International Journal of Scientific Engineering and Technology
Volume No.6 Issue No.1, pp: 29-34

ISSN:2277-1581
01 Jan. 2017

Optical Design of Two Dimension Compound Parabolic Solar Thermal Concentrator

Dr. Alaa H. Shneishil
The University of Mustansiriyah, College of Education, Physics Department
alaahussien19812@gmail.com

Abstract : The idea of concentrating solar thermal energy is an area that has received significant attention in recent years. In this study, a design model for a two dimension compound parabolic solar thermal concentrator (CPC) is theoretically analyzed. The maximum acceptance angle, the concentration ratio, the concentrator area of reflector and number of reflections have been calculated by using equations which are simulated in MATLAP program. After that the total absorbed solar radiation by CPC with three different glass covers, flat plate solar thermal collector at normal incidence and flat plate solar thermal collector at tilt angle 60^o has been calculated for seven months from September to March depending on the data of solar radiation for Baghdad. The results indicated that the acceptance angle ranging from (78.8) to (84.3) for the entrance aperture width values in the range (0.6-1.6)m for 0.1m height. The enhancement in the absorbed solar radiation at solar noon for CPC which about 120%, 141%, 151%, 153%, 152%, 146% and 131% in comparison to flat plate at normal incidence for September, October, November, December, January, February and March respectively.

Keywords: Solar Thermal Concentrators, Compound Parabolic Concentrator

1. Introduction

Concentrating collectors can be classified into two groups which are Focusing (Imaging type) and Non-focusing (non-imaging type). Compound parabolic concentrator (CPC) is of the non-imaging type concentrating solar collector. CPC has two parabolic reflectors at the two ends (right and left) of the receiver and hence it is known as compound parabolic concentrator. The main advantages of 2-D CPC are that, it can receive solar radiation arriving with large angular spread and concentrate it onto linear receivers of small transverse width. Here the incident solar rays are not focused at a point after reflection from the reflector, but are simply collected on an absorber surface. Winston, First of all developed the CPC with flat plate absorber in 1974[1]. On the other hand, it can in part be offset the necessary high material usage by reducing the length of the CPC with the so called truncated CPC, or T-CPC, which use far less material with only a minor reduction in optical efficiency and concentration ratio [2,3]. Many studies about CPC design have focused on improving the solar radiation to the available area ratio. Different types of CPC have been proposed for obtaining the maximal amount of solar radiation redirected to a Specific absorber. Gang et al. studied the effect of mirror coating on the optical performance of a solid dielectric CPC by using Ray tracing method and its results are compared with the measurements. The results indicated that a partly coated solid dielectric CPC may have a better optical efficiency than a solid CPC without coating for a certain range of incidence angles [4]. Muhammad et al. designed a CPC with wings angled toward the east and west. The CPC wings tilt and bending angles were optimized for year round operation in Tokyo, Japan. The results showed that the overall optimum settings for the proposed CPC were a 35° tilt for the south facing central part of the CPC and a 45° tilt for the east and west wings angled at 50° for year round operation [5]. Chia-Wei et al. presented a modified design of CPC by using the region below the common focus of parabolas, thus the height of the CPC could be effectively reduced without compromising the concentration ratio. It was indicated that in the case where the height of the tubular receiver was 0.46 times the aperture width, a greater range of incident rays could be collected. In addition, it was suggested that an increasing of the focal length value would not substantially affect the concentration ratio [6]. Abd-Rahman et al. presented the flux distribution of untruncated and truncated 2-D hollow compound parabolic trough concentrator. They made optical simulation design by using ray-tracing software TracePro. Results showed that the geometrical concentration ratio only decreased 10% when the CPC was truncated to 45% from initial height which lead to reducing the cost of reflector and material dielectric usage especially at manufacturing site [7]. Xu et al. investigated theoretically six asymmetrical CPC for concentrating radiation on evacuated solar tubes where the acceptance angles of both (left/right) reflectors were determined in such way that they makes the Sun within the acceptance angle for at least six hours during all days of a year. They found that the one that designed based on the cover tube of evacuated solar tubes collects the most radiation annually [8]. Six symmetric compound parabolic solar thermal concentrators with all-glass evacuated solar tubes as the receiver are designed by Qiang et al., and a comparative study on their optical performance is performed based on ray-tracing simulations and theoretical analysis. The results indicated that the average optical efficiency for radiation over the acceptance angle, CPC-6 is the optimal design due to the high solar flux on the evacuated solar tubes regardless whether CPCs are truncated or not, followed by CPC-4 for truncated CPCs and CPC-3 for full CPCs, and CPC-1 is the most inferior solution [9]. The present work focus on designing of 2-D CPC with flat absorber for a half acceptance angle θc to achieve higher concentration ratio and capture maximum absorbed solar thermal energy in the morning and afternoon without need of tracking system for solar water heating applications in Baghdad.

