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SOLAR ENERGY UTILISATION FOR PROVIDING AND MAINTAINING OPTIMAL MICROCLIMATIC CONDITIONS OF GREENHOUSE CUCUMBER. PART I: THERMAL PERFORMANCE ANALYSIS OF SOLAR WATER HEATER

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ABSTRACT

The main goal of the present study was to predict water temperature in the storage tank at the end of each day during winter season of 2007-2008. A complete solar heating system (solar collector and storage tank) was utilised for heating 400 litres of water. A mathematical computer model was developed to determine the thermal performance analysis of the solar heating system. Temperatures of outside air, water in the storage tank, and inlet and outlet water of the solar collector were measured and recorded on a data-logger to analysis their correlation with the water temperature prediction model in order to control solar energy heating in agricultural applications. The obtained data showed that, the daily average solar energy available was 13.372 kWh/day of which 7.138 kWh/day was stored in the storage tank of the solar energy system. The daily average overall thermal efficiencies of the solar collector and the storage system during the experimental period were 72.07% and 74.18%, respectively. They varied from day to another and during each month according to the solar energy available, the water temperature in the storage tank at the beginning of each day, and the ambient air temperature. The obtained results also revealed that, the predicted water temperatures were validated well with that measured during the experimental period by 94.68%, which gave an excellent agreement.

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INTRODUCTION

In order to implement optimal inside conditions of different agricultural structures, it is necessary to heat their microclimates, particularly at nighttime during the winter season. Present fuel prices and projected increased prices have emphasized the need to reduce energy consumption for space heating. To overcome these problems it is imperative to utilize alternative heating technologies, with low cost, and efficient and dependable operation, such as the use of renewable energy.

Renewable energy technologies produce marketable energy by converting natural phenomena into useful forms of energy. These technologies use the sun's energy and its direct and indirect effects on the earth (solar radiation, wind, falling water and various plants, i.e. biomass), gravitational forces (tides), and the heat of the earth's core (geothermal) as the resources from which energy is produced **(Kalogirou, 2004).** A worldwide research and development in the field of renewable energy resources and systems is carried out during the last two decades. Energy conversion systems that are based on renewable energy technologies appeared to be cost effective compared with the projected high cost of oil. Furthermore, renewable energy systems can have a beneficial impact on the environmental, economic, and political issues of the world. At the end of 2001 the total installed capacity of renewable energy systems was equivalent to 9% of the total electricity generation. By applying a renewable energy intensive scenario the global consumption of renewable sources by 2050 would reach 318 Tera-Joule **(Sayigh, 2001).** In this research work emphasis is given to solar thermal systems. Solar thermal systems are 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 major component of any solar thermal system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat energy, and transfers this heat to an operating fluid (usually water, air or oil) flowing through the collector. The solar energy thus collected 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 **(Kalogirou, 2003).**

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The flat-plate solar collector is one of the most important types of solar collectors because it is the simplest one and has a wide range of important potential applications. Considerable effort has been expended over the years to improve and increase thermal efficiency and the output temperature of flat-plate solar collectors. This effort has been made with several goals in mind. One is to store heat more efficient for use during nighttimes and cloudy days; when stored as latent heat a high temperature contains more calories per gram of matter. A second goal is to increase the temperature so that other tasks than simply providing hot water are possible **(ASHRAE, 1995).** The solar collector plate absorb as much of the irradiation as possible through the glazing, while loosing as little heat as possible upward to the atmosphere and downward through the back of the casing. The solar collector plates transfer the retained heat to the transport fluid. The absorptance of the solar collector surface for shortwave solar radiation depends strongly upon the natural colour of the coating and on the solar incident angle. Usually black colour is used, however various colour coatings have been proposed mainly for aesthetic reasons by **Tripanagnostopoulos, et al. (2000); and Wazwaz, et al. (2002).** By suitable electrolytic or chemical treatments, surfaces can be produced with high values of solar radiation absorptance (α) and low values of longwave emittance (ε). Essentially, typical selective surfaces consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to longwave thermal radiation, deposited on a surface that has a high reflectance and a low emittance for longwave radiation. Selective surfaces are particularly important when the collector surface temperature is much higher than the ambient air temperature. Lately, a low-cost mechanically manufactured selective solar absorber surface method has been proposed by **Konttinen, et al. (2003).**

The main objective of this research work was to determine the thermal performance analysis of solar heating system during winter season of 2007-2008. A mathematical thermal model was developed to simulate the water temperature in the storage tank of solar heating system.

