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TEMPERATURE GRADIENTS IN A SWEET COLOURED PEPPER COMMERCIAL GRENHOUSES EQUIPPED WITH SOLAR HEATING AND EVAPORATIVE COOLING SYSTEMS

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ABSTRACT

The study presents an experimental investigation of solar heating and evaporative cooling systems for heating and cooling sweet coloured pepper greenhouse during Agriculture season of 2010-2011. The use of solar energy system for greenhouse heating in winter and cold days helps to save fossil fuels and conserve green farm environment on the one hand, and on the other, enhances the quality of greenhouse products, reduces production costs and limits the release of greenhouse gases. To predict the air temperature gradients inside a commercial greenhouse, a simple climate model that incorporates the effect of heating cycle and ventilation rate, is functioned. In order to validate the proposed model, different measurements (included indoor and outdoor air temperatures, air relative humidity, and solar radiation flux incident) were measured and recorded in a computer fill. The commercial greenhouse was equipped with a complete solar heating system (six solar panels, storage tank and heat distributing system) for heating 750 litres of water and evaporative cooling system for ventilating and cooling 851.04 m^3 total volume. The daily average overall thermal efficiencies of the solar panels and the storage system during the experimental period, respectively, were 67.51% and 75.46%. Over 181 days heating season the solar heating system provided 37.725 kWh (66.61%) of the daily total heat energy required (56.640 kWh). This percentage could be increased by reducing heat losses from the greenhouse. The measured air temperatures held generally above the predicted one by about 1 to 2ºC, during the experimental period.

Due to the microclimatic conditions of the greenhouse were at or around the desired level, the sweet coloured pepper had have optimal vegetative growth rate, stem length, number of fruits being seated, and fresh yield. The total annual costs per square meter of greenhouse were L.E. 35.722.The fresh yield of sweet coloured pepper was 5.563 kg/m^2, which sold by L.E. 55.63, consequently, the estimated return on capital was 55.73% per annum.

INTRODUCTION

Protected agriculture in Egypt has expanded to more than 40,000 feddan in the year 2005 (Abou-Hadid, A. F., 2010). This area is in operation for high cash crops production (sweet coloured pepper, beans, cucumber, tomatoes, and cantaloupe). This area could increase in the near future, in part because of greater demand for specialty vegetable crops. Depending on the region's climate and crop-growing season, greenhouses can be a means to an economically maintain a warm environment during cool season, to protect sweet coloured pepper plants from rain, wind, and high intensity of solar radiation, and to retain pollinators and beneficial insects while excluding unwanted insect pests. In adapted greenhouses, sweet coloured pepper fruits are usually harvesting with full maturation colour, and fruit yield yields are greater, of higher quality, and usually produced at a time of the year when production in the open field is not possible and market prices for peppers are highest (Jovicich et al., 2009).

Agricultural greenhouses have a very poor efficiency of thermal conversion of the received solar energy. This is particularly in the eastern north region of Delta, where, in a cycle of 24 h, and in the winter season, the following constraints are observed. During the daylight time to maintain through ventilation, an indoor air temperature at a level lower than the excessive temperatures, harmful for the growth and development of the cultures, and at nighttime to assure, by a supply of heating energy, an optimal temperature higher than the crucial level of the culture.

Because of large heating loads and relatively high prices of fossil fuels (100-150$/barrel), alternative energy sources for greenhouse has gained utmost interest. Some of the important alternative sources of energy are; solar collectors, heat pumps, and thermal energy storage systems using phase change materials. As solar energy is available only during the daylight, its application requires efficient thermal energy storage systems. Therefore, the excess heat collected during the daylight is stored for later use at nighttime (Abdellatif et al., 2007).

Heating of a greenhouse is an essential requirement for proper growth and development of winter growing crops (Tiwari, 2003). Thermal heating of greenhouses have been studied by several researchers in employing different passive methods as well as active modes (Jain and Tiwari, 2003 ; Benli and Drmus, 2009 ; and Lu Aye et al., 2010). Among the active heating modes, a solar thermal system is one of the most practical and appropriate means for reducing the operating costs in a greenhouse. If heating pipes are galvanized or painted with aluminized paint, heat delivery rates will be approximately 15% less than from black pipe (ANSI/ASAE, 2003).

Solar energy is non-polluting and offer significant protection of the environment. Therefore, solar thermal systems should be employed whenever possible in order to achieve a sustainable future. The solar energy collected by solar thermal systems is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use at nighttime and/or cloudy days (Sayigh, 2001 ; Kalogirou, 2003).

In this research work, emphasis has been given to solar heating systems suitable for heating greenhouses, hence to contribute to the reduction of the heat energy demand of sweet coloured pepper under greenhouse climatic conditions. The main objectives of the present study were to: (1) evaluate the thermal performance analysis of solar heating system; (2) investigate the possibility of utilising the solar heating system for heating the sweet coloured pepper greenhouses during winter season of 2010-2011; and (3) develop a simple model for predicting indoor air temperature profiles and validate it against measurements of experimental data in a commercial greenhouse.

