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EXPERIMENTAL COMPARISON OF PERFORMANCE OF TWO TYPES OF SOLAR WATER HEATING COLLECTORS

مقارنه عملية لأداء نوعين من سخانات المياه الشمسية

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ملخص

تم في هذه الدراسة تحليل ومقارنة الأداء الحراري لنوعين من السخانات الشمسية، النوع الأول هو النوع العادي المكوّن من لاقط مسطّح والثاني قوسي. تم تصنيع السخانين بنفس المساحة السطحية ونفس الحجم والجودة. لتسهيل عملية تصنيع السخان القوسي تم عمله على شكل ٣ مسطحات مستوية بمساحات متساوية متصلة مع بعضها من الجوانب بزاوية ميلان مقدارها ١٥٠ درجة عن المسطّح الوسطي. تم دراسة أداء هذا السخان ومقارنة أداءه مع السخان العادي وذلك للاستفادة من أشعة الشمس في ساعات الصباح المبكّرة والساعات المتأخرة من بعد الظهر حيث تكون أشعة الشمس في تلك الأوقات عمودية على المسطّحات المائلة. تبيّن أنّ الأداء الأجمالي للسخان العادي هو أفضل من أداء السخان القوسي إلاّ أنّ هذا الأخير أبدى تفوّقا بمقدار ٧% من حيث الفعالية اللحظية في ساعات بعد الظهر المتأخرة.

ABSTRACT

The present study analyzes and compares the thermal performance of two types of water-heating solar collectors. The first type is a conventional flat-plate collector, and the second is a solar collector having an arc shape. The two collectors were fabricated having the same surface area, size and quality. For ease of fabrication, the arc collector was made of three flat panels of equal area joined together at their sides making an angle of 150° with the one at the middle. The arc collector was made and studied in an endeavor to attempt to capture sunlight in the morning and afternoon hours normal to the collector's surface. Tests were made and the comparison of the results indicated that the overall performance of the conventional collector is better than that of the arc collector. However, an improvement in the performance of the arc collector over that of the conventional one witnessed by up to 7 per cent increase in the instantaneous efficiency was attained during the late afternoon period.

INTRODUCTION

Considerable amount of work has been done on design and fabrication of the thermosyphonic solar water-heating systems, e.g. [Close (1962), and Gupta and Garg (1968)]. However, the performance of water heating solar systems depends largely on the performance of the solar collectors, which are the main component of the solar water-heating system. Thus, the measurement of the solar collector performance is a major and necessary step for the understanding of the total domestic water heating system. Analytical design procedures for flat-plate solar collectors have been advanced greatly in development [Howell et al. (1982), and Duffie and Beckman (1991)]. Nonetheless, it is preferable to base a system design on actual collector test data especially for newly designed types.

The two basic methods for the determination of fundamental collector characteristics are the intantaneous and the calorimetric procedures [Kreith and Kreider (1978)]. In the former procedure it is only required to measure simultaneously the mass flow rate of water circulating through the collector, its temperature difference, the collector inlet and outlet temperatures, and the insolation incident on the plane of the collector. The instantaneous efficiency in this case can then be computed from the relation [Hill and Streed (1976), and Simon (1976)]

$$\eta_c = \frac{q_u}{I_c A_c} = \frac{m_w C_P (T_{f,out} - T_{f,in})}{I_c A_c} \qquad (1)$$

Where η_c = solar collector efficiency,

q_u = useful heat output, W,

A_c = cross-sectional area of collector, m^2,

I_c =total solar energy incident upon the plane of collector, W/m^2,

m_w = mass flow rate of water circulating through the collector, kg/s,

C_P = specific heat of water, J/kg.K, and

$T_{f,out}$, and $T_{f,in}$ = temperature of water leaving and entering the collector, respectively, K.

The calorimetric procedure employs a closed system in which the time rate of change of temperature of a constant thermal mass is measured and related to the incident solar energy by the following relation

$$\eta_c = \frac{m_c C_{Pc} (dT / dt)}{I_c A_c}$$

Where m_c = the medium mass in the calorimeter, kg,

C_{Pc}= the medium specific heat in the calorimeter, J/kg.K,

T = the medium average temperature, K, and

t = time, s.

For the calorimetric procedure it is necessary to measure the incident solar radiation and the time rate of change of temperature of the mass in the system. For a complete review see the testing procedures prepared in 1976 by the National Bureau of Standards (NBS) [Hill et al. (1976)]. Nonetheless, the instantaneous method is the one that has been used in this work.

