10th International Conference on Mechanical Engineering, ICME 2013

Parametric and performance analysis of a naturally ventilated floriculture greenhouse using a thermal model

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Abstract

Greenhouse technology is a method of cultivation of flowers, vegetables and medicinal plants under a controlled environment. The main objective of the greenhouses located in the plains of India is to protect the plants from excessive sensible heat from the solar radiation and ambient temperature. The structure also protects the plants from the storm and pest. Natural ventilation (along with shading screens) can be employed to regulate the required greenhouse microclimate in a cost effective manner. In the present paper the authors analyze the performance of a greenhouse from the view point of cultivation of varieties of Gerbera flower using a thermal model developed and presented earlier. Parametric analysis has been done to understand the effect of various crop, design and climatic parameters on the performance of the system. From the performance analysis of the greenhouse, it is revealed that the plant leaf temperature could be maintained within the permissible limit for the cultivation of the target flowers for various seasons of a climatic cycle. The study reveals that the natural ventilation along with shading in a greenhouse can lead to the sustainable cultivation of target flowers in the region under consideration.

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Selection and peer-review under responsibility of the Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET)

Keywords: Greenhouse; Natural Ventilation; Thermal Model; Transpiration; Leaf Area Index; Characteristic Length of Leaf; Shading Effect.

1. Introduction

Greenhouses are structures covered with suitable transparent material inside which the climatic conditions are artificially nurtured to optimize the growth of plants. The structure also protects the plants from the adverse climatic conditions such as storm, cold, precipitation, excessive solar radiation, etc. The technology of greenhouse emanated earlier in the western countries of the world primarily to protect the plants from extreme cold and frost. So the main objective of the greenhouses located in the western countries is heating and humidification. But in the plains of
Indian subcontinent, the climate remains hot for greater part of a year, while the coastal areas experience a hot and humid climate. The high temperature is detrimental to the growth of plants, while high ambient humidity promotes the growth of pests that destroy considerable vegetation in open field. So for greenhouses located in the plains of India (in Gangetic Bengal), the main objectives are control of high temperature, intensity of solar radiation and protection from the storm and pests. Many artificial methods like fan-pad evaporative cooling, fogging, misting etc., have been applied to cool the greenhouse microclimate, but the main constraints for all those methods are the involvement of high cost and the requirement of electricity. In India, there are about 94000 un-electrified villages, of which 25000 villages are located in such remote areas that the extension of electricity grid there is not economically viable [1]. So natural ventilation along with shading screens continue to be the most promising and cost economic method for regulation of the microclimate in a greenhouse.

The purpose of the present work is to analyze the performance of a floriculture greenhouse under natural ventilation from the view point of cultivation of certain target flowers like varieties of Gerbera for various seasons of a climatic cycle. The analysis has been done using a thermal model developed by the authors earlier [2]. In the present work parametric analysis has also been included (using the model) to understand the effect of various crop, geometric and climatic parameters on the performance of the system. Gerbera flower can be best grown at day temperatures between 23-27°C though the flowering gets affected minimally till a temperature of 31°C [3]. After that the productivity starts reducing and beyond 35°C, the flowering gets adversely harmed [3]. On the lower side, though the optimum temperature is 23°C, yet the cultivation is feasible at still lower temperatures. As the climatic condition of Gangetic Bengal remains hot for greater part of a year and the ambient day temperature seldom decreases below 18°C in winter, so we are more concerned about the upper limit of the temperature range. So in the present analysis we have considered that the target daylong greenhouse temperature should be within 31°C.

2. Thermal Model Development

The authors have earlier presented a detailed thermal model of a naturally ventilated floriculture greenhouse [2]. The main governing equations of the thermal model are presented in brief in this section:

\[
(K_S + K_C) \Delta T + K_L \Delta e = (1 - I_{sh}) \mu C_o - Q_m
\]

\[
[\delta(T_l) - \delta(T_o)] \Delta T + \left(\frac{\gamma (r_{st} + r_a)}{\rho C_p L_A} K_I + 1\right) \Delta e - \delta(T_l) \Delta T_f = D_o
\]

\[
\frac{\rho C_p L_A}{r_a} \Delta T - K_L \Delta e - \frac{\rho C_p L_A}{r_a} \Delta T_f = -R_n
\]

\[
\lambda E = \frac{\rho C_p L_A}{\gamma} \left(\frac{e_f - e_i}{r_{st} + r_a}\right)
\]

\[
r_a = 305 \left(\frac{d_f}{U_i}\right)^{0.5}
\]

\[
r_{st} = 200 \left(1 + \frac{1}{\exp(0.05((1 - I_{sh}) \mu C_o - 50))}\right)
\]