ISSN:2277-1581
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2. Compound Parabolic Solar Thermal Concentrator

Compound parabolic Solar Thermal Concentrators are advanced technological solutions that developed for making efficient solar heat collectors for a variety of applications [10-15]. CPC solar collectors are more productive as compared to flat plate collectors [12]. On the other hand, they are less expensive, simpler design, and more reliable than other parabolic concentrators (being of either 3D-dish or 2D-trough design), since the latter needs to accurate and expensive sun-tracking devices, complicated maintenance, precise mirror shaping, and so on [14, 16]. Figure (1) shows the basic concept of the CPC. These concentrators are most useful as linear (trough-type) concentrators. There are two types of CPC, two dimensional CPC and three dimensional CPC. The following is based on the two dimensional CPC. Each side of the CPC represent a parabola; the focus and axis of only the right-hand parabola are indicated. Each parabola extends until its surface is parallel with the CPC axis. The acceptance half-angle of CPC (θ_c) represents the angle between the line connecting the focus of one of the parabolas with the opposite edge of the aperture and the axis of the CPC. When the reflector is perfect, any solar radiation entering the aperture at angles between $\pm\ \theta_c$ will be reflected to the receiver at the base of the concentrator by specularly reflecting parabolic reflectors [17].

CPCs consist basically of three elements [18]:

I. **Cover:** The perfect cover is a transparent insulation which allows the passage of solar radiation to the reflector and receiver, having a low transmittance of the thermal radiation from the receiver, and a high transmittance of solar radiation; also, it must have low cost and high durability.

II. **Reflector:** solar concentrator reflectors should have the highest reflectance as possible. Its function is to focus the direct solar radiation onto the receiver, which is located at the system focus.

III. **Receiver:** The receiver of CPC should have the highest absorptance for solar radiation as possible and must be constructed with metals of high conductivity in order to conduct efficiently the absorbed heat into the heat transfer fluid. Most materials of receiver do not have a very high absorptance, and they require to be covered with special solar selective surface coatings [19]. A commercial selective surface for solar energy applications made from a silicon polymer, with an absorptance from 0.88 to 0.94 and emissivity values from 0.28 to 0.49 was applied on the surface of this receiver.

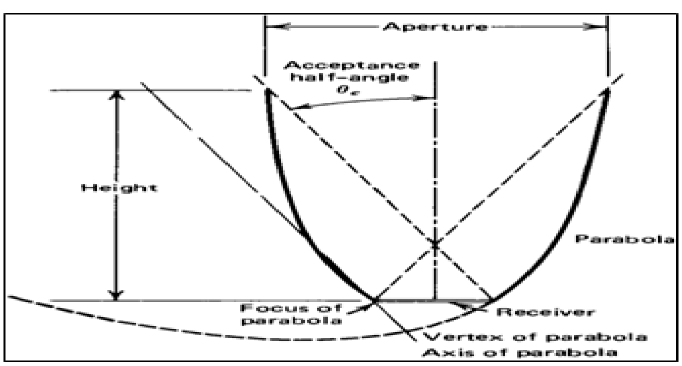


Figure (1): Cross section of a symmetrical nontruncated CPC

3. Design of the Compound Parabolic Concentrator

The solar rays entering the concentrator at maximum acceptance angle are reflected tangentially to the absorber surface. The maximum acceptance angle is given by [20]:

$$\tan = \frac{D + d}{2H} \qquad (1)$$

Where D is the entrance aperture width, d the absorber width and H the concentrator height of CPC. The concentration ratio (C) can be calculated by using the following equation [20]:

$$C = \frac{1}{sin(\theta_m)} \qquad (2)$$

Rabl has shown that the concentrator area of reflector, A_c , is related with the aperture area A_a, as [21]:

$$A_c = A_a(1 + sin\theta_m).\left[\frac{cos\theta_m}{sin^2\theta_m} + ln\left\{\frac{(1+sin\theta_m)(1+cos\theta_m)}{sin\theta_m\{cos\theta_m+(2+2sin\theta_m)^{1/2}\}}\right\} - \frac{\sqrt{2}\,cos\theta_m}{(1+sin\theta_m)^{3/2}}\right] \qquad (3)$$

