGRAPHY

Biplab Bauri is a PG student in the Department of Mechanical Engineering at Bengal Engineering And Science University, Shibpur, India. He did his UG in Power Engineering Department from Jadavpur University, India.

Dr. Aritra Ganguly is working as Assistant Professor in the Department of Mechanical Engineering at Bengal Engineering And Science University, Shibpur, India. He has about 6 years of experience in teaching students at undergraduate and post graduate level. Prior to joining here he worked as a Scientist in Indian Space Research organisation (ISRO). His research areas include solar photovoltaics, electrolyser, fuel cell and greenhouse cultivation. He has published several papers in various international journals and conferences in India and abroad.