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Predicted and Estimated Efficiency of Solar Panels for Water Heating Under Clear Sky Conditions

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ABSTRACT

A solar energy system was designed, constructed and utilized to study the effect of various environmental parameters on thermal performance and economic implications under clear sky conditions of Al-Ahsa Province-Saudi Arabia. It consisted of two components: a solar panel and an insulated storage tank. The solar panel had a surface area of $2m^2$ (2.0×1.0 m). It was mounted on a movable frame which could be adjusted so that at any time the angle of solar incidence on the surface of the solar panel could be set to zero. Water was continually cycled through the solar panel using a water pump. After passing the panel, the heated water was stored in an insulated tank (160 litters). Results showed that wind speed, water inlet temperature and total solar radiation flux incident on the panel surface strongly affected solar panel thermal performance. The daily average overall efficiency of this solar panel was found to be 69.34%.

Key Words : Solar panel, Solar Energy, Water Heating, Solar Panel Efficiency,Utilization of Solar Energy.

INTRODUCTION

Solar energy is a tried, proven and renewable source of energy, particularly for low temperature heating. The use of solar energy for agricultural applications is dependent upon the development of solar energy systems that have optimum performance, good reliability and economic characteristics so as to be compared favourably with conventional energy systems and other energy sources. This development must reach a point where satisfactory performance and reliability can be achieved for numerous solar energy applications. Also, to be economical, the solar energy systems must have high annual utilization, relatively long life and be designed properly for the location and the nature of the specific application. A solar panel is a special kind of heat exchanger that transforms solar radiant energy into useful heat. It differs in several respects from more conventional heat exchangers. In the solar panel, energy transfer is from a distant source of radiant energy to a fluid. Without optical concentration, the flux of incident radiation varies and reaches a maximum of 1100 W/m^2 . The wavelength range is from 0.29 to 2.5, which is considerably shorter than that of the emitted radiation from most energy absorbing surfaces (Duffie and Beckman, 1980) . Flat plate liquid type solar collectors (solar panels) have many potential applications as solar energy systems for agriculture. Examples of these applications include space heating for livestock shelters, greenhouses, farm shops, and human housing. Hot water heating can also used in dairy parlors, food processing plants, and possibly refrigeration for storage of crops such as apples and bananas.

When designing solar energy systems using commercially available solar panels, thermal performance data provided by the manufacturer is often based on results of tests conducted under highly favorable environmental and operating conditions. In sizing the collector array for specific agricultural applications, the designer must know the actual performance for average weather conditions. The most commonly used characteristic for rating the thermal performance of a flat plate solar collector is the thermal efficiency η taken as:

$$\eta = \frac{Q_u}{S_r A_c} \qquad (1)$$

Where: S_r = the total incident solar radiation measured in the plane of the collector, Watt.

A_c = the collector surface area, m^2.

Q_u = the useful energy delivered by the collector,Watt.

In this investigation, the solar panel efficiency is based on the absorber plate surface area rather than the gross area as specified by the ASHRAE Standard (1977). Since environmental conditions affect the efficiency measurements, allowable ranges of the significant weather parameters have been established. These ranges include:

θ	<	30.	V_w < 2.5 m/s.
S_r	>	350 W/m^2	T_a < 22 °C.

Where θ is the angle of incidence of solar beam radiation, V_w, is the wind speed, T_a is the ambient air temperature during the test period. The flow rate of the heat transfer fluid for liquid type solar collectors depend upon the collector design and the manufacturer's recommendation, although a test flow rate of 0.02 kg/m^2 of aperture area is suggested. The difference in test results attributable to different environmental conditions has been previously analyzed and found to be significant (Streed *et al.*, 1977). Studying the possibility of utilizing solar energy for heating water has had interest for many researchers (Al-Amri, 1997; Al-Amri, 1996; Studman, 1979; Vaughan et al., 1980; Misra et al., 1982; Abdellatif and Al-Amri, 1998; Abdellatif, 1989) .On the other hand, the environmental conditions encountered during practical application may differ even more from the nearly ideal test environment.

Consequently, the major purpose of this investigation is to study the effect of environmental conditions on thermal performance of solar panels and to correlate this by its economic implication.

DESCRIPTION OF DEVELOPED SOLAR ENERGY SYSTEM

A typical solar energy system consists of two major components: a solar collector panel and an energy storage usually an insulated storage tank. The solar panel consists of six components: a panel box, an absorber plate, a copper pipe, insulation material, a glass cover and a movable frame. In this research the panel box is rectangular in shape and made of aluminum, 4 mm thick. The gross dimensions of the panel box (from inside) are 2.0 m long, 1.0 m wide and 0.10 m deep with a net upper surface area of 2.0 m^2. The absorber plate is formed of an aluminum sheet 2.0 m long, 1.0 m wide and 2.0 mm thick. It was painted with matt black paint. It has a net surface area of 2.0 m^2. 12.7 mm diameter copper pipes were attached to the upper surface of the black absorber plate, using wire ties each 10 cm long throughout the length of each pipe. This relative diameter (12.7 mm) was used to increase the volume of water per unit surface area of the absorber plate. The total length of copper pipes employed in the solar panel is 20 m. It is also painted with matt black paint. These pipes are run in a parallel direction as shown in Fig. 1. In the bottom and sides of the panel envelope, 5 cm and 2.5 cm sheets of fiberglass wool insulation were placed to reduce the heat loss from the back and sides of the solar panel respectively. To minimize the reflection of radiation and reduce the heat losses by convection, a clear glass cover 5 mm thick is placed to cover the panel box. The air space between the black absorber plate and the clear glass cover is 5 cm as suggested by many researchers (Duffie and Beckman, 1980; Ashrae, 1977). The solar panel is mounted on a movable frame to track the sun's rays from sunrise to sunset throughout the experiments. This frame has two quadrants and clamps for orientation and tilt angle.

