

EFFECT OF GREENHOUSE GLAZING MATERIALS ON EVAPORATIVE COOLING SYSTEM EFFECTIVENESS FOR PRODUCTION OF TOMATOES UNDER HOT- HUMID SUMMER CONDITIONS

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ABSTRACT

To insure optimal fruit yields of greenhouse tomatoes crop in Mansoura, Egypt, when greenhouse day temperatures can be in excess of 50 °C, planting was dictated to be in late April to early September. To reduce daylight temperatures during summer months of 2007, fan-pad cooling system was examined under different glazing materials in a 32 m² greenhouses: 1) corrugated fiberglass reinforced plastic (FRP), and, 2) double layer polyethylene sheets (PE). Tomato plants (*Ebesia verity*) were transplanted on 21 April, 2007 into 60 plastic pots in each greenhouse with plant density of 2.5 m². At transplanting the cooling system of 2.4 x 1.0 m in the west wall and one extracting fan in the east wall was automatically activated when the two greenhouses air temperatures reached to 28 °C. Air temperature, relative humidity, wind speed, and total solar radiation entering the greenhouse were measured and recorded on a data-logger to analyses their correlation with tomatoes crop yield response. A mathematical model was developed to simulate microclimate on and around leaf surface for greenhouse tomatoes. The obtained results revealed that the air temperature and relative humidity inside the two greenhouses of 28.5 °C and 29.8 °C, 53.3% and 55.7%, respectively were maintained during summer months at and around noon. Furthermore, the obtained data revealed generally high uniformity of the microclimatic conditions within the greenhouse, in the lengthwise (east-west) and vertical directions. In contrast to that, there was a little variation across the width of the greenhouse (north-south) which arose as a result of solar radiation intensity and wind actions. It can be concluded that, due to the optimal level of microclimatic conditions inside the two greenhouses with an evaporative cooling system, they produced fresh yield of 8.796 and 7.356 kg/m², respectively, consequently, greenhouse 1 increased the fresh yield by 19,58% as compared with the greenhouse 2. It must also be concluded that in order to obtain completely uniform microclimatic conditions throughout the volume of the greenhouse, it is desirable to install shading black net on the roof of greenhouse.

INTRODUCTION

The prolongation of optimal growing season conditions by the operation of the greenhouse throughout the year is worthwhile for the following reasons; regular exports to keep the demands of the market supplies, maximized use of the installation, increased annual fresh yield per unit area, and increased profitability. In spite of this in most Mediterranean greenhouses such a practice is limited because the cooling methods used (mainly natural or forced ventilation) are not provided the optimal conditions, particularly during the hot – humid summer months.

High summer temperatures result in the need for constant heat removal from the greenhouse. This may be accomplished by replacing the

existing air in the greenhouse with cooler air from outside the structure. If outside temperature is low enough, and temperature inside the greenhouse is not too high, warm air may be passively (natural thermal buoyancy) exhausted through roof vents. The upward and outward movement of warm air pulls in cool air from side or end vents. This system is most effective in winter, spring, and fall. It is limited in its effectiveness for summer cooling since the incoming solar radiation load and outside air temperature may be too high for the capabilities of this system during summer months in most other climates (Papadakis *et al*, 1996; and Sethi and Gupta, 2004).

The high heat loads (high values of outside air, dry and wet bulb temperature associated with high intensity of solar radiation) during the summer months and the aim of achieving the desired growing conditions (solar radiation, air temperature, and relative humidity in the greenhouse as required for growth), are stimulating the use of evaporative systems to cool greenhouse (Arbel *et al.*, 1999). Willits (2003) and Toida *et al.* (2006) showed that in the extreme environmental locations, where ambient air temperature in the summer generally exceeds 40°C, evaporative cooling is the most efficient systems for greenhouse cooling, which can lower the inside air temperature significantly below the ambient air. These systems are based on conversion of sensible heat into latent heat through the evaporation of water, which is supplied mechanically. Evaporative cooling in a commercial greenhouse equipped with a pad-fan system for use during the summer period in arid countries was studied by Jamal (1994); and Jain and Tiwari (2002). The volume flow rate through the evaporative pad was determined by the number of air changes per hour and estimated that 20 number of air changes were sufficient to reach tolerable conditions inside the greenhouse under dry weather conditions. The water required for evaporative cooling was also determined. A mathematical model was developed to estimate water evaporation rate, airflow rate and cooling effect in an evaporative cooling system for farm structures in Saudi Arabia by Abdel-wahab (1994). It was reported that improving the cooling efficiency and covering the roof of the greenhouse with external shading would save appreciable amount of energy and water consumption. Kittas *et al.* (2001) investigated the temperature and humidity gradients during summer in a rose production greenhouse equipped with a ventilated cooling-pad system and a half shaded plastic roof. The cooling performance was achieved up to 80% and the temperature of the greenhouse was lowered by 10 °C than the outside air. Jain and Tiwari (2002) conducted theoretical and experimental studies in a 24 m² greenhouse with a fan-pad evaporative cooling system of 3 x 1.15 m² area in the west wall and two fans in the east wall. Greenhouse air temperature was reported 4-5 °C lower as compared with the outside conditions. Optimization of fan-pad cooling parameters such as length of the greenhouse, air mass flow rate, height of the cooling pad was also performed.

Kittas *et al.* (2003) attempted to lower the temperature gradients in a greenhouse equipped with fan-pad cooling system by the use of partial shading on the roof to cut down the solar radiation absorption. To predict the temperature gradients along a greenhouse, a simple climate model was proposed which incorporated the effect ventilation rate, roof shading and crop

transpiration. Experimental data revealed that the cooling system was able to keep the greenhouse air temperature at rather low levels. However, due to the significant length of the greenhouse (60 m), large temperature gradients (up to 8 °C) were observed from the pads to fans. Despite its simplicity, the model was sufficiently accurate to improve the design and the management of the cooling pad systems.

In a theoretical study, a model for fan-ventilated and fan-pad ventilated greenhouse cooling was presented by Willits (2003). Simulation runs suggested that when evaporative pad cooling was not used, little advantage was derived from increasing airflow rates. However, when evaporative pad cooling was used, both air and canopy temperatures declined with increasing airflow rates up to $0.13 \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$, the highest level considered. With no evaporative pad cooling, the evapotranspiration coefficient was predicted to range from 1.75 for an outside temperature of 36.8 °C and an outside humidity ratio of 3.3 g kg^{-1} to 0.8 for an outside humidity ratio of 29.9 g kg^{-1} at the same temperature. With evaporative cooling, the coefficient was predicted to range from 0.6 to 0.8 at the same outside temperature and the same range of outside humidity ratios. Fuchs *et al.* (2006) developed a procedure to evaluate latent heat cooling by means of crop transpiration and free water evaporation from a wet pad-fan system. Measurements in a greenhouse rose crop revealed that the numerical solution of the energy balance equation predicted accurately crop transpiration, foliage temperature, air temperature and humidity inside the greenhouse. With ventilation rates of 30 volume changes per hour and external air humidity below 50%, transpiration of a plant well supplied with water, cooled the foliage and the air in the greenhouse was below external temperature even when solar radiation was at its maximum value. Evaporation from the pad decreased when external humidity increased.

