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Optical and thermal performances improvement of an ICS solar water heater system

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Abstract

With the aim to increase the quantity of absorbed energy and improve optical and thermal performances, a new design of an integrated collector storage (ICS) solar water heater combined with a compound parabolic concentrator (CPC) is presented. This model consists of two concentrating stages. The upper part contains two symmetrical parabolic sections with focal axes rotated by $\theta = 48^\circ$ in counterclockwise sens and $\theta = -48^\circ$ in clockwise sens from vertical plane. The lower part is constituted by three involute reflectors. Its cylindrical storage tank covers the triangle formed by the three involute parts center's. The geometric concentration is about 1.34. This design has a strong connection with a previous study where an old ICS system was designed and experimentally tested. A ray-tracing model was developed to simulate the reflection of the direct solar radiation on the CPC reflectors at different angles of incidence and compute the absorbed solar radiation distribution on the absorber surface. The obtained results, when compared with the old experimented model differing on the design of the lower stage concentrator, showed a significant improvement in optical efficiency, the distribution of the absorbed energy regarding the angle of incidence and the temperature level required.

Keywords: ICS solar water heater; Compound parabolic concentrator; Improvement; Optical and thermal performance; Ray tracing technique

1. Introduction

Solar energy which is clean, free and abundant, has been the subject of several applications such as the production of hot water, desalination of sea water and solar cooking. The hot water production is one of the most prominent applications of this energy. One of the main techniques is the use of solar panels that are designed to convert the solar energy into thermal one (Adsten et al., 2005). Flat plate collectors are used to obtain a temperature of few tens of degree, while concentrating collectors can achieve higher levels of temperature and can reach few hundred degrees (Jones et al., 1990). The level of the temperature to be reached and the thermal performance of the device are directly linked to the geometry and collector dimensions. Several factors are involved in the design and realization of solar collectors, the main objective being to minimize heat losses at each component and increase the device efficiency while providing acceptable production cost and range of consumers (domestic or industrial). On the other hand several factors have an increasing effect on heat losses and thus reduce performance. These factors include reflection losses which are about of 10 of the average thermal energy in each reflection. The cosinus effect, which may be caused a lower optical concentration than the geometric one and consequently a lower proportion of the received solar radiation

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Nomenclature

A_{app}	aperture surface area (m^2)	W_{app}	system aperture width (m)
A_{ab}	absorber (receiver) surface area (m^2)	W	half exit aperture of the system (m)
C	concentration ratio	(x, y)	cartesian coordinate system
$C_{p,W}$	specific heat of water (J/kg K)	(x_{f_1}, y_{f_1})	the coordinates of focus F_1 (m)
D_{ab}	cylindrical storage tank diameter (m)	(u, v)	cartesian coordinate system rotated counter clockwise from horizontal axis x
D_s	depth of the system (m)		
f	focal distance of the parabola (m)		
F	focus of the parabola	*Greek symbols*	
h_f	heat transfer coefficient on the inside surface of the absorber (W/m^2 K)	α_r	absorptivity of the absorbing surface
		η_o	optical efficiency
I_b	beam radiation (kJ/m^2 h)	τ_s	transmissivity of the cover
I_d	diffuse radiation (kJ/m^2 h)	α_a	acceptance half angle of the CPC concentrator (rad)
I_T	flux on a tilted surface (kJ/m^2 h)		
L_{ab}	cylindrical storage tank (m)	ρ_r	reflectivity of the reflector surface
L_{app}	system aperture length (m)	ρ_e	effective reflectivity of the concentrator surface for all radiation
M_W	water mass of storage tank (kg)		
R_i	for ($i = 1$, 2 and 3) is the radius of the ith involute reflector (m)	θ	rotated angle (rad)
		τ_c	emissivity of the cover for long wavelength radiation
T	translated vector of parameter a and b		
T_a	ambient temperature (C, K)	ε_p	emissivity of the absorber for long wavelength radiation
T_i	inlet temperature (C, K)		
T_m	average storage water temperature (C, K)	α_r	Stephan constant
U_s	overall loss coefficient during night (W/K)	α_i	for ($i = 1$, 2 and 3) is the angle by which the ith involute reflector is plotted (m)
V_{ab}	cylindrical storage tank volume (m^3)		
W	half system aperture width (m)		

(Pasquetti, 1987). For an integrated collector storage systems (ICS), the thermal losses are enormous especially during the night, because the absorber represents at the same time the storage tank (Kalogirou, 2009).

Several designs have been developed by many researchers to improve the thermal performances of ICS devices (Tripanagnostopoulos and Yianoulis, 1992; Rabl, 1976; Rabl et al., 1980) combining compound parabolic concentrators (CPC) and storages tanks. Different CPC configurations are described in numerous references (Helal et al., 2011a) and different kinds of them are also discussed in Mills and Giutronich (1978), Helal et al. (2010), Rabl et al. (1979), Schmidt and Goetzberger (1990), Smyth et al. (2004), Tripanagnostopoulos and Yianoulis (1996).

In this context and with the aim to increase the quantity of energy absorbed and improve optical and thermal efficiencies, a new model ICS solar water heater is developed. The present model, by changing its geometry of reflection, has a strong connection with a previous study (Helal et al., 2011a) where an ICS system was designed and experimentally tested because the main objective of our work is both the design and the development of improved ICS system regarding its optical and thermal performances.

Helal et al. (2011a) studied an ICS solar water heater composed by two concentrating stages: the first one contains two symmetric parabolic sections and the second one comprises one parabolic part, while the absorber is located in the focal plane of the three parabolic sections.

In the new model, the concentration system is also composed by two concentrating stages. The upper one comprises two symmetric parabolic branches with focal axes rotated by $\theta = 48°$ in counterclockwise sens ($\theta = -48°$ in clockwise sens) from vertical plane and the lower one is constituted by three involute reflectors. This configuration provides a significant capture of solar radiation and allows solar rays striking the collector surface with an angle of incidence comprised between $-48°$ and $+48°$ which will be reflected back to the absorber.

The new and old collectors have the same tilt angle equal to 33° which corresponds to the latitude of the region in which the two model exist. With this new design, we studied its optical and thermal performances. For that purpose, a Matlab code was developed for data generation, plotting and simulating the reflected rays on the CPC reflectors at any instant using analytical geometry and vector calculation. Then, we have used the ray-tracing method to produce diagrams which correspond to the spatial distribution of the direct solar radiation on the absorber surface. With this new design, we studied its optical and thermal performances. For that purpose, a Matlab code was developed for data generation, plotting and simulating the reflected rays on the CPC reflectors at any instant using