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Design and experimental analysis of low-cost heat water solar collectors

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ABSTRACT

Owing to fossil fuels' consumption and environmental pollution, it is necessary to make efficient use of energy based on the different renewable energy sources such as solar energy. The present research has focused on the design, construction, and assembly of a train of solar energy collectors consisting of five concentrators, which individually have significant differences in the arrangements focus tube reflective surface and the greenhouse effect. The collectors are operated under the same environmental conditions. In the analysis presented on the train of solar energy collectors, a theoretical–experimental study was performed on the different reflecting surfaces of each collector, such as the mirrors' reflecting surface, reflecting surface of the 316 L stainless-steel mirror polished, reflecting surface of the aluminum foil's reflective surface with an aluminum paint, surface reflective type 304 stainless steel-mirror polish. The present study was developed to analyze and discuss the increase in the useful energy (Qu, kW) and efficiency of the collector (n, %). The results of the study have that the highest average increases in performance and energy experimental tool for each collector are in the following order: 316 L stainless-steel collector (50.5 kW with 37%) > 304 stainless-steel collector (43.1 kW with 31.6%) > aluminum collector (35.2 kW with 25.8%) = mirror collector (35.5 kW with 25.6%) > aluminum paint collector (0.4 kW with 0.3%). The best performance was obtained from the stainless-steel solar collectors, regardless of the type of stainless-steel quality. Thus, it is advisable to use the experimental model itself as a supporting tool for drawing up the computer design. In fact, the use of 316 L or 304 stainless-steel low-cost heat water solar collector represents an environmentally friendly alternative.

Keyword: Water solar collectors

1. Introduction

From the perspective of human beings, the solar power is regarded as an inexhaustible source of energy, whose profitability depends on the research efforts undertaken, the financial resources available at one's disposal for undertaking its study, and the interest shown towards its development. We live in a society which is under constant pursuit of conducting research and development with a crew to producing

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better goods and services, which directly contribute to energy expenditure [1–7].

The so-called renewable energy can help us toto solve any energy supply problem that is likely to inevitable appear. The renewable energy is defined as "Energy obtained from continuous energy flows and recurring in the natural world" [6].

1.1. Solar collectors

While water heating is usually brought about with the use of wood, coal, oil, gas, or any other fuel, it is also possible to heat water with solar energy, i.e. the energy emitted by the sun. Nowadays, direct use of solar radiation that is transformed by the corresponding photo-thermal and photovoltaic devices has become important. The solar panels are components which are so designed as to capture sunlight and transform it into a useful energy. These solar panels are of two types: photovoltaic modules and solar thermal collectors. These panels are also known as solar collectors, a special type of heat exchanger, which converts the solar radiation into a usable thermal energy a variety of applications such as obtaining sanitary hot water, heating of pools, domestic use heating in hotels, and in general for all those industrial activities where the process heat temperature does not exceed 60°C. With this type of energy resource it is possible to bring down by more than 25% of conventional energy consumption in homes [7–20].

The present work is based on the search for affordable and low-cost materials to build solar equipment. Therefore, the experimental analysis carried out by the present work to show which equipment yields better results into useful energy and efficiency. To achieve the said objective, we need to design, construct, and install solar concentrators with different surface characteristics in the solar concentrator connected in parallel.

Two types of solar collectors were used: compound parabolic collectors (CPCs) and parabolic concentrating collectors (PCCs) all having in common greenhouse effect, double-jacketed tube focus, and matte black receiver; the characteristics of their surfaces are as follows:

No.	Name	Feature
1	PCC	Mirrors
2	PCC	316 Stainless steel
3	PCC	Aluminum
4	PCC	Aluminum paint
5	CPC	304 stainless steel

2. Materials and methods

As far as the design criteria are concerned, a solar heater runs on two fundamental principles: the natural circulation and the greenhouse effect, based on the previous information, the planning of work leads to drawing design of equipment installation. The DIA software is used for the same, which refers to General purpose computer program for creating diagrams, network diagrams and, diagrams of electrical circuits. A train of solar concentrators is shown in Fig. 1, which shows the manner in which these concentrators are connected using different patterns. It can also be observed that this design housing a number of concentrators illustrates how each solar collector can be operated individually. Thus, it is even possible to freely access the daily data to make a comparison of the performance between all of them.

