HEAT ENERGY SUPPLIED AND TRANSFERRED TO THE GREENHOUSES MICROCLIMATE USING SOLAR HEATING SYSTEM

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Abstract

Three identical gable-even-span greenhouses were designed, constructed, and utilized to grow and produce hot pepper crops during winter season of 2005. Each one was equipped with complete solar heating systems (solar water heater, storage tank, and heat distributing system). Three similar heat distributing systems (using parallel flow) were designed, constructed and situated inside the greenhouses to utilize the stored energy from the storage tank for heating ambient air inside the greenhouses. The greenhouses were covered using three different glazing materials, corrugated fiberglass reinforced plastic, flat fiberglass reinforced plastic, and double layer of polyethylene. Each greenhouse was provided with 75 pots as a cultivation system for protected cropping, drip irrigation system for watering pots of crop (hot pepper), and microclimate control board. A microclimate computer based data-logger system was employed to read, display, and record (from sensors) various temperatures, solar radiation, air relative humidity, and wind speed. The obtained data showed that, the radiation heat transfer between the heating systems and the crop ensured that, the leaves in the lower part of the crop, particularly those facing the pipes, were commonly warmer than the ambient air, and those in the upper part colder than the ambient air, during heat up. The temperature of the crop leaves during heating process should be higher than the dew point temperature, in order to prevent condensation and thus reduce the risk of fungal diseases. The obtained results also revealed that, the solar energy system provided the following proportions of the total energy consumed in February, March, April, and May, respectively 67.51%, 69.02%, 75.59%, and 80.98%.

INTRODUCTION

The requirements for heating a greenhouse reside in the task of adding heat at the rate at which it is lost. Heat loss is proportional to the surface area of the greenhouse structure. Factors that influence the temperature and relative humidity of greenhouse air are: solar heat gain, furnace heat, heat from equipment, plant respiration, photosynthesis, evapotranspiration, thermal radiation exchange between the greenhouse and its surroundings, conduction through the greenhouse floor, conduction through the greenhouse structural cover, ventilation, infiltration-exfiltration through building cracks, and condensation (Aldrich and Bartok, 1990, and Nelson, 1996). The utilization of warm water, heated by any source for heating a greenhouse is becoming increasingly popular because the water is a low cost source of heat. Rising fuel prices are having a significant effect on heating process of the greenhouse and consequently further development of the greenhouse industry. This has directed research efforts along two paths: (a) improving the greenhouse structure to reduce energy losses, while maintaining a desirable growth environment, and (b) developing alternate energy sources such as solar, wind, reject heat from power plants, geothermal energy, and any other sources to meet greenhouse heating demand (Nelson, 1996).

The solar collector which had a capacity of 93, 105, and 128 kWh of daily solar energy in January, February, and March, respectively, from an area of 40 m^2 was used for heating a greenhouse. The efficiency of the system ranged from 44 to 64 %. Four tons of water (the optimum amount) stored in the tank could be heated from 13 – 19 ^{o}C to 33 – 40 ^{o}C in January and February and to 41 – 46 ^{o}C during March when using this system. The stored solar energy was used to heat a greenhouse, only 45.7% could be effectively used for heating, the remaining 54.3% being lost. It was more than sufficient for heating in December and March, but provided less than the total heat requirement in January and February. The estimated fuel saving using solar energy was 62% at 8 ^{o}C and about 50% at 12 ^{o}C during the winter months (Suganuma *et al.*, 1984,Hepbasli and Ozgener, 2004, and Kalogirous,2004).

Five years of horticultural experimentations in greenhouse heated by low energy water supplies (25 – 30 ^{o}C) were carried out by Monocousin *et al.* (1991). They proved that, it is possible to heat a well designed greenhouse using water at 25 – 30 ^{o}C and suitable heat exchangers. They also found that, use of thermal screen reduced heating requirements by 40% without affecting plant growth. Heating systems installed on or in the ground gave a 15 – 20% reduction in heating requirement as compared with aero convector heating, whilst maintaining good quality of tomato and chrysanthemum crops.

The stored solar energy in the storage tank was used for heating the Nutrient Film Technique (NFT) solution for growing tomato crop inside the greenhouse by Abdellatif *et al.* (1992). The obtained results showed that, the total energy consumed (solar and electrical energy) in heating processes was 1200.2 kWh of which 971.7 kWh solar energy stored in the storage tank was used, consequently, 80.96% of the total energy was provided from solar energy systems. Heating NFT solution to maintain an optimum root media temperature of 18^{o} C enhanced the rate of absorption of nutrient elements which influenced the increasing tomato stem length, stem diameter, number of leaves, fruit-set and yield of tomato crop.

The possibility of utilizing solar energy systems for heating the interiors of gable-even-span greenhouse in Saudi Arabia was studied by Al-Amri (1996). A section of the southern inclined roof of an experimental greenhouse was employed as a solar water heater to supply hot water. The solar heating process at night was needed to maintain an optimum air temperature (18 °C). The heating system was enhanced the growth rate of tomato crop and increased the fresh yield production by 46.67%. The area of the solar water heater can be assessed according to the ground surface area of greenhouse, incoming solar radiation and the temperature difference between the inside and the outside of the greenhouse.

Li *et al.* (1998) investigated the use of solar energy to heat irrigation water in a solar greenhouse during winter months under Chinese climatic conditions. They found that, during late November to early February, the average outside temperature at 8 am was – 6.1 °C and the inside temperature was 7.5 °C, while at 14 and 20 hour outside temperatures were 3.9 and – 0.9 °C, respectively, and inside temperatures were 25.8 and 15.5 °C. Water temperatures at these times without heating were 7.9, 8.9, and 9.2 °C, respectively. Water temperatures with solar heating were 12.2 °C with cream pipes, 12.5 °C with black pipes, and 12.2 °C with half black pipes at 08.00 hour, 34.5, 39.1, and 40.0 °C, respectively, at 14.00 hour and 22.2, 23.2, and 22.2 °C at 20.00 hour.

A seasonal thermal energy storage using paraffin wax as a PCM with the latent heat storage technique was attempted by Ozturk (2004) to heat the greenhouse of 180 m^2 floor area.. During the experimental period, it was found that the average net energy and exergy efficiencies were 40.4% and 4.2%, respectively. The effect of the temperature difference of the heat transfer fluid at the inlet and outlet of the LHS unit on the computed values of the energy and exergy efficiency was evaluated during the charging period.

The main objective of the present research work was to utilize the stored solar energy in the storage tank to provide and maintain positively a temperature of 18 °C inside the greenhouses at night time during winter season of 2005 for hot pepper production. Also to compare whether three glazing materials (corrugated fiberglass reinforced plastic, flat fiberglass reinforced plastic, and polyethylene sheet) differed significantly in the heat energy supplied and transferred to the microclimate of greenhouses.

MATERIALS AND METHODS

Three identical gable-even-span greenhouses were designed and constructed in the workshop of the Department of Agricultural Engineering, Mansoura University and installed on roof of the Department 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 m^2. 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 three greenhouses (greenhouse 1,2 and 3) were covered using 800 μ thick flat fiberglass reinforced plastic, corrugated fiberglass reinforced plastic (FRP), and double layer of polyethylene sheet, respectively. The greenhouse facility used in this research work during winter season of 2004/2005 was covered with the ratio of cover surface area to the total greenhouse surface area of 2.685. To maximize the solar energy available inside the greenhouses, they were orientated in East-West direction, where the southern longitudinal direction faced into the sun's rays.