The insulated storage tank is cylindrical in shape, and made from two layers of steel sheets (3mm thick). To minimize the energy losses from the storage tank , a 2.5 cm sheet of fiberglass wool insulation is placed in the space between the two layers of steel sheets. Also, the outside perimeter of the storage tank is surrounded by 2.5 cm of insulation. The storage tank is connected to the solar panel by two junctions. One junction is between the bottom of the storage tank (cold water) and the bottom of the solar panel (water inlet). The other one is between the top of the storage tank and the top of the panel (water outlet). The water is pumped from storage tank to the panel using a 0.5 hp pump. After passing through the panel, it is stored in the insulated tank with a capacity of 160 litters.

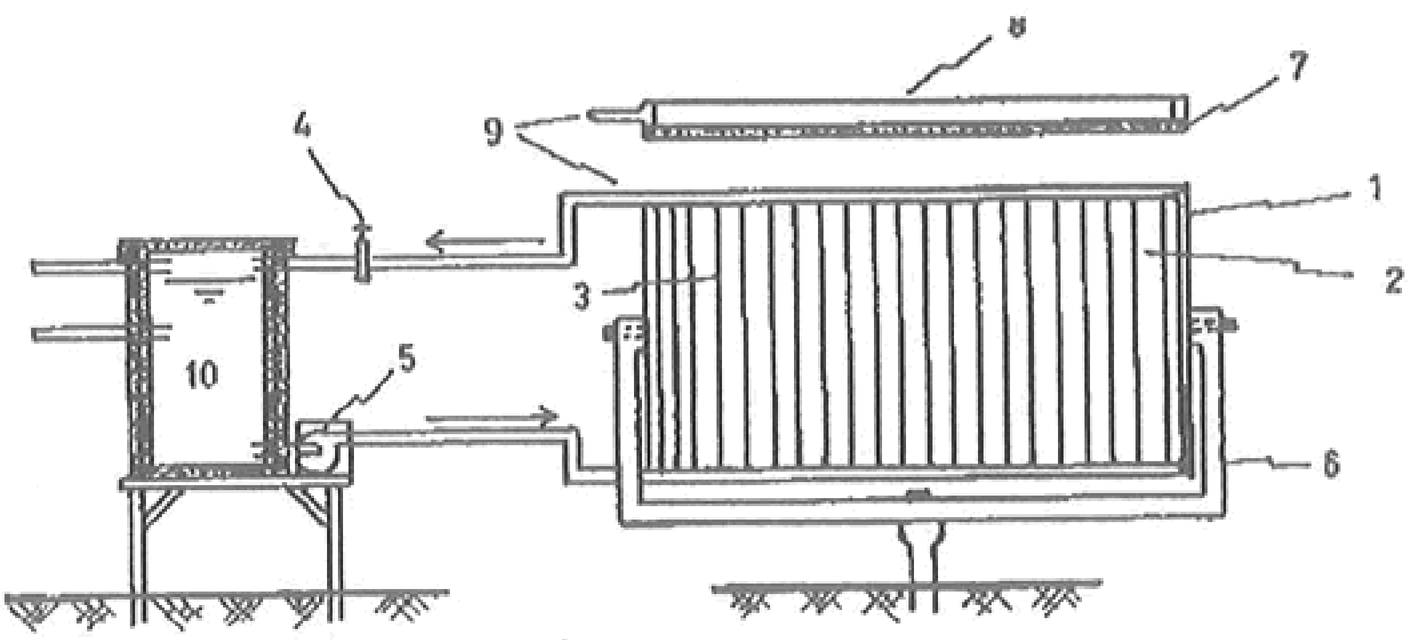

Fig.1. Schematic diagram of the solar energy system used in the experiment.

1- Casing (aluminum box).
2- 2- Absorber black plate.
3- Copper pipe.
4- 4- Flow rate control valve.
5- Water pump.
6- Movable frame used to mount the panel.
7- Insulation material.
8- Glass cover.
9- Header tube.
10- Insulated storage tank.

INSTRUMENTATION

Ten Celsius temperature sensors (Thermistor, National semi-conductor, LM34) are used to measure the temperature at various points in the solar energy system (Fig. 2). Four thermistors are placed evenly around the lower surface of the absorber plate (to reduce the influence of radiation) to measure its temperature. The water temperature in the storage tank is measured using two evenly spaced sensors. Two thermistors are employed to measure the water inlet and outlet temperatures. The thermistor of the water inlet is placed after the pump so that the heat added to the system by the pump could be measured. One thermistor is used to measure the solar panel glass cover temperature. The ambient air temperature is monitored in an aspirated screen.

An anemometer is mounted on the top of the solar panel to check excessive air currents over the panel surface. The water flow rate is tested and adjusted using a control valve and a measuring cylinder with a stopwatch to be 12 *l/min.* (0.2 kg/s).

The solar radiation flux incident on a horizontal surface is taken from the meteorological station (far about 200 m of the experiments). An arithmetic programme is employed to compute the solar radiation flux incident on a tilted surface using the meteorological data.