The average number of reflections (n) passing through the CPC inside within acceptance angle is given as [21]:

$$n = \frac{1}{2sin\,\theta_m}\left(\frac{A_c}{A_a}\right) - \frac{(1+2sin\,\theta_m)(1-sin\,\theta_m)}{2sin^2\theta_m} \qquad (4)$$

To estimate the absorbed solar radiation by the CPC receiver, it is necessary to determine if the beam radiation incidence angle is within the acceptance angle (θ_m) and then estimate the contributions of the ground reflected, diffuse and beam radiation if it is within the acceptance angle. The absorbed solar radiation (S) can be estimated as [17]:

$$S = (G_{b,CPC}\tau_{c,b}\tau_{CPC,b}\alpha_b + G_{d,CPC}\tau_{c,d}\tau_{CPC,d}\alpha_d + G_{g,CPC}\tau_{c,g}\tau_{CPC,g}\alpha_g).C \qquad (5)$$

$$G_{b,CPC} = F\,G_{bn}cos\theta \qquad (6)$$

$$G_{d,CPC} = \begin{cases} \frac{G_d}{C} & if\ (\beta+\theta_c) < 90^o \\ \frac{G_d}{2}\left(\frac{1}{C} + cos\beta\right) & if\ (\beta+\theta_c) > 90^o \end{cases} \qquad (7)$$

$$G_{g,CPC} = \begin{cases} 0 & if\ (\beta+\theta_c) < 90^o \\ \frac{G_d}{2}\left(\frac{1}{C} - cos\beta\right) & if\ (\beta+\theta_c) > 90^o \end{cases} \qquad (8)$$

Where $\tau_{c,b}$, $\tau_{c,d}$ and $\tau_{c,g}$ are the transmittance for beam, diffuse and ground reflected radiation of any cover which may be placed over the concentrator array. This serves both to reduce thermal losses from the absorber and to protect the reflecting and absorbing surfaces. Then diffuse and beam solar radiation effectively entering the CPC are reduced by the transmittance of the cover τ [22]. α_b, α_d and α_g are the absorptance of the receiver for the beam, diffuse and ground reflected radiation, respectively. The factor $\tau_{CPC,b}$ is a ‘‘transmittance’’ of the CPC that accounts for reflection losses and is a function of the average number of reflections and the specular reflectance of the concentrator, ρ, and is given as [20]:

$$\tau_{cpc} = \rho^n \qquad (9)$$

The factors in the terms for ground-reflected and diffuse radiation ($\tau_{CPC,d}$, and $\tau_{CPC,g}$) are analogous to those for the beam radiation. The ground-reflected radiation is only effective if β +

θc > 90, that is, if the receiver ''sees'' the ground. Figure (2) shows the CPC acceptance angle on a vertical north-south plane for a CPC oriented east-west. Two angles, β + θc and β – θc, are the angles from the vertical in this plane to the two limits describing the acceptance angle. The following condition must be met in order for the beam radiation to be effective that shown by Mitchell (1979) [17]:

$$(\beta - \theta_c) \le tan^{-1}(\tan(\theta_z)\cos(\gamma_s)) \le (\beta + \theta_c) \qquad (10)$$

It is convenient to introduce the **control function** *F* in Equation (6), which is 1 if the criterion of Equation (10) is met and 0 otherwise. In other words, If the beam radiation is incident on the aperture within the acceptance angle, F = 1 and the beam radiation term will be included in the calculation of S in equation (5).

