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THERMAL PERFORMANCE TEST OF THE PARABOLIC SOLAR COLLECTOR

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Abstract

An experimental solar water heater was designed, built and installed on the roof of the Ag. Eng. Research Institute, Power and Energy department in order to study, test and evaluate its thermal performance for the parabolic solar collector. It was employed to focus the direct solar radiation on the absorber plate which was fixed on a parabolic dish, having a surface area 2.1 m^2 and the solar heater box dimensions were (1.25 X 1.25 m). Solar water heater 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 absorber plate can be set at zero. The operating fluid (water) was continually cycled through the solar heater using a water pump. After passing through the heater, the heated water was stored in an insulated storage tank. The daily heat removal factor, useful heat gain, heat transfer efficiency, heat losses, overall thermal efficiency, energy stored, and storage system efficiency of the solar water heater throughout the experimental work were found to be 98.60%, 9.271 kWh/day, 89.71%, 1.063 kWh/day, 74.29%, 8.217 kWh/day, and 88.63% respectively.

INTRODUCTION

A solar water heater for domestic and industrial use was utilized by Read (1978). He found that, in industrial heating process, the potential fuel savings are greater than domestic uses, but specifications are generally more stringent. The solar energy collected with correct control, provides about 70% of the energy required by the process system. Studying the possibility of utilizing solar energy for heating water has been the interest of many researchers (Arinze *et al.*, 1979; Abdellatif, 1988; Korayem *et al.*, 1990 and many others). Korayem, *et al.*, (1987) employed a solar collector of simple design concentrating type which can deliver heat at reasonably high temperature. The tremendous heat can be used through a stirling type heat engine for water lifting in developing countries. Abdel-ghaffar (1989) used a concentrating solar collector of dish type to focus the reflected direct solar radiation on a cooking pot in which Faba Beans is stewed. He found that the solar energy can be used effectively as a source of heat for cooking Faba-Beans to produce "medammis" of good quality similar to that produced by the traditional method. He also showed that, the first period of heating beans/water mixture to reach the boiling is important to reduce the actual heating time for producing "medammis" by solar radiation. The sunny days experiment revealed higher solar collector thermal efficiency than cloudy and dusty days. Also, the collector thermal efficiency increases whenever the wind speed decreases, and the climatologyical effect and collector-surface 1988. The temperature distribution at the focal plane of a paraboloidal concentrator type solar collector was experimentally determined and mathematical expression was developed by Korayem, *et al.*, 1990. He found that the concentrator collector received 90% from the sun rays incident and the receiver radius of 18 cm would be optimum.

The main objective of the present experimental work is to investigate under clear sky conditions, the effect of the following parameters which are extremely considered to be important in relation to solar water heater; 1) heat removal factor, 2) useful heat gain, 3) heat transfer efficiency, 4) heat losses, 5) overall thermal efficiency, 6) energy stored, and 7) storage system efficiency.

MATERIALS AND METHODS

A parabolic solar water heater was designed, constructed and installed on the roof of the Agricultural Engineering Research Institute (AEnRI) in order to test, study and evaluate its thermal performance under clear sky conditions. The solar heater box is square in shape and made of plywood 12 mm thick. The gross dimensions of the heater box are 1.25 m long, 1.25 m wide, and 0.20 m deep, the parabolic absorber plate with a net surface area of 2.10 m^2 as shown in (Fig.1).The absorber plate is formed of an aluminum dish type sheet 1.20 m diameter and 2 mm thick. It is painted with matt black paint. A 12 mm diameter and 22 m long copper pipe is attached to the upper surface of the absorber plate using wire ties each 10 cm long throughout the length of pipe. The copper pipe is also painted matt black paint. In the bottom and sides of the solar heater box, a layer of fiberglass wool insulation is placed to reduce the heat losses from the sides and back of the solar heater. To reduce the reflection of radiation and minimize the losses by convection, a clear glass cover 5 mm thick is placed to cover the heater box. After the water passing through the solar heater it is stored in a 200 liters insulated storage tank. The solar water heater is mounted on a movable frame in order to track the sun's rays from sunrise to sunset.

