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Shape Optimization For Parabolic Troughs Working In Non-Ideal Conditions

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Abstract

The aim to realize more efficient solar concentrators, improves the research on the best configuration for the mirror surfaces. The optical behavior of a parabolic trough collector is investigated depending on its particular shape outside the ideal conditions. A 2D ray-tracing model of the real systems was realised taking into account a reference value for the solar radiation and different misalignment errors between the light beams and the mirrors axis.

The computational analysis shows the relationship among the collection performance and the main geometrical parameters; different boundary conditions bring to consider different optimal configurations for the concentrator shape. Generally for medium concentration levels (50-150x) and non-ideal settings the more efficient parabolas are not characterized by a rim angle equal to 90°, which is the theoretical best value.

Among the studied cases, it is interesting to note that a possible working condition for the PT system corresponds to a light beam scattering of 0.5° and a tracking misalignment of 0.2°.

With these constrains, imposing high optical performance requirements, a maximum concentration ratio near to 60 can be reached with rim angle values of about 114°.

keywords: Solar energy; parabolic trough; optical analysis; ray-tracing; concentration ratio.

1. Introduction

During the last decades the concentrating technologies for solar energy employment have gone on expanding all over the world in many different configurations [1-7]. There are some important advantages both for PV and CSP applications in respect to the flat solutions. Generally in the first case, using last generation devices, the conversion efficiency can be boosted up and also the raw material for cells can be reduced at equal output power. For what concerning the CSP systems high temperatures can be reached increasing the energy amount of the heat transfer fluids.

The common concentrating layout requires the use of lens and mirrors and, in particular, the parabolic profile is one of the most widespread because of its construction properties and a reasonably good manufacture feasibility [8].

The optimization of the mirror surfaces design is important to characterize the entire solar energy conversion system because it is the most responsible of the radiation capture and collection. In working conditions of real plants different misalignment errors between the solar rays and the collector axis would arise: some of theme depend on the external environment where the system is situated, the others concern the concentrator itself. They have to be treated in different manners in respect the their characteristics [9].

Some errors can be classified as random errors: in this case the emitted rays have a preferential direction but they are spread within an solid angle around it. Phenomena due to solar divergence, scattering effects in general, reflective surfaces properties and collector manufacturing tolerances (slope errors) are modeled in this way.

On the other hand there is the possibility that the entire collector is tilted in respect the ideal position and the rays hit the mirrors with an offset angle that contribute in illuminating the absorber incorrectly. This kind of error is described like a non-random angle and it is especially linked to solar tracking accuracy and positioning solutions.

Nomenclature

d	absorber diameter
c	chord of the parabola
φ	rim angle of the parabola
f	focal length of the parabola
r	distance between the focus and the edge of the profile
σ	incoming rays angle in respect to the parabola axis and random misalignment semi-angle
β	non-random misalignment angle
CR_g	geometrical concentration ratio
η_o	optical efficiency

1.1. Geometrical considerations

A geometrical approach can be used to describe the main features of a solar concentrator and the external constrains [10]. In this case, from an optical point of view, light is considered as rectilinear segments carrying power through a transmission medium and interacting with reflective and diffractive surfaces.
In fig. 1 we show the characteristics of a parabolic collector (frontal plane) for CSP applications:

- d is the absorber diameter;
- c is the chord of the parabola;
- f is the focal length of the parabola;
- φ is the rim angle of the parabola formed by the axis and the straight line from the focus to the end point of the profile;
- r is the distance between the focus and the end point of the profile;
- σ is the incoming rays angle in respect to the parabola axis (called misalignment angle).

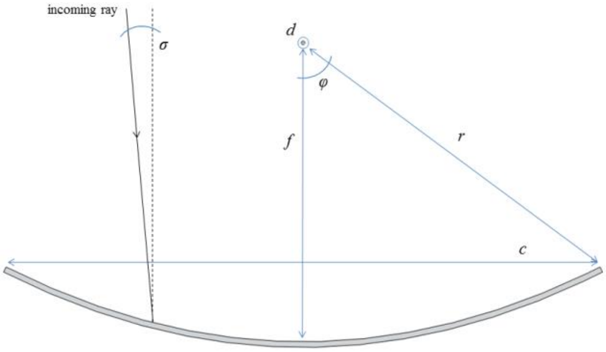

Fig. 1 - Main characteristics of a parabolic concentrator.

