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Optimal focal length of primary mirrors in Fresnel linear collectors

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A B S T R A C T

In a linear Fresnel plant adopting slightly curved primary mirrors (cylindrical or parabolic), a significant gain in the collected radiation can be achieved using primary mirrors with different focal lengths, dependent on the position of the mirror with respect to the receiver. This work introduces a universal function that provides the optimal focal length of a mirror, given only the mirror's position relative to the receiver and the latitude, for a NS-oriented collector with a flat horizontal effective target. In a solar plant with the focal lengths defined by this function, the efficiency gain with respect to a solar field adopting identical mirrors is estimated in the range 1.5–6%, with the gain increasing if mirror imperfections or tracking errors are present: this means that the regulation of the focal lengths is especially useful in containing the loss of efficiency due to defects. The given rule is tolerant to errors in the focal length regulation (up to 10%). The function can be used as a reference for future projects, or as a starting point for more refined optimizations.

1. Introduction

In Linear Fresnel concentrators (LFC in the following), a linear fixed receiver is suspended above a solar field composed of strips of mirrors (Francia, 1968; Canio et al., 1979; Feuermann and Gordon, 1991; Zhu et al., 2014; Montes et al., 2014). The mirrors are usually slightly concentrating, and each strip rotates on a fixed horizontal axis in order to reflect the sun radiation towards the receiver. LFCs received a widespread attention in recent years, because they have many advantages with respect to more traditional single-mirror concentrators: the fixed receiver, the larger collection area for each receiver, the smaller moving parts and the lower cost of the optical components. A large number of studies can be found in the literature discussing LFC configurations (Mills and Morrison, 2000; Häberle et al., 2002; Grena and Tarquini, 2011; Abbas et al., 2013; Zhu and Huang, 2014) or comparing LFCs with linear troughs (Morin et al., 2012; Giostri et al., 2013; Schenk et al., 2014). Many full scale prototypes have already been built (Bernhard et al., 2008, 2009; Novatec, 2016; Areva, 2016; Solar Power Group, 2016).

Even neglecting the measurements and specifications of the receiver, the geometry of an LFC is defined by a large number of parameters, which can be changed independently, at least in principle: the widths, positions and focal lengths of each mirror are all independent variables, therefore the solar field geometry depends on $3N_m$ degrees of freedom, where N_m is the number of mirrors. Optimization techniques were theoretically investigated and discussed in the literature. Some authors have reduced the degrees of freedom by means of simple constraints, such as the absence of shadowing up to a certain incidence angle (Nixon and Davies, 2012) or other theoretical criteria (Chaves and Collares-Pereira, 2010; Abbas and Martínez-Val, 2015). The reduction of the number of parameters is not strictly required: in Boito and Grena (2016) a method to perform a full optimization of all the geometric parameters of an LFC was presented, assuming that the dependence of the plant cost from the parameters is given. This method optimizes the ratio between the year-long collected radiation and the plant cost. Assuming a plausible cost model, it was shown that a full optimization produced a relative gain of 12% w.r.t. a uniform, adjacent-mirrors configuration, and of almost 5% w.r.t. a uniform configuration with 3 optimized parameters (mirror width, mirror focal length, spacing between mirrors). The paper also presented the results of partial optimizations: these were performed by enforcing uniformity constraints (e.g., uniform spacing, or uniform width) on some – but not all – of the parameters, in order to highlight the effect of changes on each parameter.

The method proposed in Boito and Grena (2016) cannot be used to assess universal criteria for LFC design, since its results are

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dependent on the cost model of the plant. But a result obtained in one of the partial optimizations presented in Boito and Grena (2016) suggested a possible universal rule. When optimizing the focal lengths of the mirrors, under the hypothesis of equal width and of uniform spacing, a significant gain was obtained w.r.t. a simple optimization with equal focal lengths, more than the 60% of the gain obtained with a full optimization. Note that the chosen cost model did not include the focal lengths: indeed, it was assumed that the curvature did not affect the mirror cost, a reasonable assumption for small curvatures. Therefore, the gain was only due to the increased optical collection. Moreover, the shadowing and blocking effects were small, because the mirrors were well-spaced, following the result of the previous optimization. So it is likely that the optimal focal length of a mirror is essentially linked to the properties of the considered mirror (particularly its position relative to the receiver), and it does not depend much on the properties of other mirrors in the plant.

This remark suggests the existence of a universal function that, given the position and width of a mirror, computes the focal length that maximizes the year-long optical collection. Of course, general properties of the plant structure, such as orientation, the latitude and the height and width of the receiver also need to be taken into account. Such a function does not depend on any cost parameter, so it gives useful criteria for designing solar fields, even when cost parameters are not known (e.g., in the case of innovative plants).