MATERIALS AND METHODS

Materials:

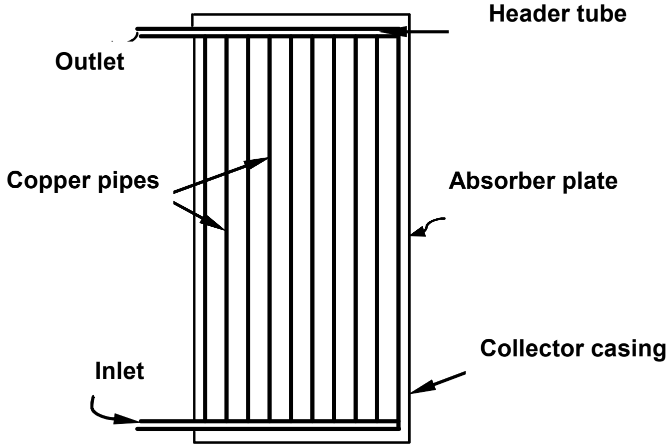
Solar heating system

Solar heating system has a net surface area of 2.0 m^2 and consisted of six components (absorber plate, copper pipes, collector casing, insulation material, glass cover, and storage tank) as shown in Fig. (1). The absorber plate is rectangular in shape, and formed of an aluminum sheet, which is a good conductor of heat. It was painted with matt black paint in order to absorb the maximum amount of the solar energy incident on it. The gross dimensions of the absorber plate are 2 m long, 1 m wide and 2 mm thick, with a net upper surface area of 2 m^2. A 12.5 mm diameter copper pipes (10 pipes) are arranged at equidistant of 10 cm and attached to the upper surface of the absorber plate using slap ties each 10 cm long throughout the length of each pipe. A 12.5 mm diameter was employed to increase the surface area per unit volume of water. These copper pipes were also painted matt black paint. The solar collector casing is rectangular in shape, and made of aluminum bar 25 mm thick. It has gross dimensions of 2.1 m long, 1.1 m wide, and 0.1 m deep, with a net upper surface area of 2.31 m^2. In the bottom and sides of the collector casing, 50 mm of fiberglass wool insulation was placed to reduce the heat losses from the sides and back of the solar collector. To reduce the reflection of radiation and reduce heat losses by convection, a clear glass cover 5 mm thick was placed to cover the collector casing. The solar collector was mounted individually on movable frame which was adjusted manually to change the orientation and tilt angle once each half an hour, so that at that time the angle of incidence of the surface of the solar collector and the sun's rays was set at zero.

The operating fluid (water) was pumped so as to pass through the solar collector. After passing through the solar collector it was stored in a 400 liters insulated storage tank. The storage tank was connected to the solar collector by two junctions of insulated rubber hose. The water pump was switched ON and OFF manually on sunny days from 5th December 2007 until 11th May 2008. The flow rate of operating fluid (18 l/min.) was adjusted and controlled every day using a control valve and a measuring cylinder with stop clock.

Measurements and data acquisition unit

The solar radiation, air temperature, air relative humidity, and wind speed and direction were measured and recorded using meteorological station (WatchDog model 550) which installed just above the solar collector. A disk solarimeter was fixed and installed on the top frame of solar water heater in order to measure the solar radiation flux incident on a tilted surface. 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) situated at different location of the solar collector. Two thermocouples were used to measure the inlet and outlet water temperatures of the solar collector. The temperature in the storage tank of the solar heating system was measured using one thermocouple, located at the centre of storage tank. The temperatures of the absorber surface at different locations were measured using an infrared thermometer (Raytek, Raynger ST60). The recorded data were stored in the memory for output to a printer or to a computer for storage on disk.



$$U_O = U_t + U_b + U_e$$

$$F' = \frac{1}{\frac{w\,U_O}{\pi\,D\,h} + \frac{w}{D + (w - D)\,F}}$$

$$F = \frac{\tanh\ m\left(\frac{w - D}{2}\right)}{m\left(\frac{w - D}{2}\right)}$$

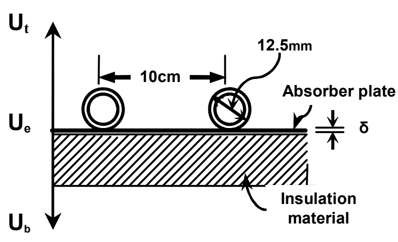


Fig. (1): Schematic diagram of solar water heater (solar collector).

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.