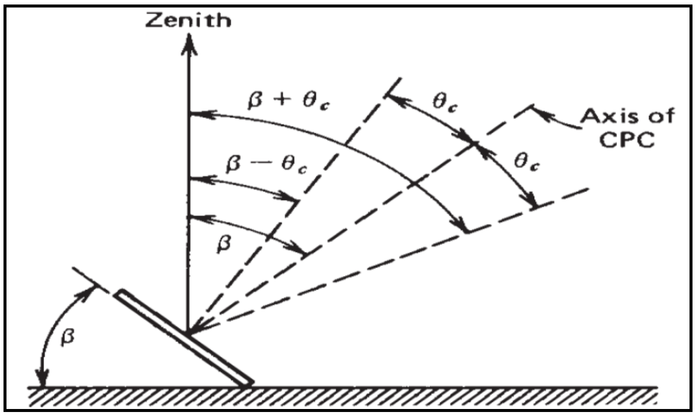


Figure (2): Projection on a north-south plane of CPC acceptance angles and slope for a CPC on an east-west axis [17]

In this design, equation (1) has been used to calculate the maximum acceptance angle for parameters in table (1), then, the concentration ratio, the concentrator area of reflector and number of reflections are also calculated by using equations (2 to 4) which are simulated in MATLAP program. After that the total absorbed solar radiation by CPC with three different glass covers, flat plate solar thermal collector at normal incidence and flat plate solar thermal collector at tilt angle 60° has been calculated for seven months from September to March depending on the data of solar radiation in table (2) for Baghdad that has been taken from reference (23, Naseer et al, 2009). These calculations are summarized in Flow chart of figure (3).

Table (1): The CPC design parameters

Parameter	value	unit
absorber width (d)	0.4	m
the height of CPC (H)	0.1, 0.12, 0.14, 0.16, 0.18, 0.2	m
width of entrance aperture (D)	0.6 to 1.6 with 0.05 increment	m
The reflectivity of the reflector (ρ)	0.89	
Absorptivity of the absorber (α)	0.94	
The acceptance angle (θ_m)	68	degree
average number of reflections (n)	0.7	

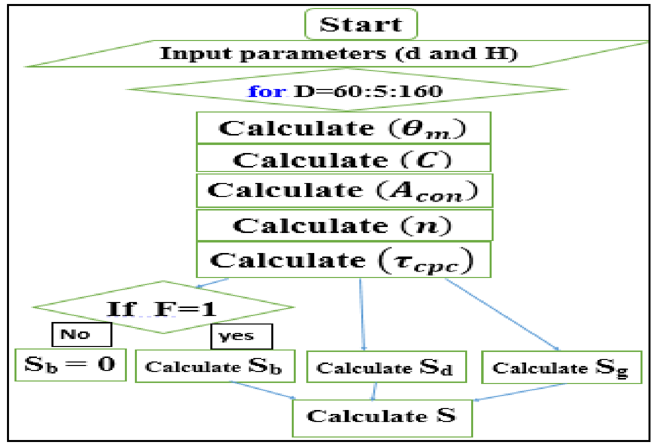


Figure (3): Flow chart of design CPC solar thermal collector

Table (2): Total solar radiation at normal incidence in Baghdad [23]

Solar time	Sep	Oct	Nov	Dec	Jan	Feb	Mar
6:00 AM	168	-	-	-	-	-	-
6:30	247	175	-	-	-	-	197
7:00	404	248	181	-	-	189	337
7:30	535	404	256	200	166	311	483
8:00	630	536	400	316	215	449	592
8:30	699	632	523	443	344	554	670
9:00	750	702	615	542	465	631	728
9:30	787	753	681	615	557	686	770
10:00	815	790	728	666	623	726	800
10:30	834	816	761	703	671	754	822
11:00	848	833	783	727	704	772	837
11:30	855	843	796	740	726	783	845
12:00AM	858	846	800	745	739	786	848
12:30PM	855	843	796	740	743	783	845
1:00	848	833	783	727	739	772	837
1:30	834	816	761	703	726	754	822
2:00	815	790	728	666	704	726	800
2:30	787	753	681	615	671	686	770
3:00	750	702	615	542	623	631	728
3:30	699	632	523	443	557	554	670
4:00	630	536	400	316	465	449	592
4:30	535	404	256	200	344	311	483
5:00	404	248	181	-	-	189	337
5:30	247	175	-	-	-	-	197
6:00 PM	168	-	-	-	-	-	-

