Optimum Tilt Angle for Solar Collectors with Low Concentration Ratio

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Abstract: The performance of any solar energy system depends very much on the availability of solar radiation and the orientation of solar collectors. Solar collectors need to be inclined at the optimum angle to maximize the receiving energy. In this work, we proposed to analyze the optimum tilt angle for compound parabolic collectors CPC with different concentration ratios. There are analyzed the energy gains when the collector keeps the same position during the whole year and when the collector changes its tilt twice a year, on summer and on winter.

Keywords: solar collectors, CPC, orientation, optimum tilt angle, useful energy gain

1. INTRODUCTION

The conversion of renewable energies become more important day by day, because of the conventional fuels cost and the environmental pollution. Solar energy is one of these renewable energies which can be converted directly into electricity or into heat. The efficiency of solar collector depends on many factors: design, construction, position, orientation, climatic condition of the place, application they are used for.

The best way to collect maximum solar energy is to optimize the position and orientation of solar collectors.

The factors which affect the value of the optimum tilt angle are [1]:

– the type of application, i.e. stand alone or grid connected;

– maximization the amount of collectable radiation for the whole year or a certain period of time;

– actual climatic condition of the site, regarding snow fall, dust storms or polluted air.

Many papers present optimum tilt angle of the collectors for different locations. Moghadam et al [2], determinate the optimum tilt angle for each month of the year, for the first half and the second half of the year and for the whole year.

First half, second half and annual optimum tilt β were determinate as $\beta=\Phi-23^0$, $\beta=\Phi+23^0$, $\beta=\Phi$, where Φ is the latitude.

Shariah et al [3] concluded that for the chosen location, Jordan, the system is operating with sufficiently high solar fraction when the tilt angle is as $\beta=\Phi+(0^o\rightarrow10^o)$ for northern region and as $\beta=\Phi+(0^o\rightarrow20^o)$ for southern region.

Skeiker [1] developed an analytical procedure to obtain formulas which require the least number of parameters to determine the angle β for any chosen day, latitude and for any value of surface azimuth angle.

The results of Gunerhan [4] and Elminir [5] suggest that for the systems which utilize solar energy throughout the year, the optimum tilt angle is taken to be equal to the location latitude, while for summer as $\beta=\Phi-15^0$ and for winter as $\beta=\Phi+15^0$. Yakup [6] concluded that changing the tilt angle 12 times in a year (monthly changing), the solar radiation gain increase by 4.5% more than the case of a horizontal stationary collector ($\beta = 0$).

Also, his studies show an increase of 3.9 % of solar energy gain when the tilt angle is changed for four times in a year (seasonal optimum tilt angle).

Being stationary and producing concentration, the CPC collects solar radiation for a more limited time than flat plate collectors.

This time depends on its design (concentration ratio) and orientation. To estimate the absorbed radiation it is necessary to determinate the instance at which acceptance of the sun's beam radiation begins and stops for the considered collector [7].

This paper presents one comparison between useful energy gains for CPC for different tilt angles. It was considered the tilt angle when the collector had the same position during the whole year and when the position of the collector was changed two times for a year (in spring and in autumn).

The diffuse radiation and total radiation data values used in this work were taken from „Instituto Nacional de Meteorologia e Geofisica", [8] for the city of Porto, in Portugal.

This city is located on latitude 41^0 N and longitude 8^0 W, in northern Portugal [8].

2. SUN'S POSITION

The azimuth angle (γ_s) and the zenith angle (θ_s) are the angles which describe the sun's position (Fig. 1) [9], [10].

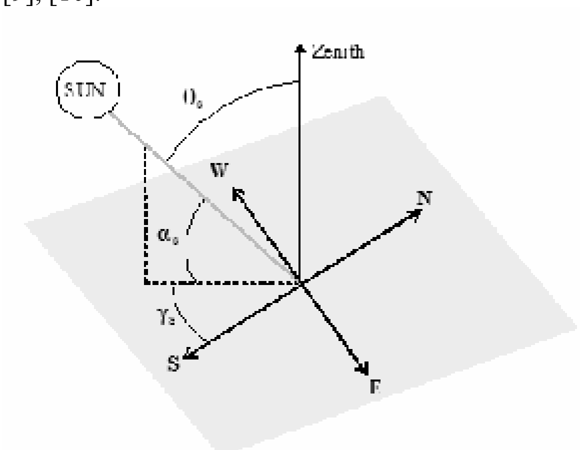

Fig. 1 - Sun's position

These two angles are defined by the equations (1) and (2):

$$\cos\theta_s = \sin\delta\sin\Phi + \cos\delta\cos\Phi\cosh = \sin\alpha_s \tag{1}$$

$$\cos\gamma_s = \frac{\sin\alpha_s\sin\Phi - \sin\delta}{\cos\alpha_s\cos\Phi} \tag{2}$$