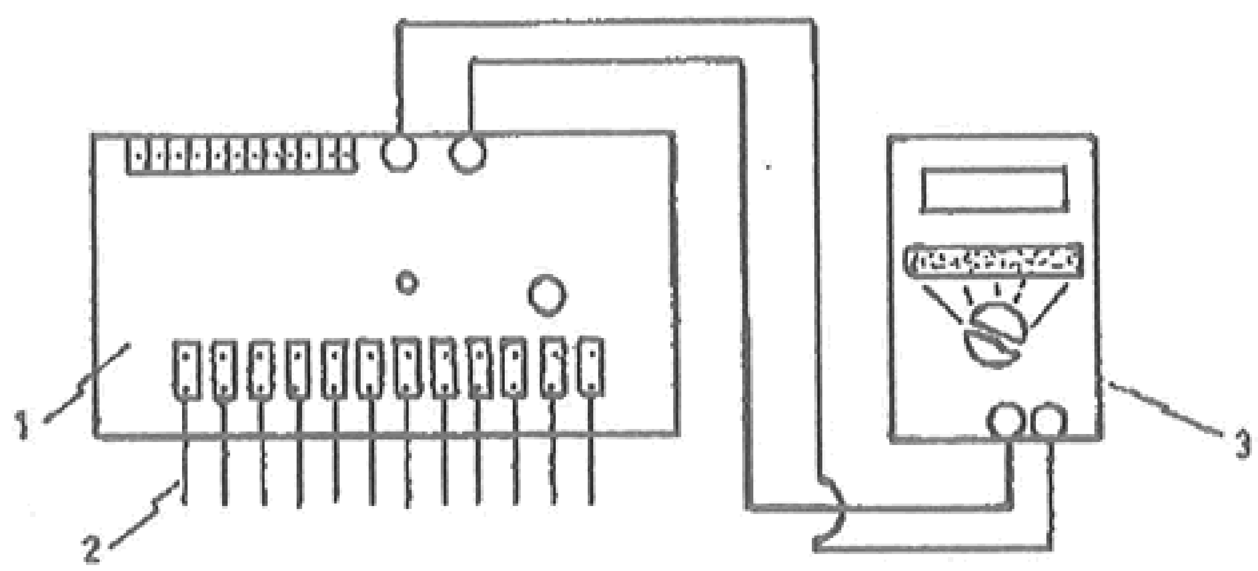

Fig.2.Thermistor sensor used to measure the temperature at various points.

1- Switch box.
2- Channels.
3- Digital voltmeter.

PERFORMANCE TEST OF THE SOLAR ENERGY SYSTEM

To measure, test and compute the performance of the solar energy system, mathematical models adopted by (Duffie and Beckman, 1980; Al-Amri, 1997; Al-Amri, 1986; Abdellatif and Al-Amri, 1988; Rumsey, 1982) are employed as follows:

The hourly useful heat collected (gained) is calculated from the equation:

$$Q_U = F_R A_c[(\tau\alpha)R - U_o(T_{w,i} - Ta)] \qquad \text{(Watt)} \qquad (2)$$

The quantity, F_R, is equivalent to a conventional heat exchanger effectiveness, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. The maximum possible useful energy gain (heat transfer) in a solar panel occurs when the whole panel is at the inlet water temperature; heat losses to the surrounding are then at a minimum. The panel heat removal factor, F_R, can be computed from the equation.

$$F_R = [1 - \exp(\frac{-A_c U_o F'}{mCp})](\frac{mCp}{A_c U_o}) \qquad (\%) \quad (3)$$

The solar panel efficiency factor, F', is calculated by:

$$F' = [\frac{1}{\frac{WU_o}{\pi D} + \frac{W}{D + (W - D)}F}] \qquad (\%) \qquad (4)$$

Where:

$$F = \frac{\tanh[\frac{m(W-D)}{2}]}{\frac{m(W-D)}{2}} \qquad (5)$$

and $$m = (\frac{U_o}{k_c\, s})^{0.5} \qquad (6)$$

The solar radiation on the tilted surface, R, was computed using the solar radiation measured on a horizontal surface (Meteorological data) from the Liu and Jordan standard method in Duffie and Beckman (1980).

The heat transfer efficiency, which is defined as the ratio of the actual useful heat gain (to storage) to the absorbed solar radiation, can be computed by:

$$\eta_{qu} = \frac{Q_u}{\tau \alpha A_c R} \quad (\%) \quad (7)$$

The effective absorbtance-transmittance product, $\tau\alpha$, is calculated for the single glass cover, and is a function of incident angle.

$$\tau = 0.90 - 0.00437 \exp. [0.0936 (\theta - 30)] \quad (\%) \quad (8)$$

$$\alpha = 0.95 - 0.00476 \exp. [0.0940 (\theta - 35)] \quad (\%) \quad (9)$$

The thermal energy lost per hour, Q_L, from the solar panel to the surroundings by conduction, convection and radiation can be represented by an overall heat transfer coefficient, U_o, times the absorber plate area, A_c, and the difference between mean absorber plate temperature, T_p, and the ambient air temperature, T_a.

$$Q_L = U_o A_c (T_p - T_a) \quad \text{(Watt)} \quad (10)$$

In effect, the absorbed solar radiation is distributed to thermal losses through the top, bottom and edges and the remainder is available for storage. The overall heat transfer coefficient is found by adding together the top, U_t, back, U_b, and edge, U_e, heat transfer coefficients referred to the solar panel area, thus:

$$U_o = U_t + U_b + U_e \quad (\text{W/m}^2\text{/K}) \quad (11)$$

The solar panel overall efficiency is defined as the ratio of useful heat gain (to storage) to the solar energy available, thus:

$$\eta = \frac{Q_u}{RA_c} \times 100 \qquad (\%) \qquad (12)$$

It is important to maximize the amount of energy stored in the storage tank using the solar panel unit. The energy stored is given by:

$$Q_s = m_s Cp(T_e - T_b) \qquad \text{(Watt)} \qquad (13)$$

Storage system efficiency can be defined as the ratio of energy stored to the useful heat gain to storage, thus:

$$\eta_s = \frac{Q_s}{Q_u} \times 100 \qquad (\%) \qquad (14)$$

The maximum possible daily hours of bright sunshine per month (i.e. the day length of the average day of the month) is given by:

$$N = 0.1333333 \arccos(-\tan\theta \tan\delta) \qquad \text{(hr)} \quad (15)$$

The declination angle, $\delta = 23.45 \sin(0.9863\,(284 + n))$ and the latitude angle for Al-Ahsa is 25.6 N.