MATERIALS AND METHODS

1. Greenhouse

The experiments were carried out from September 2010 to June 2011 in a two commercial greenhouses (gable-even-span form) cultivated by sweet coloured pepper crop at SEKEM company located in the eastern north of delta (latitude and longitude angles, respectively, are 30.38°N and 31.66°E, and 25 m above the sea level). The geometric characteristics of the gable-even-span commercial greenhouse are as follows: eaves height 4.16 m, gable height 1.91 m, rafter angle 23º, total width 9.0 m, total length 32.0 m, curtain height 0.25 m, floor surface area 288 m^2, and volume 851.04 m^3. The two greenhouses were orientated in East-West direction, where the southern longitudinal direction faced into the sun's rays and the northern longitudinal direction faced into the cold sky.

The two commercial greenhouses (G1 and G2) were covered using two different glazing materials (fiberglass reinforced plastic and polyethylene film). The first greenhouse covered using 800 µm thick corrugated fiberglass reinforced plastic (FRP) panels, with the ratio of cover surface area to the total floor surface area of 1.59. The second greenhouse (G2) was covered with one layer of 200 µm thick polyethylene film. To maintain the durability of structural frame of plastic greenhouse and prevent pad side effects of wind load on the polyethylene cover, eighteen tensile compacted plastic wires (2 mm diameter) are tied and fixed throughout the arch and vertical walls in the two longitudinal sides.

2. Solar collector area and arrangement

The first greenhouse was equipped with both; solar heating system (6 solar collectors have a net surface area of 12 m^2 with an auxiliary heater using electrical heater, and a pipe-distribution system) and cooling devices (lateral aeration and, in hot conditions, evaporative cooling by fan-pad system). Solar collectors mounted on a fixed frame adjusted with a tilt angle of 42º from the horizontal and orientated toward the equator, so that at noontime the angle of incidence of the surface of the collectors and the sun's rays was set at zero. The operating fluid (water) flow rate was adjusted and controlled using a control valve. Due to the solar collectors were stationary non-tracking the sun's rays, one water flow rate (15 litres/min.) was functioned during the heating period depending upon the intensity of solar radiation flux incident on the solar collectors. The solar collectors have been operating satisfactorily for six months without malfunction, except for a small leaking in a pipe connection between the collectors and water pump. The second greenhouse used as a control one during the experimental work. The microclimate factors inside and outside the two greenhouses were measured and recorded.

The thermal performance analysis of the solar collectors was experimentally determined, by measuring the temperature increase at various water inlet temperatures, mass flow rate, and solar energy available under clear sky conditions. Using this data the solar collector area and configuration were calculated so that the water temperature at the end of day reached to over 60ºC when the solar radiation was a maximum. Under steady-state conditions, the overall thermal efficiency (η_o) can be measured and determined using the system analysis of Duffie and Beckman (1991) ; Kalogirou (2004) ; and ASHREA (2005) as follows:

$$\eta_o = \frac{F_R\ A_c\ [R\ (\tau\ \alpha) - U_o\ (T_{fi} - T_a)]}{R\ A_c} \times 100\ ,\ \% \qquad (1)$$

Where, F_R, A_c, R, ($\tau\ \alpha$), U_o, T_{fi}, and T_a , respectively, are the heat removal factor, collectors surface area (m^2) , solar radiation on a tilted surface (W/m^2), optical efficiency, overall heat transfer coefficient (W/m^2. ºK), inlet water temperature (ºK) and ambient air temperature (ºK),. The normalized temperature rise (D_T) of the solar collector was computed from the following relation:-

$$D_T = \frac{T_{fi} - T_a}{R}\ , \qquad °K\ m^2/W \qquad (2)$$

3. Overall design and installation

The site of solar collectors was protected from the prevailing north-westerly winds by the greenhouse, but was not shaded from the sun. The storage tank (750 litres) was equipped with two supplementary electric heaters (each 3 kWh). The auxiliary heaters were used when the stored solar energy was insufficient to provide the requirements of the heat energy supply. To provide and maintain positively a temperature of 16-18°C at nighttime during cold winter months, the greenhouse was equipped with a pipe heat exchanger using parallel flow system in order to utilize the stored energy from the storage tank for heating the indoor air of the greenhouse (Fig. 1). The pipe heat exchanger was located on an iron stand to be above the floor surface by 30 cm (the coldest zone inside the greenhouse). The heated water from the insulated storage tank (heated by solar energy during the daylight) was pumped to be circulated through the heat exchanger. It was controlled by on-off controller to initiate heating at 16°C and interrupt it at 18°C (environmental control board with differential thermostat).

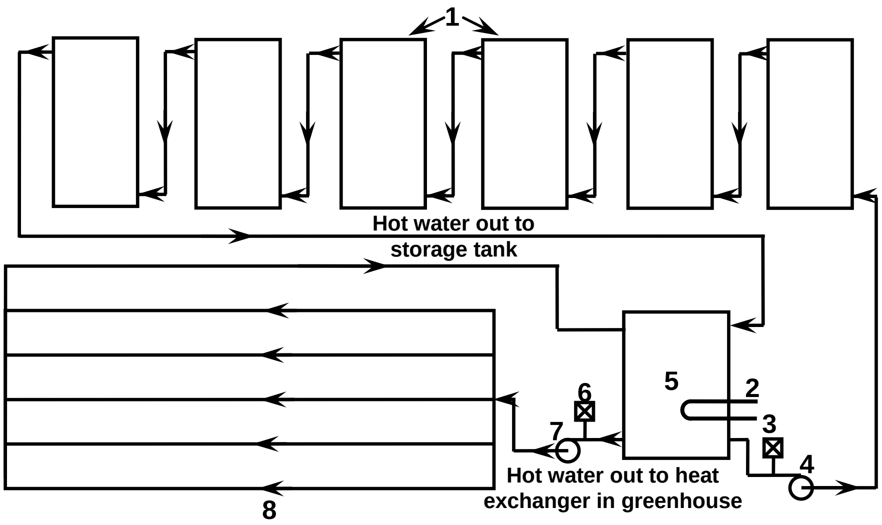

Fig. (1): Schematic diagram of solar heating system included; (1) solar collectors, (2) auxiliary electrical heater, (3) water flow control, (4) water pump for solar collectors, (5) storage tank, (6) flow control, (7) water pump for heating, and (8) heat exchanger.

