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MATHEMATICAL MODELING OF A GREENHOUSE PERFORMANCE WITH EVAPORATIVE COOLING SYSTEM

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ABSTRACT The study was conducted at the Demonstration Farm of the Faculty of Agriculture, University of Khartoum, Shambat (32° 51` E, 15° 65` N and 380 m above mean sea level) under greenhouse conditions for two conductive seasons (2009 and 2010). The objective of this study was to develop a one-dimensional conduction and convection heat transfer model to simulate the thermal behavior in a greenhouse equipped with evaporative cooling system and comparing the predicted results with measured data. The model was written in Visual Basic V. 6.0 Programming Language. A greenhouse of Quonset type with dimensions 20× 9×3m was used for carrying out the experimental work. The model predicted the temperatures inside the greenhouse using input data of outside air temperature (°C), mass flow rate of air the greenhouse from fan (kg/sec), latent heat of vaporization for both outside and inside the greenhouse, absolute humidity of the outside air and inside at the fan, overall heat conductance (U), the area of greenhouse m^2 through which heat was transferred. 100 % Evaporative cooling efficiency was recorded in September during 2009, compared to 58% in June during 2010. Statistical analysis were carried out to check the accuracy of the developed heat transfer model. The results showed that there was a close agreement between measured and predicted values during the first season while there was slightly difference in the second season. The developed heat transfer model predicted the temperature within the bounds of the experimental error (close to zero). The time taken by the computer programme to predict greenhouse temperature was 2.5 second/simulation day. It is concluded that, statistical tools for checking the accuracy of the developed mathematical models should be followed and adopted.

KEYWORDS : Mathematical modeling; Greenhouse performance; Evaporative cooling

1. INTRODUCTION

Greenhouse technology has evolved to create the favorable environment to cultivate the desirable crop all year round. It is required for crop production during summer and winter seasons, which provide a suitable environmental condition for improving crop growth and productivity (Hashem *et al.*, 2011). The outside climate conditions such as solar radiation, carbon dioxide concentration and humidity and temperature are important in greenhouse climate management (van Henten, 2003). According to James (1979), the quality of environment in agricultural buildings has become increasingly important for its influence on labour efficiency and the value of products. The control of temperature, relative humidity and solar energy is essential for high crop production (Elhussien, 2008). Temperature control requires both internal air movement and an exchange of air with the outside (David, 2005). A well designed fan and pad cooling system provides good air distribution. Air velocities within the building are relatively low and the cooled air tends to sink towards the floor in its path along the building (Osama, 2000). Predicted models of greenhouse such as heat transfer model have been successful in explaining the major features of crop performance and defining better protected crop environments. There has recently been an increasing argument that models can be of direct use for environmental control (Day, 2002). Proper software tools are needed to put into practice an adequate management strategy, namely greenhouse climate models. Improved computer systems combined with more sophisticated software are the most obvious candidates to help meet these new demands. They also serve as an efficient tool to distribute the results generated by science directly to the industry by integrating mathematical models describing crop growth and production systems (Jesper *et al.*, 2002). In Sudan, vegetable crops such as tomato have undergone major expansion during the last two decades because of the increasing demand for local consumption and export. The country is self-sufficient except for the scarcity during the hot summer period. Improving environmental management is one of the main problems facing the crop production under greenhouses conditions. Therefore, the objective of this study was to develop a mathematical model for simulating the thermal behavior in a greenhouse equipped with evaporative cooling for optimizing the greenhouse environment and to validate the develop mathematical model by comparing the predicted results with measured data.

2. MATERIALS AND METHODS

2.1 Experimental site

Two experiments were conducted at the Demonstration Farm of the Faculty of Agriculture, University of Khartoum, Shambat (15°36"N and 32°32"E) during the period from Jun to October 2009 (first season) and July to October 2010 (second season) under controlled environment greenhouse and open field conditions. In the first season seven indeterminate tomato cultivars were used to evaluate their growth, development and yield, five of them imported from the National Agricultural Research Centre (Egypt) namely; Bashair 1, 2, 3, 4 and 5 and the other two varieties namely; Po262 and Po265 from Bahri market, while In the second season, JV15 cultivar was used.