The chord is relevant to define the entire system because it indicates the aperture of the concentrator and the collected energy amount but the shape of the mirror is defined fixing the rim angle or the focal length/chord ratio. There is to-one correspondence between the two parameters and their value represents families of similar parabolic profiles. The analytical relation is:

$$\frac{f}{c} = \frac{1 + \cos\varphi}{4\sin\varphi}$$

In fig. 2 we drew some configurations with different absolute sizes for φ and f/c constant and equal to 90° and 0.25 respectively.

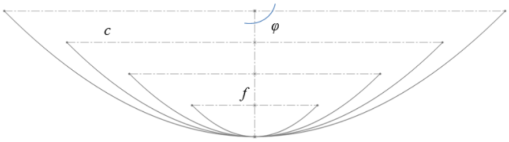

Fig. 2 - Different similar parabolas with the same value for the rim angle (90°) and the focal length-chord ratio (0.25).

Regarding to the solar energy collection skill we can also express the geometric concentration ratio as:

$$CR_g = \frac{c}{\pi d} = \frac{\sin\varphi}{\pi \sin\sigma}$$

This definition takes into account a cylindrical absorber that is fully hit by the rays reflected form the mirror. It is clear to assure that widening the incoming beam angle its diameter increases and CR_g become lower. In fig. 3 we report the trend for the rim angle equal to 90°: we can see that the parameter σ is very relevant and values near 1° are sufficient to cut down the concentration level.

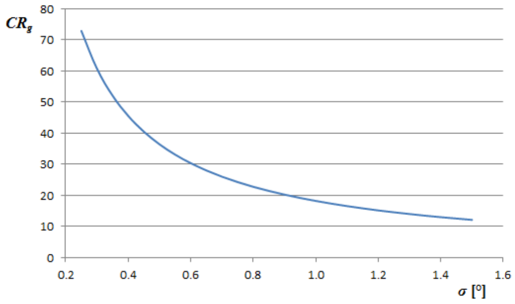

Fig. 3 - The reduction of the geometrical concentration ratio as the incoming rays angle increases.

On the other hand, for every value of σ the maximum concentration ratio can be reached when the rim angle is 90° and *f/c* is 0.25, independently from the concentrator absolute dimensions. In fig. 4 (a,b,c) we show the related curves and the particular case for σ equal to 0.25°.