Theoretical thermal analysis of the solar water heating system can be found in [Kreith and Kreider (1978), and Duffie and Beckman (1991)], from which the efficiency of the flat-plate collector operating under steady-state conditions can be described by the following relationship

$$\eta_c = F_R(\tau\alpha) - F_R U_L\left(\frac{T_{f,in} - T_a}{I_c}\right) \qquad (2)$$

Where F_R = collector heat removal factor,

$(\tau\alpha)$= effective transmittance-absorptance product,

U_L = overall heat loss coefficient, $W/m^2.K$, and

T_a = ambient temperature, K

The present work aims to investigate and compare between the performance of two types of solar water collector systems that work by thermosyphonic action (natural circulation). The first type is a conventional flat-plate collector that is highly used in the Middle East region, and the second type is an integral one having an arc shape. The purpose of the latter collector was to try to receive morning and afternoon solar radiation normal to the absorber plates surface by tilting panels towards the east and west orientations, although this was at the expense of less mid day capture of normal radiation. Both collectors were made having the same surface area and quality. Note that in natural circulation systems, piping used should not be smaller than half-inch national pipe thread (NPT) [Kreith and Kreider (1978)].

EXPERIMENTAL APPARATUS AND PROCEDURE

Two solar water-heating systems with natural circulation were constructed, a conventional flat-plate collector and an arc-plate collector. Each system has a depth of 0.1 m and collector area of 1.2 m^2.

The flat-plate collector shown in Fig. 1 incorporated the main familiar parts used in conventional flat-plate collectors. The parts comprised of a glass cover of 4 mm thickness. 12 half inch diameter longitudinal riser pipes 0.9 m long each welded at both ends to two horizontal upper and lower header pipes. 1.25 inch diameter each. The distance between the centerlines of each two successive pipes is 100 mm. The pipes are welded on top of an absorber galvanized iron plate of area 1.2 m x 1.0 m with a thickness of 1.2 mm, and the whole of the inside was painted Matt black

Rockwool insulation of 50 mm in thickness was placed at the absorber backside and on all sides. The entire assembly was enclosed in a casing made out of a galvanized iron sheet metal 1 mm thick. The outlet (upper) header is connected through a properly insulated 0.75-inch steel pipe to an insulated cylindrical hot water storage tank, whereas the inlet (lower) header is connected to the tank by a half-inch steel pipe. The tank is made out of galvanized iron and has a length of 0.5 m and a diameter of 0.3-m (71-liters capacity). The tank insulation was a 50-mm thick rockwool covered totally by a thick cloth. The water level in the storage tank is kept such that a small room for air is available to allow for water expansion when heated.

The arc collector shown in Fig. 2 forms an arc of one-quarter length of a circle circumference. This collector is an integral one comprising of three flat panels of equal area with each panel having an area of 0.4 m x 1.0 m joined together at their sides making an angle of 150° with the middle panel. The number, spacing, length and diameter of riser pipes, headers, and size of the absorber plate, insulation, glass cover, enclosure and cylindrical hot water storage tank are the same as those for the conventional collector type described above. Furthermore, the water level, head and quantity were the same for both types of collectors.

In each collector, the water temperature at inlet and outlet are measured using calibrated thermocouples of type K (Nickel-Chromium / Niekel-Aluminum) with a digital thermometer readout. The water temperature inside the storage tanks was measured using thermocouples positioned at the tank center (see Figs. 1 and 2). Pressure taps were inserted into inlet and outlet piping connected to a U-tube manometer to measure the pressure drop through each collector. A pyranometer was attached to the side of the conventional type collector in order to record the total incident insolation over the tilted surface.

The measuring device of water flow rate should cause only minor pressure losses, since the driving force during thermosyphonic action is of a buoyancy type and it is very small. Such a device like the high accuracy non-contact gauging with a magnetic sensor [Kabariti and Batarseh (1993)] can be used. Another method is by calculation of the flow rate by considering the temperature and density distribution in the system circuit and resulting flow rates based on pressure drop calculations and the assumption of a quadratic density temperature relationship as outlined by Close (1962) and Desa (1964). However, in this work a direct measuring method was employed. This method required the installation of a transparent plastic tube of 16.00 mm inside diameter in the collector outlet pipe. The injection through a hypodermic needle of a drop of a dye in the flow stream just before the transparent tube, and the measurement of the time that took the drop to travel a known distance allowed the deduction of the water flow rate.