Methods:

Thermal performance analysis of solar collector

The basic parameter to consider is the solar collector overall thermal efficiency. This is defined as the ratio of the useful heat energy delivered to the solar energy flux incident on the collector aperture. Under steady-state conditions, the thermal performance analysis can be measured and determined using the system analysis of **Duffie and Beckman (1991) ; Kalogirou (2004) ; and ASHREA (2005)** as follows:

Solar energy available (q)

The solar energy available was computed by the following equation:

$$q = R\ A_C \quad , \qquad \text{Watt} \qquad (1)$$

Where, R, is the solar radiation flux incident on the tilted surface of solar collector (Wm^{-2}) , and A_c, is the surface area of collector (m^2).

Absorbed solar radiation (q_a)

The absorbed solar energy can be calculated from data on the solar energy available and on the optical efficiency from the following formula:-

$$q_a = R\ A_C\ (\tau\,\alpha) \quad , \qquad \text{Watt} \qquad (2)$$

Where, $\tau\,\alpha$, is the optical efficiency of the solar collector (i.e. effective transmittance of glass cover, τ, multiplied by the effective absorptance of the absorber surface, α).

Heat removal factor (F_R)

It is convenient to define a quantity that relates the actual useful energy gain of a solar collector to the useful heat gain if the whole collector surface were at the fluid inlet temperature. This quantity is called the solar collector heat removal factor (F_R) and mathematically is given by:

$$F_R = \frac{m\,C_p\,(T_{fo} - T_{fi})}{A_C\,[R - U_o(T_{fi} - T_a)]} \text{, decimal} \qquad (3)$$

Where, m and C_p, respectively, are the mass flow rate (kg s^{-1}) and specific heat of operating fluid (J kg^{-1}°K^{-1}), T_{fo} and T_{fi}, are the outlet and inlet temperatures (°K) of the water, T_a, is the ambient air temperature (°K), and U_o, is the overall heat transfer coefficient (W m^{-2} °K^{-1}). The heat removal factor is affected only by the solar collector characteristics, the fluid type, and the fluid flow rate through the collector. It can be obtained from the following equation:

$$F_R = F_E\,F_F \quad \text{, decimal} \qquad (4)$$

Where, F_E, and F_F, respectively, are the solar collector efficiency factor and flow factor.

$$F_E = \frac{1}{\dfrac{W}{D + (W - D)\,F} + \dfrac{W\,U_o}{\pi\,D_i\,h_{fi}}} \text{, decimal} \qquad (5)$$

Where, W, is the central distance between two pipes (m), D and D_i, respectively, represent the external and internal diameters of copper pipe (m), F, is the standard fin efficiency factor, and h_{fi}, is the convection heat transfer coefficient inside the pipe (W m^{-2} °K^{-1}).

$$F = \frac{\tanh\lfloor m_1\,S\rfloor}{m_1\,S} \text{, decimal} \qquad (6)$$

$$m_1 = \left[\frac{U_o}{k_C\,\delta}\right]^{1/2} \text{, decimal} \qquad (7)$$

$$S = \frac{W - D}{2} \text{, m} \qquad (8)$$

Where, k_C , is the thermal conductivity of the copper pipe (W m^{-1} °K^{-1}), and δ, is the thickness of the absorber plate (m).

$$F_F = \frac{m\,C_p}{A_C\,U_o\,F_E}\left[1 - \exp\left(-\frac{A_C\,U_o\,F_E}{m\,C_p}\right)\right] \text{, decimal} \qquad (9)$$

The quantity of, F_R, is equivalent to a convectional heat exchanger effectiveness, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer.

Useful heat gain to storage (q_C)

The maximum possible useful energy gain (heat transfer) in a solar collector occurs when the whole collector is at the inlet fluid temperature, heat losses to the surroundings are then at minimum. The solar collector heat removal factor multiplied by this maximum possible useful heat energy gain is equaled to the actual useful energy gain.

$$q_C = F_R \left[q_a - U_o A_C (T_{fi} - T_a)\right] \quad \text{, Watt} \qquad (10)$$

Solar collector heat losses (q_L)

The solar collector heat losses can be defined as the difference between absorbed solar energy and useful heat gain to storage.

$$q_L = q_a - q_C \quad \text{, Watt} \qquad (11)$$

But several researchers **(Duffie and Beckman, 1991; and Bargach, et al., 2000)** reported that, the solar collector heat losses can be found from the following equation according to the overall heat transfer coefficient:-

$$q_L = A_C U_o (T_p - T_a) \quad \text{, Watt} \qquad (12)$$

Where, T_p, is the mean temperature of the absorber plate (°K).