Eight (copper, constantan alloy) thermocouples are employed by data logger to measure the temperatures at various points in the solar water heater system. Three thermocouples are placed at equal distance around the solar heater to measure the copper pipe and absorber plate temperatures. The water inlet and outlet temperatures are measured using two thermocouples. Two thermocouples are evenly placed inside the insulated storage tank to measure the water temperature at different levels. The ambient air temperature is measured using one thermocouple placed in a weather shelter. A disk solarimeter is placed beside the solar water heater in a horizontal position to measure the solar radiation flux incident on a horizontal level. The flow rate of operating fluid is tested, adjusted and controlled once a day using a measuring cylinder with stop watch to be 2 L/min. All the previous sensors are connected into the data logging system in order to read and record data from the sensors.

To test, measure and compute the thermal performance of the solar energy system a series of equations (Abdellatif, 1988 and many others) were employed as follows :

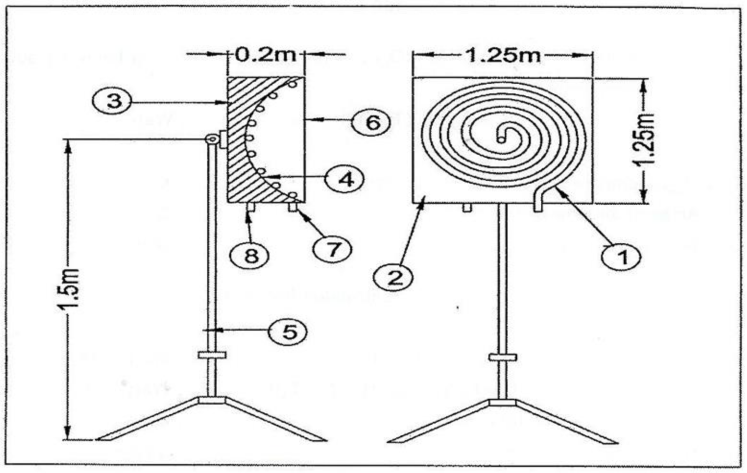

Fig. 1. Diagram of parabolic solar water heater

1. Copper pipe (12 mm diameter).
2. Panel box.
3. Fiberglass wool insulation.
4. Parabolic aluminum dish type sheet.
5. Movable frame.
6. Clear glass cover (5 mm thick).
7. Inlet hole.
8. Outlet hole.

Solar energy available (Q)

$$Q = R \times A_c \qquad \text{, Watt} \qquad (1)$$

where :

R = Solar energy flux incident on the collector surface. W/m^2

A_c = Collector surface area. , m^2

The absorbed solar radiation (Q_A) can be found from the following equation :

$$Q_a = \tau \, \alpha \, Q \qquad \text{, Watt} \qquad (2)$$

where :

τ = Effective transmittance of collector cover system. , decimal

α = Effective absorptance of the absorber plate. , decimal

The absorption efficiency is given by :

$$\eta_a = Q_a / Q \times 100 = \tau \, \alpha \qquad \text{, \%} \qquad (3)$$

The solar collector heat losses (Q_L) can be estimated from the following equation Abdel-latif (1988) :

$$Q_L = A_c \; U_o \; (T_p - T_a) \qquad \text{, Watt} \qquad (4)$$

Where :