The solar panel is moved manually once each half-hour in order to track the sun's rays from sunrise to sunset, using the tilt angle and orientation controllers. The water pump is switched on and off manually on sunny days. The flow rate is tested, adjusted and controlled every day using the control valve and a measuring cylinder with a stopwatch to be 12 *l*/min.

Two different arithmetic programmes are employed in this research work: the first one utilized to compute the solar radiation normally incident on the tilted surface (with an optimum tilt angle), the second to calculate the thermal performance of the solar energy system.

RESULTS AND DISCUSSION

Thermal performance of the solar energy system was carried out in the heating season (November, December 1997, January, February, and March, 1998). The data of solar energy system have been gathered and analyzed for a total of 40 days over a period of 152 days beginning November 1, 1997. A total of 5 tests have been conducted over this time, and the average length of each test period was 8 days. The performance data of the solar energy system throughout this experimental work is summarized in Table 1. The installation costs for the solar panel, storage tank and water pump are SR 1150, SR 355, SR 175 respectively. The hourly average solar radiation flux incident on a tilted surface (panel surface) is plotted against solar time in Fig. 3 along with the value predicted. In general, there is a good agreement between the predicted and measured values. For the duration of the experiments, the average daily solar energy converted into useful heat gain to storage is 10.615 kWh/day. This energy is equivalent to 0.743 SR/day. The measured and predicted average hourly useful heat gain to storage is plotted in Fig. 4. The measured values tend to exceed the predicted ones during the clear day periods. This result indicates that the calculation models of heat loss are over-predicting the actual values. This observation can be attributed almost completely to the effect of wind blowing over the solar panel surface, water inlet temperature and ambient air temperature surrounding the solar energy system. As the water inlet temperature is increased above the ambient air temperature, two results are noted: firstly, the overall heat transfer coefficient is increased and heat losses are thus increased; secondly, the difference between the operating temperature of the absorber plate and air temperature surrounding the panel is increased and heat losses are thus increased.

For the duration of the experiments, the average daily solar energy stored in the storage tank is 8.711 kWh/day, which corresponds to an average storage system efficiency of 82.06%. Measured and predicted average hourly values for solar energy stored in the storage tank is shown in Fig.5. The overall efficiency of the solar panel is a combination of absorption efficiency and heat transfer efficiency. Therefore if one or both efficiencies are increased the overall efficiency is usually increased. The average daily overall efficiency during these experiments is 69.34%; consequently 30.66% of the solar energy available was lost. Measured and predicted average hourly overall efficiencies are indicated in Fig. 6. The storage system efficiency is found to be affected by the ambient air temperature and water temperature in the storage tank as well as by useful heat gain to storage. The storage system efficiency is found to be closely related to the overall efficiency of the solar panel. Measured and predicted average hourly for storage system efficiencies are plotted in Fig. 7.

Table 1: Average daily useful heat gain to storage (Q_u).

Month	Q_u kWh/day	η_{qu} %	η %	SR value Energy	N hr/day	N' hr/day	E.C.kWh/day	*SR value Energy
Nov.	10.799	84.30	70.00	0.756	10.74	9.25	3.401	0.238
Dec.	10.213	81.80	67.69	0.715	10.43	8.50	3.125	0.219
Jan.	10.130	79.20	65.55	0.709	10.59	8.10	2.978	0.208
Feb.	10.800	83.60	69.46	0.756	11.16	8.05	2.959	0.207
March	11.134	89.00	73.98	0.779	11.85	8.75	3.217	0.225
Mean	10.615	83.58	69.34	0.743	10.95	8.53	3.136	0.219

*Saudi Riyal value calculated at 0.07 SR/kWh.