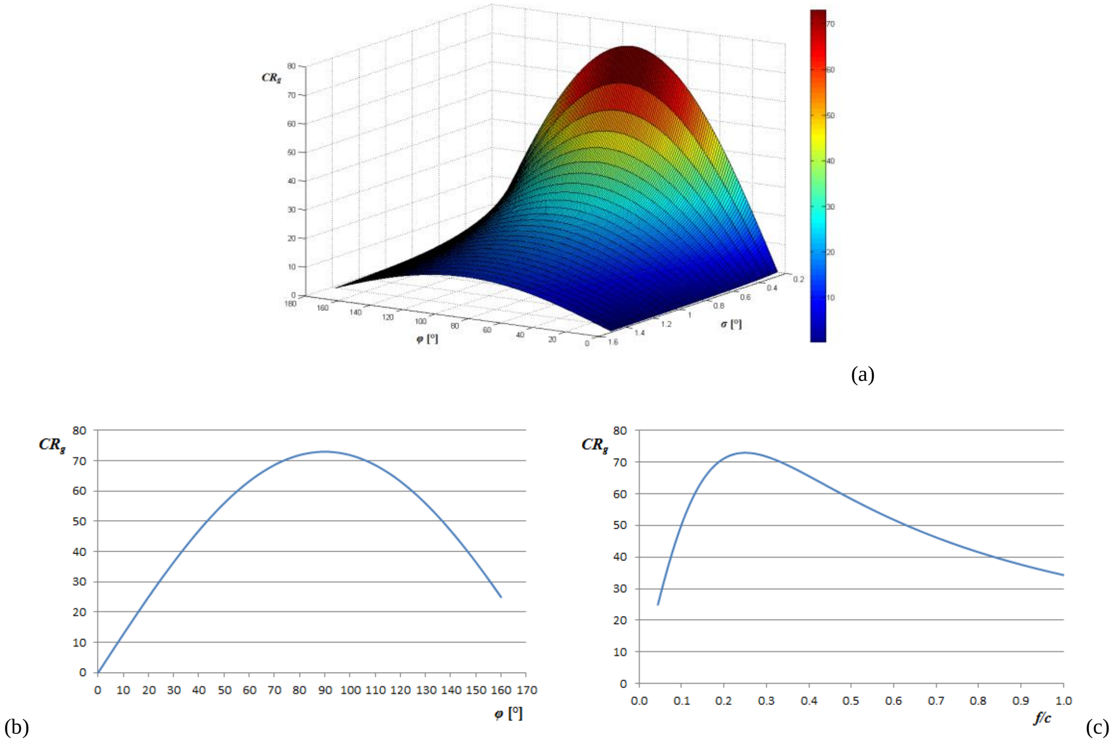

Fig. 4 - (a) The geometrical concentration ratio as a function of the rim angle and *f/c*. (b,c) The particular case for φ = 90° and *f/c* = 0.25: the solar divergence (σ = 0.25°) was considered.

2. The ray-tracing computational mode

The considerations of section 1 give the relationship among the concentrator geometrical parameters knowing a determined misalignment angle and imposing that all the rays reflected reach the absorber circumference.

In order to go deeper into the optical behavior of a PTC, a more specific analysis was conducted. The principal aim was to optimize its shape and manage how it is possible to gain medium concentration factors monitoring the losses in collection performances.

So a ray-tracing model of the system was realized through the commercial software Zemax® and a 2-D geometry was built in including a parabolic mirror with 95% of reflective index and a circular absorber detector. We chose the dimensionless parameters *f/c* and CR_g as suitable for the description of the concentrator: this permitted to generalize the investigation studying families of similar PTC in spite of their particular size.

Then a flat source was set to simulate the sun radiation and 1000000 rays were considered with a power density of 1000 W/m^2. We imposed the rays to have a normal direction in respect to the emitting surface introducing different random and non-random errors. At the beginning the first ones were treated separately; afterwards they were combined together.

An optical efficiency was finally defined to describe the performances:

$$\eta_o = \frac{P_a}{P_p}$$

where P_a is the power [W] hitting the absorber and P_p is the power [W] reaching the collector aperture.

2.1. The random errors influence analysis

The first part of the study considered only random errors on the ray path. The simulations started imposing that all the rays were characterized by an uniform distribution within a plane angle around their ideal direction (parallel to the concentrator axis). The value of semi-angle σ was fixed at 0.25°, 0.5° and 0.75°: the first one is used to estimate solar divergence due to the sun apparent size, the other ones are plausible working conditions relative to the features of the system like the manufacturing technology.

For every value of the mentioned errors, we investigated different configurations of the mirrors shape varying the focal length-chord ratio from 0.8 (φ = 35°) to 0.05 (φ = 157°) with step 0.005. Then we evaluated the optical efficiency and the geometrical concentration ratio that can be reached. The functions among the parameters are visible in the following 3D-plots (fig. 5-7). Each one is referred to a precise value of the rays distribution semi-angle σ.

At first we can say that, similar to the considerations of par. 1.1, σ influences considerably the collection skill and the performances. So it is important, during the design of the concentrator, to define the specifications of the system in order to limit this kind of error.