The two systems were positioned side by side on a yard next to the laboratories of the mechanical engineering department at Mu'tah University. Both collectors were tilted towards the south at an angle of 29° from the horizontal level, which is the annual optimum tilt angle around 32 latitude regions as recommended by El-Kassaby (1988).

The total sun insolation and the various temperatures at inlet, outlet, ambient, and tank were recorded instantaneously every hour for both types of collectors over the course of a day for many days in the summer of 1997. The mass flow rate was also measured hourly as well as the pressure drop. The data obtained were applied into equation (1) to evaluate the instantaneous efficiency every hour for both collectors. The total radiation was also recorded during the whole day at the south east facing and south west facing panels for comparison with that at the south facing panel. Furthermore, to make sure that the temperature of water inside the two storage tanks were identical early in the morning, both of the systems were drained and refilled before commencing some of the performance tests. Note that the performance tests were conducted without hot water withdrawal from the systems.

RESULTS AND DISCUSSION

Comparison between the experimental results of the thermal performance tests of the two solar energy collector systems are made on the basis of the system inlet and outlet temperatures, storage cylinder temperature, delivered energy and collection efficiency.

The global solar radiation and ambient temperature in typical summer days during the course of running the experiments are presented in Fig. 3. The radiation intensity has reached around 1000 W/m^2 at mid day and the temperature about 30°C in the afternoon. Fig. 4 displays the solar radiation incident upon each of the three panels of the arc collector. Since there was only one pyranometer available, the radiation incident on each panel was recorded in a different day. However, the maximum insolations in these days were almost identical so that comparison could justifiably be made. It can be seen that the daily radiation falling on the sout east oriented panel had its maximum at two hours before mid day (10 a.m) with very low radiation after 4 p.m. On the other hand, the daily radiation falling on the south west oriented panel was affected directly by solar radiation mainly after 8 a.m with a maximum value obtained at two hours after mid day (2 p.m). The south oriented panel had received maximum radiation at mid day with symmetrical radiation about the maximum. The total daily global radiation has shown that the amount of radiation incident on the south oriented panel was greater than that incident on either of the other two panels by about 8%. It is apparent also from Fig. 4 that the incident radiation on the whole of the arc collector panels was lower than that incident on the south oriented flat-plate collector. The drop in incident radiation amounted to about 5.3%.

The inlet, outlet, and storage temperatures for the two systems in typical summer days are shown in Fig. 5. The trends indicate that the storage temperature of the conventional system is almost the same as that of the arc system in the morning but slightly higher (about 2-3°C) in the afternoon. As for the inlet temperature, it is shown to be significantly higher for the conventional system in the afternoon. This is in contrast to the outlet temperature that is seen to be higher in the arc system, noticed only in the morning and afternoon periods, but lower around mid day time. This may be attributed to the more uniform thermosyphon action on water flow in the conventional type as compared to the presumably thermosyphon circulation within and between the three panels of the arc-type collector. The curved shape of the arc collector involved higher pressure drop as has been measured using the U-tube manometers across both systems which has been found to be about three times that of the conventional one. In thermosyphonic systems, it is well known that the pressure drop and uniformity of the flow play a major role in the system performance. This resulted in lower mass flow rates of water in the arc collector during most of the day except about a couple of hours in the afternoon as can be observed in Fig. 6. In this figure, the measured mass flow rates of water in the two systems in typical summer days are plotted against the day times. Maximum flow rates occurred around mid day.

The hourly increase in storage temperature in reference to a base morning storage temperature taken at 9 a m is tabulated for both systems in Table (1) for the day 20th of July 1997. It is clear from the table that the conventional collector starts off almost the same as the arc one, but by afternoon the former ends up maintaining higher increases in storage temperature.

Table (1) Hourly increase in storage temperature in reference to that at 9 am. (°C).

Time (hr)	9	10	11	12	13	14	15	16	17	18	19
Flat-plate	0	5	14	24	31	34	36	36	32	29	26
Arc-plate	0	6	14	23	29	32	33	32	29	27	24

The instantaneous efficiency curves are plotted for the two systems vs. time in Fig. 7. The trends embark to behave similarly with efficiency differences of up to 5 per cent in favor of the conventional collector, but late in the afternoon periods the difference has reached as much as 7 per cent in favor of the arc system.