To provide and maintain positively a temperature of 18 °C at night time during winter months, such as is required for hot pepper production , each greenhouse was equipped with a complete solar heating system (solar water heater, storage tank, and heat distributing system). To utilize the stored energy from the storage tank for heating ambient air temperature inside the greenhouses, three similar heat exchangers using parallel flow system were constructed and installed inside the greenhouses as shown in Fig. (2). The heat distributing system mainly consisted of six parallel rows of water galvanized pipes (25.4 mm diameter) were placed at a horizontal distance of about 75 cm between successive pipes, to provide adequate area of heat transfer. The heat exchangers (heat distributing systems) were placed inside the greenhouses on an iron stand arranged in six rows to be above the floor surface by 35 cm (the coldest zone inside the greenhouse). The heated water from the insulated storage tank was pumped to circulate through the heat exchanger when the ambient air temperature inside the greenhouse is less than 16 °C using environmental control board (differential thermostat). It was switched OFF when the set point (reference value) reached 18 °C.

Reducing temperatures is one of the main problems facing greenhouse management in warm climates such as in Egypt. One of the most efficient ways to reduce the difference between the inside and outside air temperature is to improve ventilation system. Natural or passive ventilation system uses very little external energy as opposed to active or forced system, but it increases the complexity of greenhouse structures and makes climate control more difficult. Therefore, the mechanical ventilation system (suction fans) was employed during this research work. One suction fan (single speed, direct driven, 60 cm diameter, and 8000 m^3/h discharge) was located on the leeward side of each greenhouse and the cooling pads on the side toward the prevailing winds as demonstrated in Fig. (3). The cooling process by ventilation was mostly used when the ambient air temperature outside the greenhouse is lower than 20 °C, but when it is greater than 20 °C, the evaporative cooling system must be used. The evaporative cooling system was mainly consisted of cooling pads and suction fan. A cross-fluted cellulose pads 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 leakage of water from the 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.

For the duration of this research work, the pots system was employed as an agricultural system for protected cropping (hot pepper). Each greenhouse was equipped by 75 pots (30 cm high and 28 cm diameter). These pots contained a mixture of three different types of soil, clay soil (pasteurized at 105 oC for 20 minutes), pure yellow sand, and Irish peat moss with ratio of 1 : 1 : 1. In addition to this mixture, each pot taking half kilogram of compost as an organic substance.

Each Irish peat moss bag (volume of 0.3 m3 and weight of 60 kg) was treated and enriched by adding some chemical substances (75 g of Rizolex-T 50% as a disinfectant substance, 30 kg of vermiculite as an enriched material, 0.5 kg fertilizer 19-19-19 + TE, 150 g of super phosphate (single), 100 g of potassium sulphate, and 75 g of iron).

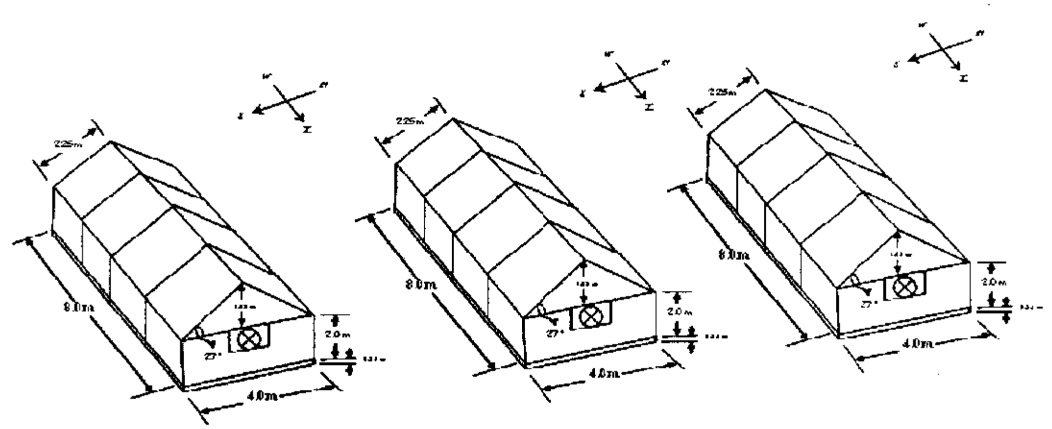

Fig. 1. Schematic diagram of gable-even-span greenhouses.

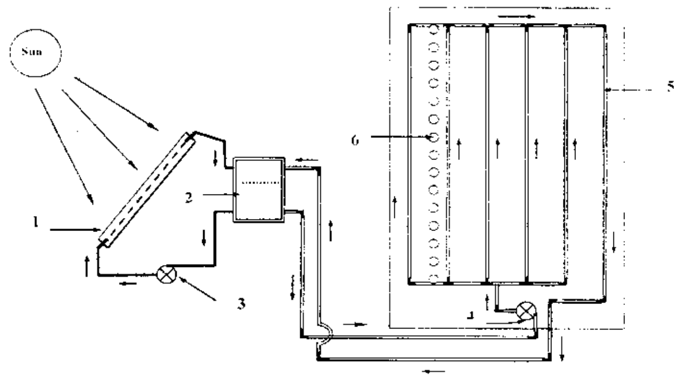

Fig. 2. Diagram showing the arrangement of solar energy system and heat distributing system (using parallel flow).

(1) Solar water heater. (2) Insulated storage tank.
(3), (4) Water pumps. (5) Heat distributing system.
(6) Hot pepper pot.

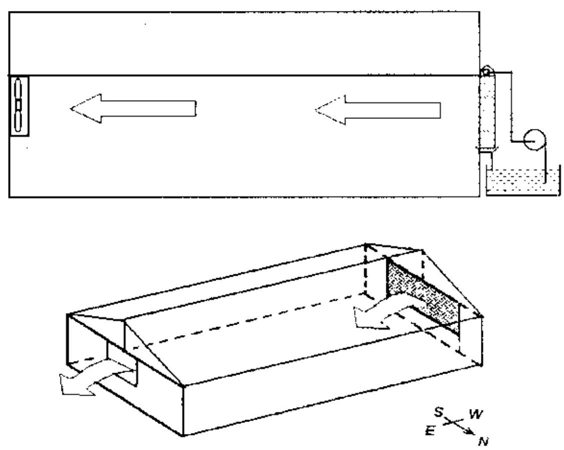

Fig. 3. Schematic diagram of ventilating and cooling systems (fan and pad system).

A correctly designed irrigation system will supply adequate amount of water needed each day of the year. This amount will depend upon the area to be watered, crop grown, weather conditions, time of the year, and whether a heating or ventilating system is operating. Drip irrigation system was employed and installed inside the greenhouses throughout this experimental work, for watering pots of hot pepper. 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 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. Fifteen drippers (14 mm diameter and 4 liter/hr discharge) were uniformly alternative distributed with 40 cm dripper spacing throughout each row of plants inside the greenhouses. Three hundreds and fifty hot pepper seeds (Hybrid, F1) were planted in the nursery on 25^{th} of December 2004. The hot pepper seedlings were raised in trays (each tray having 100 growth blocks) and vegetated out at the four leaves stage with a length on average of 4.8 cm. They were planted inside the greenhouses on 10^{th} of February 2005 in five single rows, each row having 15 plants.

