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Design and analysis of a novel ICS solar water heater with CPC reflectors

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ABSTRACT

In this paper, a new design of an integrated collector storage (ICS) solar water heater combined with compound parabolic concentrator (CPC) is presented. The ICS system consists of one cylindrical tank properly mounted in a stationary symmetrical CPC reflector through. In this solar system, the cylindrical storage tank surface is partially insulated at the back side at 50%, so as to suppress thermal losses from it to the ambiance. The system depth and aperture width are moderated. The optical efficiency of the ICS solar water heater was predicted using advanced ray tracing technique. The result shows that the acceptance angle is 40°. A theoretical study was carried out to predict the thermal behaviour of the system under Saharan climate. The results are presented and discussed.

1. Introduction

Integrated collector storage (ICS) systems are low cost solar water heaters that cover the domestic needs for water in the range of 100–200 l per day at low temperature (40–70 °C). These systems consist of one or more water storage tanks painted matt black. The cylindrical storage tank is more interesting because of its ability to resist to the main water pressure. Furthermore, it can be effectively used in combination with curved reflector. However, compared to a flat plat thermosyphonic unit FPTU, this system is not widely used because of heat losses during night and its cumbersome size.

Many researchers have studied the thermal performance of several ICS systems, suggesting improvements for their operation. In the existing literature there are works on ICS systems with different design. H. Kessentini et al. [1] studied an ICS system made up of two storage tanks combined with asymmetric CPC type reflector troughs. Another configuration of CPC reflector was proposed by R. Benredjeb et al. [2] where the concentration system is composed by two concentrating stages to provide a significant capture of solar radiation. Other authors Y. Tripanagnotopoulos et al. [3] and B.Abdullah et al. [4] used symmetric CPC-type reflectors with single and double cylindrical tank respectively. But to determine the most efficient ICS system, Tripanagnostopoulos et al. [5,6] designed, constructed and tested experimentally various ICS prototypes combining symmetric or asymmetric CPC with cylinder storage tank. Souliotis and Tripanagnostopoulos suggest that the ICS system combined with symmetric CPC-type reflectors present the most promising perspective in water heating [7], they are low cost and have practical size and moderate system depth.

However, such systems suffer from important heat losses during the night. Thermal protection of storage tank and several methods are suggested to keep water temperature at a satisfactory level. The use of a selective absorber which reduces radiation thermal losses and double glazing is suggested. A part of the cylindrical tank surface can be thermally insulated to reduce storage tank thermal losses. They can be designed with symmetric CPC reflectors and therefore these ICS systems have moderate aperture width and low depth.

Taking into account the above considerations, a new design of ICS solar water heater is presented in this work. This new model consists of a cylindrical tank mounted horizontally inside a stationary truncated symmetric compound parabolic concentrating (CPC) reflector through. 50% of storage tank surface is thermally insulated at the back side. This system also has practical size and moderate system depth. Using ray tracing method, we have determined the optical efficiency of the ICS system as a function of the incidence angle, and studied the optical and thermal performance of the system.

2. Geometric design of the ICS system

The CPC type reflector is the ideal non-imaging light concentrator that allow acceptable concentration rate without need of tracking system. Only two parameters are needed to

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specify the complete geometry of a fully developed (i.e., non-truncated) CPC namely, the radius R of the cylindrical absorber and the acceptance angle, θ_c. The analytic equations of the reflector parts, based on the rectangular axis system O, x, y, are as follows [8]:

$$\begin{cases} x = R\sin(\varphi) - \rho\cos(\varphi) \\ y = -R\cos(\varphi) - \rho\sin(\varphi) \end{cases} \quad (1)$$

Where

$$\rho(\varphi) = \begin{cases} R\varphi & for \quad |\varphi| \le \theta_c + \pi/2 \\ R\dfrac{\varphi + \theta_c + (\pi/2) - \cos(\varphi - \theta_c)}{1 + \sin(\varphi - \theta_c)} & for \quad \theta_c + \pi/2 < \varphi < -\theta_c + 3\pi/2 \end{cases} \quad (2)$$

The basic design of the proposed ICS system is shown in Fig. 1.

Using Eq. (1), an ICS solar water heater with CPC reflectors was designed, constructed and tested in Ghardaïa (32.4N, 3.6E), as shown in Fig. 2. The storage tank is mounted in symmetric curved reflector troughs. The dimensions of cylindrical tank are R = 20 cm, L = 1 m and the acceptance angle is $\theta_c = 90^\circ$ (C_a = 1X). However, 1X is not consider as concentration but it permit to illuminate the whole cylindrical receiver without tracking. There is concentration when C_a is superior to 1X ($C_a \geqq$ 1.1X). Fig. 3. present the prototype released in the research centre and tested in the site of Ghardaïa. We used polished stainless steel with reflectivity $\rho = 0.68$ to form the designed reflectors and the absorbing surface is painted matt black ($\alpha_r = 0.9$). the inclination of the system is at (32.4°) the annual optimal angle.