The direct solar radiation transmits through the covers into the greenhouse enclosure is the primary source of maximum heat gain (thermal trapping). The undesirable radiation (or light) transmits into the greenhouse can be controlled by the use of shading net screen or reflection. Application of shading compounds to the greenhouse cover can reduce the infrared portion of solar spectrum, which is responsible for enhancing the thermal energy in the greenhouse, ASHRAE (1995). Kittas *et al.* (1999) reported the influence of blanked roof, external shading net and internal aluminized shade-screen on photosynthetically active radiation (PAR) waveband, the near infrared (NIR) waveband and the whole waveband (TOTAL). Minor changes were observed on the PAR: TOTAL and PAR: NIR.

The objectives of this study were to examine the factors that influence the level and uniformity of the microclimate conditions obtained in a greenhouse during the summer months with forced ventilation system using fan-pad system, under two different greenhouse glazing materials using corrugated fiberglass reinforced plastic (FRP) and double layer of polyethylene sheet (PE).

MATERIALS AND METHODS

Two similar gable-even-span greenhouses were designed, constructed and installed on the roof of the Department at Mansura University (Latitude and longitude are 31.045 °N and 31.37 °E, respectively) as shown in Fig. (1). Each one having a gross dimensions of 8 m long, 4 m wide, and 3.25 m high, with a net floor surface area of 32 m². The greenhouse structural frame is formed of 25 mm square cross-section iron bar. The rafter length of the greenhouse gable is 2.25 m and gable height is 1.02 m, whilst the height of each side wall is 2 m. The rafters were tilted at 27° to minimize the side effects of wind load and intensity of solar radiation on the roof of the greenhouse during summer months. At the same time it may be maximized the solar radiation flux incident on the inclined roof of the greenhouse during winter months. Moreover, with this inclined angle (27°) condensation will run down the underside rather than dropping from the cover, damaging crops and encouraging diseases will be minimized. The vertical bars (side walls) were strongly connected to the concrete foundations 23 cm high in order to transfer gravity, uplift and over turning loads such as those from, crop, suspended equipment and wind, safely to the ground. The two greenhouses (G 1 and G2) were covered using two different glazing materials of 800 μ thick corrugated fiberglass reinforced plastic (FRP) and double layer of polyethylene sheet (PE) of 140 μ (as an inner layer) and 200 μ (as an outer layer). The greenhouse facility used in this research work during summer season of 2007 was covered with the ratio of cover surface area to the total greenhouse surface area of 2.685. They were orientated in East-West direction, where the southern longitudinal direction faced into the sun's rays as demonstrated in Fig. (1).

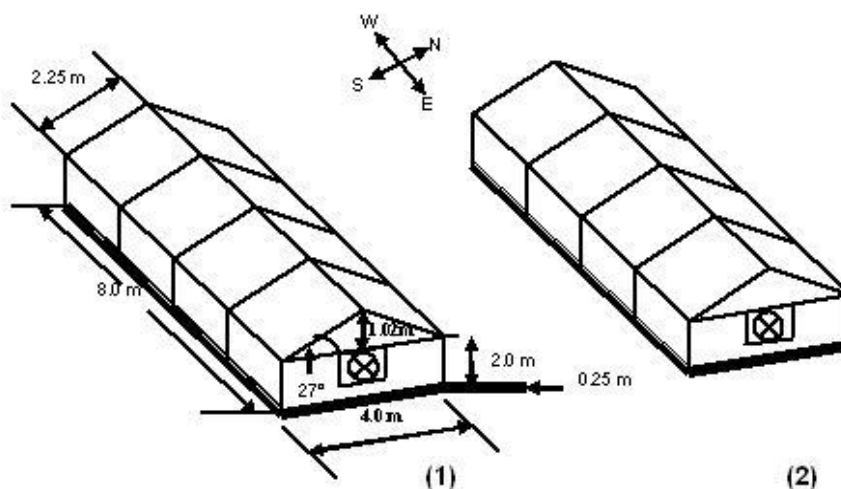
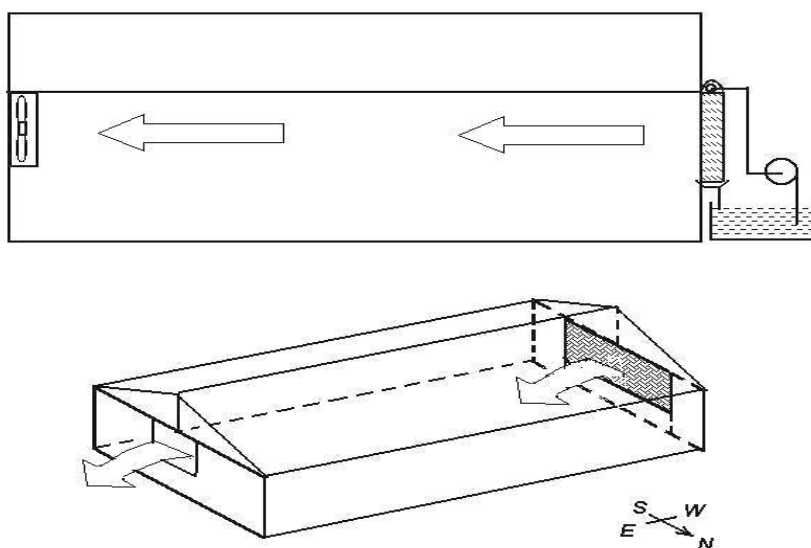


Fig. (1): schematic diagram of gable-even-span greenhouses. (1) Covered with corrugated fiberglass reinforced plastic, and (2) Covered with double layer of polyethylene sheet.

To reduce the natural heating load from the solar radiation entering the greenhouse during daylight in summer month, and otherwise to increase the cooling effect of fan-pad cooling system, a shading black net screen (60%) was used to cover only the gable roof of the two greenhouses.

