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A new approach for obtaining angular acceptance function of non-perfect parabolic concentrating collectors

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A B S T R A C T

A new approach to calculate the angular acceptance function of cylindrical parabolic collectors has been developed. The procedure is rapid, simple and enables obtaining the acceptance function with or without absorber deviations. In a simple way, it registers the view angle of an eye slipping along the reflector surface. In case there are deviations, as a result of loss of symmetry, the function splits into four branches: two for the right and left hand side of the reflector section and two for the left and right hand side of the light cone reaching the aperture. As a result of deviations some branches are affected by windows where sun light escapes, reducing the optical efficiency of the collector. Deviations are computed as: (a) distance (d) between parabola focus and deviated absorber center and (b) rotation angle of the absorber (ω). Examples of perfect and non-perfect collectors are given and a variety of situations simulated: distance (d) varying between 0 and 1.0∗Rabs and rotation angle (ω) between (−90°) and (+90°). A procedure to generate angular acceptance functions monotonically decreasing with the view angle is described and discussed. Results are exposed as sensitivity curves where the main parameters of the angular acceptance function are registered. The method described enables to map a large variety of optical configuration errors, which can be used for quality tests, design procedures and collectors development. Non-parabolic geometries can also be treated with a similar procedure, showing that the method developed is a general and versatile approach.

1. Introduction

Angular acceptance functions have been widely studied to characterize the optical structure of **perfect** concentrating solar collectors (Bendt et al., 1979; Rabl et al., 1982; Rabl, 1985). It has been recognized that this function, instead of long time demanding ray trace programs (Biggs and Vittitoe, 1979; Schrenk, 1963; Treadwell, 1976), is an appropriate tool to express functional relationships between the collector's components. The angular acceptance function is a powerful tool to be used for design developments, revealing the optical and geometrical features that define the collector geometry. Real concentrating collectors present deviations from perfect ones. Usually those deviations or errors are treated statistically and, convolved with the solar brightness function, yield an effective source that includes all significant error distributions (Bendt et al., 1979). Convolution of effective brightness with angular acceptance function leads to intercept factor (Rabl et al., 1982).

Various authors analyze the problem of optical error sources for diverse geometries: Zhu and Lewandowsky (2012) present a new optical evaluation approach (First Optic Model) to analyze parabolic trough collectors; Zhu (2013a) extends the analysis to obtain the impact of position errors of the absorber on parabolic collectors behavior; Zhu (2013b) treats optical error sources for the Fresnel geometry; Binotti et al. (2013) analyze three dimensional effects in parabolic trough collectors. Exact analytic solutions for absorber flux maps, for the main 2D concentrator classes, are derived by Fraidenraich et al. (2013). Solutions are obtained considering the convolution of effective input solar brightness distribution and a geometric function that characterizes the collector geometry and absorber shape.

In this work we generalize the angular acceptance function for the case of **non-perfect** parabolic collectors (absorber position errors). The procedure can equally be applied to other geometries, e.g. Fresnel concentrating collectors. Parabolic trough collectors are designed to accept incident radiation, making a single reflection

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Nomenclature

A	collector's aperture length (m)
d	distance between the parabola focus and absorber center with deviation (m)
f	focal distance of the parabola (m)
$F(\phi)$	acceptance function
Rabs	absorber radius (m)
Greek letters	
γ	intercept factor
θ	angle between the vector radius and focal line (degrees)
θ_B	angle between the vector radius and focal line at point B on the reflector surface (degrees)
θ_r	rim angle (degrees)
$\rho(\theta)$	vector radius at a point on the parabolic reflector (m)
$\rho(\theta_B)$	vector radius at the point B on the parabolic reflector (m)
$\rho'(\theta)$	deviated vector radius at angle θ (m)
ϕ	view angle of the absorber radius (degrees)
ϕ_P	biased view angle (ψ + ϕ) (degrees) (P means plus)
ϕ_M	biased view angle (ψ - ϕ) (degrees) (M means minus)
ϕ_s	aperture angle of the incident solar light cone (degrees)
$\phi(\theta_B)$	view angle of the absorber radius at reflector point B (degrees)
ω	angular deviation of the absorber, positive counterclockwise (degrees)
ψ	angle between $\rho'(\theta)$ and $\rho(\theta)$, positive counterclockwise with reference to $\rho(\theta)$ (degrees)

within a given angular interval, symmetrically for right and left incident angles. Incident radiation with angles exceeding the designed interval can be partially accepted. When deviations of the absorber position occur, the angular acceptance function ($F(\phi)$) has its symmetry broken. Usually, the function splits into four branches that represent the right and left hand side of the parabolic cavity and the right and left edges of the incident light cone. In this way the function $F(\phi)$ becomes a detailed expression of the geometrical and optical behavior of the collector.