In Eq. (1), \(K_C\) denotes the overall heat transfer coefficient of greenhouse roof covering, \(K_S\) the sensible heat transfer coefficient of ventilation and \(K_I\) represents the latent heat transfer coefficient of ventilation which is dependent on many factors as described in detail in the earlier paper [2]. Plant transpiration rate (\(\lambda E\)) which significantly influences the microclimate of a greenhouse mainly depends on stomatal resistance (\(r_a\)) and
aerodynamic resistance \( (r_a) \) of leaf (as given by Eq. (4)) \[4\]. The leaf resistances to transpiration \( (r_o \text{ and } r_e) \) depends on
the transmissivity of the greenhouse covering \( (\mu) \), ambient solar radiation intensity \( (G_o) \), characteristic length of
leaf \( (d_f) \) and greenhouse inside wind speed \( (U_i) \) as given by Eqns. (5) and (6) \[5\]. Knowing the greenhouse
parameters \( (K_C, K_S, K_L \text{ and } \mu) \), the crop parameters \( (I_{LA}, d_f, r_o \text{ and } r_e) \) and the measured ambient climatic conditions
\( (G_o, T_o \text{ and } e_o) \), the three unknown variables \( (\Delta T, \Delta T_{fo} \text{ and } \Delta e) \) in eqns. (1), (2) and (3) have been deduced
analytically using Gauss-Siedel iteration technique.

3. Results and Discussion

A computer code in ‘C’ language has been developed to predict the hourly greenhouse air temperature, plant leaf
temperature and the inside humidity considering monthly average values of hourly data for solar radiation intensity,
ambient temperature, relative humidity and the wind speed for Kolkata along with the crop data as input. \[6, 7\]

3.1. Parametric Analysis of the Thermal Model

Figure 1(a) shows the variation of average greenhouse air temperature \( (T_i) \), plant leaf temperature \( (T_f) \) and the air
water vapour pressure \( (e_i) \) with leaf area index (leaf area per plant to the land area per plant) for a given value of
solar radiation intensity, ambient temperature, humidity, wind speed and characteristic length of leaf \( (d_f) \). The climatic data used here pertains to the data corresponding to 12 Noon for the month of December 2009. A shading
of 50% has been applied to restrict the entry of solar radiation inside the greenhouse. As observed from the figure,
both the greenhouse air and plant leaf temperature decrease with increase in the value of leaf area index. As the leaf area index is increased from 2.5 to 5.0, there is about 1.8 °C drop in the greenhouse air temperature, while the plant
leaf temperature decreases by about 1.5°C. The reason for this is that with the increase in leaf area index, the water
loss from the plant by transpiration increases through the leaf stomata openings (as shown in Fig. 1(b)) resulting in
lowering of the temperature and the increase in greenhouse air water vapour pressure.

![Graph](image)

Fig. 1. (a) Variation of greenhouse air temperature, leaf temperature and air water vapour pressure with variation of leaf area index; (b) Variation of transpiration loss with variation of leaf area index.

Figure 2(a) shows the variation of greenhouse air temperature \( (T_i) \), plant leaf temperature \( (T_f) \), and the air water vapour pressure \( (e_i) \) for various characteristic length of leaf \( (d_f) \), for the month of December (2009) considering the leaf area index to be constant and other parameters same as used in Fig. 1(a). As evident from the figure, both the
greenhouse air and the plant leaf temperature increase with the increase in the characteristic length of leaf, while
the
greenhouse air water vapour pressure decreases. This is due to the fact that there is increase in aerodynamic resistance ($r_a$) of leaf (as given by Eq. (5)) that leads to lower water loss through transpiration as shown in Fig. 2 (b).

![Figure 2](image)

**Fig. 2.** (a) Variation of greenhouse air, plant leaf temperature and air water vapour pressure with characteristic length of leaf; (b) Variation of transpiration loss, aerodynamic resistance and stomatal resistance of leaf with variation of characteristic length of leaf.

Figure 3(a) shows the variation of greenhouse air temperature ($T_i$), plant leaf temperature ($T_f$) and greenhouse air water vapour pressure ($e_i$) with area of ventilation keeping other parameters constant. It is found that with the increase in the area of openings both greenhouse air and plant temperature decreases. Similar trend is observed with inside air water vapour pressure. This is due to the fact that with increase in the vent opening area the volume flow rate of air increases leading to more heat transfer from the greenhouse to ambient.