We performed a cost analysis of the different materials that could be used to effect the installation of solar concentrators. The suggestions put forth went in favour of the materials mentioned below: copper and CPVC pipe plus. After reviewing the cost estimates which were based on the materials, a decision was made to install these solar concentrations with copper material.

2.1. Concentrator description

A solar concentrator is designed on a base consisting of a sheet of steel drum with a 216.5 L capacity, which is cut vertically into half. Its dimensions are 85 cm long with a diameter of 57 cm. The solar concentrator is mounted on a structural base, which allows it to be floor mounted. The exterior is painted matte black and mounted inside the concentrator surface.

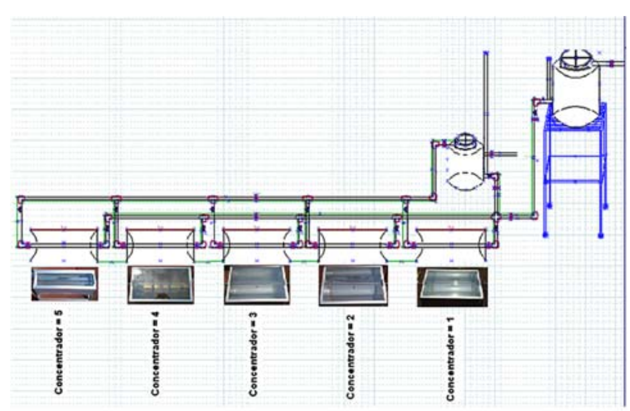

Fig. 1. A general scheme of a train of solar collectors with the fittings and tanks.

2.2. Concentrator surfaces

The concentrator is an optic system, which is responsible for leading the solar radiation to the receiver. There are different types of surface concentrators, which are important as they enhance the efficiency of collection devices. Based on these findings and with a view to bringing about a comparison between these collectors, the reflecting surfaces of all the five concentrators were modified as follows:

(1) Arrangement with mirrors: the mirror surface consists of 34 pieces of mirrors of 84 cm long, 2 cm wide, and 3 mm thick, fixed on the inside of the hub as shown in Fig. 2.
(2) Arrangement with a stainless-steel sheet: the reflective surface comprises a steel sheet 16 gauge 316 L stainless, with a mirror polish inside and rolled a half-round, shown in Fig. 3.
(3) Aluminum foil arrangement: the reflective surface consists of an aluminum foil rolled to a half-round, with the inner side polish, shown in Fig. 4.
(4) Arrangement with a reflective paint: the mirror surface is an oil painting with particles for high temperature aluminum sheet painted on the inside of the collector, shown in Fig. 5.

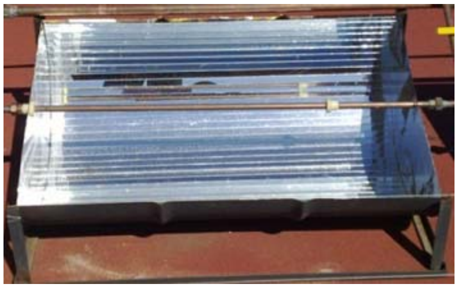

Fig. 2. Mirror concentrator.

Fig. 3. 316 stainless steel concentrator.

Fig. 4. Aluminum foil concentrator.

Fig. 5. Aluminum oil painting concentrator.

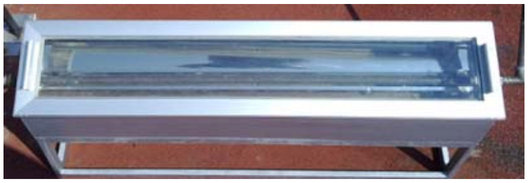

Fig. 6. 304 Stainless steel sheet concentrator.