Experimental measurement of water storage tank temperature are carried out for two different days, 13 February and 03 July in the year 2011. Figs. 4 and 5. show mean storage tank temperature and ambient temperature respectively of corresponding day. We can note that stored water temperature can reach 75 °C in July and 45 °C in February. Taking into account the ambient temperature shown in Fig. 5. we can deduce that the need of hot water must be important in February (winter) and weak in July (summer). We then see that, the production and the need for hot water do not follow each other. Moreover, the prototype is heavy and bulky by its size and takes up a lot of space. To remedy this problem, a new ICS must be designed according to Sahara climate by changing dimension and inclination angle of the ICS system.

To get a practical ICS system, the system depth must be reduced as much as possible and a maximum storage tank surface must be thermally insulated. This means judicious modification of CPC reflectors in ICS systems is necessary. These two factors improve the performance of the ICS systems for the hot water preservation during the night.

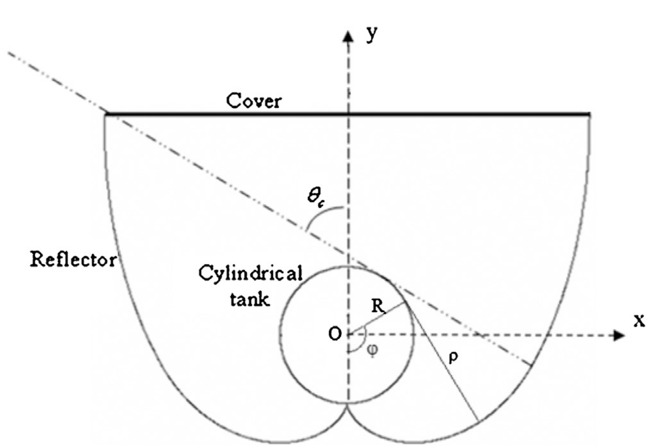

Fig. 1. Cross section of ICS system.

The studied model, which is presented in Fig. 6, consists of one cylindrical tank properly mounted in a stationary symmetrical CPC reflector through. The cylindrical tank is black mat painted in order to increase the solar radiation absorption. The back side of the tank is thermally insulated (50% of its total surface) leading to better heat preservation at night.

The analytic equations of the reflector parts according to the Cartesian coordinate system (O, x, y) as defined in Fig. 6, are the following [9]:

$$x = R\left(\cos\left(\psi - \frac{\pi}{4}\right) + \psi\sin\left(\psi - \frac{\pi}{4}\right)\right) \quad (3)$$

$$y = R\left(\sin\left(\psi - \frac{\pi}{4}\right) - \psi\cos\left(\psi - \frac{\pi}{4}\right)\right) \quad (4)$$

Where

$$\frac{\pi}{3} \le \psi \le \frac{2\pi}{3} \quad (5)$$

The angle ψ is shown in Fig. 7 and R is the receiver radius.

The cylindrical tank has a radius R = 20 cm, a length L = 1 m and therefore the total stored water volume is V = 125.6 l. However, the geometry of the CPC reflector is generated using a smaller tank radius R equal to 16.5 cm in order to increase optical efficiency. In the present case, the aperture width W = 76.6 cm and the system depth is H = 42.5 cm. The concentration ratio C_a of the system is defined by $C_a = A_c/A_r$, where A_c is the aperture area and A_r is the exposed to solar radiation cylindrical tank surface area (absorber). Considering that A_r = 62.8 cm, then C_a = 1.22X.

3. Optical analysis of the system

A two dimensional Ray tracing software by TracePro was employed in order to investigate the optical performance of the collector using 100 equally spaced rays across the collector aperture surface. The angle of incidence θ was defined as the angle between incident solar radiation and the normal to the collector. It was assumed that all reflections were specular.

The obtained diagrams for different angles of incidence are given in Fig. 8. It can be seen that at 0°, direct rays reaches the storage tank directly or after one or more reflections but there is not any ray sent outside ICS system. Beyond 20°, a proportion of solar rays is reflected towards outside, this causes a reduction in the absorbed energy. Therefore, the optical efficiency can be expressed as follows [10]:

$$\eta(\theta) = \rho\alpha_r\tau[1 - R_{loss}(\theta)] \quad (6)$$

In Eq. (6), ρ is the reflectivity of the concentrator surfaces ($\rho = 0.85$ for aluminized Mylar), α_r is the absorptivity of the absorber surface ($\alpha_r = 0.97$) and τ is the transmissivity of the transparent cover ($\tau = 0.9$). The parameter $R_{loss}(\theta)$ represents the ray losses due to the CPC reflector shape.

As illustrated in Fig. 9. The angular acceptance of the incoming rays on the aperture remains constant within the half acceptance angle (±20°), but decreases till 0.5 at incidence angle of ±70°. The optical efficiency has a similar trend with the acceptance angle. However, the values of the optical efficiencies are always lower than that of angular acceptance at any incidence angle.

It is known that this two parameters, concentration ratio and acceptance angle are not independent, thus, another parameter CAP (Concentration acceptance product) is used to show the performance of concentrators [11]. The CAP value is defined as:

$$CAP = C_a\,sin\theta_c \quad (7)$$