The meteorological data from a meteorological station (WatchDog model 550) installed just above the greenhouses were used. This station measured solar radiation flux incident on a horizontal surface (pyranometer), dry-bulb air temperature (ventilated thermistor), wind speed and direction (cup anemometer and wind vane), and air relative humidity (hygrometer). These sensors were connected to a data-logger system in order to test, display, and record the data throughout the experimental work. The data were displayed on the video screen and updated by a scan of all the sensors every 1 minute. The means of 60 scans were recorded on hard-disk every hour using a data logging programme (SpecWare 6.02).

Sensors for internal microclimate variables within the centre of the greenhouses were installed at an altitude of 1.8 m above the ground surface. The internal microclimate variables included global solar radiation above the canopy of hot pepper (at a height of 2.0 m), dry-bulb air temperatures, air relative humidity, pipe temperatures of heat distributing systems (parallel and series flow systems), and ground surface temperatures. The amount of heat added to the greenhouses was deduced from the measurements of the water temperature at the inlet and outlet of the heat distributing systems and from the water flow rate measurements. 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 logger programme. A platinum thermometer (which is very accurate and is often used as the standard against which other sensors are calibrated) was employed to calibrate the thermocouples by measuring the water temperature in the storage tank and comparing this reading with the computer reading for the relevant thermocouples. The three solarimeters (pyranometers) were calibrated with a Kipp pyranometer (Kipp and Zohne, Australia) under clear sky conditions. The solarimeters were placed in the same horizontal plane as the Kipp pyranometer outside the greenhouse. The output data were recorded every ten minutes for about nine hours each day for two days.

The steady state energy balance was computed using a series of equations (Abdellatif and Lieth, 1992, Mavrogianopoulos *et al.,* 1993, Teitel *et al.,* 1996, and Teitel *et al .,* 1999), as follows

$$Q_{supply} - Q_{Loss} + Q_{gain} = 0 \quad (1)$$

$$Q_{supply} = Q_{Loss} - Q_{gain} \quad \text{, Watt} \quad (2)$$

$$Q_{Loss} = Q_{CL} + Q_{inf} \quad \text{, Watt} \quad (3)$$

$$Q_{CL} = U_o \ A_w \ (T_{ai} - T_{ao}) \quad \text{, Watt} \quad (4)$$

$$Q_{inf} = m_a \ Cp_a \ (T_{ai} - T_{ao}) \quad \text{, Watt} \quad (5)$$

$$Q_{gain} = Q_{conv.} + Q_{ra} \quad \text{, Watt} \quad (6)$$

$$Q_{conv.} = h_g \ A_g \ (T_{gi} - T_{ai}) \quad \text{, Watt} \quad (7)$$

$$Q_{rad} = \varepsilon_g \ A_g \ \sigma \left(T_{gi}^4 - T_{ai}^4\right) \quad \text{, Watt} \quad (8)$$

$$Q_{supply} = Q_{sup,st} + Q_{sup,un} \quad \text{, Watt} \quad (9)$$

$$Q_{sup,st} = m \ Cp_w \ (T_{in} - T_{out}) \quad \text{, Watt} \quad (10)$$

$$Q_{sup,un} = (m_w \ C_{pw} + m_p \ C_{pp}) \ [T_{av} - T_e] \quad \text{, Watt} \quad (11)$$

$$Q_{rad} = \varepsilon_p \ A_p \ \sigma \ (T_{cp}^4 - T_{ai}^4) \quad \text{, Watt} \quad (12)$$

$$Q_{Load} = Q_{supply} + Q_{gain} \quad \text{, Watt} \quad (13)$$

The effectiveness of the heat distributing system can be calculated as a function of inside air temperature (t_{ai}), outside air temperature (t_{ao}), and set point temperature (t_{op}) by the following formula :-

$$E_{ff} = \frac{T_{ai} - T_{ao}}{T_{op} - T_{ao}} \times 100 \quad \text{, \%} \quad (14)$$

Data were measured and stored in microcomputer files and statistically analyzed using Excel programme. Empirical equations for energy balance on the greenhouse at night time and predicting ambient air temperature inside the greenhouse were developed. All the previous equations were employed and listed in an arithmetic programme written in BASIC. One of the most useful applications of computer models of physical problems is simulation. Once a model is tested and found to be accurate, it can be used to predict results which could otherwise be obtained with extensive and costly experimentation.

Nomenclature

- A_g bare floor surface area , m^2.
- A_p total surface area of heating pipe , m^2.
- A_w surface area of walls, m^2
- Cp_a specific heat of air J/kg.°K
- C_{pp} specific heat of the pipe materials , J/kg.°K
- Cp_w specific heat of hot water, J/kg.°K
- E_{ff} heat distributing system effectiveness, %
- h_g convective heat transfer coefficient , W/m^2. °K.
- M greenhouse volume (87.68 m^3) X air exchange rate , m^3/s.
- m mass flow rate of hot water, kg/s
- m_a mass flow rate of cold air, kg/s
- m_p mass of pipes , kg
- m_w mass of water in pipe, kg
- $Q_{conv.}$ convective heat loss from the floor, Watt
- Q_{inf} rate of heat losses due to air infiltration, Watt.
- Q_{gain} rate of heat energy gain, Watt.
- Q_{Lc} rate of combination heat losses, Watt.
- Q_{Load} rate of total heat load added to the greenhouse, Watt
- Q_{Loss} rate of heat losses from the greenhouse, Watt.
- $Q_{ra.}$ Radiative rate of heat transfer from bare floor area, Watt
- $Q_{rad.}$ radiative heat rate of transfer fromheat distributing pipes, Watt
- Q_{supply} rate of heat energy supplying to the greenhouse, Watt.
- $Q_{sup,st}$ rate of heat energy supply from the heat distributing system, Watt.
- $Q_{sup,un}$ rate of heat energy supply during the cooling-down, Watt
- T_{ai} mean ambient air temperatures inside the greenhouse, °K.
- T_{ai} mean ambient air temperatures outside the greenhouse, °K.
- T_{av} average of inlet and outlet water temperatures at the beginning of cooling –dawn phase **(T_{av} =(T_{in} , T_{out})/2), °K.**
- T_e mean pipe and water temperatures at the end of cooling –dawn, °K
- T_{in} inlet water temperatures, °K
- T_{gi} temperature of bare floor area, °K.
- T_{op} optimum air temperature (set point), °K.
- T_{out} outlet water temperatures, °K
- U_o overall heat transfer coefficient, W/m^2/°K.
- ρ density of air , kg /m^3
- E_g emissivity of floor surface area, decimal
- E_p emissivity of pipes, decimal
- σ *Stefan –Boltzmann* constant, 5.67×10^{-8} W/m^2.K^4