5. Cultivation and Watering systems

During this experimental work, the two greenhouses were transplanted by seedlings of sweet coloured pepper crop (Marqueza, and Tirza, cv., produced by Enza Zaden company, Netherlands) on 10th of September 2010 after six weeks of sowing. The floor surface area inside the greenhouse divided into 6 wide beds (90 cm from furrow to furrow), 20 cm high, and 50 cm wide space. Before transplanting of sweet pepper seedlings, the upper surface of each bed covered with Compost, Phosphoric, Magnesium and Potassium rocks on 8th of September 2010. Ninety drippers (long-bath GR 4 liter/hr discharge) were uniformly alternative distributed with 50 cm dripper spacing throughout each row of plants inside the two greenhouses. The sweet coloured pepper fruits harvested every week over seven months (December to June) with full maturation colour and higher quality.

4. Measurements and data acquisition unit

The solar radiation, air temperature, air relative humidity, and wind speed and direction were measured outside the greenhouse using meteorological station, which installed just beside the solar collectors and greenhouse. Microclimatic conditions inside the two greenhouses were also measured and recorded. Disk solarimeters installed above the top canopy of plants in order to measure the intensity of solar radiation flux incident. A 12 channel data-logger was also used for taking and storing reading from the different sensors (thermocouples type K) situated at different location of the greenhouse and the storage tank. The recorded data were stored in the memory for output to a printer or to a computer for storage on disk. The time interval for data recording was 5 min with data acquisition every 5 second for integrated measurements. The calibration of all sensors and the logger was completed successfully at the beginning of the experimental work.

5. Prediction of air temperature

To predict the air temperature gradients inside the greenhouse, a simple model developed, which incorporates the effect of heat distributing system at nighttime and the ventilation rate during daylight. The control algorithm, developed by **Spanomitsios (2001)** for the computation of the desired indoor air temperature (**T_d**) inside a greenhouse cultivated with sweet coloured pepper had the following form:

$$T_d = \bar{T}_{g,day} + A \sin\left[\frac{\pi}{720}\,(t - t_p)\right] \qquad (3)$$

Where, $\bar{T}_{g,day}$, is the set daily mean temperature, A, is the amplitude of the sine wave, t, is the elapsed time in minutes since midnight, and, t_p, is the phase of sine wave in minutes. In order to calibrate the developed model, measurements for five successive days each month performed in a commercial greenhouse equipped with heat distributing system (supplied by hot water heated by solar collectors) and cooling system using extracting fans and cooling pads. As a result the model was modified as follows:

$$T_a = T_{md} + A_1 \sin\left[\frac{\pi}{L_{dl}}\,(t - t_{sunrise} - t_p)\right] \qquad (4)$$

Where, T_{md}, is the daily mean desired air temperature (equal to 24ºC), A_1, is the amplitude of the sine wave, when the solar radiation flux incident inside the greenhouse does not exceed the value of 300 W/m^2, and is equal to the minimum difference between the night temperature (18ºC) and the desired midday temperature (desired daily temperature equals to 24ºC), L_{dl}, is the real period daylight from sunrise to sunset (in minutes) it can be computed astronomically by the following equation:

$$L_{dl} = 60\ (t_d) \qquad (5)$$

$$t_d = \left[\frac{2}{15}\cos^{-1}(-\tan\phi\ \tan\delta)\right] \qquad (6)$$

t, is the elapsed time in minutes since midnight, $t_{sunrise}$, is the elapsed time in minutes from midnight to sunrise, it can be determined as follows:

$$t_{sunrise} = 60\left[6 + \frac{1}{15}\sin^{-1}(-\tan\phi\ \tan\delta)\right] \qquad (7)$$

t_p, is the phase of the sine wave in minutes chosen with a value of 90 to give the maximum temperature at 13.00 local time during winter months and at 14.00 local time during summer months.

RESULTS AND DISCUSSION

1. Thermal performance

The solar collectors have been operating satisfactorily for six months without malfunction, except for a small leaking in a pipe connection between the collectors and water pump. Water temperatures have been monitored for six months beginning in November 2010, and the monthly average solar energy contribution is shown in Fig. (2). During the heating period six months), there were 2000 hours of bright sunshine of which 1447 hours (72.35%) were recorded and utilized in the thermal performance analysis and heating the greenhouse, slightly lower than average due to clouds. The discrepancies between months arise due to number of bright sunshine hours, solar altitude angles, water temperature in the storage tank at the beginning of each day, and number of operating hours.

The thermal performance analysis of the solar collectors is mainly determined by its overall thermal efficiency in converting solar energy into stored heat energy. The solar radiation flux incident on the horizontal and the tilted surfaces during the heating period were varied from hour to hour, day to another, and during the experimental period due to the sky conditions, solar altitude angle, and solar incident angle as shown in Fig. (3).