(5) Arrangement with a stainless-steel sheet: the reflective surface comprises a sheet of type 304 stainless steel 16 gauge with a mirror polish inside, rolled by way of compound parabolic concentrator, as shown in Fig. 6.

2.3. Receiving surface

The receiver system is an element where the radiation is absorbed and converted into some form of energy. The receiver used for the concentrators consists of a copper tube half inch diameter by 90 cm length painted matt black to have better sunlight capture.

The focus tube, jacketing the copper tube, is a tube bulb which consists of two glass tubes of different diameters joined together with screw caps on the ends, to exploit the greenhouse effect better. To make better use of the greenhouse gases and prevent any heat loss in the concentrator, it was decided to employ a cover glass 85 cm in length by 57 cm width and 5 mm thick with aluminum frame and tabs to allow free movement.

2.4. Assembly and instrumentation

The train consists of five solar concentrators with different arrangements, east-west (shown in Fig. 7).

The areas of interest for this research are the concentrator and the receiver; it is in the latter, that exchange of solar energy with heat takes place. Hence it is very much important to monitor the temperature at the beginning and at the end of the receiver tube. The temperature was measured with the help of T-type thermocouples and software acquisition card and computer equipment were employed. The thermocouples were designed in such a manner as to be inserted into a well according to the present work's needs. These thermocouples consisted of a male half perforated brass plug, which was welded to a flexible copper tube, which served as a guide for the thermocouple (shown in Fig. 8).

Fig. 7. Overview CIICAp rooftop concentrators, power piping and tank and receiving tank.

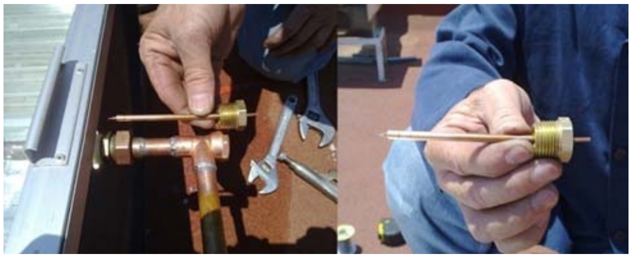

Fig. 8. Design of thermocouples well.

2.5. Energy calculations

To understand the phenomena of energy transfer from a concentrator system to a fluid receiver, establishing a thermodynamic model where the system under study is the recipient of the concentrator, Eq. (1) was used to develop the model [9].

Energy balance, manifold at a given instant of time, is the difference shown between the energy absorbed by the absorber plate and the energy lost.

$$Q_u = F_R A_a \left[I_S - \frac{A_\gamma}{A_a} U_l (T_i - T_a) \right] \times \left[I_S - \frac{A_\gamma}{A_a} U_l (T_i - T_a) \right] \tag{1}$$

where Q_u is the amount of useful energy extracted per unit of time, F_R is the heat removal factor, I_S is the useful solar irradiance. A_a is the area of opening of the hub, A_γ is the area of the absorber. U_l is the overall coefficient of losses of the collector; T_a is the ambient temperature and T_i is the average surface temperature of the collector plate.

The heat transfer coefficient (the overall coefficient of loss) is defined by convective losses in the following manner using Eq. (2) [9]:

$$U_l = hw + hr \tag{2}$$

where hw is the convective coefficient and hr is the radiative coefficient.

Performance of the concentrator. The instantaneous performance of a manifold is defined by Eq. (3) [9]:

$$h = \frac{Q_u}{A_c \cdot I_S \cdot R_b} \tag{3}$$

where A_c is the area of the receiver, I_S is the solar irradiance which is useful, and R_b is the geometric factor.

3. Results and discussion

It is common practice to determine the thermal performance of the concentrators to obtain instantaneous values of the efficiency from values and of incident radiation on the collector. These are: room temperature, inlet and outlet temperatures of the working fluid.