RESULTS AND DISCUSSION

The total solar energy available was 1523.510 kWh of which 1022.987 kWh was stored in the storage tank of each solar energy system. The total electrical energy consumed for water heating (as a supplementary heating when the solar energy was insufficient) and solar panel pumps for greenhouses 1,2 and 3 was 368.218, 359.514 and 374.144 kWh, respectively. Consequently, 72.97%, 73.26%, and 73.59% of the total energy was provided by the solar energy system for the three greenhouses, respectively. The total and daily average solar energy stored, solar energy consumed, electrical energy consumed by pumps and heaters, total electrical energy consumed, total energy consumed for heating greenhouses, solar energy as a proportion of total energy consumed, and daily average outside ambient air temperature at night during this experiment for the three greenhouses are given in Table (1). The energy provided and consumed varied from one day to another and during each month due to the variation in distribution of solar energy available, energy required by the crop, and ambient air temperature outside the greenhouses. The main parameters which affect the proportions of energy consumed in the form of electrical and solar energy were, exterior ambient air temperature, amount of solar energy stored, solar panel surface area, and volume of water in the storage tank. The lowest amount of solar energy provided as a proportion of total energy consumed for greenhouses 1,2 and 3 was 67.09%, 67.61%, and 67.82%, respectively, in February. This proportion could be increased if the mass flow rate of water passing through the solar panel was increased, or the volume of water per unit area of greenhouse was increased. As the ambient air temperature outside the greenhouses is reduced below the optimal temperature (set point 18 °C) inside the greenhouse, more energy is consumed to maintain that temperature. Therefore the greenhouses 1,2 and 3 consumed the greatest amount of energy (453.340, 445.691, and 464.220 kWh) in March when the ambient air temperature at night was on the average 11.3 °C. The lowest amount of energy consumed for the three greenhouses was 181.232, 182.685, and 189.287 kWh, respectively, in May when the ambient air temperature was on the average 15.5 °C. Although the ambient air temperature in February was on the average lower than that in April, the electrical energy consumed in February was less than in April. This can be attributed to the vent sides (cold air inlet) which affected the heat losses from the greenhouses, when they left open at night in April and completely closed in February. The relationships between exterior and interior ambient air temperatures, and optimal ambient air temperature are shown in Fig.(4).

The effectiveness of heat distributing system was varied from time to time, from day to another, and during the experiment according to the water temperature in the storage tank of the solar panels and the temperature difference between the interior and exterior ambient air of the greenhouses. The effectiveness of the parallel system was 91.96%, 89.87%, 93.95%, and 97.01% for February, March, April, and May, respectively. As the water temperature in the storage tank is increased over the optimal temperature inside the greenhouse, more energy is supplied to the greenhouse making the system more efficient. As the temperature difference between the inside and outside ambient air of the greenhouse is increased, the rate of heat losses is increased and thus more energy is also supplied making the heat distributing system more efficient. The effectiveness of heat distributing system was plotted against heating time (from 20.0 to 7.0 hour) as shown in Fig. (5). Regression analysis revealed a highly significant linear relationship ($R = 0.974$, $P \leq 0.001$) between these parameters. The regression equations for the best fit were:

$$\mathbf{E_{ff} = 99.185 - 1.4333\ H_T}$$

Table 1. Total and daily average solar energy stored, solar energy consumed, electrical energy consumed by pumps and heaters, total electrical energy consumed, total heat energy consumed for heating greenhouse, solar energy as a proportion of total energy consumed, and daily average ambient air temperature at night during this experiment for greenhouses 1, 2 and 3.

Energy kWh	Greenhouse	Month				Total	Average
		February (19 days)	March (31 days)	April (30 days)	May (13days)		
Solar energy stored		184.927	334.668	350.401	152.991	1022.987	11.000
Solar energy consumed	G1 G2 G3	167.636 165.434 176.873	311.576 308.568 320.745	334.808 331.129 353.257	146.183 147.636 154.238	960.203 952.767 1005.113	10.325 10.245 10.808
Electrical energy consumed By pumps		51.225	83.578	80.882	35.049	250.734	2.696
Electrical energy consumed By heaters	G1 G2 G3	31.008 28.033 32.716	58.186 53.545 59.897	28.290 27.202 30.797	_ _ _	117.484 108.780 123.410	1.469 1.009 1.543
Total electrical energy consumed	G1 G2 G3	82.233 79.258 83.941	141.764 137.123 143.475	109.172 108.084 111.679	35.049 35.049 35.049	368.218 359.514 374.144	3.959 3.866 4.023
Total energy consumed by solar and electricity	G1 G2 G3	249.869 244.692 260.814	453.340 445.691 464.220	443.980 439.213 464.936	181.232 182.683 189.287	1328.421 1321.281 1379.257	14.284 14.111 14.831
Percentage of energy provided	G1 G2 G3	67.09 67.61 67.82	68.73 69.23 69.09	75.41 75.39 75.98	80.66 80.81 81.48	_ _ _	72.97 73.26 73.59
Daily average outside air temperature at night, °C		10.8	11.3	13.4	15.5	_	12.8

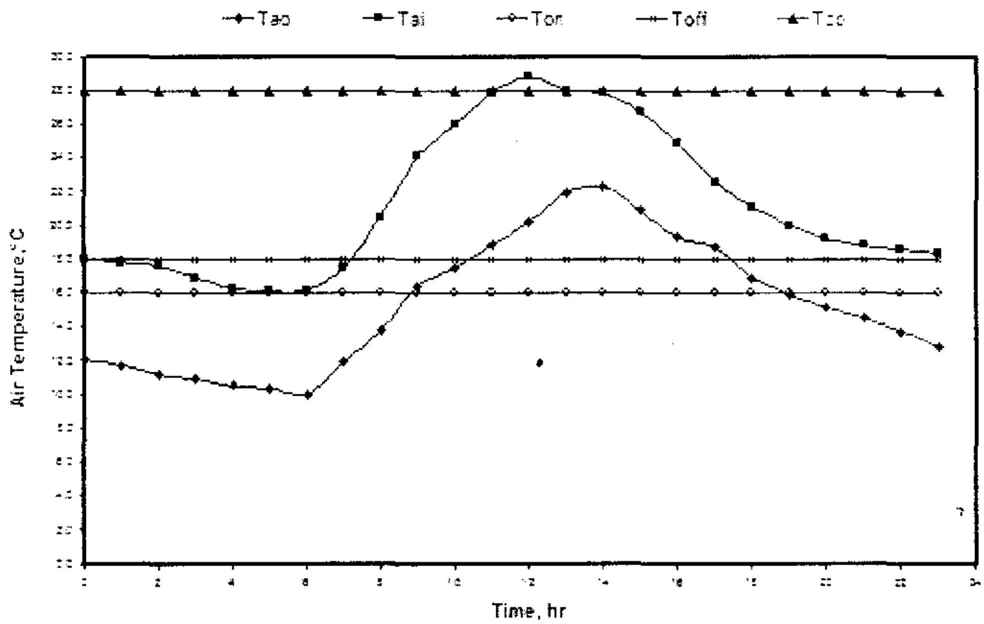

Fig. 4. Relationships between outside ambient air temperature (T_{ao}), inside ambient air temperature (T_{ai}), set point for switching ON (T_{on}), set point for switching OFF (T_{off}), and optimum ambient air temperature during daylight.

The hourly average total heat losses from the greenhouses (by convection, radiation, and infiltration), heat energy gained from the concrete floor, heat energy supplied from the heat distributing system, and total heat load required to provide the optimal temperature for the three greenhouses during this experiment are given in Table (2). It obviously reveals that, the total heat losses, heat energy supplied, and total heat load increased gradually with heating time from 20.0 hour until they reached maximum values at 6.0 am, because of the reduction in ambient air temperature outside the greenhouses. The heat load requirements which almost equivalent to the heat losses were varied from hour to hour according to the temperature difference between the interior (set point) and exterior (varied from time to time) ambient air of the greenhouses. The greatest values of heat losses for greenhouses 1,2 and 3 (5.182, 5.026, and 5.641 kW, respectively) occurred at 6.0 am when the hourly average ambient air temperature outside the greenhouse was 10.9 °C.

