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Temperature gradient modeling in a greenhouse equipped with fan-pad operated evaporative cooling system

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Abstract
Protected cultivation is a technology for off-season crop cultivation based on market requirements. Temperature and relative humidity are always higher inside the polyhouses than outside climate and maintenance of favorable microclimate under the polyhouse is a tedious job. Fan-pad operated evaporative cooling system is a better method for maintaining suitable temperature and relative humidity under the polyhouses. But the main drawback of this cooling system is the thermal gradient development along the direction of the airflow from the cooling pad to exhaust fans. High-temperature gradients of this cooling system can affect plant growth. Different ventilation rates were experimented in this study to reduce the temperature gradients and to maintain favourable climate inside the greenhouse. A climate model was used to predict the temperature gradients along the greenhouse which incorporates the effect of ventilation rate, roof shading, and crop transpiration. The model was calibrated and validated with the experimental data and used to study air temperature profiles along the length of the polyhouse with the influence of the outside air temperature and humidity. The temperature gradients up to 8 ˚C were observed from pads to fans at hot times (during 13:00-15:00) and with the experiment of high ventilation rates thermal gradients were lowered to 2 ˚C in all the times. Experimental data showed that the cooling system was able to keep the polyhouse air temperature at low levels. Despite its simplicity, the climate model is sufficiently accurate to improve the design and the management of the cooling system.

Keywords: climate model, cooling system, polyhouse, temperature, and ventilation

1. Introduction
Greenhouse technology is rapidly expanding worldwide. Natural ventilation can be effectively used when the incident solar radiation intensity is low and the ambient humidity is sufficient. In the Indian subcontinent, for the arid and semi- arid climatic conditions during summer periods, the natural ventilation system is not effective.

Goren *et al.* (2011), Willits and Peet (1993) showed that externally mounted black polyethylene films were less than 50% effective in reducing energy and temperature gains compared to their commercially given values, while white shading cloths were only slightly more effective. Ventilation reduces greenhouse overheating, but it may even enhance the risk of water stress because it often increases plant transpiration (Santosh *et al.* 2017; Seginer, 1984) [9].

Bhosale *et al.* (2016) [4], Kittas *et al.* (2003) [7], Carpenter & Willis (1957) reported that evaporative cooling substantially improves the greenhouse climate. It can be done by spraying water droplets in a naturally ventilated building (by low or high-pressure fog systems), or by forcing ambient air through wet pads. Both produce a temperature drop with an absolute humidity rise in the greenhouse, which contributes to decreasing the vapor pressure deficit and moderate the transpiration demand (Katsoulas *et al*., 2001) [3]. The efficiency of fog systems is often limited by insufficient natural air convection, in the absence of wind, and by the risk of wetting the plants when water droplet evaporation is not complete.

Fan pad operated evaporative cooling system is the ultimate method to reduce the temperature inside the polyhouse, it can efficiently contribute to maintain greenhouse temperature and humidity at acceptable levels during warm periods; but adequate models are necessary to estimate the cooling loads and its uniformity to manage micro-climate in the greenhouse. But the main drawback of this system is temperature gradient development from cooling pad to fan. High-temperature gradients of this type can markedly affect plant growth.

To reduce the temperature gradients along the polyhouse an experiment was conducted in a greenhouse with higher ventilation rates (within plant permissible limit) provided with a fan-pad evaporative cooling system combined with shading (50% shade net material). A simple climate model is used to analyze the temperature gradients in a greenhouse, which incorporates the effect of ventilation rate and roof shading. The present paper discusses temperature gradient profiles along the greenhouse with different ventilation rates under shading condition of the experimental greenhouse.

2. Materials and Methods

2.1 Experimental site

The study was conducted at Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Kumulur The latitude 10°55′49″ N, longitude 78°49′41″ E and 86 m above from the mean sea level located in Lalgudi Taluk of Trichy District, Tamil nadu, India. The maximum and minimum temperature of the study area is 41 °C and 16 °C respectively. The relative humidity varies from 15-85% based on the outside climate variation. The annual rainfall is about 860 mm.

2.2 Experimental Greenhouse

The greenhouse erected with 10 m wide and 20 m long made of two adjacent 5 m wide arches. The greenhouse is covered with anti-drip-lock, UV-reflected polyethylene cladding made of 200-micron thickness. A white color shade net (50% shading) was provided as roof shading.