Overall thermal efficiency (η_o)

Solar collector overall thermal efficiency depends strongly upon the useful heat gain to storage and the energy collected by the collector. The solar collector overall thermal efficiency can be found from the following equation:-

$$\eta_o = \frac{q_C}{q} \times 100 = \frac{q_C}{A_C R} \times 100 \quad \text{, \%} \qquad (13)$$

Normalized temperature rise (D_T)

Normalized temperature rise of the solar collector is the difference between the inlet water and ambient air temperatures per solar radiation flux incident. It can be computed from the following relation:-

$$D_T = \frac{T_{fi} - T_a}{R} \quad , \quad °K\ m^2/W \qquad (14)$$

Solar energy stored (q_s)

The solar energy stored in the storage tank can be calculated from data on the mass of water in the storage tank, and on the difference between mean tank temperatures just prior to sunset and after sunrise as:-

$$q_s = M_W C_p (T_{ke} - T_{kb}) \quad , \text{Watt} \qquad (15)$$

Where, M_w, is the mass of water in the storage tank (kg), and T_{ke} and T_{kb}, respectively, are the water temperatures in the storage tank at the end and the beginning of each day (°K). The storage system efficiency can be computed as a ratio of the solar energy stored in the storage tank to the useful heat gain to storage as:

$$\eta_s = \frac{q_s}{q_C} \times 100 \quad ,\% \qquad (16)$$

A computer model has been developed and functioned for computing the thermal performance analysis of solar collector using the previous equations. The model was implemented as a stand-alone program running on IBM compatible microcomputer. The developed mathematical model has been solved with the help of computer program based on **MATLAB**. The program requires two input files: one contains the simulation parameters and the other contains the input data. Table (1) lists all inputs data required to run the program together with the parameter values used for the simulations runs. The program outputs data are also listed in Table (1). Simplified flowchart of the developed program is shown in Fig (2).

Table (1): Parameters and variables required as input and variables output by MATLAB program:

Configuration file inputs	**Value**
Surface area of solar collector (m^2)	2.0
Optical efficiency (decimal)	0.855
Overall heat transfer coefficient ($W.m^{-2}.°K^{-1}$)	6.80
Distance between copper pipes (m)	0.10
External diameter of copper pipe (m)	0.012
Internal diameter of copper pipe (m)	0.010

Thickness of absorber plate (m)	0.002
Mass flow rate of Water (kg.s $^{-1}$)	0.300
Mass of water in the storage tank (kg)	400
Thermal conductivity of aluminium material (W.m $^{-1}$°K $^{-1}$)	204
Thermal conductivity of copper material (W.m $^{-1}$°K $^{-1}$)	385
Specific heat of operating fluid (J.kg $^{-1}$ °K $^{-1}$)	4186

Data file inputs:

Solar radiation flux incident on the tilted surface (W. m $^{-2}$)
Ambient air temperature (°K)
Inlet water temperature (°K)
Water temperature at the beginning of each day (°K)
Water temperature at the end of each day (°K)

Data outputs:

Heat removal factor (decimal)
Solar radiation available (W)
Absorbed solar energy (W)
Useful heat gain to storage (W)
Heat energy losses (W)
Overall thermal efficiency (%)
Stored solar energy (W)
Storage system efficiency (%)
Normalized temperature rise (m ^{2}. °K.W $^{-1}$)
Storage tank water temperature (°K)

Heat energy balance on the storage tank:

For many solar system water is ideal material which can be used to store usable heat energy **(Duffie and Beckman, 1991 ; and Kalogirou, 2004).** Heat energy added and removed from this type of storage unit by transport of the storage medium itself (water), thus eliminating the temperature drop between transport fluid and storage medium. The typical system in which water tank is used can be represented by the solar water heating system. Implicit in the following discussion is the idea that flow rates into and out of the tanks, to solar collector and load, can be determined. For the non-stratified an energy balance on the water tank attains the following equation:

$$\mathbf{q_S = q_C - q_L \quad , Watt \qquad (1)}$$

Where, q_s is the heat energy storage capacity (W), q_c, is the useful heat gain to storage (w), and q_L, is the heat energy loss from the storage tank (W).