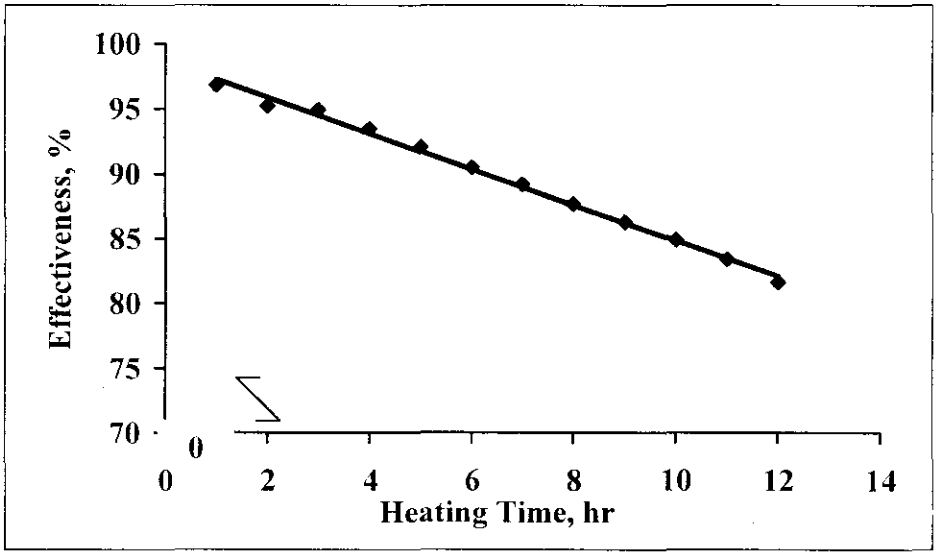

Fig. 5. Effectiveness of heat distributing system against heating time.

Table 2. Hourly average total heat losses (Q_{Loss}), heat energy gained (Q_{gain}), heat energy supplied (Q_{supp}), and total heat load (Q_{Load}) for the three greenhouses.

Time	Q_{loss}, kW			Q_{gain}, kW			Q_{supp}, kW			Q_{load}, kW		
	Greenhouse			Greenhouse			Greenhouse			Greenhouse		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
20	3.309	3.147	3.562	1.847	1.750	1.560	1.388	1.324	1.589	3.235	3.074	3.149
21	3.484	3.322	3.756	1.706	1.618	1.442	1.708	1.653	1.984	3.414	3.271	3.426
22	3.672	3.519	3.965	1.539	1.460	1.301	2.078	2.034	2.441	3.617	3.494	3.742
23	3.835	3.694	4.146	1.372	1.301	1.159	2.425	2.389	2.867	3.797	3.690	4.026
0	3.947	3.804	4.270	1.247	1.183	1.054	2.658	2.629	3.155	3.905	3.812	4.209
1	4.165	4.021	4.512	1.089	1.033	0.920	3.027	3.024	3.629	4.116	4.057	4.549
2	4.375	4.228	4.745	1.060	1.005	0.895	3.256	3.244	3.893	4.316	4.249	4.788
3	4.519	4.371	4.905	1.001	0.950	0.846	3.406	3.399	4.079	4.407	4.349	4.925
4	4.529	4.381	4.916	0.922	0.875	0.780	3.496	3.491	4.189	4.518	4.366	4.969
5	4.961	4.808	5.396	0.865	0.820	0.731	4.082	4.094	4.913	4.947	4.914	5.644
6	5.182	5.027	5.641	0.807	0.766	0.683	4.355	4.374	5.249	5.162	5.140	5.932
7	4.475	4.327	4.774	0.714	0.678	0.604	3.624	3.622	4.346	4.338	4.300	4.95
Average	4.204	4.054	4.549	1.181	1.120	0.998	2.959	2.940	3.528	4.148	4.060	4.526

Consequently, the greatest amounts of heat energy supplied for the three greenhouses (4.355, 4.374, and 5.249 kW, respectively) were added at the same time. While, the lowest values of heat losses from the three greenhouses (3.309, 3.147, and 3.562 kW, respectively) occurred at 20.0 hour (at the beginning of heating period) when the hourly average ambient air temperature outside the greenhouses was on the average 16.1 °C. This table also shows that, the greatest values of heat energy gained for the three greenhouses (1.847, 1.750, and 1.560 kW, respectively) were achieved at the beginning of heating time (at 20.0 hour) when the concrete floor surface temperature was 26.4 °C (due to solar energy absorbed during daylight). The heat energy gained from the concrete floor was gradually decreased as the surface temperature of the floor reduced. Therefore, the lowest heat energy gained from the concrete floor for the three greenhouses (0.714, 0.678, and 0.604 kW, respectively) occurred at the end of heating period (at 7.0 am). To assess and examine the best model which can be employed to correlate heat supplied (Q_{supp}), heat energy gained (Q_{gain}) and total heat losses (Q_{Loss}), all the obtained data over eight successive nights for greenhouse 1 (covered with flat fiberglass), greenhouse 2 (covered with corrugated fiberglass) and greenhouse 3 (covered with polyethylene) were used in regression analysis. Multiple regression analysis revealed a highly significant linear relationship ($P \leq 0.001$) between these parameters for the three greenhouses, respectively. The multiple regression equations for the best fit were:

$$Q_{supp}(G1) = -1.0117\, Q_{gain} + 0.9880\, Q_{Loss} \qquad R = 0.9990$$

$$Q_{supp}(G2) = -1.0782\, Q_{gain} + 1.0232\, Q_{Loss} \qquad R = 0.9991$$

$$Q_{supp}(G3) = -1.4957 Q_{gain} + 1.1037\, Q_{Loss} \qquad R = 0.9994$$

The above equations evidently indicate that, the suggested and expected models for predicting heat energy supplied to the greenhouses can be used with high confidence. The total heat load which added to the inside greenhouses (Q_{Load}) was plotted as a function of total heat losses (Fig. 6). Regression analysis revealed a highly significant linear relationship ($R^2 = 0.987$, $P \leq 0.001$) between these parameters for the three greenhouses, respectively. The linear regression equations for the best fit were:-