The relationship between the solar energy collected per day (49.752 kWh) and the available solar radiation (73.495 kWh) was correlated very well (91.03%), except that the solar collectors appear to be more efficient during the last three months (69.83%) than the first three months (64.85%). This due to the available solar radiation during the last three months (83.994 kWh) was higher than that during the first three months (62.995 kWh). The overall thermal efficiency is the ratio of the solar energy collected by the solar collectors to the solar energy available. The daily average overall thermal efficiency of the solar collectors during the experimental period was 67.51%, consequently, 32.49% of the solar energy available was lost.

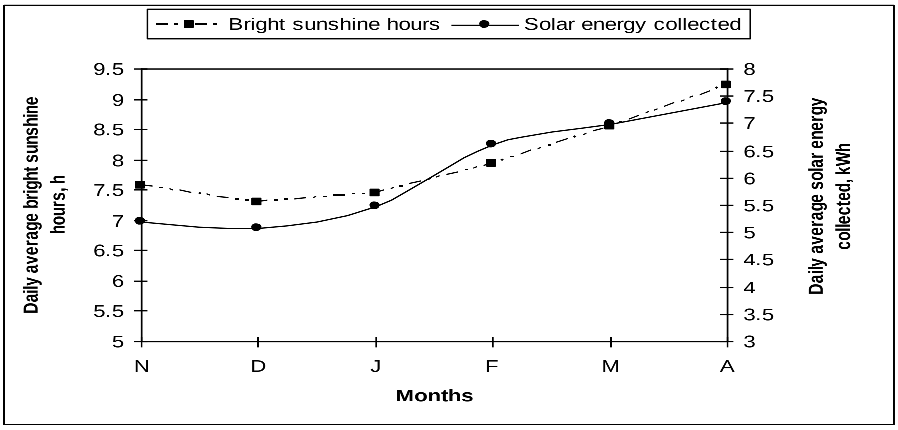

Fig. (2): Daily average solar energy collected by solar collectors and daily average sunshine hours during the experimental period.

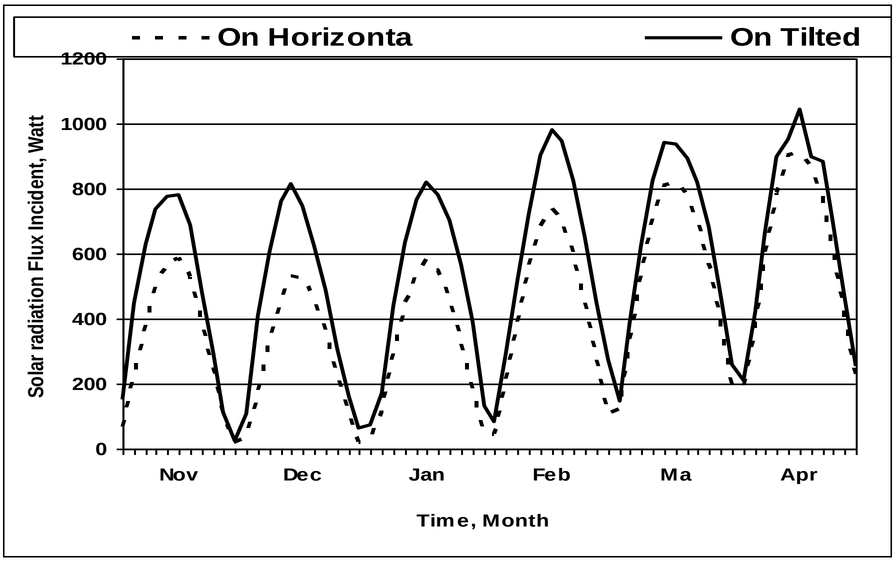

Fig. (3): Fluctuation of solar radiation flux incident on horizontal and tilted surfaces of solar collectors during the heating period

2. Heat energy providing

During the 181 day heating season, the solar collectors collected useful heat energy to storage about 6 828 kWh. The daily average heat energy provided by the solar collectors during this period is given in Table (1), where it is compared with total heat energy requirements for providing and maintaining optimal level of indoor air temperature. During the heating period the useful solar energy collected was 49.752 kWh of which 37.725 kWh was stored in the storage tank and consumed during the heating period of the greenhouse. It was provided 66.61% of the daily total heat energy required (56.640 kWh).

Table (1): Daily average total heat energy normally required (kWh) during heating season (181 days).

Energy	**Heat energy, kWh per day**	**Providing of total, %**
Greenhouse 1		
Solar energy		
Total useful heat energy collected	49.752	-
Total heat energy stored in the storage tank	37.725	66.61
Electrical energy		
Total electrical energy for water pump operation (1)	2.250	3.97
Total electrical energy for water pump operation (2)	5.980	10.56
Total electrical energy used by electrical heater	10.685	18.86
Total energy actually used by greenhouse 1	**56.640**	**100.00**