Below are analyzed and presented the theoretical and experimental results obtained in the present work. Using the experimental values it is possible to obtain the useful energy output per day for each of the concentrators. Based on the same values, I_S, the useful energy concentrator performance in each minute can be evaluated during the collection of data at different temperatures. It was observed, experimentally and theoretically, that the concentrators are much more efficient in a normal working day.

The outlet temperatures are presented in the receiver of each of the PCCs. For day conditions. Fig. 9 shows the outlet water temperatures throughout the day, and we noted that concentrators # 2 and # 5 are the best in providing heat to the system. Whereas, Table 1 shows the useful energy and performance of the concentrators, being concentrator No. 2 the most stable in terms of the energy input to the system and owing to its design features and material properties.

Fig. 10 shows the maximal and the minimal temperatures reached during the day at different days for each of the concentrators. In this figure, it can be observed that concentrators 2, 3, and 5 are the major contributors to the temperature system.

The day wise energy efficiency achieved at different days for each of the concentrators is shown in Fig. 11. This figure shows that concentrators 2 and 5 showed the best reported efficiencies. However, this comparison did not apply to concentrator 4 whose surface did not get ansy direct light nor was the light reflected by the atmosphere, being in this case the efficiency near zero or zero.

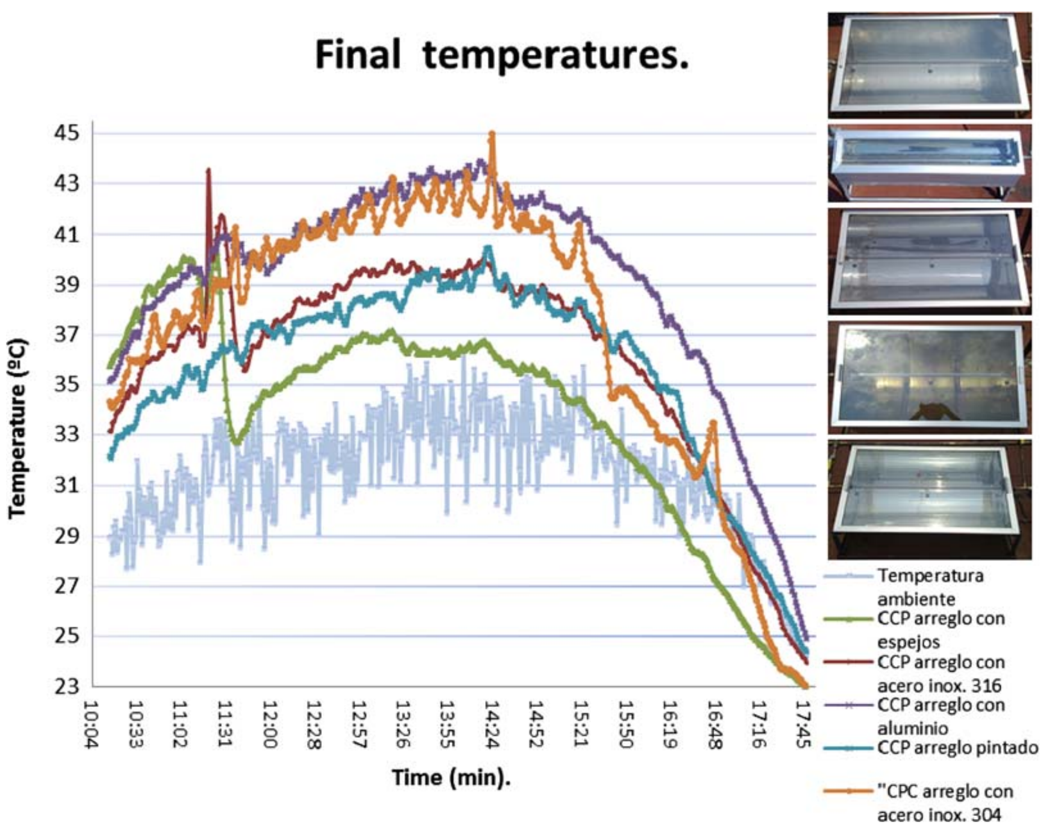

Fig. 9. The water outlet temperatures for the five concentrators, 5 January 2011.