T_p = Mean temperature of the absorber plate , °C

T_a = Ambient air temperature surrounding the collector , °C

U_o = Overall heat transfer coefficient , $W/m^2/°C$

The useful heat gain (Q_c) can be calculated from the following equation (Arinze *et al.*, 1979) :

$$Q_c = m \, C_p \, (T_{fo} - T_{fi}) \qquad \text{, Watt} \qquad (5)$$

$$Q_c = F_R \, [Q_a - A_c \; U_o \; (T_{fi} - T_a)] \qquad \text{, Watt} \qquad (6)$$

m = mass flow rate of operating fluid. , kg/s

C_p = Specific heat of operating fluid. , J/kg/°C

T_{fo} = Fluid outlet temperature. , °C

T_{fi} = Fluid inlet temperature. , °C

F_R = Heat removal factor , decimal

Heat transfer efficiency (η_c) can be computed from the following formula:

$$\eta_c = Q_c / Q_a \times 100 \qquad \text{, \%} \qquad (7)$$

Overall thermal efficiency (η_o) can be found from the following equation :

$$\eta_o = \frac{Q_c}{Q} \times 100 \qquad \text{, \%} \qquad (8)$$

Temperature rise (D_T) can be found from the following equation :

$$D_T = \frac{T_{fi} - T_a}{R} \quad , °C/W/m^2 \quad (9)$$

Energy stored (Q_s) can be found from the following equation :

$$Q_s = m_s C_p (T_e - T_b) \quad , Watt \quad (10)$$

m_s = Mass of water in the storage tank , kg

T_e= Mean tank temperature at the end of each hour. , °C

T_b= Mean tank temperature at the beginning of each hour. , °C

Ultimately, the storage system efficiency (η_s) can be determined from the following equation :

$$\eta_s = Q_s / Q_c \times 100 \quad , Watt \quad (11)$$

RESULTS AND DISCUSSION

Experimental testing was performed during one season (winter 2000 - 2001) under clear sky conditions. Solar water heater data have been collected and analysed for a total of 20 days over the last 75 days since December 2000. A total of five tests have been carried out during this time, and the average length of each test period was four days.

For the duration of the experiments, the daily average solar energy available was 12.479 kWh/day. Actual solar radiation data recorded on a clear day ranged from near zero to about 850 W/m^2 (Fig.2). Therefore the absorbed solar radiation varied from sunrise to sunset according to the incoming solar radiation and the average transmittance absorptance factor ($\tau\,\alpha$) as revealed in (Fig.3). The daily average absorbed solar radiation was 10.334 kWh/day with an average absorption efficiency (transmittance - absorptance combination) of 82.81%.

The daily average absorbed solar radiation (10.334 kWh/day) which was converted into useful heat gain to storage was 9.271 kWh/day with an average heat transfer efficiency of 89.71%. The hourly average useful heat gain to storage was plotted in (Fig.4). Mathematical analysis of the measured data revealed that, during early morning just after sunrise and just prior to sunset (when the solar radiation at these times is less than 300 W/m^2), very little useful heat was gained by the water passing through the solar heater. In some cases, it was noticed that, the operating fluid (water) dissipated some of its heat energy to the absorber plate particularly before sunset (when

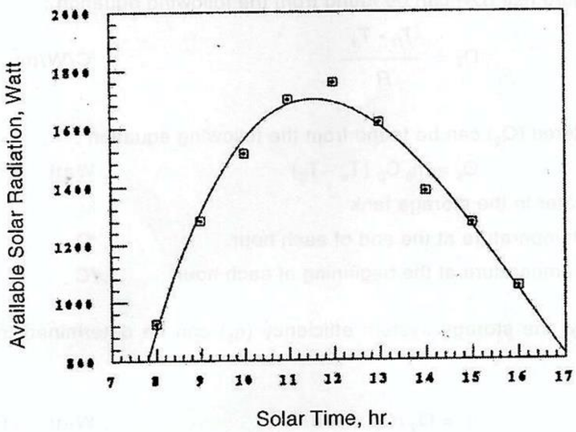

Fig. 2. Hourly average solar radiation available throughout the daylight.