In these equations, Φ is the location latitude, δ is the declination given by equation (3) and h is the hour angle determinated by equation (4).

$$\delta = 23.35\sin\frac{360(284+d)}{365} \tag{3}$$

where d is the day of year starting from the first of January:

$$h = -15\,(12 - \text{hour}) \tag{4}$$

The position of the sun can be described by the terrestrial horizon coordinate system, where axis V represents the vertical direction, axis E points the east and axis S points south (Figure 2).

In this coordinate system, the unit vector from the earth to the sun can be expressed by [7], [11]:

$$\overline{SUN} = (\cos\sigma\bar{S}\ ,\cos\xi\bar{V}\ ,\cos\pi\bar{E}\,) \tag{5}$$

where:

$$\cos\sigma = -\sin\delta\cos\Phi + \cos\delta\sin\Phi\cosh \tag{6}$$

$$\cos\xi = \sin\delta\sin\Phi + \cos\delta\cos\Phi\cosh \tag{7}$$

$$\cos\pi = \cos\delta\ \sinh \tag{8}$$

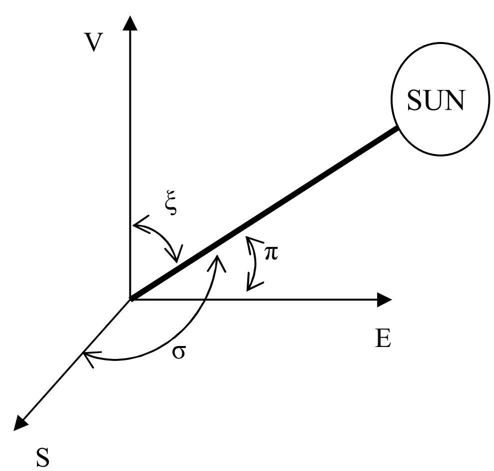

Fig. 2 - Angles for the Sun

3. COLLECTION ANGLE

The collection angle (θ_c) must be calculated and compared with the acceptance half-angle θ_a (Figure 3), to determine when the CPC is receiving energy from the sun.

This angle θ_c represent the angle between sun's position vector and normal to the collector surface projected onto the transverse plane (Fig. 3).

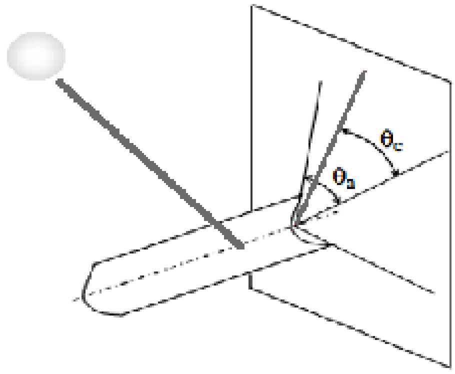

Fig. 3 - Representation of collection angle and acceptance half angle

The CPC is a linear two-dimensional concentrator of two distinct parabolas, with their axes inclined at angles ± θ_a with the respect to the optical axis of the collector. This is characterized by its ability to collect all the radiation within acceptance half angle θ_a (Figure 4) and to direct it towards a receiver.