2.3 Cooling System

The greenhouse is provided with a fan and pad evaporative operated cooling system. A 10 m width, 2 m height corrugated cellulose pad of 10 cm thickness was placed on the north wall of the greenhouse at 1.2 m above from the ground, and two exhaust fans each 1.5 hp capacity were arranged opposite to the cooling pad i.e. the south wall of the greenhouse. Each fan generates a flow rate of about 13.5 m^3s^{-1}.

2.4 Different ventilation Rates

The exhaust fans were provided with three different pullies of size 2 inch 3 inch and 4 inches respectively to increase the fan speed to achieve higher ventilation rates.

2.5 Crop Trial

The experiments were conducted with cucumber (Fadia F1 variety) crop from July to October of 2020 and 2021.

2.6 Equipment Used & Observations

Temperature and relative humidity were recorded by using temperature and relative humidity sensors placed at three different locations inside the greenhouses; one just next to the cooling pads, one in the middle of the polyhouse, and one just in front of the exhaust fans. The temperature and relative humidity sensors were fixed with accuracy at ± 0.1%. Three pyranometers were used to record solar radiation in polyhouses as well as control (open condition). Among three, one is placed in the middle of the blue polyhouse, one is in the middle of the white polyhouse, and another one at outside of the polyhouses (open condition). All these temperature, relative humidity, and pyranometer sensors were connected to the data logger system placed outside of the polyhouses. One thermo-hygrograph was used to record temperature and relative humidity at control conditions (outside the polyhouses).

2.7 Theoretical considerations

The energy balance equation is used to find the temperature distribution along the greenhouse length which is influenced by ventilation rate, crop transpiration, shading water evaporation from the cooling pads, heat loss coefficient of the cover.

The heat balance expressed for a differential increase in dx along the airflow path leads to the following equation for the local internal greenhouse temperature.

$$VC_p\, dT_{in} = \left[\tau(1-\alpha)R_g - \beta e_{s,in}\right]L\, dx - K_c P[T_{in}(x) - T_o]\, dx \quad (1)$$

where: L in m is the greenhouse width (perpendicular to the airflow), P is the roof perimeter in m corresponding to the width; V is the ventilation rate in m^3s^{-1}, C_p is the specific heat of air in J kg^{-1} $°C^{-1}$, r is the air density in kg^{-3}, R_g is the outside global solar radiation in Wm^{-2}, $e_{s,in}$ is the water vapour saturation partial pressure in mb of the inside air, K_c is the heat loss coefficient of the greenhouse cover in Wm^{-2} $°C^{-1}$, T_o is the outside air temperature in °C and τ is the cover transmissivity.

The coefficient α characterizes the fraction of solar radiation incident on the canopy and directly converted into transpiration (which highly depends on plant water status). The term β refers to the advective part of plant evaporation due to the saturation deficit of the air.

However, under conditions in which evaporative cooling operates, solar radiation alone accounts for most of the variation of the transpiration and it hides the influence of vapour pressure deficit (Jolliet & Bailey, 1994). Therefore the term β is considered that it is included in the overall coefficient α.

$$T_{in}(x) = T_o + (T_{pad} - T_o - A_1)\exp[-A_2 * x] + A_1 \quad (2)$$

Where T_{pad} is the dry-bulb temperature of cooled air leaving the pads in ˚C and the

$$A_1 = \frac{[\tau(1-\alpha)R_g]L}{V_\rho C_p} \quad (3) \text{ and}$$

$$A_2 = \frac{K_c L}{V_\rho C_p} \quad (4)$$

The temperature of the air leaving the cooling pads T_{pad} can be calculated from the following equation (ASAE Standards, 1995)

$$T_{pad} = T_o - \eta(T_o - T_{o,w}) \text{ ---} \quad (5)$$

$$\eta = (T_o - T_{pad})/(T_o - T_{o,w}) \text{ ---} \quad (6)$$

Where η is the cooling efficiency, and $T_{o,w}$ is the wet-bulb temperature of outside air in °C.

Two parameters the roof heat loss coefficient K_c and the coefficient α expressing the part of solar energy converted into plant transpiration will be used for an accurate prediction of the greenhouse temperature profile according to Eq. (7)

$$T_{in}(X) = T_o + \left[-\eta\left(T_o - T_{o,w}\right) - A_1\right]exp[-A_2 x] + A_1 \quad (7)$$

3. Results

3.1 Calibration of the model

A set of data of 20 days was collected for the calibration of the model with a constant ventilation rate of 24m^3/sec. The second set of data was experimented with 36 m^3/sec and the third experiment was conducted with 42 m^3/sec ventilation rate. Table 1 gives the values of the outside climate variables during these experimental days (average over the period 9·00 – 19·00 h local time).