During the heating season the storage tank in the greenhouse was taken 10.685 kWh per night as supplementary heat energy from the electrical heater. Therefore, the solar energy system with the greenhouse provided 37.725 kWh (66.61%) of the daily total heat energy required (56.640 kWh). The potential savings from solar power was not fully realized for three main reasons: Firstly, little solar energy was collected in the first two hours after sunrise and the last before sunset due to low solar altitude angle and water temperature in the storage tank. As the heat energy stored in the storage tank was not continually consumed at night times, therefore at the beginning of some days more than two hours of sunshine were lost. Secondly, the solar collectors (six solar water heaters) were not orientated and tilted to track the sun's rays from sunrise to sunset (stationary non-tracking). They were tilted with an angle of 42º and orientated to the equator (south direction). Therefore, the solar energy collected by this array system was lower than that collected by the tracking system if it used. About 30% increasing in heat energy collected can be achieved in this way (Duffie and Beckman, 1991). Thirdly, during the coldest month (January) the outdoor air temperature at night times lowered to 7.5ºC for the majority of nights resulted in great amount of heat energy loss. As the heat energy supplied into the greenhouse reside in the task of adding heat at the rate at which it is lost, accordingly, there was 66.573 kWh of electrical energy was added into the water in the storage tank inside the greenhouse during this month. Therefore, a movable thermal curtain should horizontally be spread at a height of 2.25 m above the floor surface at nighttimes to reduce heat losses during this period. About 40% saving in heat energy supply can be achieved in this way. During the daylight, the thermal curtain can be withdrawn, but 4% light loss due to the rolled-up material is produced (Critten and Bailey, 2002). A movable baffle should also be used to close the outside surface area of the cooling pads at the end of daylight to minimize the heat losses due to infiltration of cold air. In spite of these heat energy losses solar power is providing a significant proportion of the total heat energy required for heating the greenhouse. In spite of these heat energy losses solar power is providing a significant proportion of the total heat energy required for heating the greenhouse.

3. Microclimatic conditions

3.1 Air Temperature

The air temperature inside the greenhouse was compared with the outside air temperature as an important measure of the effectiveness of heating system. The fluctuations of air temperature surrounding the crops play an important role for their growth rate, development, and productivity. Fluctuation changes in air temperature, caused by the on-off control board, were evidently observed inside the greenhouse one. The nightly averages air temperatures inside (G1) for November, December, January, February, March, and April, respectively, were 17.4, 17.0, 16.8, 17.1, 17.3, and 18.7ºC. While, the nightly average air temperatures inside (G2) during the same period were 13.4, 11.5, 9.8, 12.4, 16.4, and 17.8ºC, respectively. Meanwhile, the nightly averages outdoor air temperature of the greenhouses during the same period were 14.8, 12.0, 8.7, 11.1, 12.3ºC, and 17.4ºC, respectively.

During January month (coldest month), the highest air temperatures inside the two greenhouses (17.7ºC and 11.6ºC, respectively) recorded at 19.00h, just two hours after sunset. These air temperatures inside the greenhouse one gained from the heat energy stored in the floor and the structural frame during the daylight by solar energy available inside. The lowest air temperatures inside the two greenhouses (15.7ºC and 2.9ºC, respectively) also recorded during January month at 06.45 h just prior to sunrise. The low temperature, requirements of the most commonly cultivated horticultural crops (minimum air temperatures) for tomato, cucumber, and pepper, respectively, are 13, 15, and 15ºC as recommended by Kittas et al. (2003) and Nelson (2006). During the experimental period (six months) the heated greenhouse (G1) acquired an air temperature over the recommended minimum level by an average 2.4ºC, which provided the possibility of good productivity for a limited cost. While, the air temperature inside the unheated greenhouse (G2) was lower than the recommended minimum level by an average 1.4ºC. During winter periods with a series of few consecutive cold days, limited heating application delays crop growth. However, that delay is reversed during intermediate sunny days, when growth rate acceleration compensates for the previous unfavourable environmental conditions.

To compare between the predicted and measured data by fitting the actual indoor air temperatures with that obtained from the modified model, all the obtained data used in the regression analysis. The comparison between predicted and measured values throughout the days recorded each month (five days) during the experimental period then performed and plotted in Fig. (4) and Fig. (5). These comparisons were satisfactory where the average coefficient of determination during the first four months and the last two months, respectively, were 0.95 and 0.89 (R^2 = 0.95 and 0.89) as shown by the proximity of dots with and around the bissextile line. Having obtained a good agreement between measured and predicted indoor air temperature values during daylight and at nighttime, the modified model can use to study the influence of different ventilations rates and heating cycles on the air temperature regime inside the greenhouse for different outdoor climate conditions (air temperature, intensity of solar radiation, and wind speed). The modified model is therefore, accurate to improve the design and management of the cooling and heating systems.