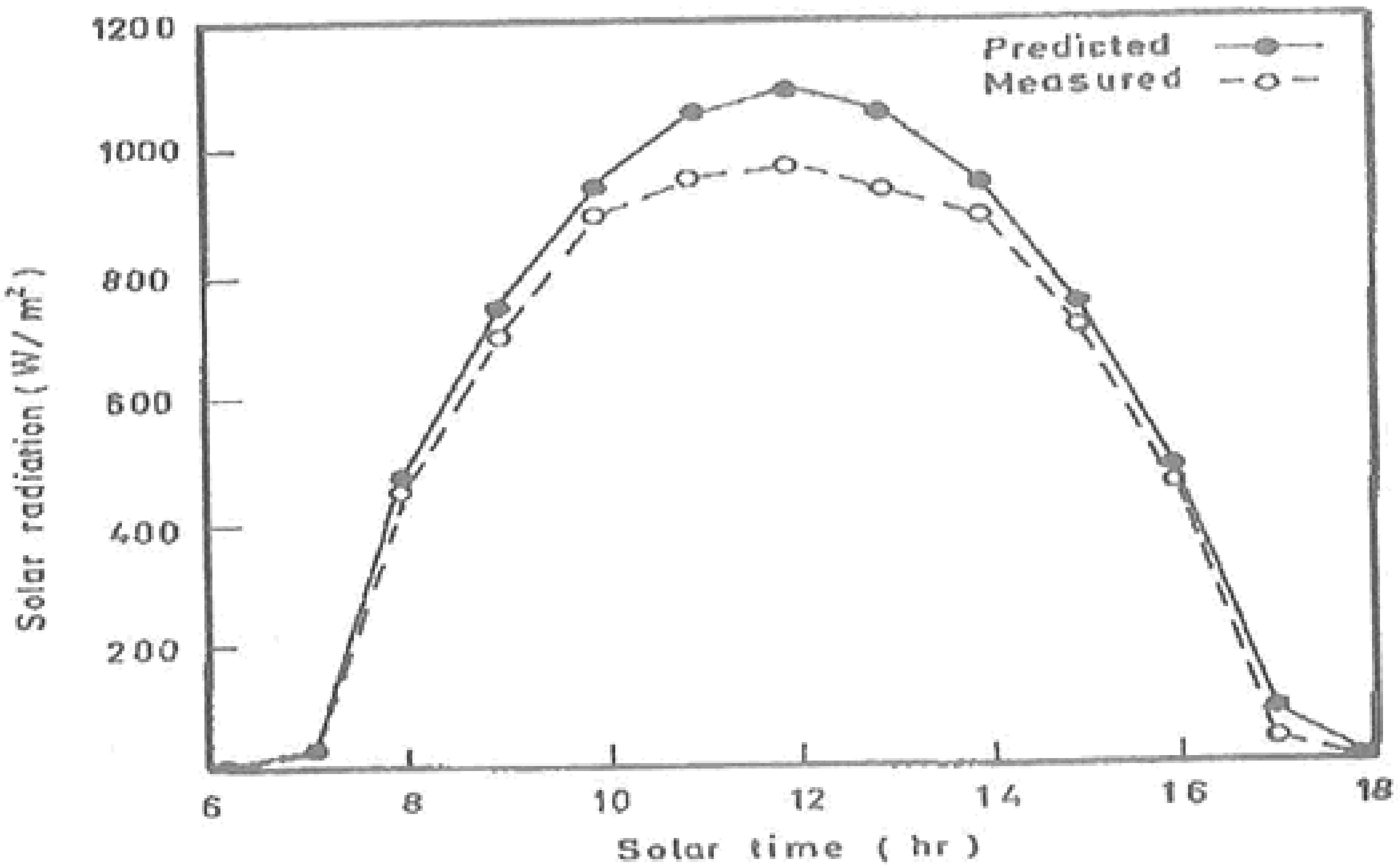

Fig.3.Average hourly measured and predicted solar radiation flux incident on a tilted surface.