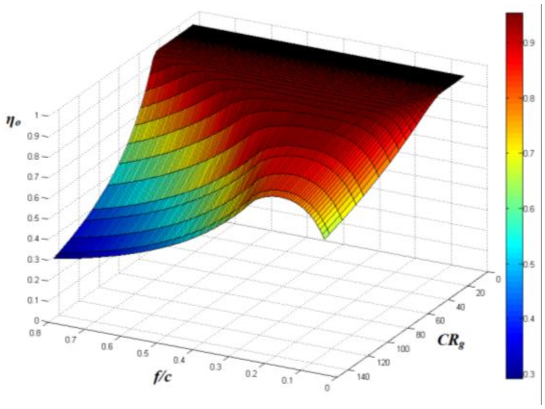

Fig. 5 - The optical efficiency as a function of the *f/c* factor and the geometrical concentration ratio for $\sigma = 0.25°$.

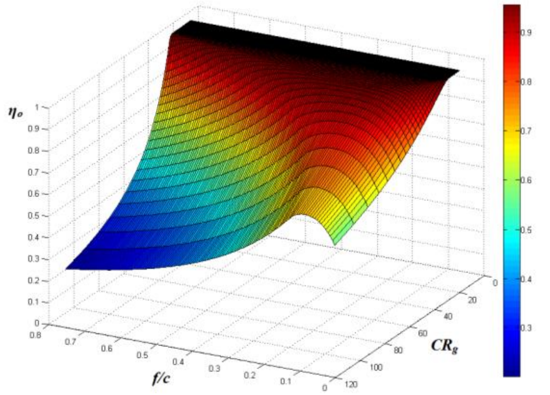

Fig. 6 - The optical efficiency as a function of the *f/c* factor and the geometrical concentration ratio for $\sigma = 0.5°$.

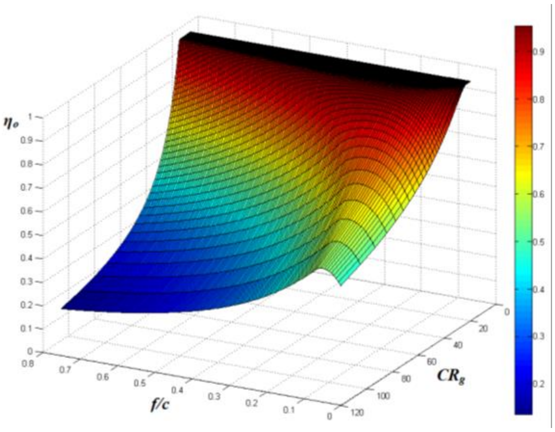

Fig. 7 - The optical efficiency as a function of the *f/c* factor and the geometrical concentration ratio for $\sigma = 0.75°$.

Considering the solar divergence effect (fig. 5, σ = 0.25°) and the reflective index of the mirrors, the efficiency keeps values near to 0.95 only for a concentration level under 71. In the worst analyzed conditions (fig. 7, σ = 0.75°) instead, the same target of the concentration ratio would guarantee an optical efficiency of 0.66.

Another important aspect concerns the variation of the optimal focal length-chord factor depending on the imposed external constrains. In general, worsening them, we noted that the more compact geometries for parabolic mirrors with the focus point below the extreme edges help in reducing the performance losses.

For example, considering the first case related to CR_g near to 71, f/c should be fixed at 0.281 (φ = 83°); in the second one f/c has to be equal to 0.131 (φ = 125°). If this parameter was kept constant at 0.281, the efficiency would drop to 0.48.

In Tab.1 we report the configuration characteristics with a concentration level of 71 and increasing σ.

Table 1. Characteristics of the collector configurations for a concentration ratio equal to 71.

Rays spreading semi-angle σ	Optical efficiency η_o	Focal length-chord ratio f/c	Rim angle φ
0.25°	0.95	0.281	83°
0.5°	0.81	0.175	110°
0.75°	0.66	0.131	125°

In order to optimize the shape of a PTC, it is important to monitor the optical efficiency and design the collector assuming that it would not fall under a target value. So the data showed in the previous graphs were elaborated differently. At this step the aim was to extrapolate the values of the concentration ratio as a function of f/c within the locus of the points where the efficiency keeps higher than 0.8.