Table 1
Useful energy and performance of the concentrators, 5 January 2011

No.	Solar concentrator	Useful energy Q_u (kW)	Performance of the concentrators ($h = \%$)
1	PCC. Mirrors	40.3	29
2	PCC. 316 Stainless steel	53.0	39
3	PCC. Aluminum	36.5	27
4	PCC. Aluminum paint	−43.0	−31
5	CPC. 304 stainless steel	49.2	36

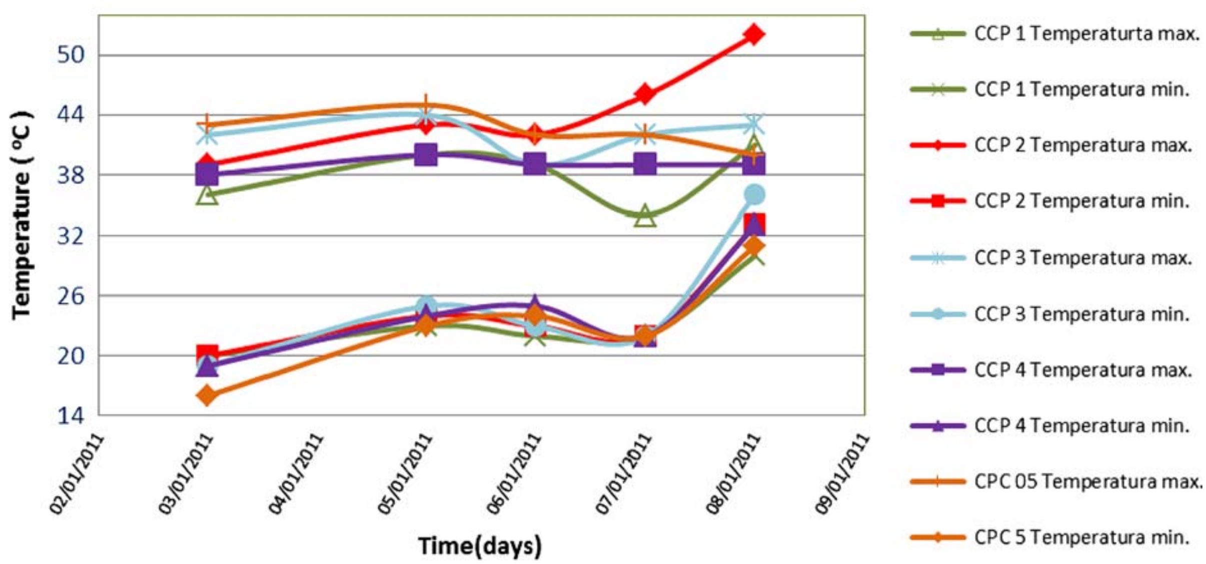

Fig. 10. Highest and lowest and lowest temperatures at different days for all concentrators.