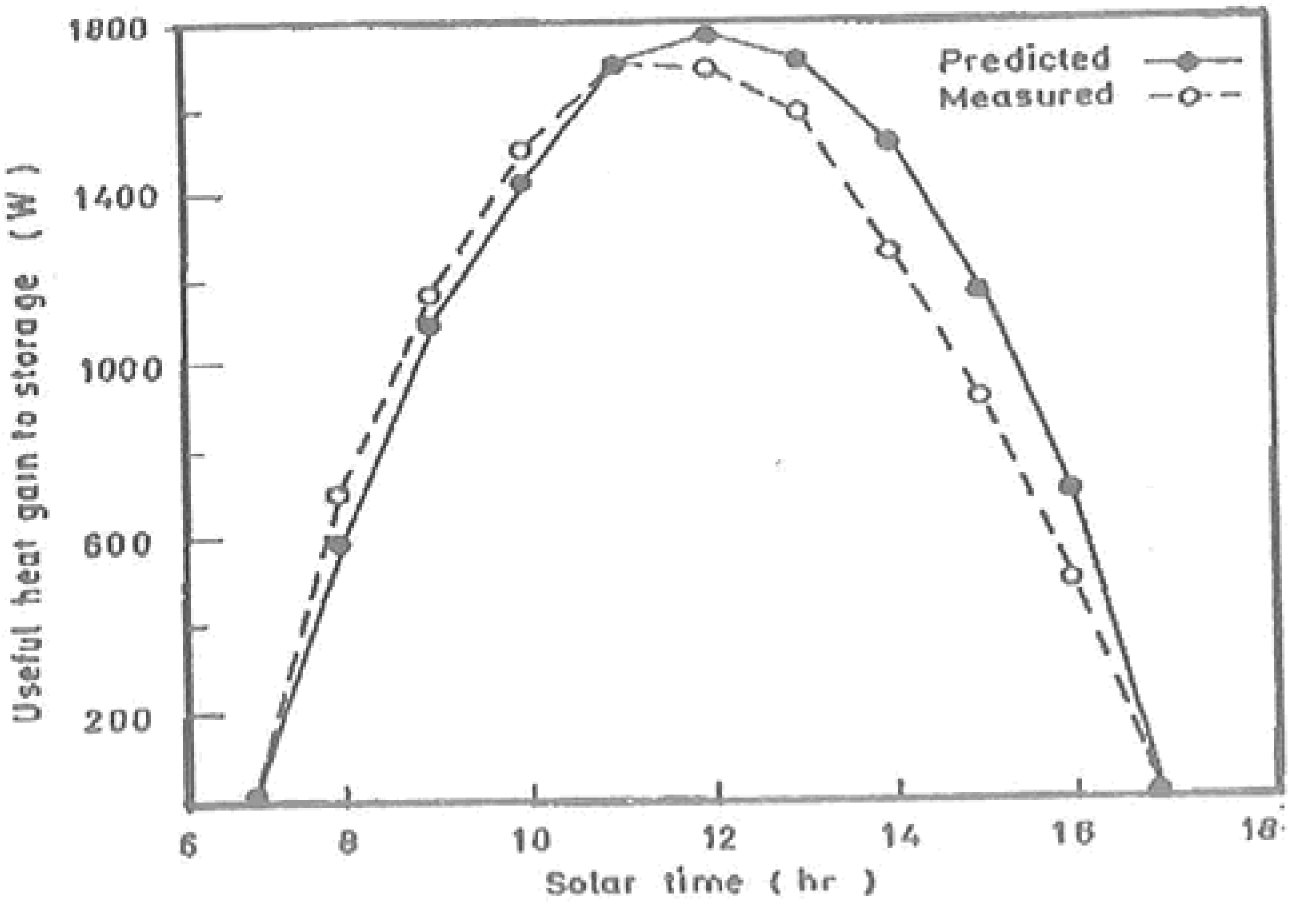

Fig.4.Average hourly measured and predicted useful heat gain to storage.

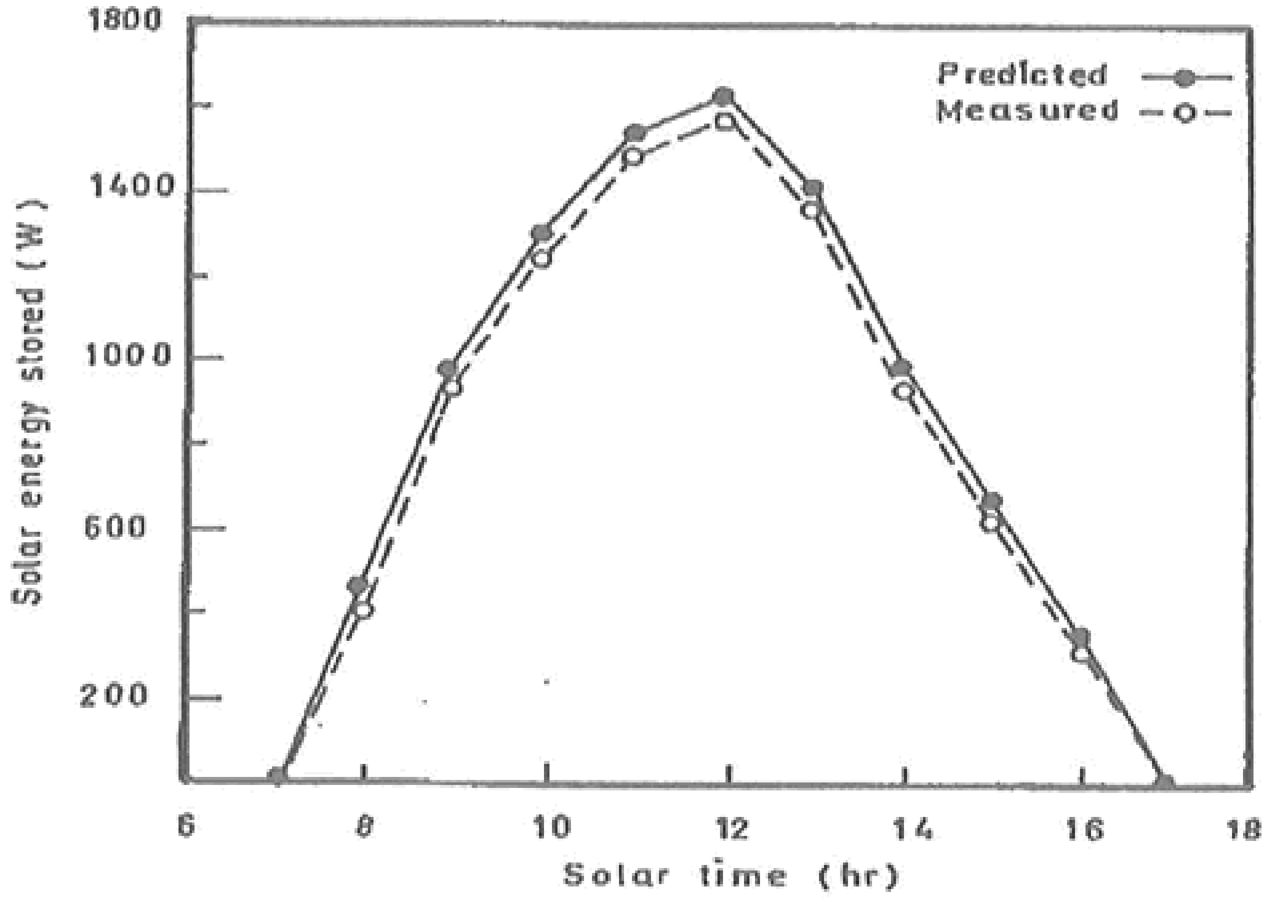

Fig.5.Average hourly measured and predicted energy stored in the storage tank.