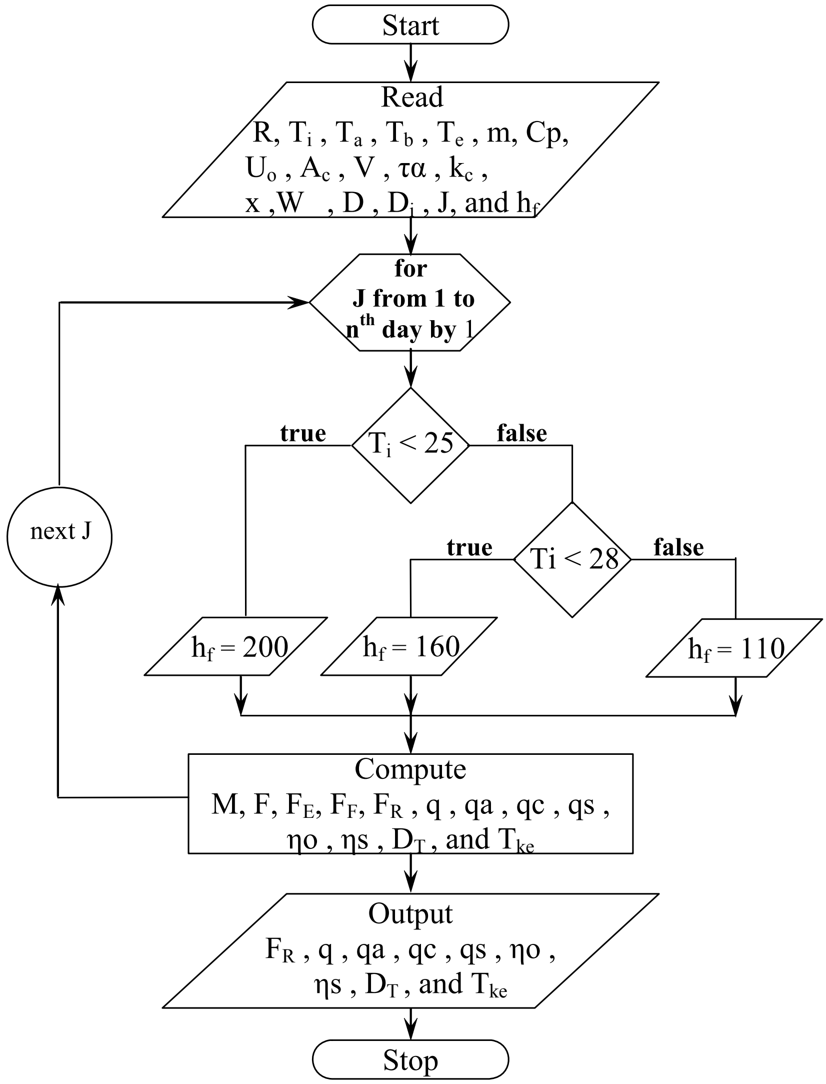


Fig. (2): Simplified flowchart for MATLAB program.

The heat energy balance on the water storage tank during daylight is represented by equation (1) which can be rewritten in a finite temperature difference form and solved for water tank temperature at the end of each day (T_{ke}) with respect to the water tank temperature at the beginning of each day (T_{kb}) as follows:

$$q_s = q_C - q_{loss} \text{, Watt} \qquad (17)$$

$$M_s C_{PW} \left(\frac{dT_k}{d\tau}\right) = q_C - q_{loss} \qquad (18)$$

$$dT_k = \frac{d\tau}{M_s C_p} (q_C - q_{loss}) \qquad (19)$$

$$T_{ke} = T_{kb} + \frac{3600}{M_s C_p} [q_C - q_{loss}] \text{, } ^\circ K \qquad (20)$$

Data were measured and stored in microcomputer files and statistically analyzed using Excel program. Once a computer model is tested and found to be accurate, it can be used to predict the results which could otherwise be obtained with extensive and costly experimentation.

RESULTS AND DISCUSSION

During the experimental work, the solar energy system operated satisfactorily for six months without any malfunction. For the duration of the experimental period, there were 928 hours of bright sunshine of which 812 hours (87.5%) were recorded and used in the thermal performance analysis and applications. The solar collector was orientated and tilted to track the sun's rays from sunrise to sunset (i.e. adjusted once each half an hour to set an incident angle of zero). Under clear sky conditions, the solar energy available, absorbed solar energy, useful heat gain to storage, overall thermal efficiency, and solar energy stored in the storage tank increased gradually with solar time from sunrise until they reached a maximum values at noon. They then declined till they reached a minimum values just before sunset. The thermal performance analysis of the solar heating system is mainly determined by its overall thermal efficiency in converting solar energy into stored heat energy. The obtained data during the experimental period are summarized and listed in Table (2).

Solar energy available:

The total solar radiation, measured by a solarimeter, flux incident on the effective collecting area of the solar collector under clear sky conditions

Table (2) : Daily average thermal performance analysis of the solar heating system included; solar energy available (q), absorbed solar energy (q_a), useful heat gain to storage (q_c), heat removed factor (F_R), heat losses (q_L), overall thermal efficiency (η_o), normalized temperature rise (D_T), solar energy stored (q_s), and storage system efficiency (η_s) during the experimental period.