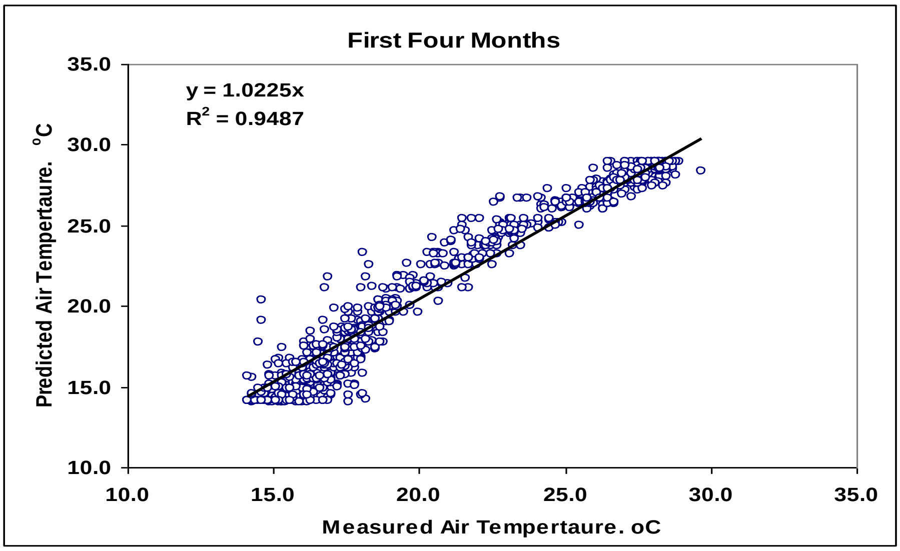

Fig. (4): Predicted and measured values for the indoor air temperatures during the first four months (November to February) R^2 coefficient of determination.

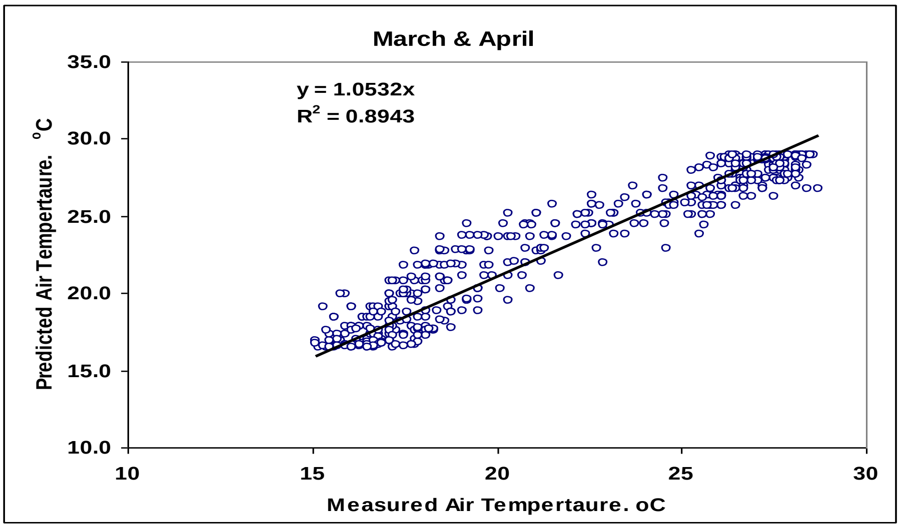

Fig. (5): Predicted and measured values for the indoor air temperatures during the last two months (March and April) R^2 coefficient of determination.

3.2 Air Relative Humidity

Most protected cropping grows best within a restricted range of air relative humidity, typically 60% to 80% for many varieties (Öztürk and Başçetinçelik, 2003). High air relative humidity is the response of pathogenic organisms. Most pathogenic spores cannot germinate at air relative humidity below 85%. Low air relative 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. Normal plant growth inside the greenhouse generally occurs at air relative humidity ranged from 50 to 80% (Hanan, 1998). The nightly average air relative humidity inside the two greenhouses (G1 and G2) during the experimental period was 72.4% and 91.0%, respectively. Whilst, the nightly average relative humidity of the outside air was 60.6% during the experimental period. This means that at nighttime, the air relative humidity inside the two greenhouses was greater than that of the outside by about 11.8% and 30.4%, respectively. Accordingly, the air relative humidity inside the greenhouse two was higher than that of the greenhouse one by about 18.6%. This variation may attribute to the effectiveness of the solar heating system using for heating up the indoor air inside the greenhouse one and the greenhouse two is not heated.

Cyclic changes also observed in the air relative humidity, and the humidity ratio, which measured inside the two greenhouses. The cyclic variation in air relative humidity occurred at the peak of the heating cycle in the greenhouse one. Thus, the air relative humidity inside the greenhouse one (G1) decreased by 8.1% at the peak of each heating cycle, whereas at the end of the cooling down it increased by 7.3 %. The air relative humidity inside the greenhouse one increased every night at the end of the heating period (just before the sunrise time) due to the heat energy supplied during that time was insufficient to absorb more moisture from the indoor air. Air relative humidity inside the greenhouse one during the experimental period was at and around the optimal level (68%) as recommended by (Hanan, 1998). Whilst, the air relative humidity inside the greenhouse two (84.2%) was higher than the optimal level particularly at nighttime. Furthermore, stable microclimate conditions (air temperature and relative humidity) could reduce greenhouse heat losses and meet the physiological requirements for growth, development, and fresh yield of the planted crop. Since leaf temperature, air temperature, air relative humidity and dew-point temperature are very important parameters, affecting growth rate, fresh yield and quality, these parameters in each greenhouse measured during the five successive nights every month.

Cyclic changes in both the leaves and the air temperatures, with a peak-to-peak difference of 0.5 – 1.8ºC, were observed during those particular nights. At 02:30 h the indoor air temperature of the greenhouse one dropped to a level at which only continuous operation of the heating system could balance the heat losses from the greenhouse, and from that time the leaves and air temperatures were approximately constant with respect to time. Linear changes in the leaf temperature that were correlated very well with the changes in air temperature were also observed with the greenhouse two due to this greenhouse was unheated at nighttime. The nightly averages indoor air, leaves, and dew-point temperatures inside the greenhouse one during the heating period, respectively, were 17.4ºC, 19.3ºC, and 12.1ºC, whereas, these averages inside the greenhouse two were 13.6ºC, 15.3ºC, and 11.8ºC, respectively.