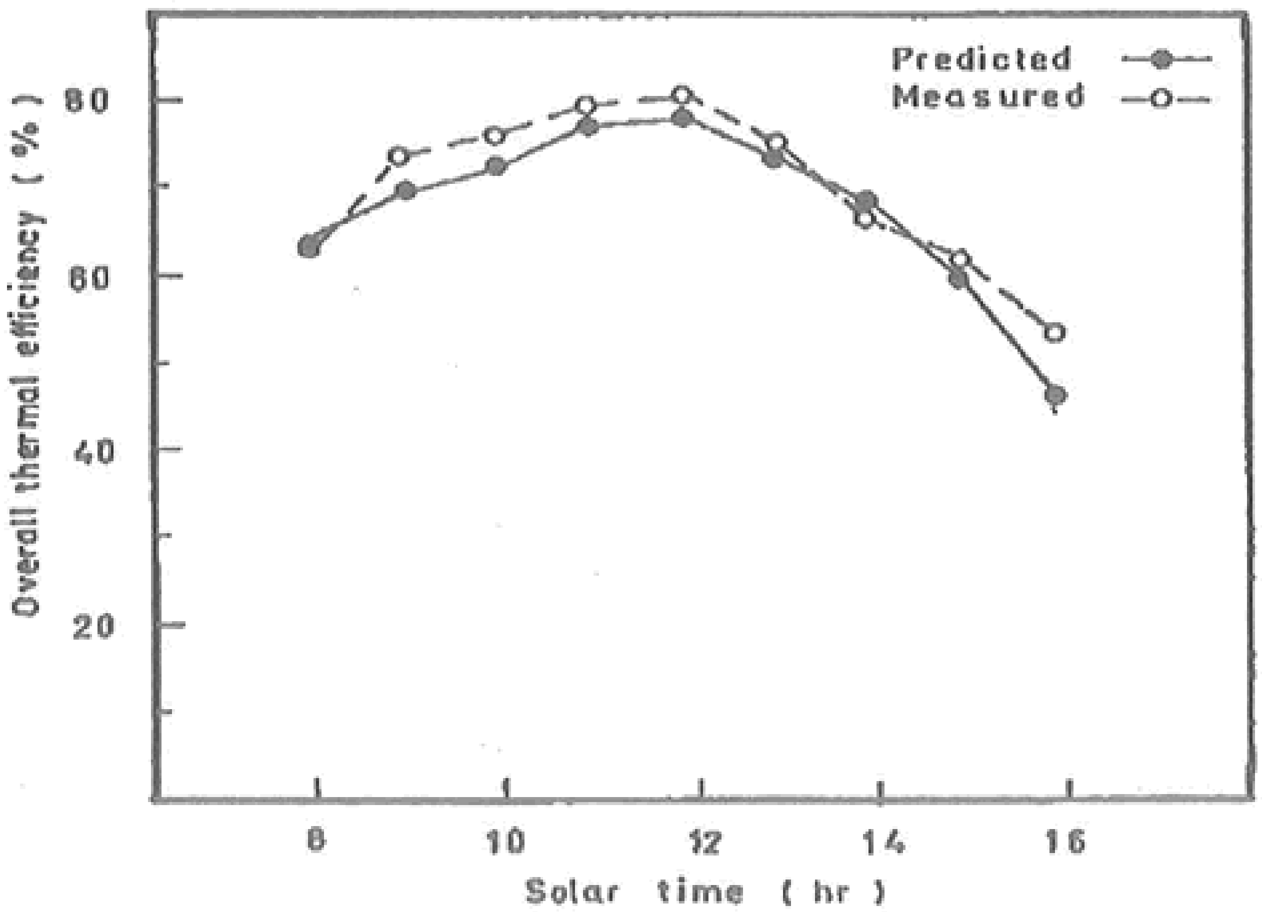

Fig.6.Average hourly measured and predicted overall thermal performance.