2.2 Experimental Design

The experimental works were carried out in order to collect some environmental factors such as temperature, relative humidity and air velocity inside the greenhouse and under the open field conditions. These experiments were adopted in a completely randomized design (CRD) with three replicates.

2.3 Cultural Practices

a.Greenhouse

The tomatoes were sown in a modified arch shape greenhouse. The arch shaped greenhouse covered an area of 20 9 m (180 m^2) with 3 m in height and 200 – 220 m thick of the cover plastic film. Orientation of the greenhouse was north south. The greenhouse was made from galvanized pipe with aluminum extrusion. The cover was made from plastic film and the house was cooled by fan and pad evaporative cooling system. The wetted pad was fixed along the south wall of the greenhouse was 6 2 m in dimension. While two exhaust fans were installed along the North side. Drip irrigation was used in the greenhouse at a rate of 850 ml/day/plant.

b.Open field

In the open field, seeds were sown in the nursery of the Faculty of Agriculture, University of Khartoum, Shambat a month before transplanting. Plastic cell trays were used to grow the seedlings. The trays were filled with mixed soil. Pre-watering was applied and then tomato seeds were sown. Soil was ploughed, harrowed, leveled and ridged. Every ridge was 4.2 m in length in the first season and 7.5 m in the second season. Furrows were located north to south direction; spacing between plants was 30 and 45 cm for the first and second seasons, respectively. One a heavy irrigation was applied before transplanting and the second was applied directly after transplanting.

2.4 Measurements

The climate factors measured during the day at 8:00 am, 12:00 pm and 3:00 pm were air temperature, relative humidity (RH%) and air velocity. The measurements inside the greenhouse were made at three locations at one meter distance from the pad, at the middle of the greenhouse and at one meter distance from the fans. The same factors were measured at the same period and times outside the greenhouse to assess the efficiency of the greenhouse in controlling the environment. The effective cooling efficiency (hECE) of the cooling system used was calculated using the following equation stated by Abdalla *et al.* (1986):

$$hECE = \frac{t_{oa} - t_{hm}}{t_{oa} - t_{wb}}$$

2.5 Modeling of Heat Transfer in the Greenhouse

To develop the mathematical heat transfer model, the following assumptions were made:

I- Heat transfer is due to combined effect of conductive and convective heat transfer modes only i.e no radiation heat transfer.

ii- Heat will transfer from outside into the greenhouse through side walls and the roof of the greenhouse only.

iii- Heat gained by the greenhouse equal heat lost by the greenhouse i.e operate ideal.

2.6 Model development equation

The following equations were derived for model development according to Jesper (2002).

Heat balance:

Heat gained = latent heat gained × factor

$$U \times A \times (T_{Out} - T_{in}) = m \times hfg \times (AH_{fan} - Ah_{out}) \qquad 3.2$$

$$U = \frac{1}{h_0} \times A(1m^2) + x_{plastic} \times \frac{(m)}{k \times A(m^2)} + \frac{1}{h_i \times A(1m^2)}$$

Where:

U = overall heat conductance

Where:

U = 1/ho×A(1m^2) + x plastic (m) / k×A(m^2) + 1/hi×A (1m^2)

A= area of greenhouse through which will transfer, m^2

T_{Out} = outside air temperature °C

Tin= inside temperature °C at fan

m = mass flow rate of air inside the greenhouse kg/sec. will be calculated after knowing volume flow rate (cross sectional × velocity) at fan.

m = volume flow rate / specific volume.

hfg = latent heat of vaporization for both outside and fan (average).

AH = absolute humidity (specific humidity).

2.7 Model equation

$T_{i=}$ $T_{out-}m \times hfg \times (AH_{fan-}AH_{out) \times}$ factor/U×A

Where:

Tout = Temperature out of the greenhouse, C

Hfg = Latent heat of vaporization for both outside and fan, units.

M = mass flow rate of air inside the greenhouse, kg/sec

M = volume flow rate/specific volume, kg/sec

AH = Absolute humidity (specific humidity),

A = area of greenhouse through which heat will transfer, m^2

U = overall heat conductance units.