The results are showed in fig. 8: it is clear that growing σ the collection skill has to reduce and its maximum gradually become 145, 73, 48.

Furthermore, we underline how, even in this case, the best focal length-chord is not 0.25 (φ = 90°) as we found by pure geometrical considerations. The specific values are reported in the conclusion section.

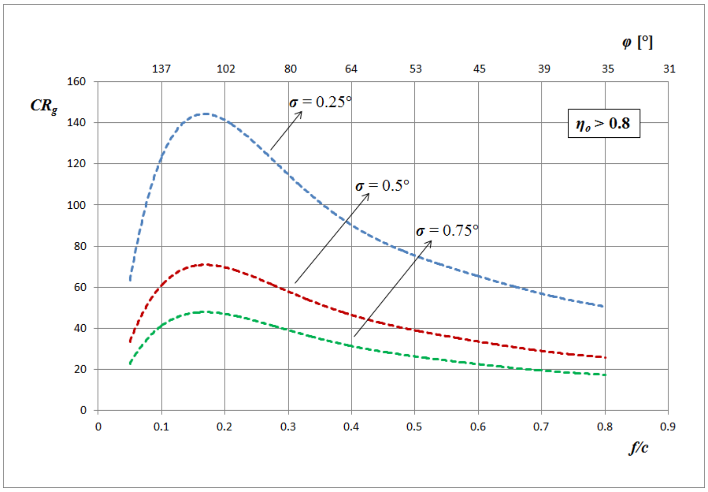

Fig. 8 - The geometrical concentration ratio as a function of the f/c ratio and σ when optical efficiency is over 0.8.

2.2. The non-random errors influence analysis

The analysis conducted in the previous paragraph takes into account a kind of errors in illuminating the absorber due to the spreading effects of the light beam. In order to improve the optimization in the design of the concentrator shape a value for σ was fixed at 0.5° according to [9] and a new set of simulations was computed.

From this point we investigated the influence of an additional misalignment non-random error: the geometry of the entire concentrator was rotated around the parabolic mirror vertex clockwise with angles β equal to 0.1°, 0.2° and 0.3°. For every condition we evaluated again the optical efficiency as a function of the concentration ratio and the focal length-chord factor. In fig. 9 we show the new 3D-plot relative to β equal to 0.2°.

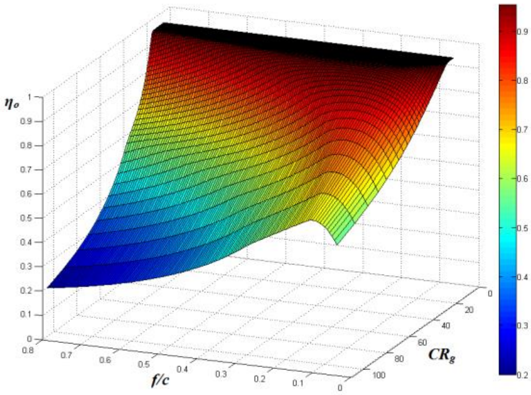

Fig. 9 - The optical efficiency as a function of the *f/c* factor and the geometrical concentration ratio for $\sigma = 0.5°$ and $\beta = 0.2°$.

The specific value for β was chosen because it represents a result come out from experimental data on sun tracking accuracy of a real prototype.

The trends of the optical efficiency are similar to the ones of the previous analysis and the characteristic of the system are reported in Tab. 2 underlining the comparison between the configurations with the same random error (0.5°) and β equal to 0° and 0.2°. It is clear that adding the tracking error, the optical efficiency decrease at same concentration ratio even if the variation is not predominant (on average 6.6%). Furthermore the *f/c* parameter has to be set at lower values to reach the maximum performances (the rim angle grows).

Analogue results came out analyzing the locus of the point within the efficiency is maintained over 0.8: in fig. 10 we note how the concentration ratio gradually drop from 70 to 60 and 50. The corresponding values for *f/c* and φ are reported in the next section.

Table 2. Characteristics of the collector configurations for the same concentration ratios with and without the influence of β equal to 0.2° (σ = 0.5°).