4. Results and Discussion

Figure (4) illustrates the variation of the acceptance angle of compound parabolic concentrator for different heights under the effect of entrance aperture width. This figure explains the rise of the acceptance angle with increasing entrance aperture width for all heights, thus, the acceptance angle ranging from (78.8) to (84.3) for the entrance aperture width values in the range (0.6-1.6)m and 0.1m height. On the other hand, the acceptance angle decreases with increasing height when compared this curve with other curves. Figure (5) illustrates the effect of entrance aperture width on the concentration ratio of compound parabolic concentrator for different heights. It can be seen from this figure that the increase in the entrance aperture width leads to decrease in the concentration ratio, while the increase in the height leads to increase in the concentration ratio. The maximum concentration ratio in this design is about 3.2 for D=0.6m and H=0.2m. The effect of entrance aperture width on the concentrator area of compound parabolic concentrator for different heights is shown in figure (6). It is clear from this figure that the concentrator area decreases from 0.16 to 0.08 m^2 with increasing entrance aperture width from 0.6m to 1.6m for H=0.1m, but these values increase with increasing height, therefore, when H=0.2m the concentrator area decrease from 0.34m^2 to 0.16 m^2. Figure (7) appears the effect of entrance aperture width on the number of reflections of compound parabolic concentrator for different heights. It is obvious that the number of reflections increase from 1.3 to 2.55 with increasing entrance aperture width from 0.6m to 1.6m for H=0.1m, while these values decrease with the range of 0.67 to 1.3 for height of 0.2m. Figures (8a-h) shows the variation of the absorbed solar radiation by CPC with three different glass covers, flat plate solar thermal collector at normal incidence and flat plate solar thermal collector at tilt angle 60^o during the time period from 6:00 AM to 6:00 PM for solar water heating system in Baghdad in months of September to March, respectively. This is also summarized at solar noon in Table 3. It is clear from this figure that the radiation increases with time to get maximum value at solar noon and then decrease to get minimum value in the last day for all curves which represent all case under study. The minimum insolation when the flat plate solar thermal collector at tilt angle 60^o and increases for normal incidence and for CPC, thus, in September (figure 8a) the absorbed solar radiation at solar noon is 1888 W/m^2, 858 W/m^2 and 755 W/m^2 for CPC, flat plate at normal incidence and flat plate at 60^o tilt angle, respectively which means that 120% enhancement in performance when using CPC in comparison to flat plate solar thermal collector at normal incidence. Figure (8b) illustrates the absorbed solar radiation in October. It is obvious that the radiation is about 2043 W/m^2, 846 W/m^2 and 806 W/m^2 for the three cases which means that there is 141% enhancement in performance. Figures (8c, 8d, 8e, 8f and 8g) illustrate clearly the enhancement in the absorbed solar radiation at solar noon for CPC which about 151%, 153%, 152%, 146% and 131% in comparison to flat plate at normal incidence for November, December, January, February and March respectively.

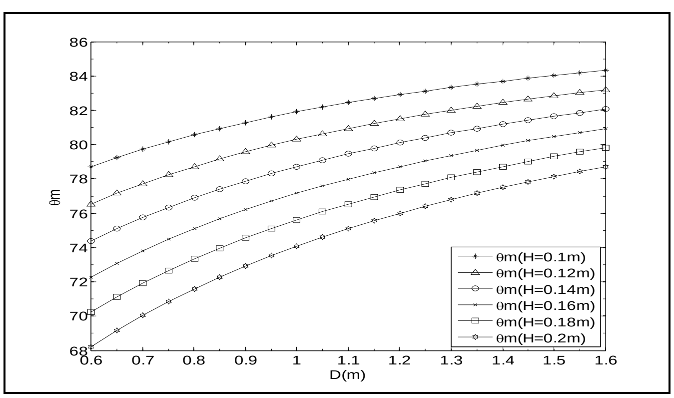


Figure (4): Effect of entrance aperture width on the acceptance angle of CPC for different heights

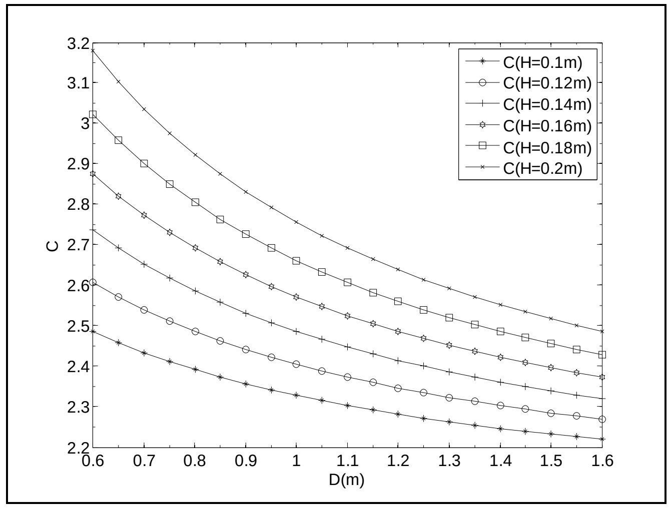


Figure (5): Effect of entrance aperture width on the concentration ratio of CPC for different heights