Fig. 8 shows the correlation plot of η_C vs. $\Delta T/I_C$ for the two types of collectors where $\Delta T = T_{f,in} - T_a$. A best-fit line was drawn for each system to represent the data points that are scattered around the lines. On this graph $F_R(\tau\alpha)$ corresponds to the intercept of the best fit through the experimental data points on the ordinate, while $F_R\ U_L$ is the absolute value of the slope of the line. It seems that both of the two collector systems have nearly similar characteristics regarding their heat-loss conductance. It is worth noting that the wind speed at the site of the experiments was measured during the data collection period and was found to be less than 2 m/s.

The inlet-outlet temperature differences for the two collectors are presented in Fig. 9. Up till 1 p.m. the trends seem to be identical although greater values of temperature difference for the arc collector were measured. However, a noticeable increase in the conventional collector temperature difference is observed in the afternoon up to 4 p.m before it dropped sharply in late afternoon periods. This is in contrast to the rather uniform with only slight gradual increase in the temperature difference of the arc collector that persists on to late afternoon periods.

Fig. 10 portrays the hourly useful heat output from the two systems along with the incident solar energy. The conventional system delivers higher energy around mid day, but in the late afternoon periods the arc collector outperforms the conventional collector.

CONCLUSIONS

The thermal performance of two types of tube solar energy collectors working on thermosyphon action is tested systematically. The test results have indicated the following conclusive remarks:

1- The total daily radiation incident on the flat-plate collector is greater than that incident on the arc-plate collector by as much as 5.3 per cent in summer time.

2- In general, the water flow rate driven by the buoyancy force is greater in the conventional type collector than in the arc type collector, probably due to the lower pressure losses in the former system.

3- The conventional type collector seems to outperform the arc type collector chiefly around mid day periods by as much as 5% increase in the efficiency. although the arc collector possessed higher efficiency late in the afternoon. Furthermore, the conventional collector is observed to increase the storage temperature more than the arc one in the afternoon.

4- The conductance heat-losses, in general, were seen to be nearly identical.

5- Generally, the overall performance of the conventional collector was slightly higher than that of the arc collector, but an improvement in the performance of the latter over that of the former was noticed late in the afternoon.

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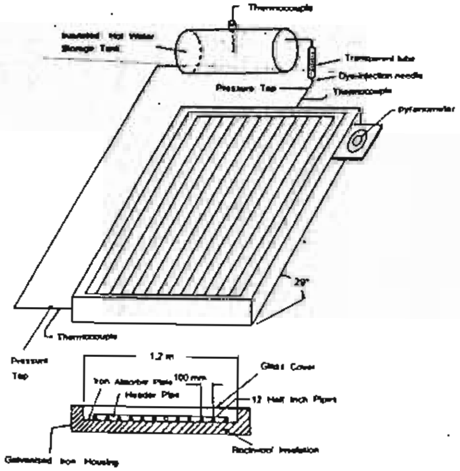

Fig. 1 Flat-plate type collector.

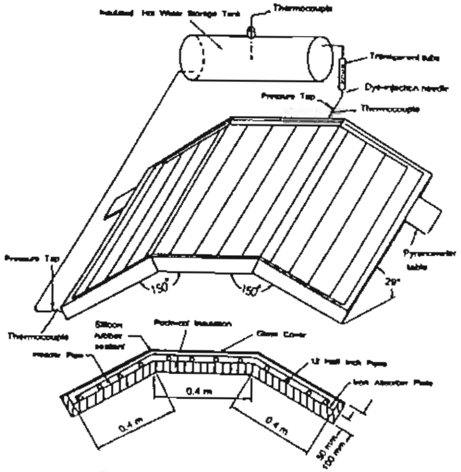

Fig. 2 Arc-plate type collector.

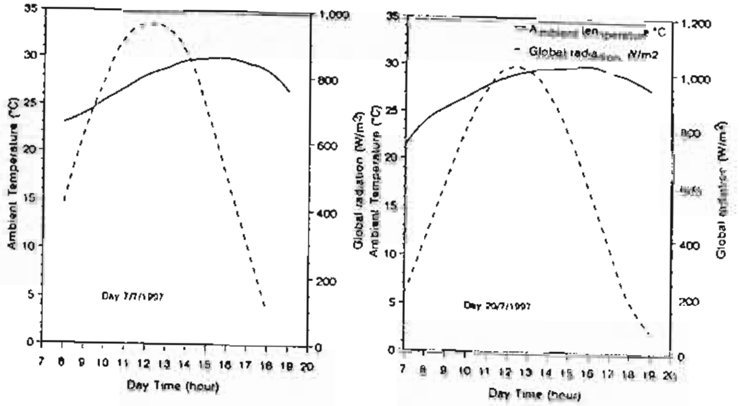

Fig. 3 Global radiation and ambient temperature variation in typical summer days.