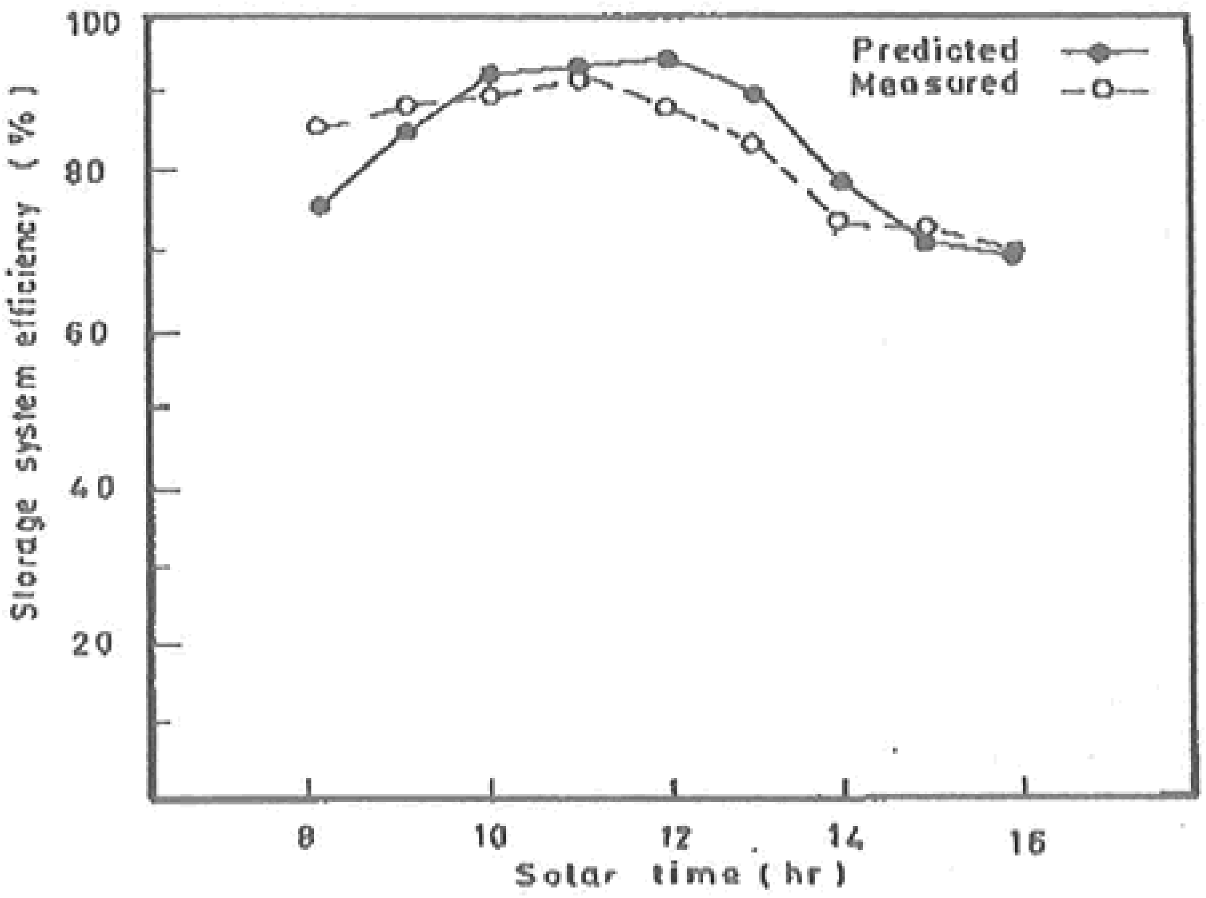

Fig.7.Average hourly measured and predicted storage system efficiency.

CONCLUSION

The solar energy system was operated satisfactorily for over five months on sunny days only without any malfunction. For the duration of the experiments, there were 1296.80 hours of actual bright sunshine, of which only 384.40 hours (29.64%) were recorded and used in the results and tests. The thermal performance of the solar energy system was determined by its overall efficiency in converting solar energy to stored heat energy. The solar energy system, which was employed in these experiments, can be utilized in agricultural applications, such as protected cropping, greenhouse conditioning, providing hot water for animal and poultry houses, and many other applications. Further work will employ this system for maintaining an optimum air temperature inside a 32 m^2 Gable even-span Greenhouse.

NOMENCLATURE

Q_u Useful heat gain to storage per hour, Watt.

η_{qu} Heat transfer efficiency.

E.C Energy consumed by the water pump, Saudi Riyal value calculated at

0.7 SR/kWh .

F_R Heat removal factor.

A_c Solar panel surface area, m^2

τ,α Effective transmittance and absorbtance of glass cover and absorber plate.

R Solar radiation flux incidence on a tilted surface, Watt/m^2.

$T_{w,i}$ Water inlet temperature, °C.

T_a Ambient air temperature, °C.

m Mass flow rate of water, kg/s.

C_p Specific heat of water, J/kg/°C.

W Copper pipe spacing, m.

D Copper pipe diameter, m.

k_c Thermal conductivity of copper pipe, W/m/°C.

s Absorber plate thickness, m.

θ Solar angle of incidence, degree.

U_O Overall heat transfer coefficient.

Q_s Energy stored in the strong tank, Watt per hour.

m_s Mass of water in the storage tank, kg.

T_p, T_c Mean tank temperature at the beginning and end of each hour,°C.

N Maximum possible daily hours of bright sunshine.

N' Actual daily hours of bright sunshine.

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مجلة الإمارات للعلوم الزراعية (١٩٩٧) ٩: ٣٤-٥٠

تقدير و توقع كفاءة جهاز تسخين مياه التدفئة الشمسي تحت ظروف السماء الصافية

علي بن مفرح العمــــري
قسم الهندسة الزراعية – كلية العلوم الزراعية والأغذية –جامعة الملك يصل
ص . ب ٤٤٢١ ، الأحســاء ٣١٩٨٢ ، المملكة العربية السعودية

ملخص:

تم إعداد وتنفيذ سخان شمسي لتدفئة الميــاه بورشــة قســم الهندســة الزراعية بجامعة الملك فيصل بالأحساء من المملكة العربية السعودية وذلــك لدراسة الأداء الحراري وكفاءة واقتصاديات ذلك الجهاز تحت ظروف السماء الصافية. يتكون ذلك الجهاز من وحدتين هما سخان شمسي وخزان معــزول لتخزين المياه حيث تبلغ المساحة الصافية لهذا الجــهاز ٢م^{٢} (٢م × ١م) . ثبت هذا الجهاز على إطار متحرك يمكن من خلاله ضبــط زاويــة سـقوط الشعاع الشمسي عند الصفر في أي وقت من اليوم . وكـــان المـــاء يــدور باستمرار خلال السخان الشمسي بواسطة مضخة مياه حيث يخــزن المــاء الساخن في خزان معزول سعته ١٦٠ لترا ولقد أخذ في الاعتبار عند إعــداد هذا السخان الشمسي الاختلافات اليومية والموسمية للظروف المناخية وكذلك التكاليف الاقتصادية للتصميم والتشغيل ، والسخان الشمسي يستخدم للتطبيقات العملية والتي عادة ماتعمل عند ظروف مختلفة من سرعة الرياح ودرجـــات حرارة الجو وكمية الإشعاع الشمسي .

أظهرت النتائج أن سرعة الرياح ودرجة حرارة الماء الداخل وكميــة الأشعة الشمسية الساقطة على سطح السخان الشمسي قد أثرت بقوة في الأداء الحراري للسخان الشمسي حيث بلغت متوســط كفــاءة الســخان الشمســي ٦٩,٣٤% .

كلمات مفتاحية : السخان الشمسي ، الطاقة الشمسية ، تدفئة المياه ، كفـــاءة السخان الشمسي ، استغلال الطاقة الشمسية .