2.8 MATHEMATICAL MODEL

A mathematical model was developed and written into a computer programming language to simulate the thermal behavior inside the greenhouse. The developed mathema tical model was validated by comparing the model predicated results with measured data.

2.9 Statistical Analysis

Data collected was statistically analyzed using T-test.

3. RESULTS AND DISCUSSION

a. Statistical validation of the developed model

Table 1 shows the average model error, absolute difference and standard error of measured and predicted temperature during two seasons. The results indicated that, there was agreement between monthly measured and predicted temperature during the first season while there was slightly difference in the second season along the experimental periods. The model predicted heat transfer successfully and within the bounds of experimental error. The results were in agreement with the result obtained by Abbouda (1984) who reported that, an accurate model should have an average model error and average absolute difference close to zero and small standard error of estimate.

b. Evaporative cooling efficiency

As presented in Table 2, the cooling efficiency significantly difference between two seasons. The first season gave the lower cooling efficiency than the second season. The highest value of cooling efficiency (100%) was recorded in September, while the lowest value (58%) was gave in June. The results were in agreement with the result obtained by Abbouda *et al.* (2012) who mentioned that, in the hot climate of Sudan, evaporative cooling systems have been commonly employed to reduce the interior ambient air temperature of greenhouses, under these conditions the evaporative cooling system provided a cooling effect (air temperature difference between outside and inside the greenhouse) of 10 °C or more.

c. Average temperature, relative humidity and air velocity inside and outside the greenhouse

As shown in Figs 1, 2, 3 and 4, average temperature, relative humidity and air velocity inside the greenhouse and outside conditions during two seasons were significantly difference. Air temperature inside the greenhouse was found to be lower than outside conditions for the two seasons, while relative humidity increased inside the greenhouse as compared to outside throughout the study period for the two seasons. Relative humidity inside the greenhouse was found to be higher near the pad as compared to the area near or around the exhaust fans. This may be due to the variations in air velocity. The results agreed with the result obtained by Elhussien (2008) who mentioned that, average and air temperatures significantly increased in outside conditions as compared to inside greenhouse conditions. Average temperature increased from the evaporative pad towards exhaust fans, while air velocity decreased at the middle of the greenhouse. The results were agreement with the result obtained Diyana (2009) who reported that the temperature increased from the evaporative pad towards exhaust fans, while air velocity decreased at the middle of the greenhouse.

Table 1. Statistical validation of the developed model

Month	Model error	Absolute difference	Standard error estimate
Season 2009			
June	- 0.23500	1.788333	1.988739
July	-1.27235	2.801756	3.626349
August	-1.61538	2.484615	2.626349
Season 2010			
August	- 0.04762	1.400000	1.702100
September	- 0.81533	1.246000	1.524338
October	- 0.87632	2.181579	2.630222

Table 2 Evaporative Cooling efficiency (%)

Month	Cooling efficiency (%)					
	season 2009			season 2010		
	8am	12pm	15pm	8am	12pm	15pm
June	58^{b}	63^{b}	63^{b}	-	-	-
July	73^{a}	72^{a}	72^{a}	-	-	-
August	70^{a}	73^{a}	73^{a}	83^{c}	94^{a}	86^{b}
September	-	-	-	100^{a}	89^{b}	93^{a}
October	-	-	-	87^{b}	82^{c}	83^{b}
LSD	7.3	5.8	5.9	3.7	6.2	4.1

Fig 1. Average temperature, relative humidity and air velocity inside the greenhouse (2009)

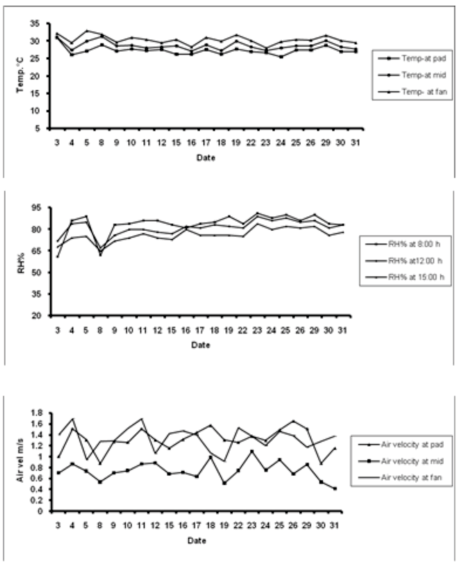
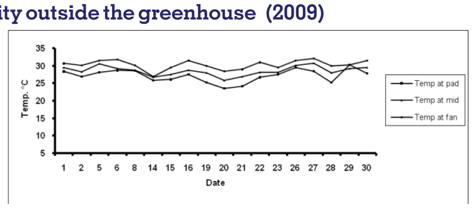