Higher vapour pressure deficit means that, the air surrounding the plant has a higher capacity to hold water, stimulating water vapour transfer (transpiration) into the air in this low air relative humidity conditions. Lower vapour pressure deficit, on the other hand, means the air surrounding the plant is at or near saturation, so the air cannot accept moisture from the leaf in this high air relative humidity condition. The nightly average water vapour pressure deficit (VPD) during the experimental period was 0.58 kPa. When the air vapour pressure deficit is too low (VPD < 0.43 kPa) at air relative humidity too high (RH >85%) and air temperature very low (Ta < 15 °C), the water may condense out of the air onto leaves, fruits, and other plant parts. This can provide a medium for fungal growth and disease.

The VPD of the air surrounding the sweet coloured pepper plants decreased gradually with time from 0.74 kPa (G1) and 0.47 kPa (G2) at 17.00h until they reached the minimum values (0.60 and 0.10 kPa) at 6.30h, as the indoor air temperature decreased, and the air relative humidity was increased. They then increased until approached the maximum values (1.96 kPa and 1.90 kPa, respectively) just at and around noon. The VPD inside the two greenhouses (G1 and G2) showed the same trend during the experimental period. They varied from hour to hour, day to another, and during the experimental period, owing to the indoor air temperature, and air relative humidity. The daily average VPD of the air surrounding the plants in the two greenhouses, respectively, was 0.86 and 0.52 kPa. In the greenhouse two the VPD at nighttime was at low levels allowed the plants to be unable to evaporate enough water to enable the transport of minerals (such as calcium) to growing plant cells, even though the stomata may be fully open. Therefore, a VPD target threshold can be used to influence heating equipment used to increase the VPD by reducing the air relative humidity level. Where the vapour pressure deficit is extremely low, water may condense out of the indoor air onto leaves, fruit, and other plants. This can provide a medium for fungal growth and disease.

4. Sweet coloured pepper growth, development and productivity

Due to the air temperatures (17.4 and 13.6 ºC), relative humidity (64.1 and 82.0%), and vapour pressure deficit (0.86 and 0.52 kPa) within the two greenhouses were at or around the desired level particularly during the cold winter season (G1), the sweet coloured pepper plants were grown better than that for the greenhouse two. Therefore, the weekly averages increasing rate in number of leaves inside the two greenhouses, respectively, was 2.4 and 1.70 leaf/plant. As the number of leaves is increased, the green surface area is increased, and the biochemical reactions are thus increased making the photosynthesis process more active. The weekly averages stem length of sweet coloured pepper plants was 4.9 and 2.7cm. As the indoor air temperature reduces lower than 15°C, slower growth rate, shorter internodes, thinner xylem, and smaller rate of fruit set occurs. Due to these reasons discussed previously, the numbers of fruits being seated on the plants within the two greenhouses (G1 and G2) were on the average 9.43 and 4.27fruit/plant, respectively. Some of these seated fruits approximately 34% eliminated according to the breading policy (bio-agriculture system) of the sweet coloured pepper. Owing to all the previous reasons, the fresh yield of sweet coloured pepper varied from season to another. The fresh yield harvested from the greenhouse one during autumn, winter, and spring, respectively, was 560.264, 459.657, and 582.172 kg, and whereas, the fresh yield from the greenhouse two during the same period was 357.972, 229.523, and 115.154 kg, respectively as demonstrated in **Fig. (6)**. The total fresh yield of sweet coloured pepper crop harvested from the two greenhouses (G1 and G2) respectively, was 1602.093 and 702.649 kg. Consequently, the greenhouse one increased the fresh yield by 128.0% as compared with greenhouse two. Good quality of sweet coloured pepper was obtained from greenhouse one, which associated with the number of seeds in each fruit (225 seed/fruit)**.** Whereas, the quality of fresh fruits from greenhouse two was adversely affected by 'shrink crack' in the skin

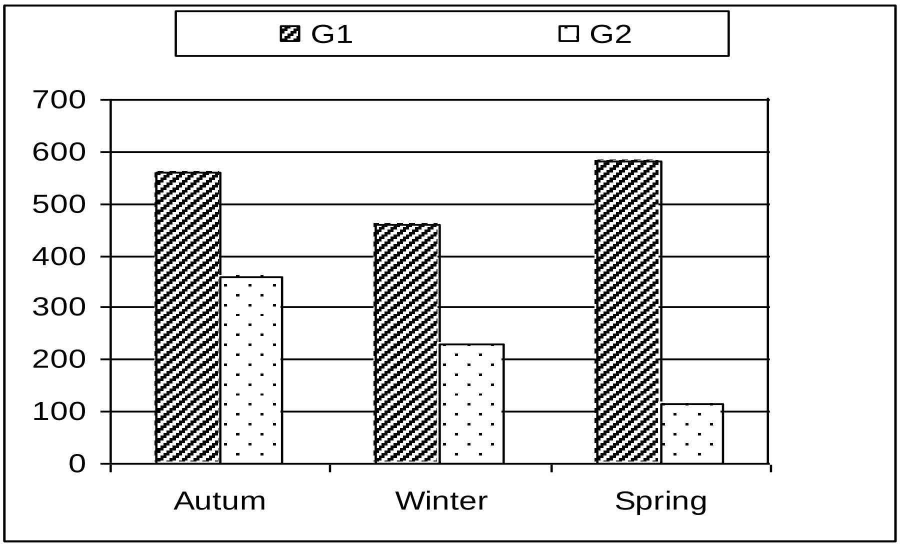

Fig. (6): Fresh yield of sweet coloured pepper harvested from the two greenhouses during autumn, winter, and spring.