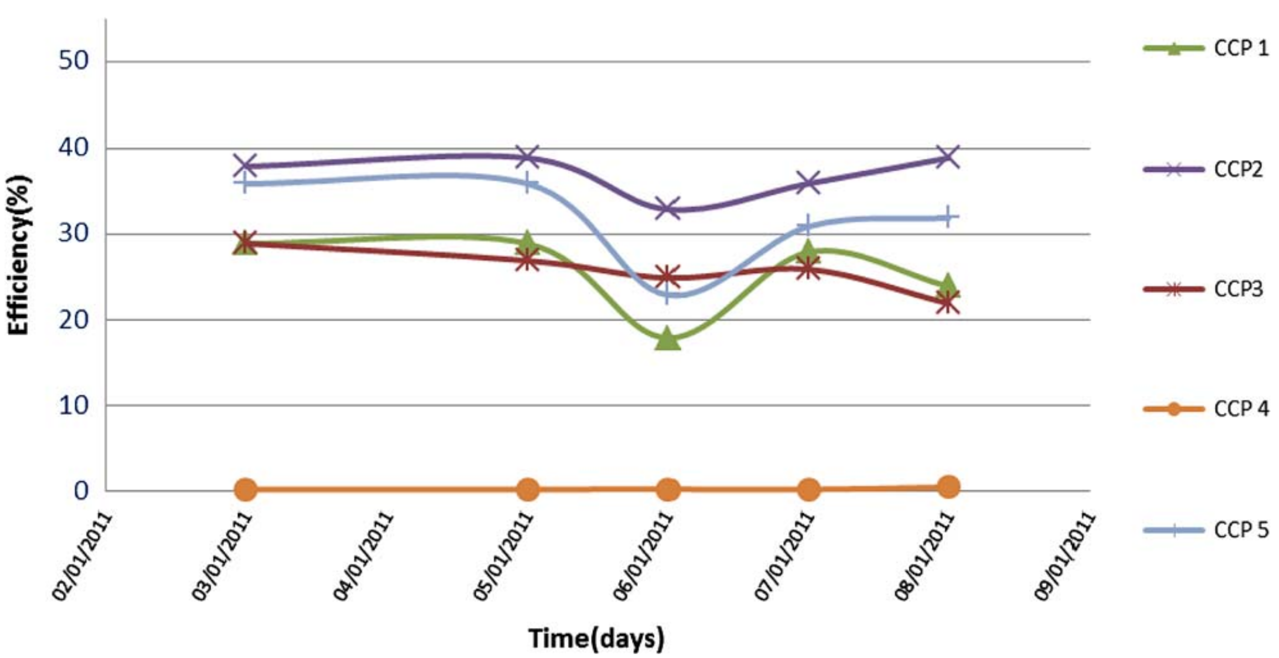

Fig. 11. Efficiency reached different days for the five concentrators.

Fig. 12 shows the useful energy that is reached during the day at different days for each of the concentrators. Concentrators 2 and 5 provide more useful energy in the first 3 days of measurement, while the number 2 maintained practically constant the useful energy throughout the test period. There are differences in design between these two concentrators, being concentrator 2 in accordance with a parabolic reflective surface of stainless steel 316 L, with a mirror polish inside. Concentrator 5 under a parabolic reflector surface made with type 304 stainless steel with a mirror polish inside.