Reducing temperatures is one of the main problems facing greenhouse management during daylight even in winter season such as in Egypt. Ventilation is basically used to exchange air between the inside and outside of the greenhouse as a means of temperature, relative humidity, and carbon dioxide control. Exhaust fans should be sized to exchange the total volume of air in the greenhouse at a range of rates adjustable to the particular crop being grown. Ventilation requirements vary with the climatic conditions, the season, and the greenhouse usage. Therefore, the forced ventilation system (extracting fans) was used during this research work. One extracting fan (single speed, direct driven, 60 cm diameter, and 8000 m³/h discharge) was located on the leeward side of each greenhouse and the cooling pads on the side toward the prevailing winds as shown in Fig.(2). The cooling process by ventilating was mostly used when the ambient air temperature outside the greenhouse is lower than 20 °C. But when the ambient air temperature outside the greenhouse is raised above 20 °C, then the evaporative cooling system must be used. Cross-fluted cellulose pads of 2.4 x 1.0 m were mounted in a vertical fashion. A polyvinyl chloride (PVC) pipe (12.5 mm diameter) was suspended immediately above the pads. Holes were drilled in a line about 5 cm apart along the bottom side, and the end of this pipe was capped. A baffle was placed above the water pipe to prevent any leaking of water from the system.



**Fig. (2): Diagram of ventilation and cooling systems.
(Fan and pad system)**

A sump (gutter) was mounted under the pads to collect the water and return it into the water tank from which it can be recycled to the pads by the pump. During this research work, the pots system was used as an agriculture system for protected cropping (Tomatoes crop). Each greenhouse was equipped by 60 plastic pots (30 cm high and 28 cm diameter), which arranged in five rows (each row having twelve pots). These pots contained a mixture of three different types of soil; clay soil (pasteurized at 105 °C for 20 minutes), pure yellow sand, and Irish peat moss with ratio of 1 : 1 : 1. In addition to this mixture, half kilogram of compost as an organic substance was added to each pot's mixture (for the purpose of bio-agriculture system).

Drip irrigation system was employed and installed inside the greenhouses throughout this experimental work, for watering pots of tomatoes plant. It consisted of four components; water tank, main piping line, sub-main piping line, and drippers. A 200 liters scaled plastic water supply tank (96 cm high, and 55 cm diameter) was located inside the greenhouse on 1 m above the ground surface in order to provide adequate hydrostatic pressure for maximum use rate of water. A galvanized water pipe (25.4 mm ~ 1 inch diameter) was used as a main line to pass the irrigation water from the water tank into the sub main lines. A polyvinyl chloride (PVC) pipe (19 mm ~ 3/4 inch diameter) was used to pass the water uniformly throughout the drippers. Twelve drippers (long-bath GR 4 liter/hr discharge) were uniformly alternative distributed with 50 cm dripper spacing throughout each row of plants inside the greenhouses. One hundred and twenty tomato plants (*Ebesia verity*) were transplanted on 21 April, 2007 into 60 plastic pots in each greenhouse with plant density of 2.5 m².

The meteorological data included solar radiation flux incident on a horizontal surface (pyranometer), dry-bulb temperature (shelter and vented thermistor), wind speed and its direction (cup anemometer and wind van), and air relative humidity (hygrometer) were obtained from the meteorological station (WatchDog model 550) which installed just above the greenhouses. The data were displayer on the video screen and updated by a scan of all the sensors every one minute. The mean of 60 scans was recorded on a hard-disk every hour using a data logging program (space Ware 6.02). Another meteorological station (WatchDog model 550) for internal microclimate variables within the centre of the greenhouse 2 was installed at an altitude of 1.8 m above the ground surface. The internal microclimate variables included global solar radiation above the canopy of tomatoes plant, dry-bulb air temperatures, air relative humidity, air temperature just leaving the cooling system, and ground surface temperature. These sensors were also connected to a data-logger system to examine, display, and record the data throughout this research work. The microclimate data inside the greenhouses were also displayed on the video screen and updated by a scan of all the sensors every 60 seconds. The means of 60 scans were also recorded and stored in a computer file every hour using the same data logging program. A 12 channel data-logger (Digi-Sense Scanning Thermometer Type) was also used for taking and storing reading from the different sensors (thermocouples type K, with an accuracy of ± 0.2 °C). They were uniformly distributed and located inside the two greenhouses on the centerline of longitudinal and

lateral directions. Infrared thermometer (Raytek, Rayner ST60) was also used to measure the temperatures of the cover materials and the leaves surface of plant. The recorded data were stored in the memory for output to a printer or to a computer to store on a hard-disk. The time interval for data recording was 60 min. with data acquisition every one minute for integrated measurements. The calibration of all sensors and the logger was completed successfully at the beginning of the experimental work. Two microclimate control boards were attached to the extracting fans in the two greenhouses. They were switched the fans ON and OFF whenever the air temperature inside the greenhouses increased above 28 °C and dropped below 28 °C, respectively.

A microclimatic energy balance can be developed to predict the ambient air temperature inside the greenhouse as shown in Fig.(3). It can be simulated by several sources of heat energy which affect the greenhouse microclimatic conditions (Wang and Boulard 2000 ; and Bartzanas *et al.*, 2002). The heat energy balance on the two greenhouses can be determined by limiting heat energy input (Q_i) to solar radiation available inside, if the heat energy absorbed by the bare area of the greenhouse floor (Q_g), heat energy consumed in evapotranspiration process (Q_{ev}), and total heat losses by conduction, ventilation, and thermal radiation (Q_{loss}) are known or measured. Thus, the heat energy balance was computed from the following formula:-

$$Q_i = Q_g + Q_{ev} + Q_{loss} \quad , \text{ Watt} \quad (1)$$

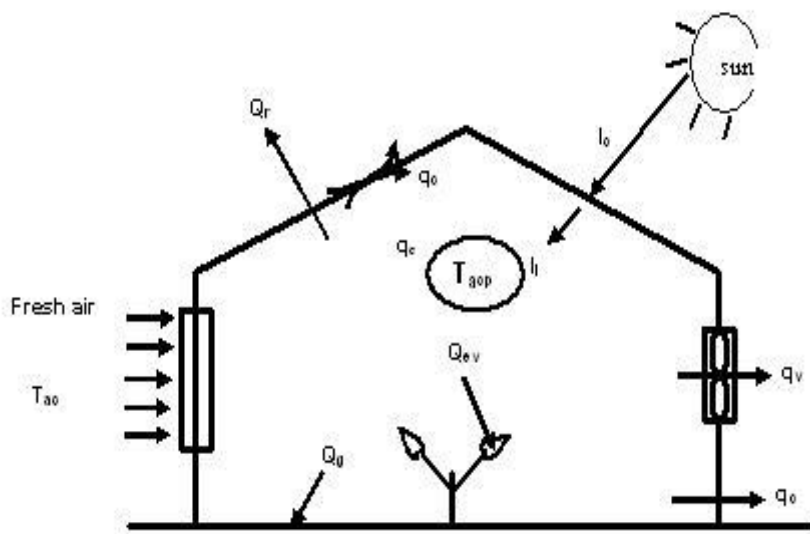


Fig.(3): Schematic diagram of the greenhouse microclimatic energy balance

The heat energy input from the solar energy (Q_c) was obtained by measuring the solar radiation flux incident on a horizontal surface (I_i) in $W m^{-2}$ just above the canopy of plants and the floor surface area of the greenhouse (A_f) in m^2 , as:

$$Q_i = I_i A_f \quad , \text{ Watt} \quad (2)$$

The solar energy absorbed by the floor surface (Q_g) was obtained by determining the bare area of greenhouse floor (A_b) in m^2 , and the absorptivity of the floor surface (α_g), as:

$$Q_g = I_i A_b \alpha_g \quad , \text{ Watt} \quad (3)$$

The heat energy consumed in the evapotranspiration process (Q_{ev}) can be calculated by determining the rate of evapotranspiration to solar radiation (R) which ranged between 0.48 – 0.52 according to growth stage (Nelson, 1996), ratio of floor surface area covered by tomato plants to the total floor surface area (F), and the solar energy available inside the greenhouse (Q_i), as:

$$Q_{ev} = R F Q_i \quad , \text{ Watt} \quad (4)$$

The total heat energy losses by conduction and convection, ventilation, and thermal radiation can be computed from the following equation:-

$$Q_{loss} = q_c + q_v + q_r \quad , \text{ Watt} \quad (5)$$

The heat losses from the greenhouse by conduction and convection can be determined by limiting the heat transfer to conduction and convection, if the overall heat transfer coefficient (U_o) in $Wm^{-2}C^{-1}$ total surface area of the greenhouse cover (A_c) in m^2 , and inside (T_{ai}) and outside (T_{ao}) air temperatures in $^{\circ}C$ are known or measured. The procedure does not require the separation of the conduction and convection components. It can be calculated from the following formula:-

$$q_c = U_o A_c (T_{ai} - T_{ao}) \quad , \text{ Watt} \quad (6)$$

The heat energy loss by forced ventilation (q_v) can be calculated by determining the rate of extracting fan discharge (V) in $m^3 s^{-1}$, density of air (ρ) in $kg m^{-3}$, specific heat of air at constant pressure (C_p) in $J kg^{-1}C^{-1}$, and temperature difference between inside and optimal air temperature inside (T_{aop}) in $^{\circ}C$, as:

$$q_v = V \rho C_p (T_{ai} - T_{aop}) \quad , \text{ Watt} \quad (7)$$

The heat energy loss by thermal radiation (q_r) can be computed by the mean emittance factor of the inside substances (ϵ), average transmissivity coefficient at long wave radiation (τ), Stefan-Boltzmann constant (σ) in $W\ m^{-2}\ k^{-4}$, and absolute temperature difference between inside air and the sky (T_{sky}) in $^{\circ}K$, as:

$$q_r = \epsilon \tau \sigma A_f (T_{ai}^4 - T_{sky}^4) \quad , \text{Watt} \quad (8)$$

$$T_{sky} = 0.0552 (T_{ai})^{1.5} \quad , ^{\circ}K \quad (9)$$

To understand the air exchange between the inside and outside of greenhouses and to validate the results of theoretical computation with that measured, experimental methods are essential to use. The energy balance on greenhouse during daylight through the experimental period is represented by Eq. (1). A mathematical model was developed and used to compute the hourly average heat energy balance on the greenhouse during daylight. It can be rewritten in finite difference form and solved for the greenhouse air temperature (T_{ai}) at each hour with respect to the optimal temperature (T_{aop}), and input and output energies, as:

$$T_{ai} = T_{aop} + \frac{1000}{m C_p} (Q_i - Q_g - Q_{ev} - q_c - q_r) \quad , ^{\circ}C \quad (10)$$

The effectiveness of the evaporative cooling system can be computed by determining the cooling effect (T_{dd} , temperature difference between outside and inside) and wet-bulb depression (T_{wd} , temperature difference between dry and wet-bulb of outside air) as follows (ASHRAE, 1995):-

$$\eta_{ev} = \frac{T_{dd}}{T_{wd}} \times 100 \quad , \% \quad (11)$$

This research work was carried out from 21st April until 13th September 2007. For the rest of this experimental work, the greenhouse covered with corrugated fiberglass reinforced plastic, and the greenhouse covered with double layer polyethylene sheets are referred to as G1 and G2, respectively. Data were statistically analyzed using Excel 5.2 program. Linear regression analysis was used to examine the relationship between the different microclimatic factors.

RESULTS AND DISCUSSION

The effectiveness of evaporative cooling system (fan-pad system) under different glazing materials was investigated in particular for the hottest days during the experimental period. The intensity of solar radiation, air temperature and air relative humidity inside the two greenhouses were compared with that data outside as an important measure of the effectiveness of the fan-pad cooling system.

Data were measured and collected for a period of 166 days at Mansoura. The hourly average data are summarized and listed in Table (1). During this time, fan-pad system was automatically operated by the control

board according to the optimal set-point temperature inside (28 °C). Actual solar radiation data recorded outside (I_o) and inside (I_i) on a clear day ranged from near zero to about 1000 W m^{-2} . The lowest values during the experimental period were in the range of $25\text{-}110 \text{ W m}^{-2}$, which occurred just after sunrise and prior to sunset. They varied from day to another and during the month according to the sky cover (clouds), solar altitude angle, and solar incident angle. The actual solar radiation recorded inside the two greenhouses was lower than that outside, due to the reflectance, absorptance, and transmittance factors of the two different covering materials and shading black net screen. The hourly averages solar radiation recorded outside and inside the two greenhouses were 523.5 , 274.3 , and 245.9 W m^{-2} , consequently, the effective transmittance of the covering materials was on the average 52.4% and 46.97% , respectively. To determine the solar radiation entering the two greenhouses (I_i) as a function of the actual solar radiation outside (I_o), all the data recorded during the experimental period was plotted in Fig. (4). Regression analysis showed a highly significant linear relationship between these factors. The regression equations for the best fit were:

$$I_i(\text{G1}) = 0.5287 (I_o)$$

$$I_i(\text{G2}) = 0.4790 (I_o)$$

Table (1): Typical data of microclimatic conditions outside and inside the greenhouses