+**Table 1:** Mean values of observed air temperature for three different ventilation rates

Condition	Temperature (T), °C at Location		Outside Temperature °C	Solar Radiation Rg, (W/m^2)
	T_{pad}	T_{fan}	T_o	R_g
Ventilation-1 (24 m^3/sec)	27.8	37.4	38	954
Ventilation-2 (36 m^3/sec)	26.9	33	39	955
Ventilation-2 (42 m^3/sec)	26.2	27.4	38	981

subscripts: o, outside; pad, at the pad; fan, at the fans

Due to the long air path through the greenhouse (20 m), strong thermal gradients were observed in its direction. Figure 1 shows the temperature at various locations (near the pad, at 4 m, 8 m, 12 m, 16 m, and at exhaust fan) inside the greenhouse. Near the cooling pad the lowest temperature was observed for all the ventilation conditions and while increasing the length from the pad to fan, the temperature increasing linearly. A gradual temperature rise from the pads to the fans reaches 37 °C with the first ventilation rate at noon when solar radiation reaches its maximum level. The thermal gradients were more (8 °C) pronounced with the first ventilation rate while being lowered with the second ventilation (5 °C) and much lowered (completely a uniform temperature achieved) with third ventilation rate (1-1.7 °C) at even noon (13:00 -14:00 h) when solar radiation reaches its maximum level.

The experimental data showed that the cooling system was able to keep the greenhouse temperature below 37 °C with 24 m^3/sec ventilation rate, and below 33 °C with second ventilation and below 28 °C with third ventilation rate in all circumstances. Moreover, the internal temperature stayed 9-11 °C lower than outside temperature with the first ventilation rate (24 m^3/sec), 12-14 °C with the second ventilation rate, and 15-18 °C with the third ventilation rate (42 m^3/sec) respectively.

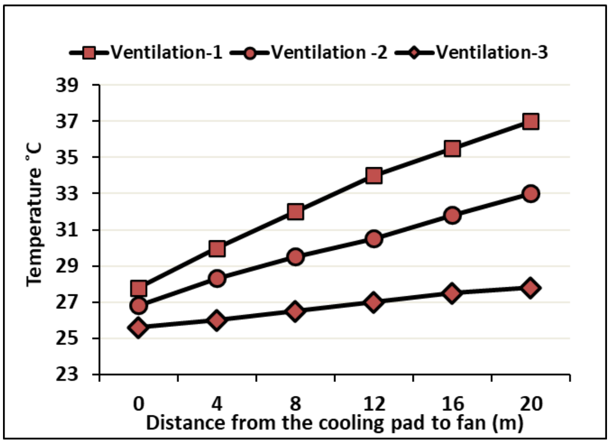

Fig 1: The temperature profile along the length greenhouse with different ventilation rates

The model [Eq. (2)] was calibrated with the experimental data and the heat loss coefficient K_c and the transpiration coefficient α, were determined and which may vary with micro-climatic conditions in the greenhouse and depends on plant status, were determined by fitting the experimental data in Eq. (7). This leads to an estimated value for the coefficient K_c with 1st, 2nd and 3rd ventilation rates are 1·2±0·7 W m^{-2} °C^{-1}, 2.17 W m^{-2} °C^{-1} and 3.21 W m^{-2} °C^{-1} respectively. The higher heat loss coefficient was observed with a high ventilation rate of third ventilation rate followed by second ventilation rate, and lowest value observed for first ventilation rate. The estimated value for the transpiration coefficient *α* of 0·21±0·1 for the first ventilation rate, 0·29±0·1 for the second ventilation rate and 0.36±0.1 for the third ventilation rate. This determined K_c and α values in-lined with Kittas *et al.* (2003) [7].

3.2 Validation of the model

The model [Eq. (7)] was validated for two different locations i.e. at near the cooling pad, and near the exhaust fan respectively. The comparison between measured and predicted values were performed without changing the parameters of K_c and α during the crop period. Fig. 2 and Fig. 3 show the correlation between predicted and measured values of air temperature near the cooling pad and exhaust fan for the first ventilation rate, and the R^2 values are 0.9685 and 0.9853 respectively. Fig. 4 and Fig. 5 show the correlation between predicted and measured values of air temperature near the cooling pad and exhaust fan for second ventilation rates and the R^2 values are 0.9545 and 0.9503 respectively. Fig. 6 and Fig. 7 show the correlation between predicted and measured values of air temperature near the cooling pad and exhaust fan for the third ventilation rate and the R^2 values are 0.9640 and 0.9541 respectively.