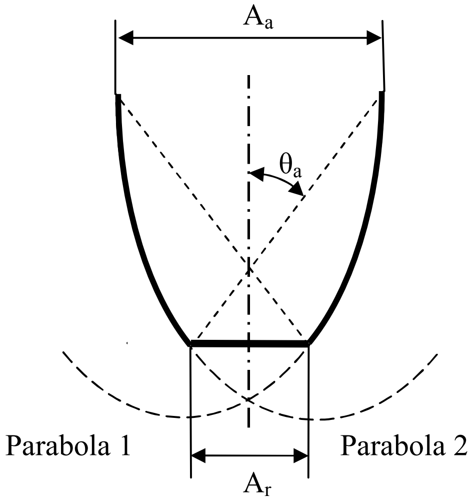

Fig. 4 - Schematic diagram of symmetrical compound parabolic collector with a flat receiver

This angle is defined as the angle between the axis of CPC and the line connecting the focus of one of the parabolas with the opposite edge of the aperture. The concentration ratio for a non - truncated two dimensional CPC is given by [11, 13].

The position of a CPC collector is determined by three angles, the tilt β, surface azimuth γ and rotation ω. When all these angles are zero, the collector is horizontal and oriented east - west.

The tilt angle β represents the tilt of surface with respect to the horizontal.

The azimuth angle γ shows the orientation in relation to the east-west direction. Therefore, when the azimuth surface angle $\gamma=0^o$, the collector is orientated east - west and when $\gamma=90^o$, it is orientated north - south.

The rotation angle ω is the result from a rotation around an axis perpendicular to the collector surface.

The collection angle is given by [7]:

$$\theta_c = \operatorname{atan} \frac{S_c}{V_c} \tag{9}$$

where:

$$S_c = (\cos\omega\cos\beta\cos\gamma - \sin\omega\sin\gamma)\cos\sigma - \cos\omega\sin\beta\cos\xi + (\cos\omega\cos\beta\sin\gamma + \sin\omega\cos\gamma)\cos\pi \tag{10}$$

and:

$$V_c = (\sin\beta\cos\gamma)\cos\sigma + (\cos\beta)\cos\xi + (\sin\beta\sin\gamma)\cos\pi \tag{11}$$

For any solar collector, the useful energy gain is equal to the absorbed radiation, *S* minus the heat losses, U_l. Therefore the useful energy gain by a CPC is:

$$Q = F_r A_a \left[S - \frac{U_i (T_i - T_a)}{C} \right] \quad [W] \tag{12}$$

where:

A_a [m^2] – aperture area
A_r [m^2] – receiver area
C [-] – concentration ratio
F_R [-] – heat removal factor
S [W/m^2] – energy absorbed
T_a [^{o}C] – air temperature
T_i [^{o}C] – inlet temperature
U_l [W/m^2 K] - overall loss coefficient of collector per unit aperture

The absorbed solar radiation S is given by:

$$S = G_t \tau_{cover} \tau_{CPC} \alpha_r \left[1 - \left(1 - \frac{1}{C}\right) \frac{G_D}{G_t} \right] \tag{13}$$

The transmissivity τ_{CPC} of the CPC depends on its reflectivity *ρ* and on the average number of reflections:

$$\tau_{CPC} = \rho^n \tag{14}$$

where:

G_t [W/m^2] – total radiation;
G_D [W/m^2] – diffuse radiation
τ_{cover} [-] – cover transmissivity;
τ_{CPC} [-] – CPC transmissivity;
α_r [-] – receiver absorptivity
ρ [-]– reflectivity

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4. Results and Discussions

For this paper we selected some usual values for various properties and parameters for the CPC collector. The aperture area is considered equal by unit (A_a = 1m^2). The optical parameters are: cover transmissivity (τ_{cover} = 0.9), the reflectance (ρ =0.88) and the receiver absorptivity (α_r =0.87).
The entering fluid temperature is 120 ^{0}C. The overall loss coefficient per unit aperture is considered 2.5 W/m^2 K.
Based on the mathematical model described above and using the same parameters of the collector, it was possible to determine the optimum collector tilt angle (depending on the energy gained) for each concentration ratio considered.

Table 1

C (concentration ratio)	β (tilt angle)	Q [kWh/m^2] (useful energy gain)
1	Φ-20	96.431
1.2	Φ -19	95.042
1.5	Φ -18	97.898
1.7	Φ -20	98.556
2	Φ-15	100.89
2.5	Φ -9	99.795
3	Φ -9	91.809
3.5	Φ -18	91.658
4	Φ -16	89.088
4.5	Φ -22	78.928
5	Φ -21	77.676

Table 1 presents the collector tilt optimized for different concentration ratios, for the whole year. The maximum useful energy gain is for a concentration of C = 2 and a tilt of 15^0 less than the latitude of the location.