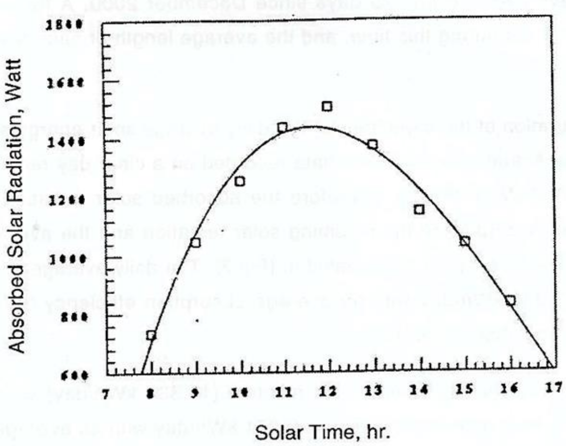

Fig. 3. Hourly average absorbed solar radiation throughout the daylight.

the operating temperature is lower than the water temperature and at the same time, the incoming solar radiation is less than 300 W/m^2). This phenomenon may be referred to the large area (2.1 m^2) and large mass (11.57 kg) of the absorber plate and thus, the amount of solar radiation required to increase the operating temperature (absorber plate temperature) above the water temperature was insufficient.

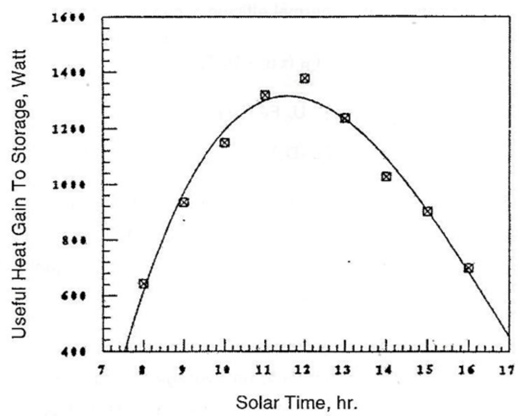

Fig. 4. Hourly average useful heat gain to storage.

The useful heat gain to storage was affected by the water inlet temperature, ambient air temperature surrounding the solar heater, and available solar radiation. As the ambient air temperature increased, the difference between the operating temperature of the solar heater and ambient air temperature decreased and heat gain is thus increased. As the water inlet temperature increased, firstly, the operating temperature of the solar heater increased above the ambient air temperature and heat losses are thus increased, secondly, the rate of heat transfer between the absorber plate and the water is reduced, making the heat transfer less efficient.

The daily average heat losses from the solar water heater was 1.063 kWh/day. The heat losses of the solar water heater were strongly affected by the water inlet temperature and ambient air temperature surrounding the solar heater.

The overall thermal efficiency of the solar water heater is a combination of absorption and heat transfer efficiencies. For the duration of the experimental work, the daily average overall thermal efficiency was 74.29%, consequently 25.71% of the solar energy available was lost (Fig. 5). The overall thermal efficiency of the solar water heater (η_o) was plotted as a function of temperature rise (D_T) to examine their relationship (Fig. 6). Regression analysis revealed a highly significant linear relationship (R = - 0.967; P = 0.001). The regression equation for the best fit was :

$$\eta_o = 81.654 - 268.740\ (D_T) \qquad (12)$$

The solar water heater overall thermal efficiency can be expressed as :

$$\eta_o = \frac{Q_c}{Q} = F_R\ (\tau\ \alpha) - U_o\ F_R\ [\frac{T_{fi} - T_a}{R}] \qquad (13)$$

$$\eta_o = F_R\ (\tau\ \alpha) - U_o\ F_R\ (D_T) \qquad (14)$$

$$\eta_o = a - U_o\ F_R\ (D_T) \qquad (15)$$

Equation (12) is definitely the numerical expression of equation (14). The y-intercept (a) is equal to the product of heat removal factor (F_R), transmittance of glass cover (τ) and absorptance of the absorber plate (α). The slope is equal to the product of heat removal factor (F_R) and overall heat transfer coefficient.

The daily average solar energy stored in the insulated storage tank during this experimental work was 8.217 kWh/day, with an average storage system efficiency of 88.63%. The solar energy stored in the storage tank was affected by the ambient air temperature and water temperature in the storage tank as well as useful heat gain to storage. The hourly average solar energy stored and storage system efficiency were plotted in (Fig. 7 and Fig. 8 respectively).