5. Economic considerations

The total annual costs included the three different items (greenhouse construction, solar heating system, and operating costs) for the greenhouse one was about L.E. 10,288. However, the total costs per square meter of greenhouse were L.E. 35.722. The fresh yield of sweet coloured pepper per square meter was 5.563 kg/m^2, which sold by L.E. 55.63. Consequently, the estimated return on capital was 55.73% per annum. The total annual costs included the two different items (greenhouse construction and operating costs) for the greenhouse two was about L.E. 8,970. However, the total costs per square meter of greenhouse were L.E. 31.153. The fresh yield of sweet colour pepper per square meter was 2.440 kg/m^2, which sold by L.E. 19.52.

CONCLUSSION

The primary objectives of this solar heating system are to increase the solar radiation converted into stored thermal energy and to investigate effective uses of that stored energy for heating sweet coloured pepper greenhouse. A complete solar heating system has installed beside a commercial greenhouse at SEKEM Company. The system has operated satisfactorily for over six months.

The solar collectors, which are orientated and tilted with an optimum, tilt angle and orientation at noon will allow maximum values of both; the absorptance of the absorber surface and the transmittance of the glass cover to be reached at noon only. The overall thermal efficiency and heat losses are mainly affected by the water inlet temperature and ambient air temperature.

Over the period November 2010 to April 2011, the solar heating system collected about 6 828 kWh 3813 kWh (24.581 GJ) of solar power. During the heating period the useful solar energy collected was 49.752 kWh of which 37.725 kWh was stored in the storage tank and consumed during the heating period for the greenhouse one. It provided 66.61% of the power required by the greenhouse (56.640 kWh).

Due to the microclimatic circumstances within the adapted greenhouse were at or around the desired level during the daylight (27.6°C) and at night (17.4°C) particularly at the critical period (from 02.00 to 06.00h) during winter season, optimal vegetative growth rate, stem length, number of fruits being seated, and fresh yield were achieved. The nightly average vapour pressure deficit (0.86 kPa) was at the optimal level during the experimental period.

The economics of such a system remains marginal at present power prices in Egypt, although changes in power costs may drastically alter the situation.

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معدلات الزيادة والنقص فى درجة حرارة البيوت المحمية التجارية للفلفل الألوان الحلو والمزودة بنظام تسخين بالطاقة الشمسية ونظام تبريد بالتبخير

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يهدف هذا البحث إلى تقييم إستخدام المجمعات الشمسية فى تحويل الإشعاع الشمسى إلى طاقة حرارية قابلة للتخزين، وأيضاً دراسة تأثير إستخدام هذه الطاقة المخزنة لتدفئة بيت محمى تجارى للفلفل الألوان الحلو. تم وضع نظام تسخين شمسى للماء مكون من ٦ سخانات مثبت بجوار بيت محمى تجارى (٩ × ٣٢ م) فى شركة سيكم (بلبيس محافظة الشرقية).

تم تثبيت المجمعات الشمسية عند زاوية ميل واحدة مقدارها ٤٢° وتوجية المجمعات ناحية الجنوب الجغرافى. وجد أن الكفاءة الحرارية الكلية والفواقد الحرارية تتأثر بشكل رئيسى بدرجة حرارة دخول الماء ودرجة حرارة الهواء الخارجي.

خلال الفترة من نوفمبر ٢٠١٠ وحتى أبريل ٢٠١١ تم تجميع ٦٨٢٨ كيلووات.ساعة من الطاقة الشمسية (أى مايعادل ٢٤.٥٨١ جيجا جول) بواسطة نظام التسخين الشمسى. وخلال فترة التسخين (الستة أشهر) أضاف نظام التسخين الشمسى ٣٧.٧٢٥ كيلووات .ساعة فى اليوم بمتوسط ٦٧.٥١ % من متطلبات الطاقة الحرارية اللازمة للمحافظة على درجة حرارة هواء البيت المحمى التجارى عند أو حول المستوى الأمثل.

أدت الظروف المناخية داخل البيت المحمى المكيف والتى كانت عند أو حول المستوى المرغوب (درجات حرارة الهواء الداخلى ٢٧.٦°م نهاراً و ١٧.٤°م ليلاً) خاصةً عند الفترة الحرجة (من الساعة ٢ وحتى ٦ ص) أثناء موسم الشتاء إلى تحقيق معدل نمو خضرى أمثل وكذلك طول السلميات وعدد الثمار التى عقدت وجودة المحصول، كما كان متوسط النقص فى الضغط البخارى أثناء الليل ٠.٨٦ كيلوباسكال والتى تعتبر عند المستوى الأمثل خلال فترة الليل. هذا وتظل إقتصاديات هذا النظام متماشية مع أسعار الطاقة الحالية فى مصر على الرغم من أن التغير فى تكاليف الطاقة يمكن أن يبدل الموقف بشدة.

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