$$Q_{Load}(G1) = 0.9870\, Q_{Loss} \qquad R = 0.998$$

$$Q_{Load}(G2) = 1.0027\, Q_{Loss} \qquad R = 0.996$$

$$Q_{Load}(G3) = 1.0003\, Q_{Loss} \qquad R = 0.966$$

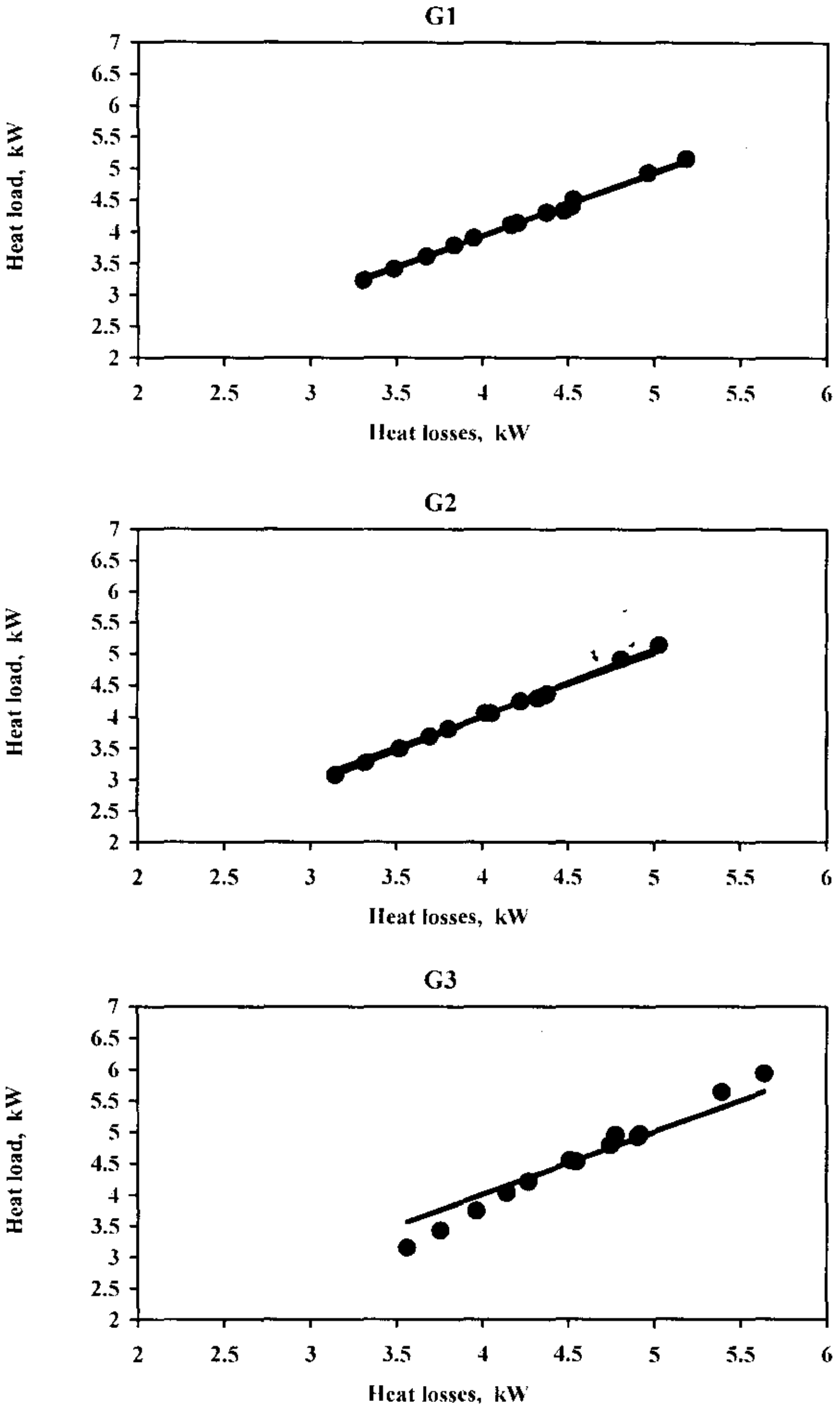

Fig. 6. Total heat energy load added to the greenhouse against total heat losses from the greenhouse for the three greenhouses.

As revealed in Table (2) the differences between the total heat load added to the greenhouses and the total heat losses for greenhouses 1, 2 and 3 were very small. The ambient air temperature gradients that develop along the greenhouses depend on many parameters. They depend upon the type of glazing materials and the mass flow rates of hot water in the pipes. The high flow rate of hot water in the pipes has to be sufficient with parallel flow system to avoid too much cooling of the water and thus to prevent undue variation of heat output along the pipes as compared with low flow rate. The air temperature gradients varied slightly with time, from one heating cycle to another. The variations with time, between any two successive points of measurement along the greenhouse, were found to be uniformly distributed. The radiation heat transfer between the heat distributing system and the crop ensured that, with pipe heating, the leaves in the lower part of the crop (where the pipes were installed), especially those facing the pipes, were generally warmer than the ambient air, and those in the upper part colder than the ambient air. This is in agreement with the data published by Teitel *et al.* (1999). The ambient air temperature at crop level was uniform throughout the greenhouse. The temperature of the leaves during heating period was higher than the dew point temperature which prevented condensation and thus reduced the risk of fungal diseases. It is imperative to predict the hourly average ambient air temperature inside the greenhouse at night according to the ambient air temperature outside the greenhouse. Because of, the obtained results show that, there was no significant difference between the three glazing materials in interior ambient air temperatures, the hourly averages air temperature of the three greenhouses were used in regression analysis (Fig.7). This analysis showed a highly significant linear relationship (R^2 = 0.999 , $P \leq 0.001$) between these parameters. The best fit equation relating the ambient air temperature inside the greenhouse (under specific conditions) to that outside was:-

$$T_{ai}\,(G1) = 10.787 + 0.629\,(T_{ao}) \qquad R = 0.999$$

$$T_{ai}\,(G2) = 11.793 + 0.522\,(T_{ao}) \qquad R = 0.999$$

$$T_{ai}\,(G3) = 9.792 + 0.652\,(T_{ao}) \qquad R = 1.000$$

Vertical changes in air temperature, caused by the ON-OFF control, were observed in the three greenhouses during this experiment. A temperature gradient developed along the centerline of each greenhouse and value varied with time during each heating cycle. With greenhouse using flat fiberglass reinforced plastic cover its value reached a maximum of about 1.5 to 2.2 °C over a vertical distance of 1.80 m at the peak of the heating cycle, while with greenhouses covered using corrugated fiberglass reinforced plastic and double layer of polyethylene the temperature gradients were 1.0 to 1.8 °C and 2 To 2.5 °C, respectively. At the end of cooling-down period of each heating cycle, the temperature difference of ambient air between the crop zone and the monitoring (over 1.8 m) decreased to about 0.8 °C,0.5 °C, and 1 °C in the three greenhouses, respectively. It occurred because the heat distributing system in the three greenhouses were placed in the lower region (35 cm over the floor surface). As the hot water stopped circulating, the temperatures in the upper and the lower regions become approximately equal since, on the one hand, the temperature of the pipes decreased and, on the other, warm air continued to rise, owing to thermal buoyancy effects.