Fig 2. Average temperature, relative humidity and air velocity outside the greenhouse (2009)



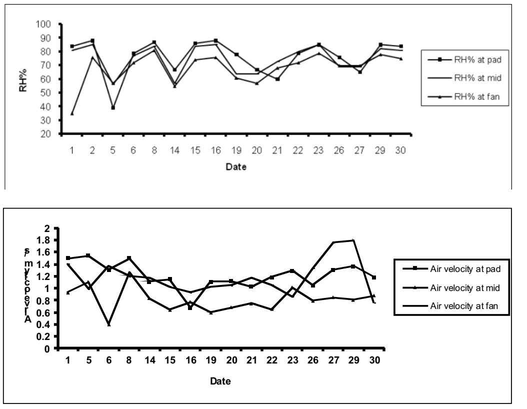


Fig 3. Average temperature, relative humidity and air velocity inside the greenhouse (2010)

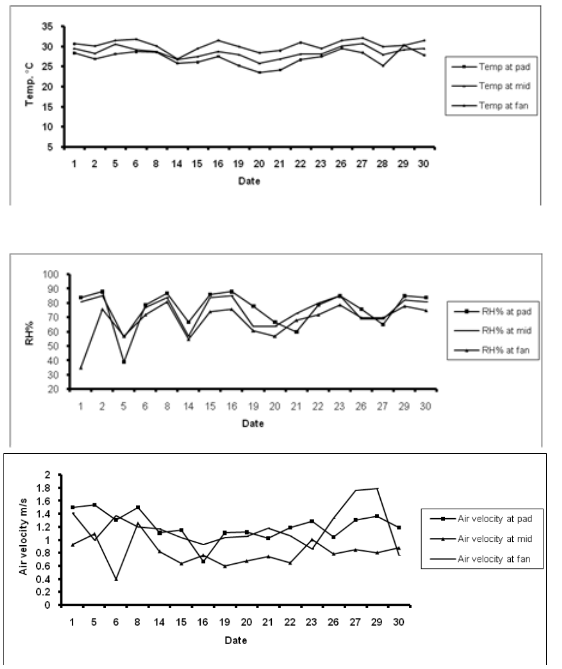
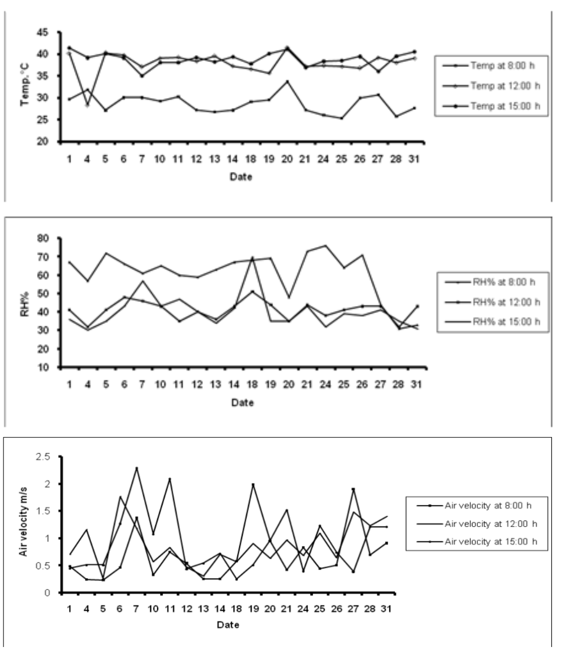


Fig 4. Average temperatures, relative humidity and air velocity outside the greenhouse (2010)



4. CONCLUSION

The developed heat transfer model predicted temperature close to those measured during the experimental periods and accurately and within the bounds of experimental error.

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