Month	q (kWh/day)	q_a (kWh/day)	q_c (kWh/day)	F_R	q_l (kWh/day)	η_o %	$D_T \times 10^{-4}$ $m^2.°C/W$	q_s (kWh/day)	η_s %
Dec. 24 days	13.608	11.634	9.983	0.8664	1.652	73.36	6.407	6.111	61.21
Jan. 21 days	11.61	9.927	8.733	0.8884	1.194	75.22	6.252	6.3	72.14
Feb. 18 days	14.083	12.041	10.351	0.8694	1.69	73.52	6.382	8.504	82.16
March 20 days	13.289	11.362	9.339	0.8311	2.024	70.28	6.686	6.977	74.7
April 22 days	14.132	12.083	9.896	0.8289	2.187	70.06	6.709	7.662	77.39
May 11 days	13.509	11.551	9.453	0.8289	2.098	69.97	6.712	7.323	77.47
Average	13.372	11.433	9.626	0.852	1.808	72.068	6.525	7.146	74.178

is the solar energy available. The daily average solar energy available during the experimental period was 13.372 kWh/day. There were obvious differences in solar energy available for the days recorded each month. These differences can be attributed to the effect of the climatic conditions during the experimental work.

Absorbed solar energy

The daily average absorbed solar energy during the experimental work was 11.433 kWh/day, which gave an average optical efficiency of 0.855 The amount of absorbed solar energy depends on the effective transmittance of the glass cover (τ) and the effective absorptance of the absorber surface (**α**). These two parameters depend strongly upon the solar incident angle. Once each half an hour from sunrise to sunset the rays of the sun were perpendicular to the solar collector tilted surface which tracked the sun's rays. Consequently, the angle of solar incidence equal zero at those times and the optical efficiency was at the maximum value of 0.855

Useful heat gain to storage

The daily average useful heat gain to storage during the experimental period was 9.626 kWh/day, which gave an average heat transfer efficiency of 84.19% The useful heat acquire to storage varied from day to another and during each month due to the variations in water inlet temperature, ambient air temperature surrounding the solar collector, and heat removal factor. The absorbed solar energy converted into useful heat gain to storage depends upon the heat removal factor. Heat removal factor depends on the differences in temperature between the operating temperature of the absorber surface and the temperature of the water passing through the solar collector. Heat removal factor also depends highly upon the water volume inside the solar collector in contact with the absorber surface and its flow rate, and the ambient air temperature surrounding the solar collector. As the differences in temperature between the absorber surface and the water passing through the solar collector are increased the heat transfer rate between the absorber surface and the water is increased. As the water inlet temperature is increased, the difference in temperature between the absorber surface and the water passing through the solar collector is reduced and heat removal factor is thus decreased. Useful heat gain to storage during the experimental period was plotted against the solar energy available (Fig. 3). Regression analysis revealed a highly significant linear relationship ($r = 0.982$; $p = 0.001$) between these parameters. The regression equation for the best fit was:

$$\mathbf{q_C = 0.7289\ (q)}$$

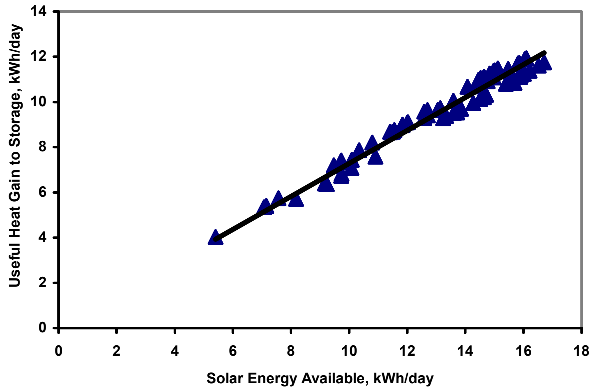


Fig.(3): Useful heat gain to storage versus solar energy available.

The regression analysis also showed that the slope of the regression equation is equalled to the daily average overall thermal efficiency of the solar collector during the experimental period.

Solar collector heat losses

The difference between the absorbed solar energy and the useful heat gain to storage is the actual solar collector heat losses **(Duffie and Beckman, 1991).** The daily average heat losses during the experimental period were 1.808 kWh/day. They varied from day to day and month to another according to the inlet water temperature and the ambient air temperature surrounding the collector. As the inlet water temperature is increased above the ambient air temperature, the operating temperature of the absorber plate is increased and heat losses are thus increased and vice versa.