One may reasonably think that the optimal focal length of a mirror should equal the distance from the receiver. However, in Boito and Grena (2016) it was shown that this is not a good criterion: if in the optimal configuration the computed focal lengths were substituted by the distances from the receiver, the efficiency gain completely disappeared. This is due to the fact that a Fresnel mirror almost never works in-focus, and the regulation of the focal length assuming an in-focus concentration is useless. Optimization of the focal lengths is a more subtle issue that requires specific computations.

In this work we perform such computations on a plant with NS orientation and a flat, horizontal receiver. The cases of cylindrical and of parabolic mirrors are both studied. First, it is assessed which of the geometric parameters of the mirrors are really useful for defining an optimal focal length, with the aim of reducing the number of parameters as much as possible. The results of this study will show that, allowing a small tolerance (1.2%) on the collected radiation w.r.t. the optimal value, the only relevant parameters that determine the optical focal lengths are the position of the mirror relative to the receiver, and the latitude of the plant. Neither the width of the mirror nor the width of the receiver affects significantly the results, for any plausible configurations.

This means that it would be possible to define a simple function that determines the optimal focal length of the mirror, given only the latitude and the position of the mirror w.r.t. the receiver. Such a function is numerically computed and the results are fitted to give a very simple, analytic form of the function, valid both for parabolic and cylindrical mirrors. Tests on some plant configurations are then performed, with a full optical simulation, in order to compute the efficiency gain that would be obtained when applying this design criterion.

2. Model and computations

In the computations, a single mirror is considered: no shadowing or blocking from adjacent mirrors are taken into account. The mirror is NS-oriented. The distance between its rotation axis and the center of the solar field (the point directly below the center of the receiver) will be called X, its semi-width will be called W and its focal length will be called F. Both cylindrical and parabolic mirrors are considered. The receiver is flat and horizontal; its semi-width will be denoted as L. The shadow projected from the receiver on the mirror is neglected too. The scheme of the system considered in the computations is shown in Fig. 1.

The system is scale invariant, i.e., if h, X, W, L and F are all multiplied by a same quantity, the efficiency does not change. For this reason, we define the adimensional variables $x = X/h, w = W/h, l = L/h$ and $f = F/h$ that will be used in the following. So, all the quantities appearing in the resulting formulas (and the optimal focal lengths too) will be ratios w.r.t. the height of the receiver (e.g., for a 10 m high receiver, a resulting optimal $f = 1.5$ corresponds to an optimal focal length of 15 m). From now on, all the references to position, widths and focal lengths will be understood as these adimensional quantities.

The quantity optimized in order to find the ideal focal length is the average geometrical collection over a year, i.e., all the reflectivities are considered to be 1. This is computed according to the scheme presented in Boito and Grena (2016), which we quickly recall:

- The average efficiency is computed integrating the pointwise efficiency (i.e., the efficiency given the sun position) over the distribution of the sun position during the year. Corrections due to the variations of the distance Earth-Sun and to the air mass are included. The sky is assumed to be "averagely clear", i.e., meteorological effects on the radiation distribution are supposed to be independent of the day of the year and of the hour of the day. The integration variables are the declination δ and the hour angle H of the sun, and the integration methods are Gauss-Lobatto over H and Gauss-Chebyshev on δ. The integral to compute is

$$R_m(x,w,l,f) = \frac{1}{\pi^2}\int_{-\epsilon}^{+\epsilon} d\delta \frac{\cos\delta}{\sqrt{(\sin\epsilon)^2 - (\sin\delta)^2}} \times \int_{-H_c(\delta)}^{+H_c(\delta)} dHAM(\delta,H)R(\delta,H,x,w,l,f) \tag{1}$$

  where ϵ is the inclination of the Earth axis, that is, $[-\epsilon, +\epsilon]$ is the domain of the declination $\delta, \pm H_c(\delta)$ are the two hour angles corresponding to a Zenith of 90 deg when the declination is $\delta, AM(\delta,H)$ is the air mass correction (Ineichen, 2008) and $R(\delta,H,x,w,l,f)$ is the pointwise efficiency. The factor appearing only in the $d\delta$ integration is a weight that summarizes the distribution of the sun position during the year and the variation of the radiation intensity due to the change in Sun-Earth distance. See Boito and Grena (2016) for a more detailed explanation.
- The pointwise efficiency is computed integrating on the sun profile the efficiency for collimated rays; the sun profile is considered to be Lambertian.
- The efficiency for collimated rays is computed by calculating numerically with high precision the fraction of the mirror that projects the reflected rays within the receiver opening.

Some comments on the sun model and on the (neglected) reflection errors are in order. The sun shape is represented as a Lambertian uniform cone of radiation with angular size of 0.004563 rad. The computation weighs the results for collimated radiation on this sun shape to obtain the effect of solar divergence. Upon reflection, no slope errors are considered when computing the optimal focal lengths, so no degrading of the sun profile is used. This choice is necessary in order to obtain a universal law that does not depend on the quality of the mirrors. However, the effect of the errors on mirror slope is considered when testing the law on a full