Geometrical concentration ratio CR_g	β (σ = 0.5°)	Optical efficiency η_o	Focal length-chord ratio f/c	Rim angle φ
40	0°	0.95	0.238	93°
	0.2°	0.90	0.200	103°
46	0°	0.93	0.225	96°
	0.2°	0.86	0.188	106°
53	0°	0.90	0.206	101°
	0.2°	0.84	0.169	112°
64	0°	0.84	0.188	106°
	0.2°	0.79	0.156	116°
80	0°	0.77	0.163	114°
	0.2°	0.72	0.138	122°
106	0°	0.66	0.131	125°
	0.2°	0.61	0.113	131°

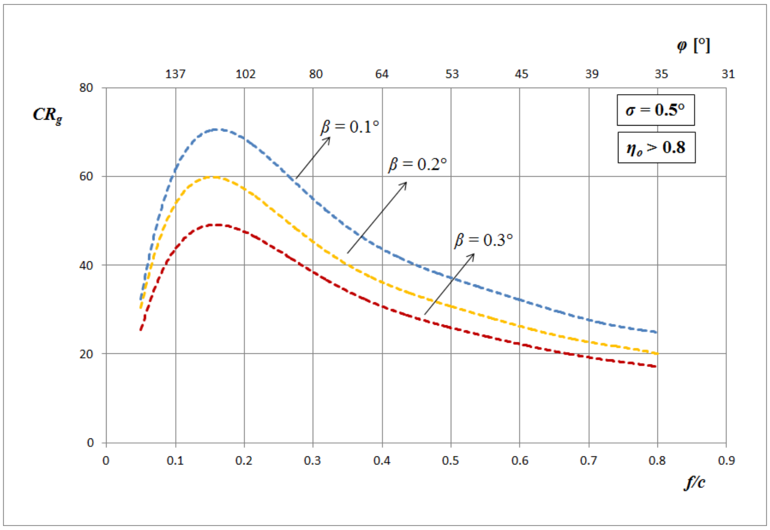

Fig. 10 - The geometrical concentration ratio as a function of the *f/c* ratio and β when optical efficiency is over 0.8 and σ equals 0.5°.

3. Conclusion

The study permitted to define the shape of a Parabolic Trough Concentrator System (PTC) that optimizes the optical efficiency and the concentration ratio under precise boundary conditions. Two different kind of ray misalignment angles in (with respect to the collector axes) were taken into account with the aim to model real phenomena arising during the operation of the system. First of all we considered random errors only and we found that the shape of the concentrator slightly varies depending on misalignment constrains in the range of interest and different geometrical concentration levels can be reached. The characteristics of the configurations which keep optical efficiency over 0.8 are reported in tab. 3.

Table 3. Characteristics of the collector configurations considering σ and optical efficiency over 0.8.

Optical efficiency η_o	Rays spreading semi-angle σ	Geometrical concentration ratio CR_g	Focal length-chord ratio f/c	Rim angle φ
> 0.8	0.25°	145	0.1725	110.8°
	0.5°	73	0.170	111.6°
	0.75°	48	0.169	111.9°

Then the analysis was extended adding variable values of non-random errors: in this case σ was fixed at 0.5° as a reference point. The new optimized solutions are described in tab. 4. We proved that the focal length-chord factor should be gradually decreased if β grows.

Table 4. Characteristics of the collector configurations considering β and optical efficiency over 0.8.

Optical efficiency η_o	Tracking error angle β (σ = 0.5°)	Geometrical concentration ratio CR_g	Focal length-chord ratio f/c	Rim angle φ
> 0.8	0.1°	70	0.1675	112°
	0.2°	60	0.1625	114°
	0.3°	50	0.16	115°

We can conclude that there is not an unique configuration that maximizes the collection skill of a PTC for what concerning the optical efficiency and the geometrical concentration factor; then the value for the rim angle calculated as the best in par. 1.1 (90°) is not appropriate but it should be widened in almost cases.
The shape of the parabolic mirrors, finally, has to be designed supposing to know the average working conditions and the manufacturing features of the system.

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