Another possibility to improve the energy gain for the whole year is to change the tilt angle of the collector twice a year, determining the optimal tilt angle values for summer and winter.
The results are given in Table 2.
We can notice the highest energy gain can be obtained in summer, which is a concentration ratio equal to 3 and the tilt angle $\beta = \Phi$-21^0 .
For the winter months, the tilt angle β=Φ+13^0 is chosen for C = 5.
Therefore the best result is for C = 3, with the tilt angle $\beta = \Phi$-21^0 in summer and $\beta = \Phi$+8^0 in winter.
By comparing this optimal result (114.299 kWh/m^2 when C = 3) with the result for the stationary collector the whole year (91.809 kWh/m^2), an improved energy gain of about 24% is found.
In Fig. 5 is shown the energy gain when the collector tilt is optimizing for different concentration ratios for the whole year (ω=0, γ=0) compared with the energy gain when the tilt angle is equal by the latitude.

Table 2 - The optimum tilt angles for different concentration ratio, when γ = 0 and ω = 0 for summer and winter

C (concentration ratio)	β (tilt angle)	Q[kWh/m^2] (useful energy gain)	β (tilt angle)	Q [kWh/m^2] (useful energy gain)	Q [kWh/m^2] (useful energy gain)
	Summer		Winter		Year
1	Φ -23	86.065	Φ +2	11.91	97.975
1.2	Φ -23	84.258	Φ +2	12.668	96.926
1.5	Φ -23	85.747	Φ +3	14.435	100.182
1.7	Φ -23	87.035	Φ +4	15.686	102.721
2	Φ-23	89.248	Φ +5	17.419	106.667
2.5	Φ -25	91.248	Φ +4	19.771	111.019
3	Φ -21	92.923	Φ +8	21.376	114.299
3.5	Φ -18	91.658	Φ +10	22.522	114.18
4	Φ -16	89.088	Φ +13	23.396	112.484
4.5	Φ -22	78.928	Φ +15	24.089	103.017
5	Φ -21	77.676	Φ +13	24.2	101.876

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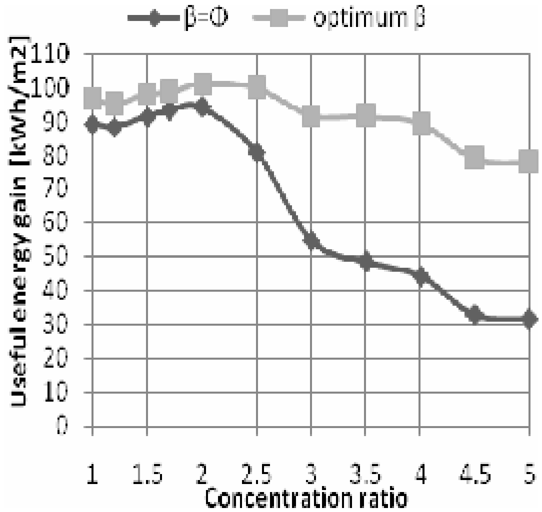

Fig. 5 - Energy gain for the tilt equal by latitude and the optimum tilt

There is the possibility for enhancing the useful energy gain of the whole year is to change the position (tilt) of the south facing collector twice a year, one angle for the summer and another for the winter.

We considered that the tilt angle in changed seasonal, for two times for a year, one time in April and the second time in October.

Fig. 6 shows the increase of useful energy gain when the tilt angle is changed for 2 times for a year.

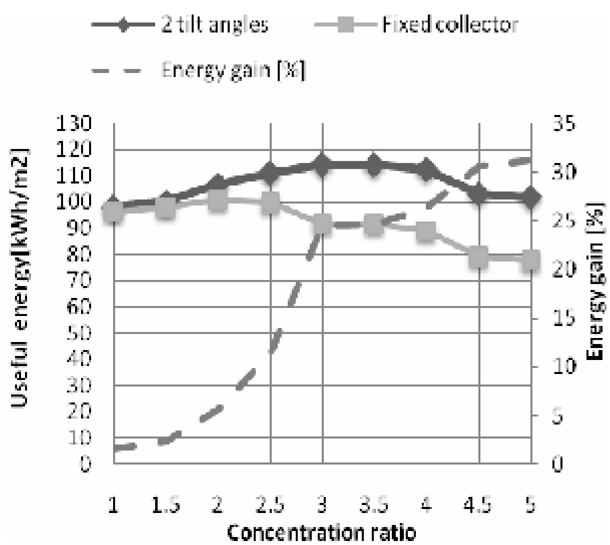

Fig. 6 - The useful energy gain against concentration ratio and collector tilt angle for fixed collectors and changing the tilt angle for 2 times (summer and winter)