Hr.	Solar time	Solar Radiation, Wm^{-2}			Ambient air temperature, °C			Air relative humidity, %		
		I_o	$I_i(\text{G1})$	$I_i(\text{G2})$	T_{ao}	$T_{ai}(\text{G1})$	$T_{ai}(\text{G2})$	RH_o	$RH_i(\text{G1})$	$RH_i(\text{G2})$
0	23.92	0.0	0.0	0.0	22.7	23.8	25.4	84.7	72.0	77.0
1	0.92	0.0	0.0	0.0	22.3	23.6	25.1	87.4	73.5	78.7
2	1.92	0.0	0.0	0.0	22.0	23.5	24.8	88.8	74.2	79.5
3	2.92	0.0	0.0	0.0	21.5	23.1	24.6	89.9	74.8	80.1
4	3.92	0.0	0.0	0.0	21.2	22.9	24.5	90.5	75.1	80.5
5	4.92	0.0	0.0	0.0	21.0	22.7	24.2	91.2	75.5	80.9
6	5.92	66.7	17.7	14.1	21.6	23.3	25.8	92.4	76.2	81.7
7	6.92	235.6	107.4	94.7	23.2	24.1	27.3	89.9	74.8	80.1
8	7.92	445.9	229.6	205.6	25.4	25.3	27.9	83.3	71.3	73.9
9	8.92	646.4	344.4	309.5	27.3	26.4	28.8	72.7	65.7	68.1
10	9.92	748.7	402.7	362.3	28.9	27.3	29.5	63.2	60.6	63.8
11	10.92	850.8	458.8	412.7	30.1	27.8	29.9	55.8	57.0	59.5
12	11.92	900.2	486.1	436.9	31.0	28.3	30.5	50.5	54.1	56.6
13	12.92	861.8	464.8	418.0	31.7	28.7	30.8	47.3	52.2	54.7
14	13.92	759.5	408.5	367.5	32.1	28.9	31.4	45.7	51.4	53.8
15	14.92	599.6	319.4	287.1	31.9	28.8	31.1	45.8	51.7	54.0
16	15.92	414.3	213.4	191.0	31.3	28.5	30.2	47.9	52.5	55.3
17	16.92	206.8	94.3	83.1	30.0	27.9	29.3	52.5	54.9	57.8
18	17.92	69.6	18.5	14.7	28.0	26.8	28.2	58.9	58.3	63.6
19	18.92	0.0	0.0	0.0	26.0	25.7	27.0	66.4	62.3	66.4
20	19.92	0.0	0.0	0.0	25.0	25.2	26.7	71.9	65.1	69.3
21	20.92	0.0	0.0	0.0	24.2	24.7	26.3	75.8	67.3	71.7
22	21.92	0.0	0.0	0.0	23.5	24.4	26.0	79.3	69.2	73.8
23	22.92	0.0	0.0	0.0	23.0	24.2	25.8	82.3	70.8	75.6

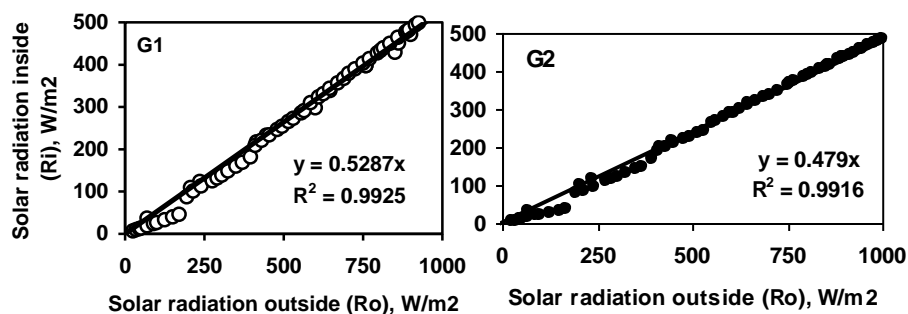


Fig. (4): Solar radiation recorded inside the two greenhouses versus solar radiation outside.

The air temperature in G2 varied between 24.5 and 31.4 °C, whereas the air temperature in G1 ranged from 22.7 to 29.8 °C. The hourly average air temperatures recorded outside and inside the two greenhouses at and around noon (critical period) were 31.4, 28.5, and 29.8 °C, respectively. Accordingly, the compiled data showed that fan-pad cooling system was an effective method for lowering air temperature of the greenhouse as inside air temperatures in the two greenhouses were lowered 2.9 and 1.6 °C at that period, respectively. A compiled information from many researchers (Nelson, 1996 ; Arbel *et al.*, 1999 ; Kittas *et al.*, 2003 ; and Sethi and sharma, 2007) showed that air temperature inside the greenhouse without cooling system are frequently between 11-20 °C higher those outside in spite of open ventilators. Therefore, the fan-pad cooling system could be lowered inside air temperatures between 13.9 to 22.9 °C and 12.6 to 21.6 °C, respectively, as compared with any greenhouse without cooling system. In spite of the solar radiation entering G2 during the experimental period was lowered than that entering G1, the air temperature in G2 was higher than that in G1, since the fiberglass cover reflected and transmitted long-wave thermal radiation greater than the polyethylene cover. This phenomenon can be attributed to the high level of thermal trapping (greenhouse effect) that occurred in G2, due to radiometric thermal properties pf polyethylene cover. The radiometric thermal properties of the covering material plat a very important role in the case of thermal trapping. As a consequence, the average transmittance coefficient to long-wave thermal radiation of the covering materials (FRP and PE) is 0.55 and 0.29, respectively (Papadakis *et al.*, 2000). The air temperatures at the level of tomatoes canopy were uniform in the two greenhouses, due to the inside air was continuously moved by the extracting fans. This is in agreement with the data published by Kittas *et al.* (2003) and Sethi and Sharma (2007) when they stated that, as the air inside the greenhouse is continuously moving, air temperatures are uniform, humidity surroundings leaf surface is reduced, and carbon dioxide levels are thus decreased. The temperature of the tomatoes plant leaves recorded during the majority of daylight time was lower than the inside air temperature which prevented

occurrence of plant thermal stress and consequently, reduced the risk of plant water stress and fungal diseases. The air temperatures recorded inside the two greenhouses during the experimental period (T_{ai}) were used as a function of air temperature outside the greenhouse (T_{ao}) as shown in Fig. (5). Regression analysis revealed a highly significant linear relationship between these factors. The best equations relating the air temperature in the two greenhouses under specific conditions to that outside were:-

$$T_{ai} (G1) = 11.406 + 0.5485 (T_{ao})$$

$$T_{ai} (G2) = 12.656 + 0.5842 (T_{ao})$$

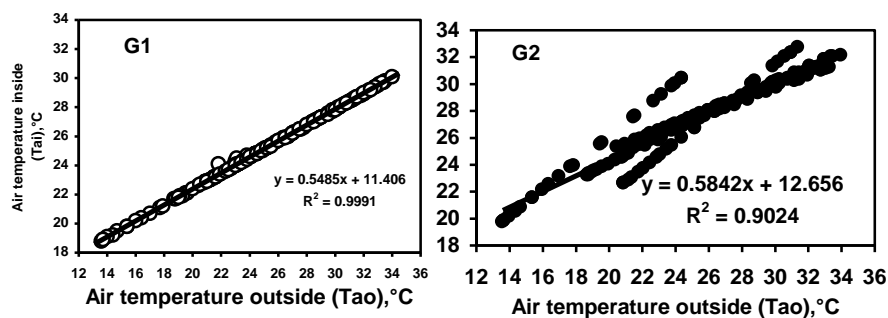


Fig. (5): Air temperature recorded in the two greenhouses versus air temperature outside