![Figure 3](image)

**Fig. 3.** (a) Variation of greenhouse air, leaf temperature and air water vapour pressure with ventilation area; (b) Variation of greenhouse air, leaf temperature and air water vapour pressure with ambient wind speed.

Figure 3(b) shows the variation of greenhouse air temperature ($T_i$), plant leaf temperature ($T_f$), and air water vapour pressure ($e_i$) as predicted by the model for different ambient wind speeds keeping other parameters constant. It is found from the figure that with the increase in the wind speed, the temperature decreases. This is due to the fact that with increase in the wind speed, the ventilation rate increases and the aerodynamic resistance of the plant leaf
reduces (as given by Eq.(5)), increasing the rate of plant transpiration (Eq. (4)). Thus, due to the combined effect of both increase in the transpiration rate and the rate of ventilation, there is a sharp decrease in the greenhouse air and plant leaf temperature. Also, the inside air water vapour pressure is found to decrease with wind velocity.

3.2. Performance Analysis of the Greenhouse for Different Seasons of a Climatic Cycle

In the present section, the thermal model has been used to analyse the performance of the greenhouse for cultivation of the Gerbera flower for various seasons of a full climatic cycle. Figure 4(a) shows the hourly variation of ambient temperature (T₀), greenhouse air temperature (Tᵢ) and plant leaf temperature (Tᶠ) for the month of January 2009 for a given value of leaf area index (3.5) and characteristic length of leaf (0.025m). As revealed from the figure, the greenhouse air and plant leaf temperature increases with the time of the day reaching a maximum value around 12 Noon and then again decreases. The leaf temperature is found to increase again instantaneously at 5 PM (during sunset) due to momentary decrease in the rate of plant transpiration at that instant of time owing to increase in aerodynamic resistance (due to reduction in wind speed) and maximum value of stomatal resistance (due to minimum intensity of solar radiation). It is observed from the figure that the greenhouse plant temperature can be restricted within 26°C all through the day which is highly conducive for the growth of the target flowers considered in the study. The greenhouse air temperature can also be maintained within 28°C throughout the day.

Figure 4(b) shows the hourly variation of ambient temperature (T₀), greenhouse air temperature (Tᵢ) and plant leaf temperature (Tᶠ) for the month of March 2009 keeping leaf area index and characteristic length of leaf as constant. As seen from the figure, the greenhouse air and the plant leaf temperature increases with the time of the day reaching a maximum at around 1PM and then reduces. The leaf temperature is found to increase again instantaneously at 6 PM (during sunset) as discussed earlier (for Fig. 4(a)). It is observed from Fig. 4(b) that the plant leaf temperature can be restricted within 28°C all through the day which is highly conducive for the growth of the varieties of Gerbera flower. The air temperature can also be maintained within 31°C almost throughout the day except during the peak radiation hours (12 Noon to 3PM) when it marginally exceeds beyond 31°C.

Figure 5(a) shows the hourly variation of ambient temperature (T₀), greenhouse air temperature (Tᵢ) and the plant leaf temperature (Tᶠ) for the month of July for a given value of leaf area index and characteristic length of leaf. It is
observed that the plant temperature can be restricted within 30°C all through the day. The air temperature can also be maintained within 31°C almost throughout the day except during 11AM to 1PM when the air temperature marginally exceeds beyond 31°C. Figure 5(b) shows the hourly variation of ambient temperature (T_o), greenhouse air temperature (T_i) and plant leaf temperature (T_f) for the month of September keeping other parameters same as mentioned in the Fig. 5.(a). It is observed from Fig. 5(b) that the plant temperature can be restricted within 30°C all through the day which is within the target range. The air temperature can also be maintained within the target value of 31°C almost throughout the day except during the peak radiation hours when it marginally exceeds 31°C.

4. Conclusion

The present work discusses the parametric and performance analysis of a naturally ventilated floriculture greenhouse for the climatic conditions of Gangetic Bengal in Indian subcontinent using a thermal model. It is revealed from the study that the microclimate in the greenhouse is significantly influenced by the crop parameters such as leaf area index, characteristic length of leaf and the rate of plant transpiration. The ambient wind speed and the greenhouse design in terms of vent area also play a significant role. From the year round performance analysis, it is revealed that the greenhouse plant temperature and the inside air temperature can be maintained within the target range for the cultivation of the varieties of Gerbera except few instances in the month of March, July and September when the temperature values marginally exceed the target. The study thus reveals that the natural ventilation along with shading in a greenhouse can lead to sustainable cultivation of the target flowers in the region.

References