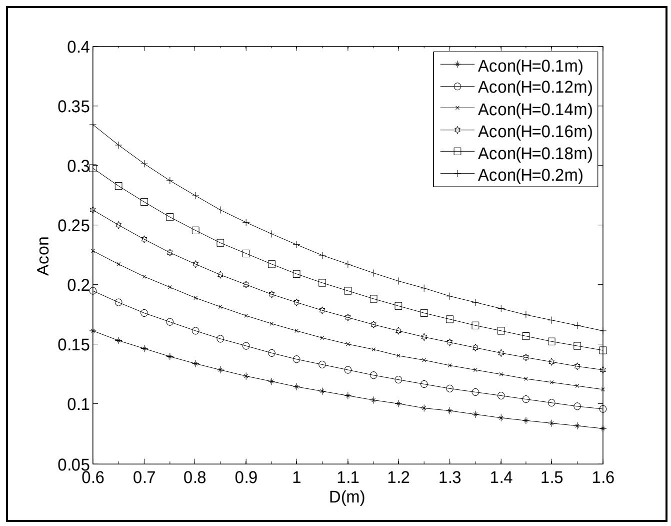


Figure (6): Effect of entrance aperture width on the concentrator area of CPC for different heights

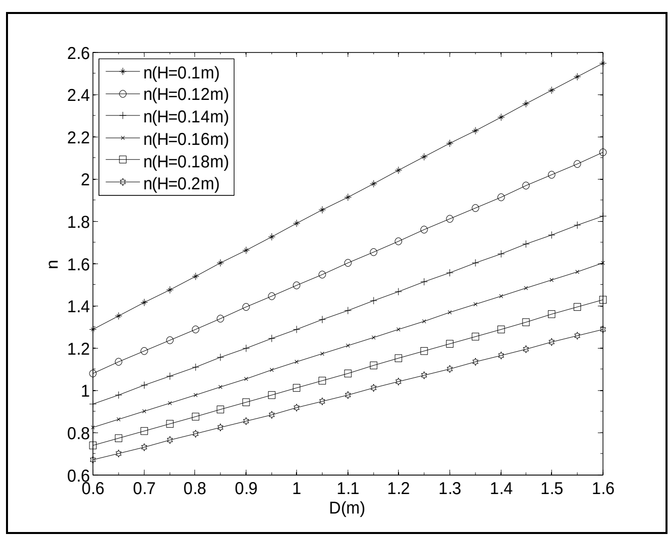
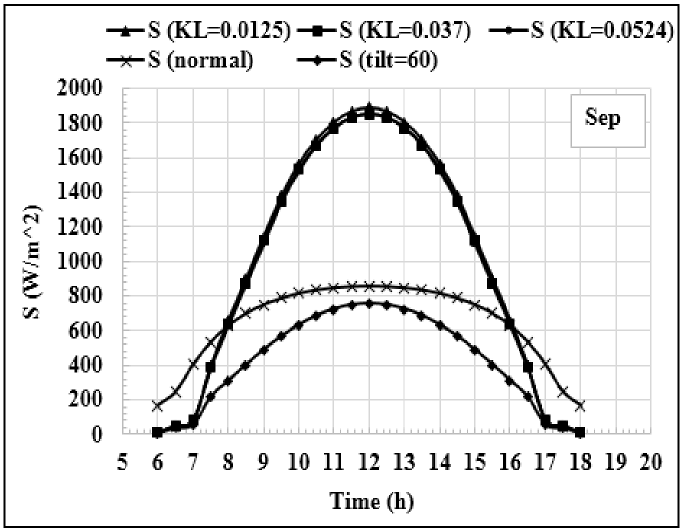
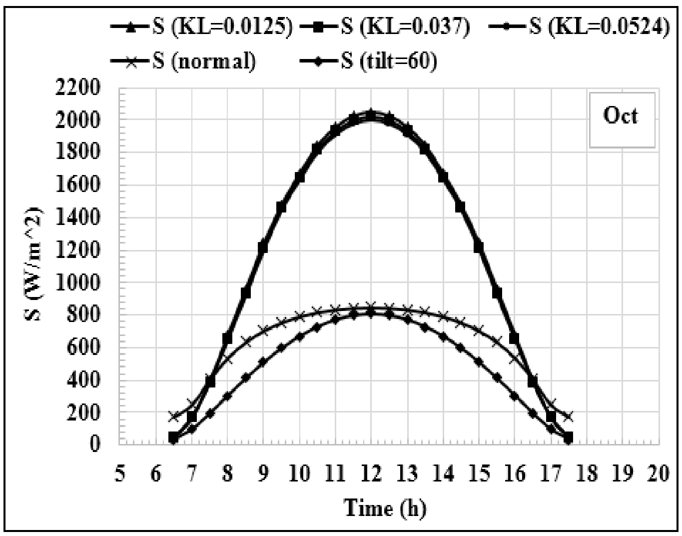