The air relative humidity in the two greenhouses during the daytime ranged from 48.0% to 58.6% and from 50% to 61.4%, respectively, whereas, the outside relative humidity was in the range 38.5 – 49.0%. Most protected cropping grow best within a fairly restricted range, typically 55% to 70% relative humidity for many species (Nelson, 1996 ; and Ozturk and Bascetincelik, 2003). Low humidity increases the evaporative demand on the plant to the extent that moisture stress can occur, even when there is an ample supply of water to the roots system. The water loss from the plant and add to the inside air is often determined by; the difference in water vapor concentration between inside the leaf and outside, and by the resistance to movement of water molecules from inside the leaf to outside. The resistance varies according to the length of the path which water molecules must traverse, and the size of the stomata opening. As The leaf temperature is reduced due to evaporative cooling, the internal vapor pressure of the leaf is lowered and thus the water loss from the plant is less, and vice versa. With fan-pad cooling system, lowering of the dry-bulb temperature will generally raise the air relative humidity. Furthermore, water is always being added to the air in the greenhouse from transpiring plants and evaporating water from cooling system. The solar radiation entering the greenhouse is often utilized to evaporate free water from the leaf, rather than raising leaf temperature and increasing water loss from the plant into inside air. When a non-saturated air comes in contact with free moisture and the two are thermal isolated from outside heat source, there is a transfer of mass and heat, Because of the vapor pressure of the free water surface is higher than that of the unsaturated

air, water transfers in response to the differential. The transfer involves a change of state from liquid to vapor, requiring heat of vaporization. In spite of the pad face air velocity of fan-pad cooling system used with the two greenhouses was on the average 1.8 m/s, the air relative humidity inside G2 was greater than that in G1. This may be due to high thermal trapping occurred in G2 which demanded cooling operation for a long time. Due to all the reasons discussed above, the air relative humidity in G1 was lower than that in G2 by 3.1%.

The effectiveness of the cross-fluted pads as a cooling media was experimentally examined from Aril to September 2007. Cooling capacity is dependent upon the volume of air flow and the saturation efficiency. Saturation efficiency is in turn depend strongly upon such factors as; length of cooling operation period, air velocity through the pad, water temperature in the cooling system, and water flow rate through the cooling media. The daily average effectiveness of the fan-pad cooling system inside the two greenhouses (1&2) during the experimental period was on the average 72.0% and 73.6%, respectively. Accordingly, the cooling system of G2 was on the average more efficient than the cooling system of G1 by 1.6% due to cooling operation period in the G2 was longer than that in G1; consequently, the water temperature of cooling system (2) was always lower than that in cooling system (1). The effectiveness of fan-pad cooling system varied from time to time, from day to another, and during the experimental period, according to the air relative humidity and dry-bulb air temperature outside the greenhouses. As the exterior air relative humidity is decreased lower than 30%, more cooling effect is achieved making the cooling system more efficient. Substantial temperature decreases were obtained when the air relative humidity recorded outside was less than 30% and outside air temperature exceeded 35°C. Therefore, the two cooling systems achieved a cooling effect ranged between 6.4 to 4.0°C at air relative humidity ranged from 30.5 – 60.2%, respectively. Cooling effect (degree of cooling) and consequently evaporative cooling efficiency was strongly dependent upon the wet-bulb depression that mainly affected by air relative humidity and water temperature in the cooling system. Therefore, the greatest value of cooling effect for G1 and G2 (6.4°C and 6.5°C, respectively) and cooling efficiencies (80.0% and 81.3%, respectively) were achieved with the greatest value of wet-bulb depression (8°C) and lowest value of air relative humidity (30.5%). Whereas, the lowest value of cooling effect for G1 and G2 (0.8°C and 0.9°C, respectively) and cooling efficiencies (38.1% and 42.9%, respectively) were recognized with the lowest value of wet-bulb depression (2.1) and greatest value of air relative humidity (75.3%). To determine and examine the best model which can be used to correlate cold air temperature just leaving the pad cooling system (T_{idd}) in G1 and G2, and wet-bulb depression (T_{wd}) all the obtained data were used in regression analysis and plotted in Fig. (6). Regression analysis revealed a highly significant linear relationship between these parameter. The linear regression equations for the best fit were:-

$$T_{idd} (G1) = 29.09 - 0.7200 (T_{wd})$$

$$T_{idd} (G2) = 29.09 - 0.7355 (T_{wd})$$

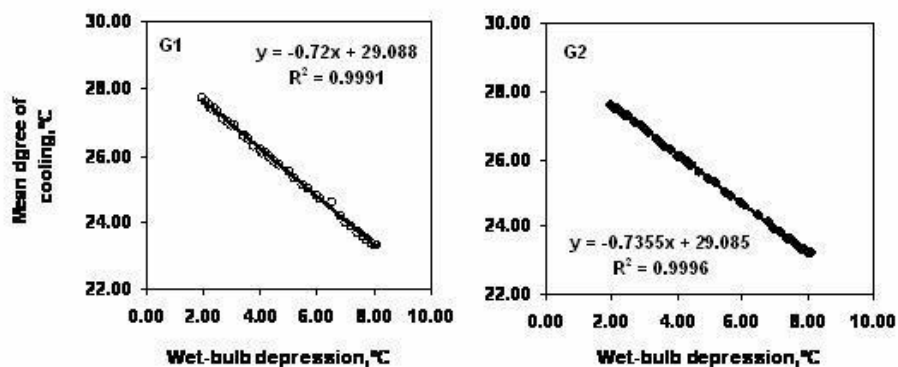


Fig. (6): Air temperature just leaving the cooling system against wet-bulb depression for the two greenhouses.

The above equations are definitely the numerical expression of the obtained data which showed that, the fan-pad cooling system for G1 and G2 was reduced the dry-bulb air temperature recorded outside by 0.72 and 0.74 of the wet-bulb depression, respectively. Therefore, the previous equations can be rewritten as follows:-

$$T_{idd} (G1) = T_{odd} - 0.7200 (T_{wd})$$

$$T_{idd} (G2) = T_{odd} - 0.7355 (T_{wd})$$

Thus, the y-intercept is equaled to the mean dry-bulb temperature of outside air. Whereas, the slopes are equal to the mean efficiencies of cooling systems. The previous models predict the cold air temperature just leaving the cooling pads for the two greenhouses showed enough accuracy for use in hot climatic conditions. This is in agreement with the data published by Aldrich and Bartok (1990) when they reported that, most cooling systems reduced the dry-bulb temperature of outside air 0.7 to 0.8 of the wet-bulb depression. Finally, the fan-pad cooling system in G2 consumed electrical energy of 166.8 kWh by extracting fan, whereas, the cooling system in G1 consumed 104.8 kWh. This obvious difference due to the extracting fan was operated for a long time period per day throughout the season, to reject the excessive heat energy accumulated inside, and to provide optimal conditions in G2. Furthermore, the air temperature in G2 is rapidly increased just after the sunrise as compared with G1 (Anna *et al.*, 2003).