Overall thermal efficiency

The optical efficiency multiplied by the heat transfer efficiency is the overall thermal efficiency of the solar collector. Otherwise the overall thermal efficiency is the ratio of the absorbed solar energy transferred into the water leaving the solar collector to the solar energy available. The daily average overall thermal efficiency of the solar collector during the experimental period was 72.07%, consequently, 27.93% of the solar energy available was lost. The overall thermal efficiency (η_o) was plotted against the normalized temperature rise (D_T) as shown in Fig. (4). Regression analysis revealed a highly significant linear relationship (r = 0.996 ; p = 0.001) between these parameters. The regression equation for the best fit was:-

$$\eta_o = 0.7578 - 6.7290 (D_T)$$

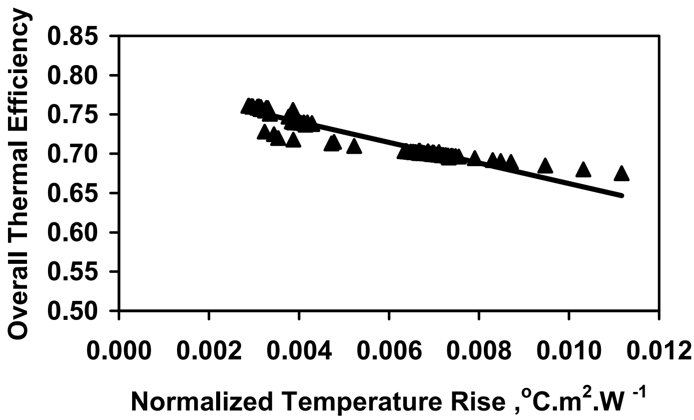


Fig.(4): Overall thermal efficiency versus normalized temperature rise.

The regression equation also showed that, the solar collector overall thermal efficiency can be expressed as:-

$$\eta_o = \frac{q_c}{q} = F_R (\tau\alpha) - U_o F_R \left[\frac{T_{fi} - T_{ao}}{R}\right] \quad (15)$$

$$\eta_o = F_R (\tau\alpha) - U_o F_R (D_T) \quad (16)$$

$$\eta_o = a - U_o F_R (D_T) \quad (17)$$

Regression equation is definitely the numerical expression of equation (16). The y-intercept (a) is equalled to the product of the heat removal factor **(F_R)**, and optical efficiency **$(\tau\alpha)$**. The slope is equalled to the product of the heat removal factor and overall heat transfer coefficient

(U_o). The plot of overall thermal efficiency versus normalized temperature rise was straight line with Y-intercept **F_R ($\tau\alpha$)** and slope **(-F_R U_o)**. It is clear that U_o is a function of temperatures difference between absorber plate and ambient air, and wind speed. Also heat removal factor is a weak function of overall heat transfer coefficient. And, some variations of the relative proportions of beam, diffuse, and ground reflected components of solar radiation occurred. Therefore, some scatter in the data was expected because of temperature dependence and wind effects as shown in Fig (5). The previous obtained data are in agreement with the data published by **Duffie and Beckman (1991) ; and Ismail and Goncalves (1999).**

Solar energy stored in the storage tank

The daily average solar energy stored in the storage tank during the experimental period was 7.138 kWh/day which gave storage system efficiency of 74.18% The solar energy stored in the storage tank varied from day to another and during the experimental work due to the effect of ambient air temperature, inlet water temperature, wind speed, solar energy available, and heat energy consumed at nighttime during the application. Because the solar collector was functioned from 5th December 2007 until 11th May 2008 in an application experiment, the majority of heat energy stored in the storage tank was consumed at nighttime in warming up the microclimate of the greenhouse.

Heat energy balance on the storage tank

The mathematical model of energy balance on the water storage tank which functioned to predict the water temperature at the end of each day (T_{ke}) in terms of the water temperature at the beginning of each day (T_{kb}), heat energy gained to storage (q_{gain}), and heat energy lost (q_{loss}) showed that, there are many factors affecting heat energy balance on water storage tank during daylight. These factors and their effects on heat energy balance were: absorbed solar energy that converted into useful heat gain, convection heat transfer coefficient, variation in the water temperatures in the storage tank during the daylight, and ambient air temperature surrounding the solar energy system. Therefore, it is imperative to determine the water temperature in the storage tank at the end of each day to check whether there are differences between the actual heat energy stored in the storage tank and the heat energy required to keep the air temperature within a greenhouse at a desired level. According to the predication equation (20), the predicted water temperatures were plotted as a function of the measured water temperatures (Fig. 5). The predicted water temperatures were validated well with that measured during the experimental period by 94.68%, which gave an excellent agreement.