Figure (7): Effect of entrance aperture width on the number of reflections of CPC for different heights

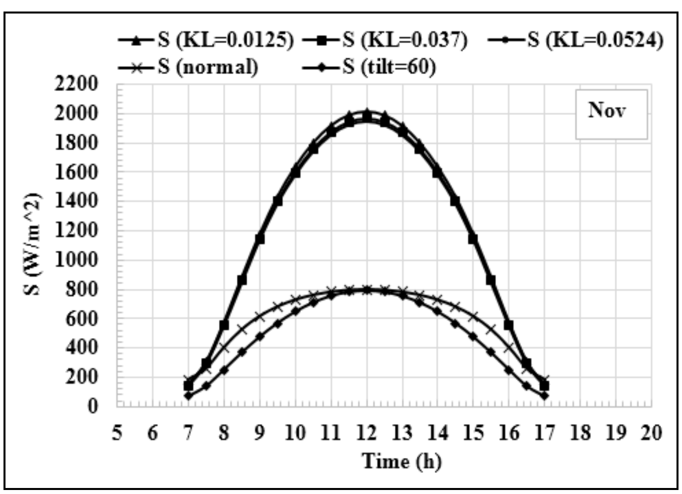
ISSN:2277-1581
01 Jan. 2017



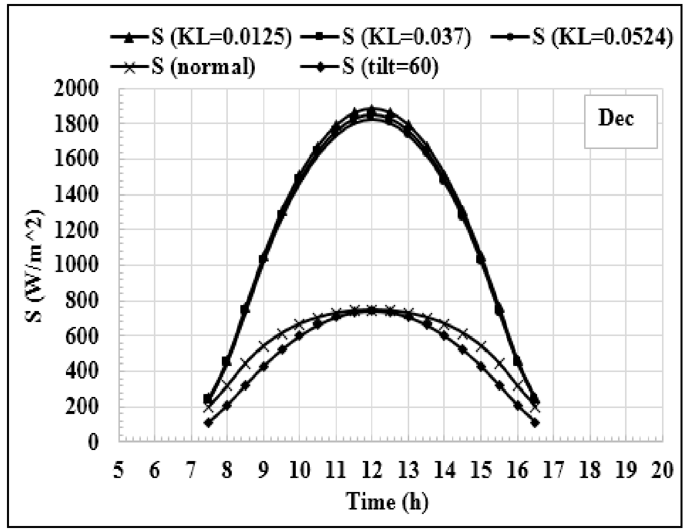
(a)



(b)



(c)