The arithmetical model of energy balance that was marked out previously, revealed that, there are many factors affecting microclimatic conditions of the greenhouse during daylight. These factors and their influence on thermal energy balance were as; solar radiation inside the greenhouse (Q_i), solar radiation absorbed by the bare floor surface area (Q_g), solar radiation consumed in evapotranspiration process (Q_{ev}), and total heat energy losses (Q_{loss}). The solar radiation absorbed by the bare floor area in the two greenhouses represented 29.12% and 27.43 of the total solar radiation entering the greenhouses, respectively. Whereas, the evapotranspiration process from the plants in the two greenhouses during the experimental period represented 30.27% and 28.85% of the solar radiation

entering the greenhouses, respectively. The total heat energy losses from the greenhouses during daylight by conduction, sensible and latent heat due to forced ventilation, and thermal radiation were examined, measured, and computed, They were represented 38.07% and 39.94% of the total solar radiation entering the two greenhouses, respectively. The computed data of the mathematical model showed that, the difference between input and output heat energies yielded the accumulated heat energy in various substances inside the two greenhouses. It also revealed that, the ratio of output heat energy to the input heat energy presents the validation of the model of heat energy balance. The validation of the model which described the relationship between the input and output heat energies for the two greenhouses was 97.46% and 96.22%, consequently about 2.54% and 3.78% of the total input heat energy was accumulated, respectively.

Statistical validation of the model was also performed by comparing the measured and predicted air temperatures to determine how well, statistically, the model simulated the fan-pad cooling system performance. The predicted air temperature (T_{aip}) of the model was plotted against the air temperature recorded inside the two greenhouses (T_{aim}) as shown in Fig. (7). Regression analysis showed a highly significant linear relation between the predicted and measured data. The regression equations for the best fit were:-

$$T_{aip} (G1) = 1.0389 (T_{aim})$$

$$T_{aip} (G2) = 1.0377 (T_{aim})$$

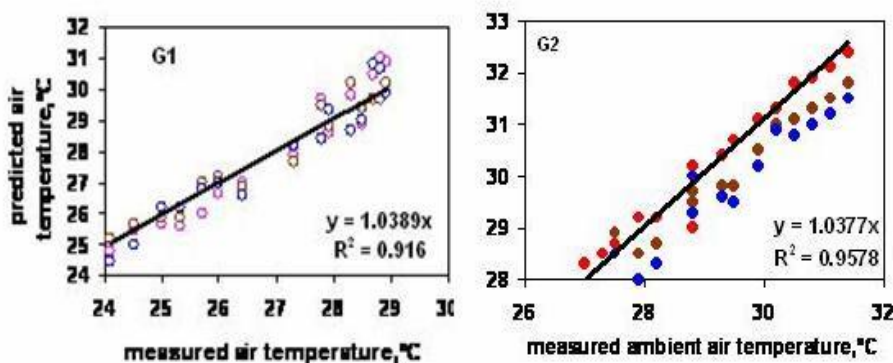


Fig. (7): Predicted air temperature versus measured air temperature.

The coefficient of determination (R^2) denotes the percentage of variation in the measured air temperature explained by the variation in the predicted air temperatures. There is a good agreement between the obtained results from the mathematical model and those obtained experimentally. In general, the results of the mathematical model are valid in the wide range of air temperatures.

For the duration of the experimental period, the weekly average leaves number of tomatoes plant in G1 and G2 were 3.2 and 2.8 leaf/week, respectively. The number of leaves varied from row to row, from greenhouse to another, and during the experimental period, according to the location of

each row and the microclimatic conditions in the two greenhouses. The number of leaves in G1 was on the average 14.29% more than that in G2, due to the radiometric thermal properties of covering materials and the microclimatic conditions. Therefore the weekly average stem length of tomatoes plant in G1 and G2 was 12.6 and 11.0 cm/week, respectively. Accordingly G1 increased the growth rate of plants on the average by 14.55% as compared with G2. This variation can be attributed to the reaction rates of various metabolic processes, absorption rate of nutrient elements, and release of water by root system, which strongly affected by the inside air and relative humidity. The air temperatures recorded in the two greenhouses were at and little over the optimal daylight temperature (28 °C) particularly at the critical period (from 10 to 15) during the hot summer season. A linear increase of the air temperature with distance in the two greenhouses and parallel decrease in the air relative humidity were evidently observed during the experimental period. These changes were expressed in an air temperature increase of 2.8 and 3.5 °C, and 12% and 15% decrease in air relative humidity, over the distance of 8 m between the cooling pads and extracting fans in the two greenhouses, respectively. As the air temperature surrounding the plants is increased over 35 °C, the percentage of flowerage, vitality of insemination seeds, and stem strength are reduced making the growth rate and the fruit set at minimum level. The biochemical reactions in all crops particularly tomatoes crop are mainly controlled by enzymes that are heat sensitive. Numerous biochemical reactions involved in the photosynthesis and respiration processes. These all have the net effect of building carbohydrates and storing energy. Due to the reasons discussed previously, the number of fruits being seated on the plants inside the two greenhouses was on the average 18.76 and 15.70 fruit/plant, respectively. Accordingly, G1 increased the rate of fruit set on the average by 17.83% as compared with G2. Therefore, the fresh yield of tomatoes crop per square meter inside the two greenhouses was 8.796 and 7.356 kg, respectively.

CONCLUSION

This research work examined the factors that influence the level of the obtained climatic conditions and their degree of uniformity, in a two greenhouses equipped with a fan-pad cooling system and covered using two different glazing materials (fiberglass reinforced plastic (FRP) and double layer of polyethylene sheets (PE)). The factors that have been tested were; solar radiation entering the greenhouse, air temperature inside the greenhouse, and air relative humidity and their effect on the growth rate, fruit set, and fresh yield of tomatoes crop during the summer season of 2007. From this study the following conclusion can be drawn as:-

1. The hourly average solar radiation recorded outside and inside the two greenhouses during the experimental period were 523.5, 274.3, and 245.9 W m⁻², respectively. Consequently, the effective transmittance of the FRP and PE glazing materials with shading black net screen was 52.40% and 46.97%, respectively.