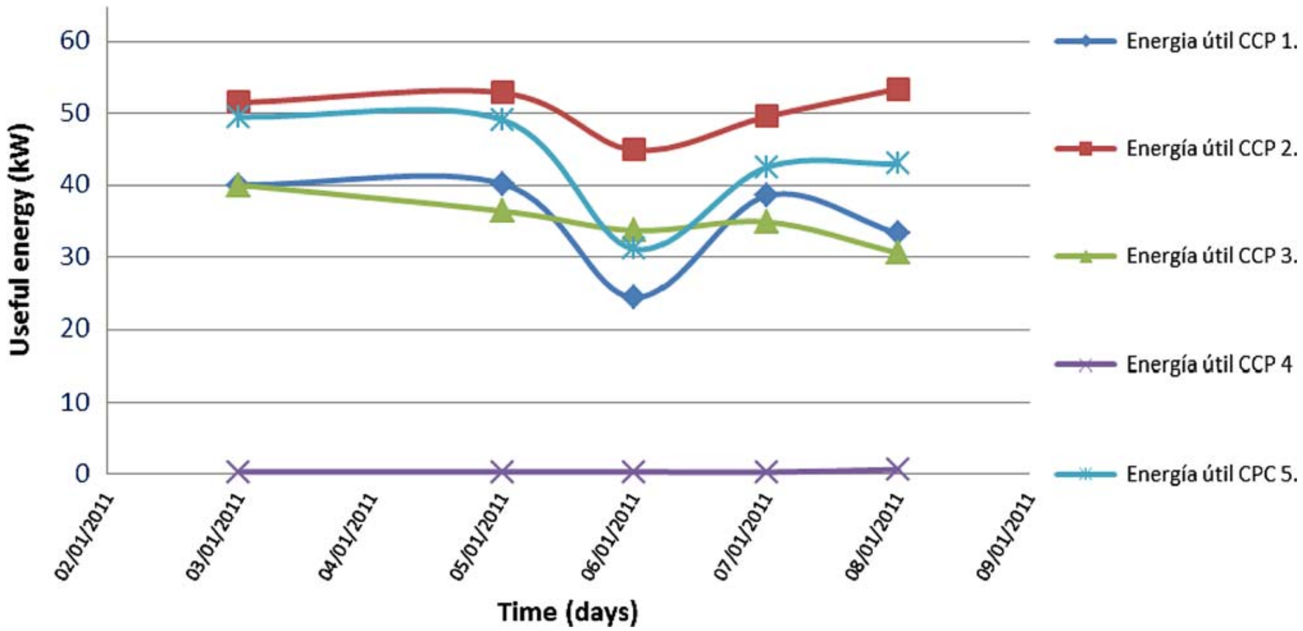

Fig. 12. Useful energy achieved at different days for the five concentrator.

Table 2
Cost of each collector

No.	Name	Feature	Cost (US$)
1	PCC	Mirrors	123.66
2	PCC	316 Stainless steel	292.00
3	PCC	Aluminum	209.28
4	PCC	Aluminum paint	133.18
5	CPC	304 stainless steel	157.53

Table 2 shows the unit cost of each collector load according to the design criteria.

4. Conclusions

The conclusions are presented for each concentrator and in the order they were installed. The first one (No. 1): PCC arrangement with mirrors, the concentrator for the time period reported in figures and tables shows a low heat input to the system (underperformance), for moreover the ability of the mirrors to reflect light is highly effective. It would be feasible to consider a sheet of plate glass as a concentrating plate.

The second concentrator is the PCC (No. 2) in accordance with type 316 stainless steel. This collector, based on the results, is the best collector, has brought useful energy, and has given a better performance to the system. The properties of the thermal stainless-steel mirror polish achieved a better efficiency throughout the day as directly affected by increasing awareness of the direct and diffuse light.

The third of the solar concentrator arrangement with aluminum has a stable system temperature, but it has significantly changed the environmental conditions. Therefore, it is suitable to install both in sunny regions like partially cloudy. This is mainly due to properties of thermal conductivity of the aluminum; a visible disadvantage is that it is very difficult to make a mirror polish concentrator plate. This considerably affects the efficiency and useful energy of the system, also in the light gathering.

The fourth of the solar concentrator array with aluminum paint is a concentrator that showed particularly strange behavior as the results have shown that far from warm water over the receiving tube is was cold. This is because the paint reflective plate does not make any visible positive contribution to the system, which means that it neither captures direct light nor diffused or reflected light to the environment. Therefore, the useful energy and efficiency are negative. While it is apparent that it maintains higher temperatures than the glass concentrator. Probably the paint containing the aluminum particles in the suspension causes the greenhouse effect and the temperature increases in the system.

The fifth and the last of the solar concentrators, has a different design to others, better known as a compound parabolic concentrator, or CPC. This solar concentrator composed of a parable on which the receiver tube rests, thanks to this design, it is smaller but it has the possibility to capture better the diffuse light reflected by the atmosphere; this benefit is reflected in the contributions of the useful energy efficiency and heat that is visible in comparison with the aluminum concentrator and in some cases even better. This arrangement makes it comparatively and esthetically better, it also has better convective features that avoid the losses for being smaller.

According to the above results, it can be concluded that the application of renewable energy must be the future of national and global research owing to the perennial problem with fossil fuels.

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