Therefore as presented in Figures 2-7, the predicted and observed air temperature near the cooling pad and exhaust fan were satisfactory ($R^2 > 0.95$ in all the conditions), as shown by the proximity of dots with the bissectric line. Hence, the climate model is useful to predict the temperature inside the greenhouse for various outside climates and also useful to design a greenhouse.

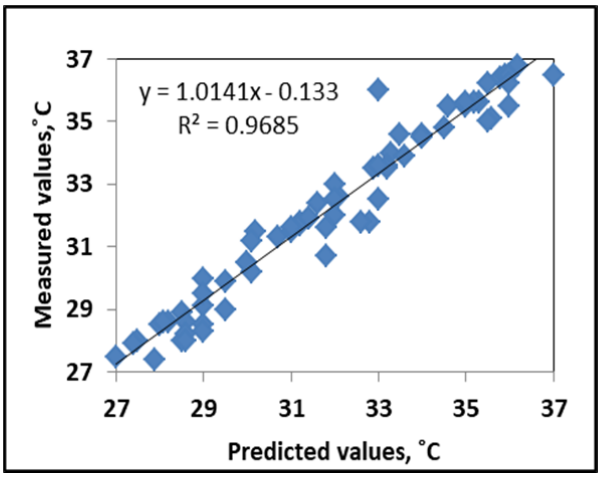

Fig 2: Predicted and measured values of air temperature near the cooling pad with ventilation -1

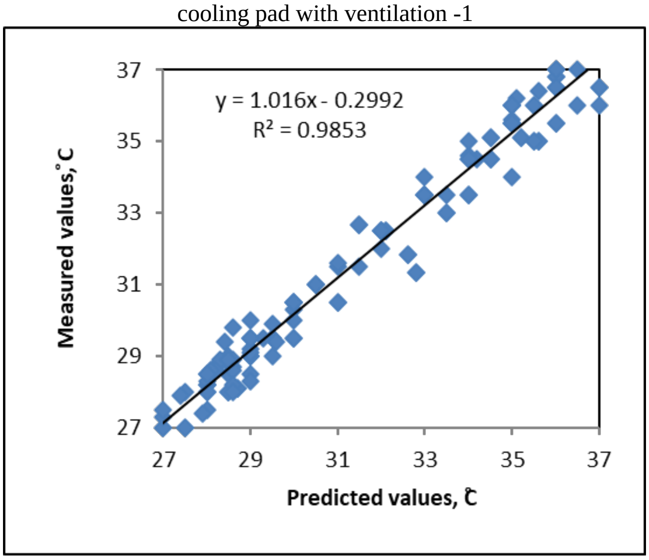

Fig 3: Predicted and measured values of air temperature near the exhaust fan with ventilation-1

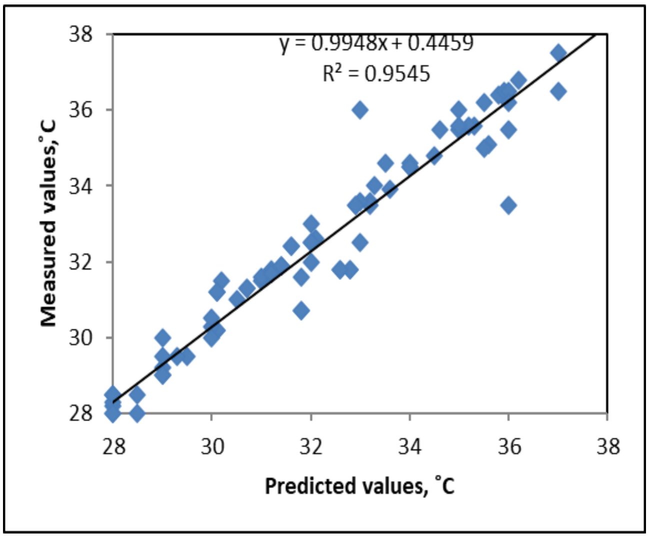

Fig 4: Predicted and measured values of air temperature near the cooling pad with ventilation -2