CONCLUSION

The solar water heater and storage system were operated satisfactorily during this experimental work on sunny days only. The thermal performance of the parabolic solar water heater is determined by its overall thermal efficiency in converting solar energy into stored heat energy. Overall thermal efficiency is a combination of absorption efficiency and heat transfer efficiency. The specific conclusions of this experimental work may be listed as follows :

1. The parabolic absorber plate was found to receive and absorb large amount of solar radiation and convert this tremendous amount into useful heat gain to storage.

2. The useful heat gain to storage, heat removal factor, overall thermal efficiency, and energy stored in the storage tank were found to be directly proportional to solar radiation available and ambient air temperature surrounding the solar heater, and in-

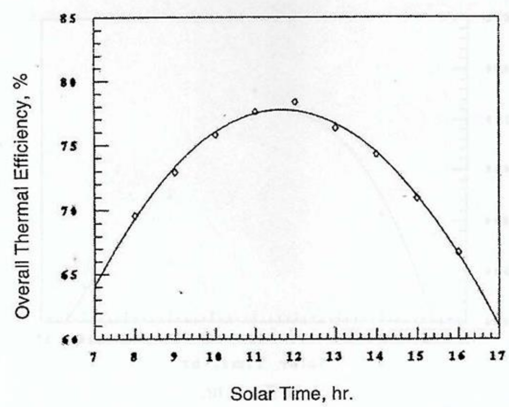

Fig. 5. Hourly average overall thermal efficiency.

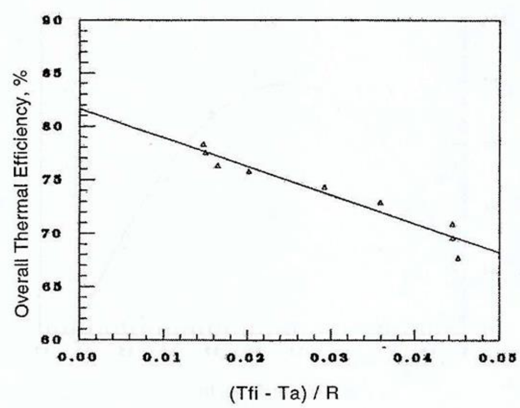

Fig. 6. Overall thermal efficiency versus temperature rise.

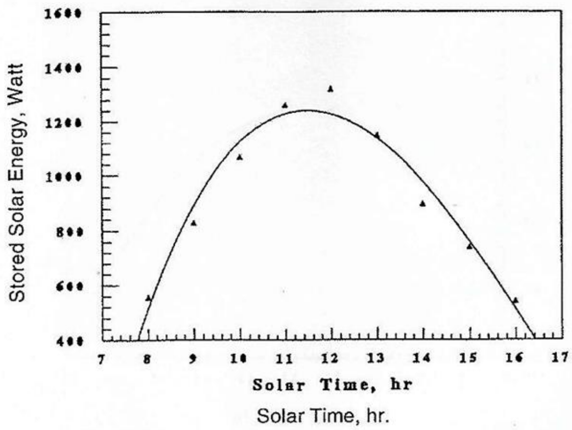

Fig. 7. Hourly average solar energy stored in the storage tank.

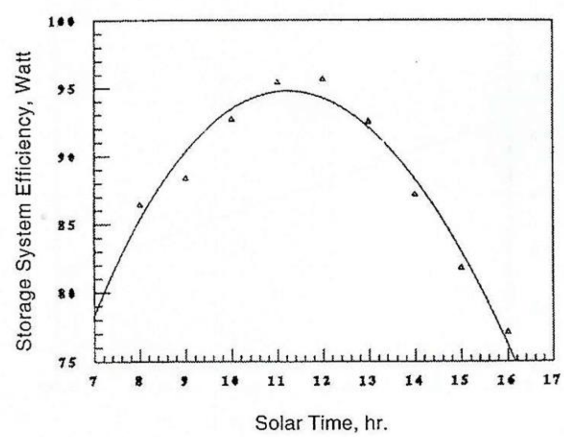

Fig. 8. Hourly average storage system efficiency.

versely proportional to water inlet temperature and overall heat transfer coefficient.