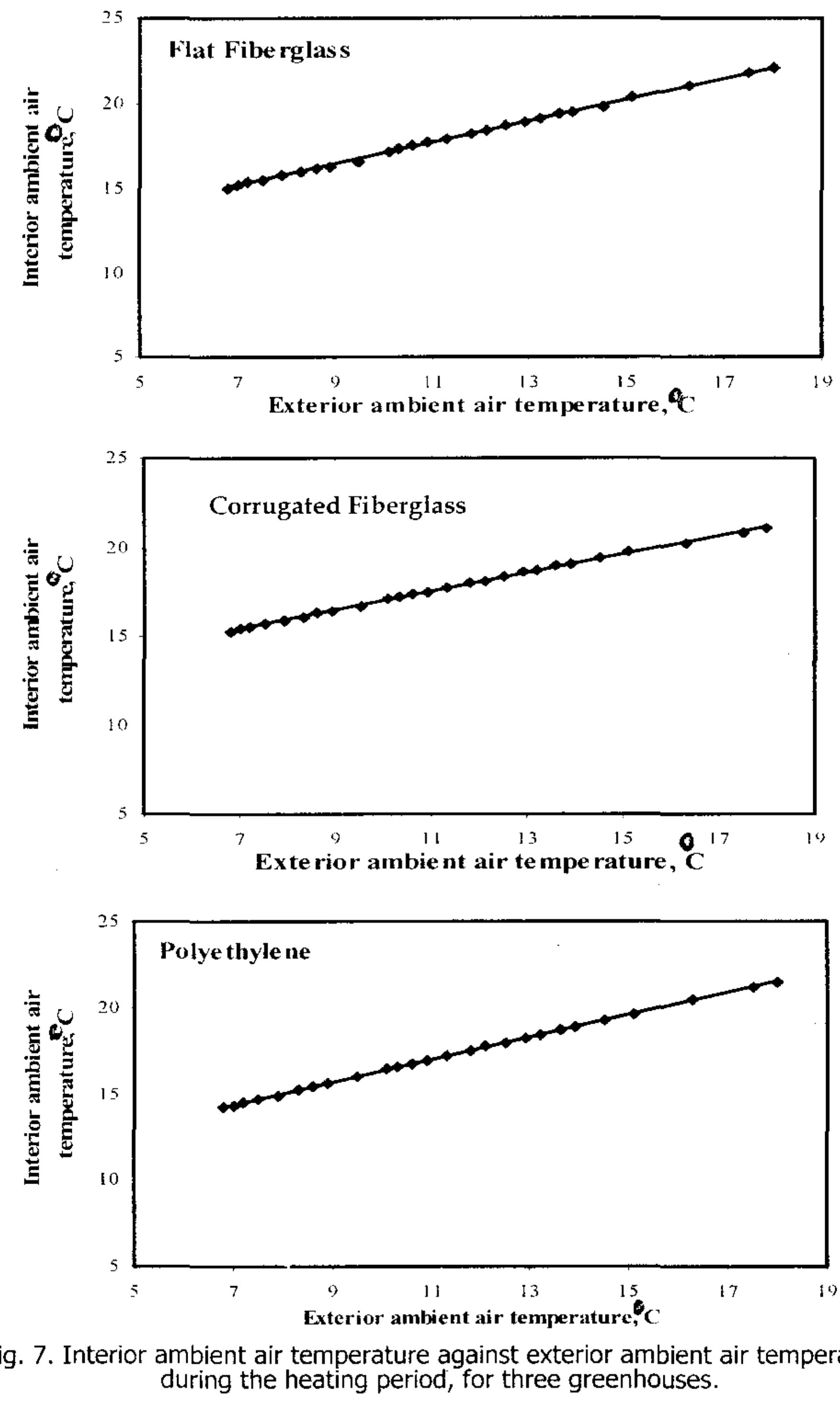

Fig. 7. Interior ambient air temperature against exterior ambient air temperature during the heating period, for three greenhouses.

For the duration of the experimental work, the weekly average leaves number of hot pepper plants for the three greenhouses 1,2 and 3 were 5.20, 5.90, and 4.90 leaf/week, respectively. These numbers of leaves were varied from row to row, from greenhouse to another, and during this experiment. The greatest number of leaves was mainly obtained from the southern rows (Row No.5) in the three greenhouses because they were more exposed to the solar radiation flux incident inside the greenhouse during daylight, and on the other hand, it faced the hot sky at night time. The number of leaves inside the greenhouse 2 was on average 13.46% and 20.41% more than that in greenhouse 1 and greenhouse 3, respectively, due to the effect of glazing materials. The difference in stem length of hot pepper crop varied with growing season from one row to another in each greenhouse according to the location of each row inside the greenhouse. The weekly average stem length of hot pepper crop for greenhouses 1, 2, and 3 was 2.93, 3.32, and 2.76 cm/week, respectively. Consequently, greenhouse 2 increased the growth rate of crop on average by 13.3% and 20.29%, as compared with greenhouses 1 and 3, respectively. Variations in stem length were achieved, caused by the glazing materials, and the location of row inside the greenhouse. The greatest stem length was achieved from the southern row in the three greenhouses due to the same reasons discussed previously. This achievement usually occurred throughout the experiment, because of the great number of leaves (the leaf being the main source of energy for process of photosynthesis and consequently the building up of carbohydrates). These differences may 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 interior microclimate (Nelson, 1996). As the green area of leaves is increased (due to increase the number of plant leaves), the biochemical processes are increased making the process of photosynthesis more efficient. Maximum reactions of metabolic process are mainly dependent upon the ambient air temperature surrounding the crop, and air relative humidity. The rate of vegetative growth was high and maintained the same throughout the growing season for the three greenhouses. Water vapour basically moves from one location to another because of vapour pressure difference, so air relative humidity affects transpiration from plant leaves by influencing the vapour pressure difference between the leaves and surrounding air. Normal vegetative growth of protected cropping is generally occurred at air relative humidity between 25 – 55% (Nelson, 1996). The ambient air temperatures inside the three adapted greenhouses were consequently at and around the optimal night temperature ($16\ ^{o}C < T_{ai} < 18\ ^{o}C$) particularly at the critical period (from 3 to 7 am) during winter season. As the ambient air temperature surrounding the crop is reduced lower than 15 ^{o}C, the percentage of flowerage and vitality of insemination seeds are decreased making the fruit set rate at minimum level. All biochemical reactions in all crops are mainly controlled by enzymes that are heat sensitive. Numerous biochemical reactions are involved in the processes of photosynthesis and respiration. These all have the net effect of building carbohydrates and storing energy. Photosynthesis occurs during the daylight hours because of its dependence on light. Another extensive set of biochemical reactions is involved in the overall process of respiration. The net effect here is a breakdown of carbohydrates and a release of energy. When photosynthesis exceeds respiration, net vegetative growth occurs. When they equal each other, net vegetative growth stops, and if respiration exceeds photosynthesis, the crop declines vigour and will eventually die. To insure that photosynthesis exceeds respiration, crops are grown cool at night (at 16 - 18 °C) to keep the respiration rate down and warmer by day to promote photosynthesis. (Nelson, 1996 and Teitel *et al.,* 1999). Due to the previous reasons, the number of fruits be seated on the crop for the three greenhouses on average were 35.68, 41.08, and 34.85 fruit/plant, respectively. Consequently greenhouse 2 increased the rate of fruit set on average by 15.13% and 17.88% as compared with greenhouses 1 and 3, respectively. Owing to all the previous reasons discussed above, the total fresh yield of hot pepper crop for greenhouses 1, 2, and 3 was 27.024, 32.193 and 26.501 kg, respectively. Consequently, greenhouse 2 was found to be on average 5.169 kg (19.13%) and 5.692 kg (21.15%) more productive than greenhouses 1 and 3, respectively . A statistical analysis showed that there was a highly significant difference between the greenhouses 1, 2, and 3 in the yield of hot pepper crop. Fig. (8) indicates the variation of fresh yield from different glazing materials for the three greenhouses. Ultimately, control and maintain the microclimate inside the greenhouse at desired level particularly at night during cold winter season affecting the fresh yield of hot pepper crop. These obtained data confirmed the finding by Yang *et al.* (1995), when they reported that, in all cases of heating greenhouses, more rapid growth and higher final yield were achieved than crops grown without heating the ambient air.

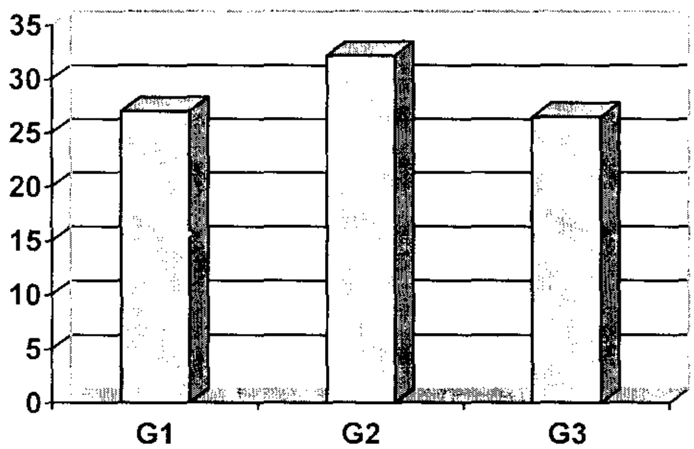

Fig. 8. Total fresh yield of hot pepper for the three greenhouses.