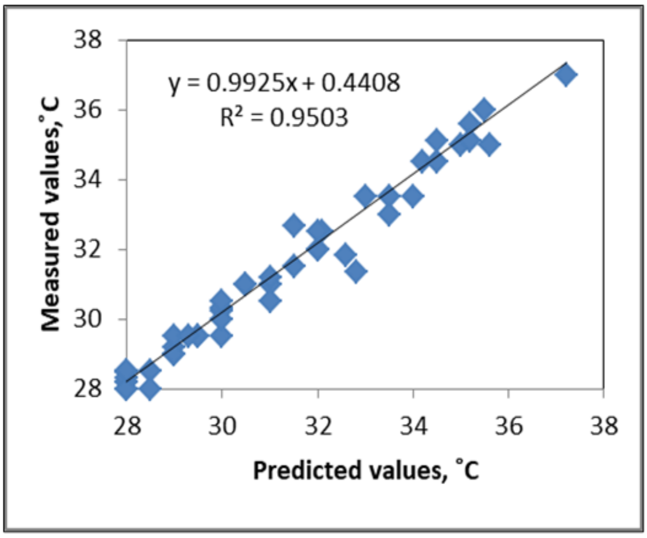

Fig 5: Predicted and measured values of air temperature near the exhaust fan with ventilation-2

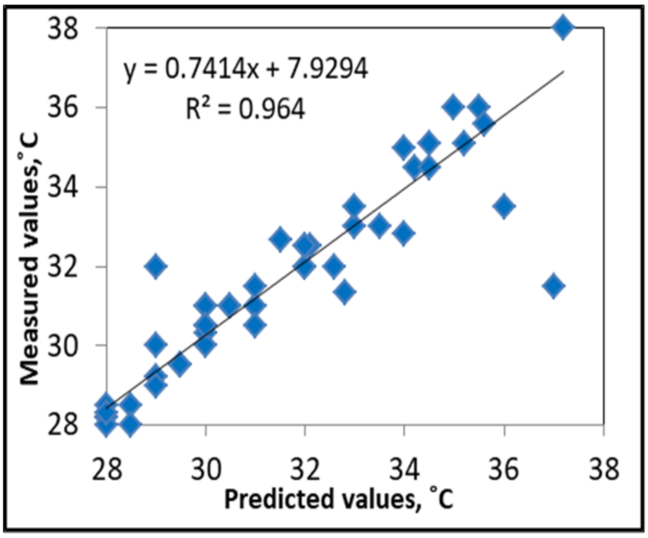

Fig 6: Predicted and measured values of air temperature near the cooling pad with ventilation -3

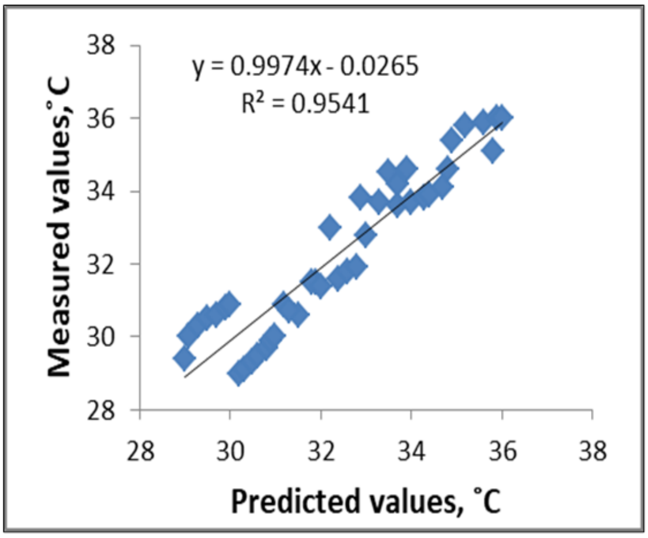

Fig 7: Predicted and measured values of air temperature near the exhaust fan with ventilation-3

4. Conclusion

A simple climate model, used to predict the air temperature profiles along a fan and pad ventilated greenhouse was presented. The model was calibrated with experimental data and a good fit was obtained with validated data. The influence of different ventilation rates combined with the thermal shade nets (50% shading) were examined. The high ventilation rates and shading contribute to reduce the temperature gradients created by the fan and pad cooling system inside a greenhouse. Increasing ventilation rate reduces temperature gradients and also lowered 15-20 °C temperature than outside temperature. The thermal gradients were reduced from 8 °C to 1.5 °C with the increasing ventilation rates and uniform micro-climate was maintained along the greenhouse with increasing ventilation rate of 43 m^3/sec even in high sun-lighting time (from 13:00 h to 14:00 h). The climate model is a useful tool to understand the performance of cooling system and to design a greenhouse.

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