3. The heat losses of solar water heater were found to be directly proportional to water inlet temperature and inversely proportional to ambient air temperature surrounding the solar energy system.
4. The storage system efficiency is related to the overall thermal efficiency of the solar energy system.
5. The solar water heater which was employed in this experimental work can be utilized in several agricultural applications, such as protected cropping, greenhouses conditioning, providing hot water for livestock and poultry housing, and many other agricultural applications.

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اختبار الأداء الحراري لمجمع شمسي مقعر الشكل

احمد محمد قاسم

باحث بمعهد بحوث الهندسة الزراعية – مركز البحوث الزراعية – وزارة الزراعة.

تعتبر الطاقة الشمسية هي الحل لمعظم دول العالم النامي والمتقدم فهي طاقة نظيفة و صديقة للبيئة تغطى سطح الأرض بالكامل ولكن يعيبها أنها طاقة خفيفة تحتاج لتركيز و طاقة مشتتة تحتاج إلى أجهزة لتجميعها (المجمعات الشمسية) و تركيزها . كما إنها طاقة متغيرة من ساعة إلى أخرى و من يوم إلى آخر و من فصل الى الآخر على مدار السنة لذا فان هذا البحث يهتم بتصميم جهاز لتجميع الطاقة الشمسية و تحويلها إلى طاقة حرارية تمتص بواسطة وسط مائي يمر داخل المجمع الشمسي حيث يتم تخزينها فى خزان معزول سعته ٢٠٠ لتر. تم قياس الطاقة الشمسية الساقطة على سطح أفقي بواسطة جهاز قياس شدة الأشعة و تحويل هذه الطاقة المقاسة من سطح أفقي الى سطح مائل. و أيضا تم قياس درجات الحرارة باستخدام المزدوجات الحرارية (Thermocouple) بواسطة جهاز تجميع البيانات (Data Logger) وتم حساب أداء السخان الشمسي موضوع هذا البحث و كانت النتائج المتحصل عليها على النحو التالي :

١- اللوح المعدني الماص للأشعة و المقعر الشكل استقبل و امتص كمية كبيرة من الأشعة الشمسية الساقطة عليه و قام بتحويل هذه الكمية الكبيرة من الأشعة الى طاقة حرارية مكتسبة للتخزين فى خزان حراري للماء الساخن.

٢- وجد أن الحرارة المكتسبة و المستفاد بها للتخزين و معامل إزاحة الحرارة و الكفاءة الحرارية الكلية لهذا النوع من سخانات المياه الشمسية تتناسب تناسبا طرديا مع كمية الأشعة المتاحة و درجة حرارة الهواء المحيط بالسخان الشمسي كما وجد إنها تتناسب تناسبا عكسيا مع درجة حرارة دخول الماء للسخان الشمسي و معامل انتقال الحرارة الكلى.

٣- وجد أن كمية الحرارة المفقودة من السخان الشمسي تتناسب تناسبا طرديا مع درجة حرارة دخول الماء للسخان الشمسي و عكسيا مع درجة حرارة الهواء المحيط.

٤- كفاءة جهاز تخزين الطاقة الشمسية ترتبط بالكفاءة الحرارية الكلية للسخان الشمسي.

٥- يمكن استخدام هذا النوع من السخانات الشمسية فى العديد من التطبيقات الزراعية و ذلك عن طريق تخزين الطاقة الشمسية فى وسط مائي داخل خزانات معزولة تماما بغرض استخدامها فى عمليات الزراعات المحمية و تكييف البيوت المحمية. وامداد مساكن الماشية و الدواجن بالماء الساخن اللازم لها وكذلك فى كثير من التطبيقات الزراعية الأخرى.