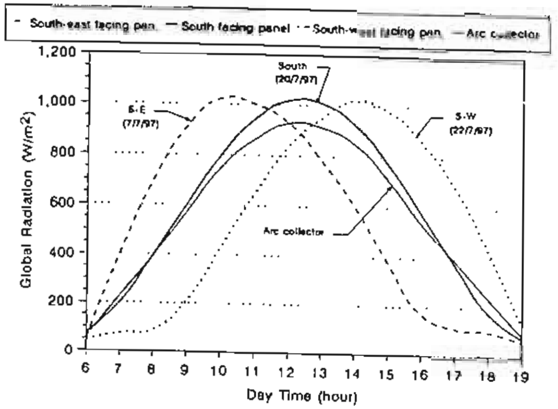

Fig. 4 Global radiation incident on each of the three panels of the arc collector and the arc collector as a whole.

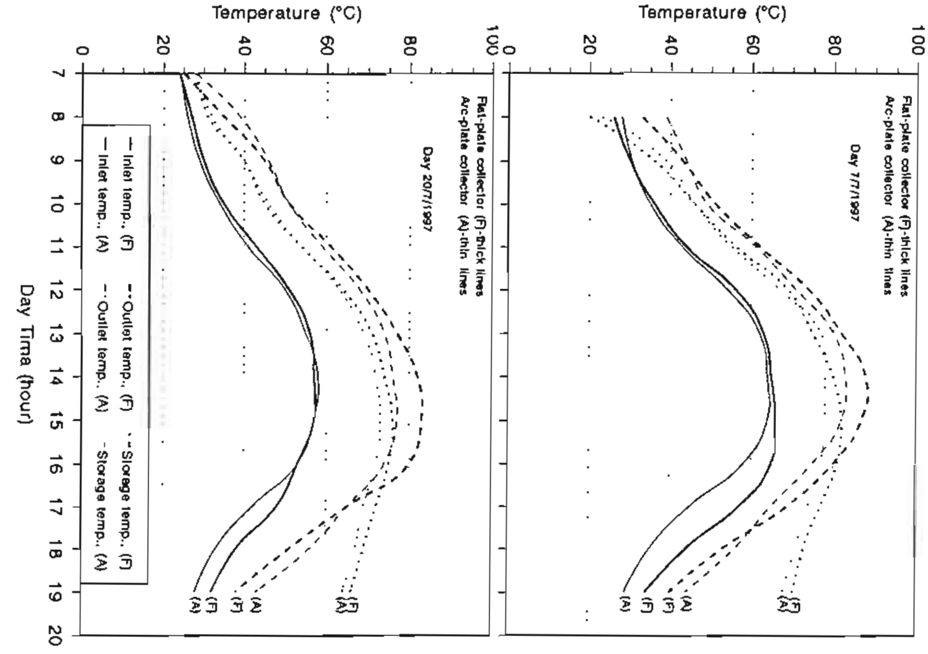

Fig. 5 Variation of inlet, outlet and storage temperatures for tha two collector types.