2. Due to various radiometric and thermal properties of the two different covering materials, thermal trapping occurred in G2 by a rate greater than that in G1. Therefore, the air temperature recorded in the two greenhouses at and around noon (critical period) was on the average 28.5 and 29.8 °C, respectively.
3. The fan-pad cooling system was an effective method of lowering the air temperature of the greenhouse as inside air temperatures in the two greenhouses were lowered 2.9 and 1.6 °C, respectively.
4. A linear increase of the air temperature with distance in the two greenhouses, and a parallel decrease in the air relative humidity were evidently observed during the experimental period. These changes were represented in a temperature increase of 2.8 and 3.5 °C, and 12% and 15% decrease in air relative humidity over the distance between cooling pads and extracting fan.
5. Operation of the fan-pad system forced the outside air into the greenhouse through the wet cooling pads, which humidified and cooled it only at the entrance, where the wet pads were saturated. Cooling effect fan-pad cooling system was strongly dependent upon the wet-bulb depression that mainly affected by air relative humidity and water temperature in the cooling system.
6. There is a good agreement between the obtained results from the mathematical model and those obtained experimentally. In general, the results of the mathematical model are valid (96.8%) in the wide range of solar radiation, air temperature, and air relative humidity conditions which induced in Egypt at midday during the summer.
7. As the air temperature around the plants is exceeded 35 °C, the percentage of flowerage, vitality of insemination seeds, and stem strength are reduced making the growth rate and the fruit set at minimum level. The biochemical reactions in all crops are mainly controlled by enzymes that are heat sensitive. Therefore, the fresh yield of tomatoes crop per square meter in the two greenhouses was 8.796 and 7.356 kg, respectively, consequently G1 was more productive than G2 by 19.58%.
8. Finally, it can be concluded that the greenhouse equipped by fan-pad cooling system and covered with FRP glazing material are an effective method of providing and maintaining desirable conditions inside the greenhouse under hot-humid weather conditions.

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تأثير مواد تغطية البيوت المحمية على فاعلية نظام التبريد بالتبخير لإنتاج محصول الطماطم تحت ظروف الصيف الحار والرطب صلاح مصطفى عبد الطيف ، مجدي عبد الهادي السعدنى و حسام وحيد حواس قسم الهندسة الزراعية – كلية الزراعة – جامعة المنصورة.

يهدف هذا البحث إلى إختبار العوامل التى تؤثر على مستوى الظروف المناخية المتحصل عليها ومدى إنتظامها داخل صوبتين مجهزتين بنظام كامل للتبريد بالتبخير ومغطاتين بمادتين مختلفتين من مواد التغطية (الصوبة الأولى مغطاه بالياف الزجاج المدعم بالبلاستيك والمجدد السطح والأخرة مغطاه بطبقتين من البولى إيثيلين) وتم تغطية الصوبتين بشبك تظليل أسود (60%) بغرض دراسة تأثير نظم التغطية المختلفة للصوب الزراعية على فاعلية نظام التبريد بالتبخير أثناء نمو وإنتاج محصول الطماطم . العوامل التى تم إختبارها خلال هذه الدراسة كانت: الأشعة الشمسية النافذة للصوبة، درجة حرارة الهواء داخل الصوبة، الرطوبة النسبية للهواء داخل الصوبة. أهم النتائج المتحصل عليها من هذه الدراسة يمكن تلخيصها فى التالى:-

- 1- متوسط الأشعة الشمسية فى الساعة والمسجلة خارج وداخل البيوت المحمية خلال فترة التجارب كانت 323.5 , 274.3 , and 245.9 W m^{-2} على التوالى وبالتالى فإن متوسط معامل نفاذية الغطاء الفيبرجلاس والبولى إيثيلين مع شبك التظليل كان على التوالى 52.40% and 46.97%
- 2- أدى الإختلاف فى خصائص التكتيف الأشعاعى والحرارى بين مواد تغطية البيوت المحمية إلى حدوث ظاهرة الإحتساب الحرارى بمعدل أعلى داخل البيت المغطى بالبولى إيثيلين عنه فى البيت المغطى بالفيبرجلاس، لذا فإن درجة حرارة الهواء داخل البيتين عند وحول الظهر كانت فى المتوسط 28.5 and $29.8 \text{ }^\circ\text{C}$ على التوالى.
- 3- يعتبر التبريد بالتبخير طريقة فعالة فى خفض درجة حرارة الهواء داخل البيوت المحمية حيث إنخفضت درجة حرارة الهواء داخل البيتين على التوالى 2.9 and $1.6 \text{ }^\circ\text{C}$ عن تلك المسجلة خارج البيوت المحمية.

- 4- حدوث زيادة خطية فى درجة حرارة هواء البيتين المحميين خلال المسافة بين ألياف التبريد ومروحة سحب الهواء يوازئها إنخفاض فى الرطوبة النسبية للهواء خلال هذه المسافة. هذه التغيرات تمثلت فى حدوث زيادة فى درجة حرارة الهواء مقدارها على التوالي 2.8 and 3.5 °C وإنخفاض فى الرطوبة النسبية مقدارها على التوالي 12 and 15%
- 5- يودى تشغيل نظام التبريد بالتبخير إلى دفع الهواء الخارجى إلى داخل البيوت المحمية من خلال ألياف التبريد المبللة بالماء التى تودى إلى تبريد وترطيب الهواء المار خلالها فقط أثناء الدخول عندما تكون ألياف التبريد فى مرحلة التشبع بالرطوبة. تعتمد فاعلية التبريد بالتبخير بقوة على إنخفاض درجة الحرارة الرطبة للهواء وبالتالي على الرطوبة النسبية للهواء خارج البيوت المحمية وأيضاً درجة حرارة الماء المار خلال ألياف التبريد.
- 6- تم الحصول على ملاءمة جيدة بين النتائج المتحصل عليها من النموذج الرياضى والنتائج المتحصل عليها تجريبياً حيث كانت نسبة تدقيق البيانات حوالى 96.8% وذلك فى مدى واسع من ظروف الأشعة الشمسية ودرجة حرارة الهواء والرطوبة النسبية للهواء التى كانت متوفرة فى مناخ مصر خلال فصل الصيف.
- 7- بلغ متوسط إنتاج المتر المربع الواحد من مساحة أرض البيتين المحميين على التوالي 8.796 and 7.356 kg بالتالى فإن البيت المغطى بالفيرجلاس كان أعلى فى الإنتاجية من البيت المغطى بالبولى إيثيلين بنسبة 19.58%
- 8- يمكن الخلاصة إلى أن البيوت المحمية التى يتم تغطيتها بغطاء من الفيرجلاس المجدد مع تغطية السقف الجمالونى بشبك تظليل خلال فصل الصيف وأيضاً تجهيزها بنظام تبريد بالتبخير تودى إلى توفير وأيضاً المحافظة على المستوى الأمثل للظروف المناخية داخل البيوت المحمية تحت ظروف الطقس الحار والرطب.