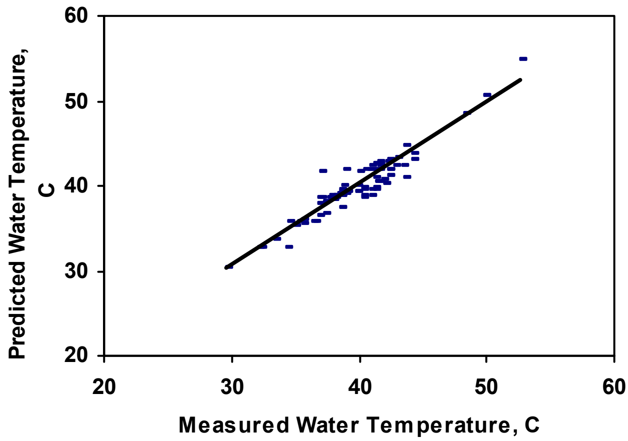


Fig. (5): Predicted water temperature in the storage tank at the end of each day versus measured temperature.

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. A solar collector which is continuously orientated and tilted to maintain an incident solar angle of zero from sunrise to sunset will allow maximum values of both; the effective absorptance of the absorber surface and the effective transmittance of the glass cover to be reached. **Bargach, et al. (2000)** have shown that efficient thermal performance of a flat-plate solar collector depends strongly upon the transmittance of the solar radiation of its glazing. Matt black paint is considered as a good absorber of the solar energy. Therefore, maximum value of optical efficiency (0.855) was achieved during the experimental period. For the duration of this research work the solar energy available was considered as the most important parameter affecting thermal performance of solar energy system. The absorbed solar energy, useful heat gain to storage, normalized temperature rise, and solar energy stored in the storage tank were found to be affected mainly by the solar energy available. Whereas, the solar energy system heat losses and the overall thermal efficiency were slightly affected by the solar energy available. The overall thermal efficiency and heat losses were mainly affected by the water inlet temperature and ambient air temperature. The ambient air temperature during the experimental period was inversely proportional to the solar energy system heat losses. Consequently it was directly proportional to the solar energy system thermal performance.

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الملخص العربى

إستغلال الطاقة الشمسية لتوفير والمحافظة على الظروف المناخية المناسبة للبيت المحمى المزروع بمحصول الخيار. الجزء 1 : تحليل الأداء الحرارى لسخان الماء الشمسى

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يهدف هذا البحث الى التنبؤ بدرجة حرارة الماء المخزنة بداخل خزان تخزين الطاقة الشمسية فى نهاية كل يوم خلال فصل الشتاء لموسم 2008/2007 م. حيث تم استخدام نظام تسخين شمسى متكامل مكون من سخان مياه شمسى وخزان تخزين وذلك لرفع درجة حرارة 400لترمن الماء المخزن بداخل هذا الخزان. تم تطوير نموذج رياضى لحساب وتحليل معدل الآداء الحرارى لنظام التسخين الشمسى المستخدم. كما تم الإستعانة بجهاز قياس وتجميع البيانات (Data-logger) وذلك لقياس وتخزين درجات حرارة الهواء, ودرجات حرارة الماء داخل الخزان ودرجات حرارة الماء الداخل إلى والخارج من المجمع الشمسى أثناء التشغيل, وكذلك تم تحليل علاقة تلك الدرجات ومدى إرتباطها بدرجة حرارة الماء المتنبأ بها وذلك بغرض تحديد كميات الطاقة الشمسية المستخدمة فى عمليات التدفئة التى تجرى فى العديد من التطبيقات الزراعية.

أوضحت البيانات المتحصل عليها أن المتوسط اليومى للطاقة الشمسية المتاحة بلغ 13.372 كيلووات.ساعة/يوم , وكان المتوسط اليومى للطاقة الحرارية المخزنة بنظام تخزين الطاقة الشمسية 7.138 كيلووات.ساعة/يوم. كما بلغ المتوسط اليومى للكفاءة الحرارية الكلية للمجمع الشمسى ولنظام التخزين خلال فترة التجربة 72.07% و 74.18% على التوالى, والتى كانت تتغير بدورها من يوم لآخروخلال كل شهر طبقاً لكمية الطاقة الشمسية المتاحة, ودرجة حرارة الماء بخزان التخزين فى بداية كل يوم, ودرجة حرارة الهواء الخارجى المحيط. أشارت النتائج إلى أن هناك توافق كبير بين درجات حرارة الماء المتنبأ بها ودرجات الحرارة المقاسة والتى بلغت نسبته 94.68%.

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