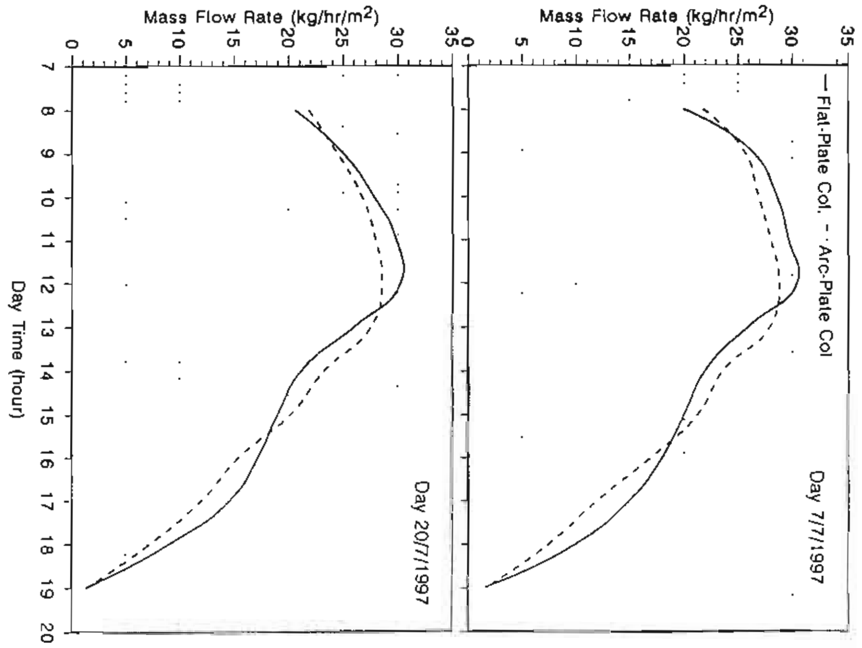

Fig. 6 Mass flow rate for the two collector types.

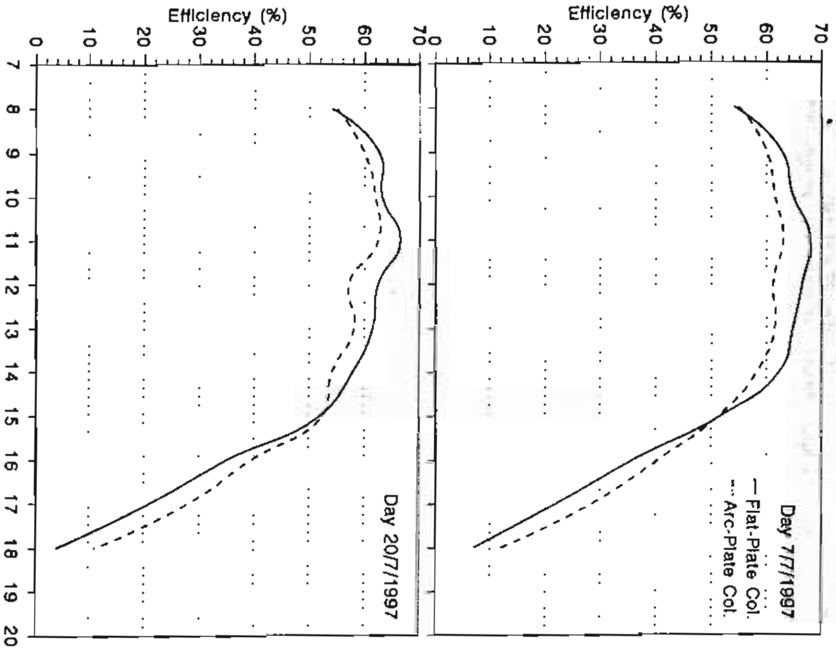

Fig. 7 Instantaneous efficiency of the two types of collectors.

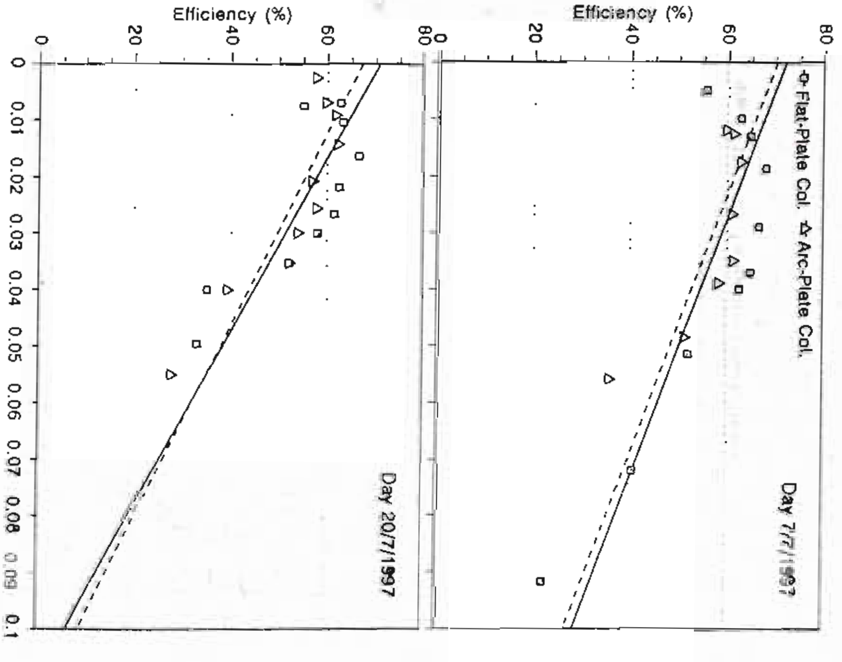

Fig. 8 Performance curves of the two types of collectors.