CONCLUSION

The specific conclusions of this experimental work can be summarized and listed as follows:-

1) Solar energy system provided 72.28, 72.60, and 72.87% of the total energy for greenhouse 1 (covered with flat fiberglass reinforced plastic), greenhouse

2 (covered with corrugated fiberglass reinforced plastic), and greenhouse 3 (covered by double layer of polyethylene), respectively.

2) The daily average effectiveness of the heat distributing system during the heating season was 93.20%
3) The total heat losses, heat energy supplied, and total heat load increased gradually with heating time from 20 hour until they reached maximum values at 6 am, because of the reduction in outside ambient air temperature of the greenhouses.
4) The greatest values of heat losses for the three greenhouses occurred at 6 am when the hourly average ambient air temperature outside the greenhouse was 10.9 °C. Consequently, the greatest amounts of heat energy supplied for the three greenhouses were added at the same time.
5) The lowest values of heat losses for the three greenhouses occurred at the beginning of heating period (at 20 hour) when the hourly average ambient air temperature outside the greenhouses was 16.1 °C.
6) The greatest values of heat energy gained for the three houses were achieved at the beginning of heating time when the concrete floor surface temperature on the average was 26.4 °C, due to solar energy absorbed during daylight. Thus, the heat energy gained from the concrete floor was gradually decreased as the surface temperature of the floor reduced.
7) The rate of vegetative growth was high and maintained the same throughout the growing season for the three greenhouses.
8) The number of fruits be seated on the crop for the three greenhouses on the average were 35.68, 41.08, and 34.85 fruit/plant, respectively.
9) The total fresh yield of hot pepper for greenhouses 1, 2, and 3 on the average was 27.024, 32.193, and 26.501 kg, respectively, due to control and maintain the microclimate inside the greenhouses at a desired level particularly at night during cold winter season.
10) The best cover can be used for protected cropping is the corrugated fiberglass reinforced plastic, due to its great thermal resistance.

ACKNOWLEDGEMENT

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إمـــداد ونقل الطاقة الحرارية للبيئة الداخلية للبيوت المحمية بإستخدام نظام الطاقة الشمسية

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يهدف هذا البحث الى إستغـــلال الطاقة الشمســـية في تهيئة البيئة الداخلية للبيوت المحميـــة عند المستوى المرغوب أثناء الليل في موسم الشتاء البارد وذلك من خلال تجميع وتخزين وإستغلال الطاقة الشمسية فى تدفئة البيوت المحمية والمحافظة على درجة الحرارة داخلها عند المستوى الأمثل لمحصول الفلفل الحار. تم تصميم و تشييد ثلاثة من البيوت المحمية من النوع الجمـــالونى المتـــزن الجوانب gable-even-span أبعاد كل بيت محمى ٨ × ٤ × ٣,٢٥ م . تم تجهيز كل بيـــت بعـــدد ٧٥ قصرية كنظام للزراعة فى قصارى (١٥ قصرية فى كل صف) تحتوى كل قصرية على خليط مـــن التربة الطنية والرملية والبيتموث بنسب متساوية. كما تم تجهيز كل بيت من البيوت المحمية بنظـــام رى بالتنقيط يتكون من خزان عمومى (سعته ٢٠٠ لتر) وخطوط توزيع رئيسية (مواسير مياه مجلفنة قطر ١ بوصة) وخطوط فرعية من البولى فينيل قطر ١٨مم مركب عليها النقاطات (تصرف كل نقاط ٤ لتر/ساعة). تم تنفيذ هذا البحث فوق سطح قسم الهندسة الزراعية بجامعة المنصورة بغرض دراسة إمكانية إستخدام نظم الطاقة الشمسية (سخان شمسى– خزان لتخزين الطاقة– نظام توزيـــع الحـــرارة داخل البيوت المحمية) فى تسخين وتوفير درجة الحرارة المثلى لمحصول الفلفل الحار داخل ثلاثـــة بيوت محمية مختلفة الأغطية – البيت الأول مغطى بطبقة من الفيبرجلاس المسطح والبيـــت الثـــانى مغطى بالفيبرجلاس المجعد والبيت الثالث مغطى بطبقتين من البولى إثيلين المعالج.

(١) أوضحت النتائج المتحصل عليها من إستغلال الطاقة الشمسية في تسخين البيئة الداخليـــة للبيوت المحمية المزروعة بمحصول الفلفل الحار أن نظام الطاقة الشمســـية وفـــر فـــى المتوسط ٧٣,٢٨ % من إجمالى الطاقة المستهلكة في عملية التســـخين. إختلفـــت نســـبة التوفير من يوم إلى يوم و من شهر لآخر طوال فترة التجارب وفقا للإختلاف في كميـــة الطاقة الشمسية المتاحة و الطاقة المخزنة واللازمة للمحافظة على البيئة الداخلية للبيـــوت المحمية عند المستوى المرغوب.

(٢) إختلفت فاعلية نظام توزيع الحرارة داخل البيوت المحمية طوال فتـــرة التجـــارب تبعـــا لإختلاف درجة حرارة الماء في خزان التخزين وفرق درجة الحرارة بين الهواء داخـــل البيوت وخارجها. بلغت فاعلية نظام توزيع الحرارة فى المتوسط حوالى ٩٣,٢٠ %

(٣) أوضحت النتائج المتحصل عليها من إتزان الطاقة، أن كمية الطاقة الحرارية التى يجب إضافتها للبيت لابد وأن تساوى كمية الطاقة الحرارية المفقودة من البيوت أثناء الليل. وحيث أن كمية الحرارة المفقودة من داخل البيت المحمى تعتمد أساسا على الفرق في درجة الحرارة بين الهواء داخل البيت وخارجه فإن حمل التسخين المضاف يزيد تدريجيا من أول عملية التسخين عند الساعة ٨ مساءا وحتى يصل إلى أقصى حد له عند الساعة ٦ صباحا عندما تنخفض درجة حرارة الهواء خارج البيوت إلى أقل حد ممكن. أكبر كمية من الطاقة الحرارية المكتسبة من أرض البيوت المحمية كانت في الساعات الأولى من الليل وتأخذ في التناقص التدريجي حتى تصل إلى أقل كمية عند الساعة ٦ صباحا.

(٤) نظام التحكم البيئى داخل البيوت المحمية أوضح كفاءة عالية في المحافظة على درجة حرارة الهواء المحيط عند المستوى المرغوب في أسوء الظروف علاوة على المحافظة على درجة حرارة أوراق النبات أعلى من درجة حرارة نقطة الندى وبالتالى حماية المحصول من الإصابة بالأمراض الفطرية.لذا فإن معدل النمو الخضرى وبداية التزهير وعقد الثمار كانت جميعها عند أفضل المعدلات خلال هذه التجربة وإن إختلفت من صف الى آخر داخل البيت المحمى الواحد تبعا للوضع الجغرافى للصف و نظام تغطية البيوت المحمية ففى نظام التغطية بأستخدام الفيبر جلاس المجعد أعطى أعلى إنتاجية من المحصول يليه الفيبر جلاس المسطح ثم آخيراً البولى إثيلين و يمكن أن يرجع ذلك إلى المقاومة الحرارية العالية للفقد الحرارى من داخل البيت المحمى إلى خارجه بالنسبة للفيبر جلاس المجعد.