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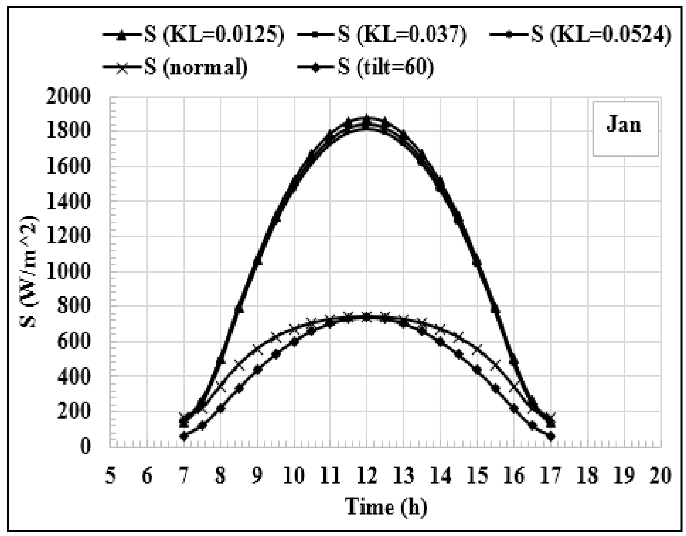

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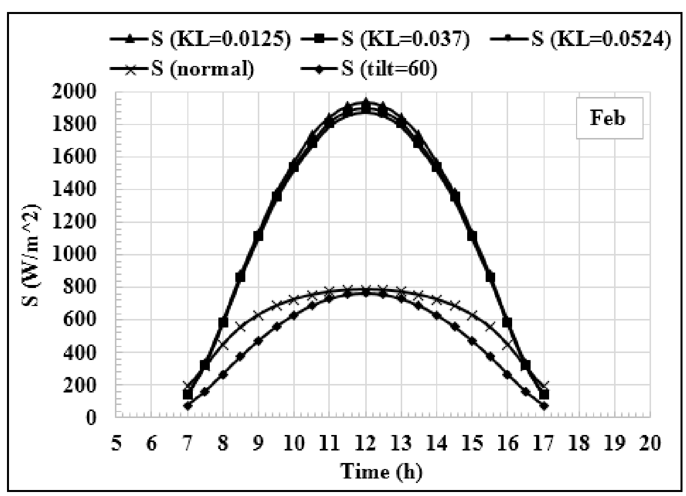
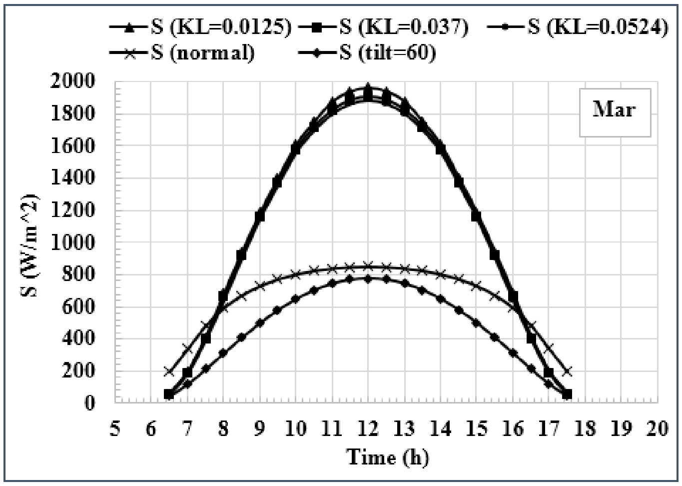


(f)



(g)

Figure (8) : Absorbed solar radiation by CPC with three different glass covers, flat plate solar thermal collector at normal incidence and flat plate solar thermal collector at tilt angle 60^o for months (from (a) Sep. to (g)Mar.)

Table (3) : Absorbed solar radiation by CPC with three different glass covers, flat plate solar thermal collector at normal incidence and flat plate solar thermal collector at tilt angle 60^o at solar noon for seven months.

	S (W/m^2) (KL= 0.0125)	S (W/m^2) (KL= 0.037)	S (W/m^2) (KL= 0.0524)	S (W/m^2) normal	S (W/m^2) tilt=60
Sep	1888	1849	1849	858	755
Oct	2043	2022	2001	846	806
Nov	2009	1968	1947	800	791
Dec	1886	1848	1828	745	743
Jan	1876	1837	1818	743	739
Feb	1938	1898	1878	786	764
Mar	1965	1905	1885	848	776

5. Conclusions

1. The use of compound parabolic concentrator (CPC) with flat absorber leads to enhance the absorbed solar thermal energy more than 100% without using tracking system, therefore, this design can be used for solar water heating applications in Baghdad which leads to energy saving in consuming electrical energy.
2. The tilt angle of CPC must be adjusted according to the position and the season of application.
3. The acceptance angle of CPC must be adjusted according to the position and the season of application.

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