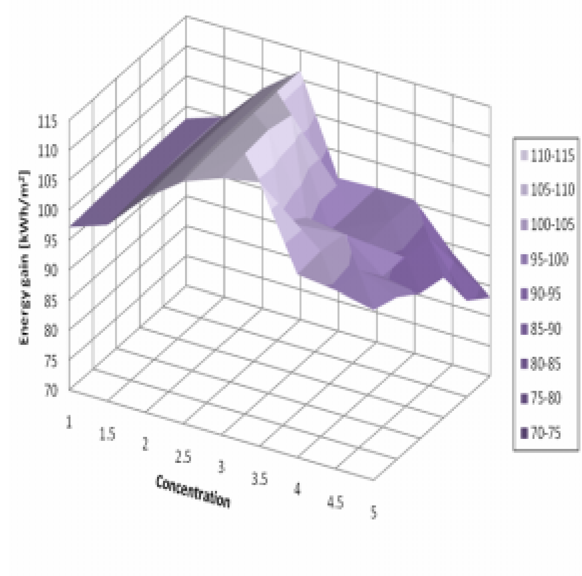

Fig. 7 - The useful energy gain against concentration ratio and collector tilt angle for 2 different tilt angles (summer and winter)

Figure 8 illustrates the increase of the useful energy when using sun tracking systems.

For flat collectors (C = 1) the increase is 20.6%, 23.06% and 32.52% compared to the situation when β = Φ where β is seasonaly changed and β is optimized for the entire year, respectively.

For concentrating collectors the gain is much higher, reaching up to 300% for C = 5.

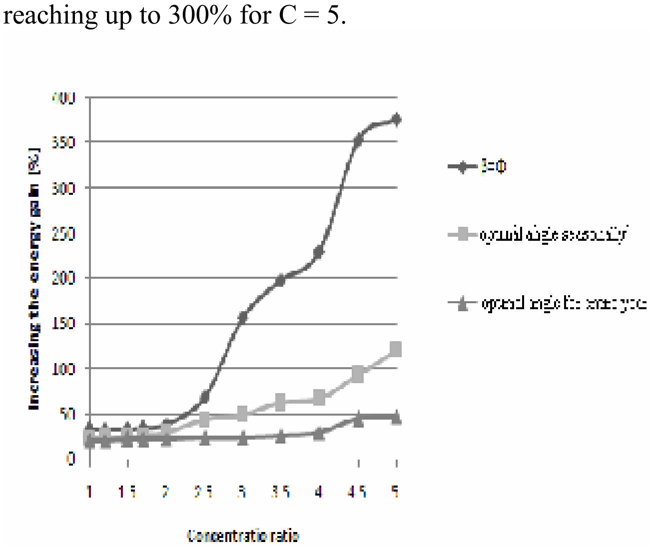

Fig. 8 - Increasing the useful energy gain when a sun tracking system is used

5. Conclusions

In this paper there were analyzed the influence of the tilt angle when the collector has the same position during the whole year and when the tilt angle is changed for two times for a year (in spring and in autumn).

From this study the following conclusions can be drawn:

- When the collector tilt is optimizing for different concentration ratios for the whole year ($\omega = 0$, $\gamma = 0$), the result was the same, with the maximum useful energy gain being for a concentration of C = 2 and a tilt of 15^0 less than the latitude of the location.
- Changing the tilt angle for 2 times for year (April and October) the best concentration ratio is obtained for C = 3, the improvement been equal to 24.5% then the situation when the CPC remain in the same position whole year.
- The useful energy gain is bigger during the winter, when the tilt angle is changed seasonal, special for C higher then 3.

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