Computer ray-tracing is always an option to analyze optical configurations, in particular optical errors. But it is time-intensive for extensive sensitivity studies. Nominally analytic solutions as mentioned above have been developed for obtaining the acceptance function for line-focus collectors (Bendt et al., 1979).

Here we derive an analytic procedure to obtain a general angular acceptance function ($F(\phi)$) when absorber deviations occur. Different from conventional approach, the sun ray deviation angle becomes the argument of the angular acceptance function, unveiling the nature of optical errors and its influence on the solar collector behavior. The method described can be developed with simple spreadsheet, without any special programming. Simplicity, accuracy and speediness with which deviations can be transcribed into the $F(\phi)$ language make of it an attractive general procedure.

An order relationship could be established between angular acceptance function and intercept factor. While the former provides the details of misalignments, windows localization from which incident light escapes, the intercept factor constitutes an integral over the angular acceptance function weighted by projected solid angle and the source brightness distribution.

2. Parabolic collectors with cylindrical absorber- perfect case

Parameters of the parabolic trough collector are focal distance of the parabola (f), rim angle (θ_r) and absorber radius (*Rabs*) (Fig. 1). The absorber radius, usually designed to be reached by all the light rays of the incident solar light cone (ϕ_s), satisfies

$$Rabs = \sin(\phi_s) \cdot \rho(\theta_r) \tag{1}$$

where $\rho(\theta_r)$ is the parabola radius of the rim angle.

Points on the reflector surface are identified by angle θ, formed by radius ρ and focal line of the parabola (Fig. 1).

Engineering considerations may suggest designing absorbers larger or smaller than the one given by Eq. (1). There is a well established tradeoff between collection efficiency and flux concentration. If absorber radius is large, the collector is less sensitive to optical deviations and errors, although the concentration ratio is reduced. Smaller absorber radius increase flux concentration but also might increase optical losses.

The collector's aperture length is denoted as (A), an internal line parallel to the aperture as (b) and the reflector angle at point B as θ_B. Let us consider the view angle $\phi(\theta_B)$ at point B, defined as

$$\phi(\theta_B) = a\sin(Rabs/\rho(\theta_B)) \tag{2}$$

where $\rho(\theta_B)$ is the focal radius at angle θ_B. If all the view angles $\phi(\theta)$ for $\theta < \theta_B$ are larger than $\phi(\theta_B)$ ($\phi(\theta) > \phi(\theta_B)$), incident light rays at BB, with angles $\phi(\theta_B)$ will reach the absorber when hitting any point of the parabola cross section BBCB (Fig. 1). In fact, inside the cavity BBCB the view angles are larger than $\phi(\theta_B)$. The focal radius $\rho(\theta)$ for every angle ($\theta < \theta_B$) satisfies the inequality $\rho(\theta) < \rho(\theta_B)$ (property of the parabola) and therefore $\phi(\theta) > \phi(\theta_B)$. Then, the view angle at point B, being smaller than the view angles inside BBCB, is contained in all of them. Rays with $\phi(\theta) < \phi(\theta_B)$ will reach internal points of the absorber.

Since light rays incident at the aperture PP with an angle ϕ_s reach the absorber, the angular acceptance function is considered equal to one. Light rays incident at the cord BB with angle $\phi(\theta_B)$ and able to reach the absorber, cover a normalized aperture b/A, equal to the angular acceptance function for $\phi(\theta_B)$. It can be calculated as

$$F(\phi(\theta_B)) = \frac{\rho(\theta_B) * \sin(\theta_B)}{\rho(\theta_r) * \sin(\theta_r)} \tag{3}$$

This expression can be justified as follows. If we consider section BBCB part of a nested system of parabolic sections, we can state that light incoming from a given nest, with view angle $\phi(\theta_B)$, e.g., will be able to travel all along smaller nests and be received by the absorber, but not when travelling along larger nests (e.g. larger than BB). The largest nest is an infinite one. The view angle at the edge of this nest is zero. Light rays incident at the aperture PP with $\phi = 0$ will reach the absorber after reflecting on surface of all possible nests inside the parabola section PPCP. The same is valid for all the (ϕ) angles smaller than or equal to the light cone (ϕ_s). It explains why $F(\phi)$ is equal to one (1) up to ϕ_s. From this point on it starts to diminish because of the reduction of (b/A) relation (Eq. (3)), and becomes zero at the parabola vertex.

An example of angular acceptance function, obtained by the described procedure, for a parabola with f = 1.84 m, a light cone ϕ_s of 0.009 radians, an absorber radius (Rabs) of 0.0331 m and rim angle equal to 90° is given in Fig. 2. Rim angle can be different from 90°. This is just one particular value, since collectors can be designed with a variety of rim angles, even larger than 90°.