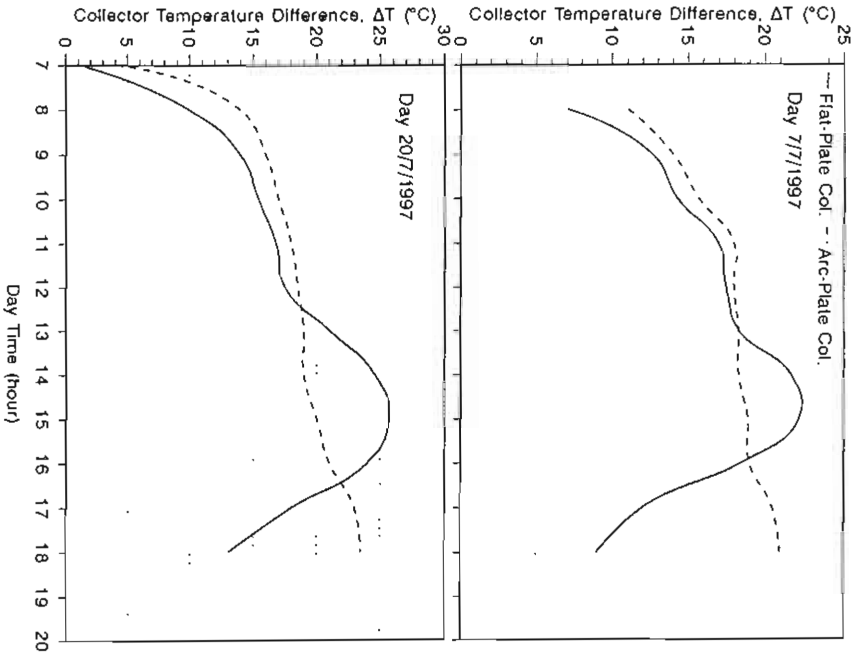

Fig. 9 Collector temperature difference (out-in) during typical summer days.

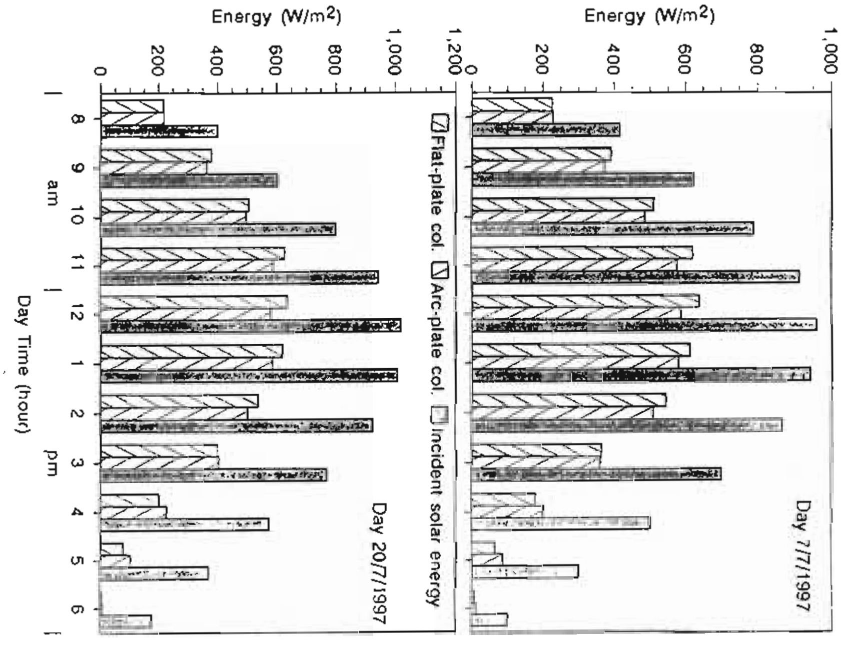

Fig. 10 Hourly useful output energy for the two systems.