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Optimization of the geometry of Fresnel linear collectors

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ABSTRACT

Methods and results concerning the optical optimization of a linear Fresnel collector are presented. The variables considered in the optimization are the positions, widths and focal lengths of the mirrors; the mirrors can be of variable size and focal length, and they can be nonuniformly spaced. The target function to be optimized is the plant cost divided by the collected solar radiation in a year. The computation of the collected radiation and of its average on the year, and the optimization of the cost/radiation function are carried out via suitable mathematical methods and the choice of a plausible cost function. Four different levels of optimization (uniformly spaced identical mirrors; nonuniformly spaced identical mirrors; mirrors of the same width with uniform spacing and variable focal lengths; and finally a full optimization) are presented, with a discussion of the resulting gain on the target function (i.e. the reduction of the ratio between the plant cost and the collected radiation). The results show that the application of suitable optimization strategies can lead to an estimated gain around 12% with respect to the initial configuration (all mirrors identical and adjacent), and that a full optimization leads to a gain of 4.5% over a simple uniform optimization. This gain is due in large part to the possibility of regulating the focal lengths (the optimization of focals leads to a 2.8% gain over the uniform case), while only a minor improvement (less than 0.4%) is obtained with nonuniformly spaced identical mirrors.

1. Introduction

Linear Fresnel systems (Di Canio et al., 1979; Feuermann and Gordon, 1991; Montes et al., 2014; Zhu et al., 2014) are among the most promising technologies for energy production from concentrated sun radiation. In such plants, a linear fixed receiver is suspended above a solar field composed by strips of mirrors, flat or slightly concentrating; each strip rotates on a fixed horizontal axis in order to reflect the sun radiation towards the receiver. Several studies have been devoted to plant configurations (Abbas et al., 2013; Grena and Tarquini, 2011; Häberle et al., 2002; Mills and Morrison, 2000; Zhu and Huang, 2014), study and simulation of various aspects of the plant work (Abbas et al., 2012; Munoz-Anton et al., 2014; Pino et al., 2013; Velazquez et al., 2010; Zheng et al., 2014), analysis of different types of receivers (Abbas et al., 2012; Facao and Oliveira, 2011; Lin et al., 2013; Natarajan et al., 2012; Singh et al., 2010), or comparisons with linear trough systems (Giostri et al., 2013; Morin et al., 2012; Schenk et al., 2014); prototypes have been proposed and built (Areva, 2015; Bernhard et al., 2008, 2009; Novatec Solar, 2015; Solar Power Group, 2015). The main advantages with respect to trough systems are the fixed receiver, the larger collection area for each receiver (which reduces the cost of the receivers and simplifies the management of the fluid circulation), the small moving parts (mirrors are far smaller than the single-block mirror of a solar trough) and the lower cost of optical components (mirrors are almost flat, and their construction is simpler). The main disadvantages are the reduced optical efficiency, especially when the sun is far from the focal plane,[1] and the larger sensitivity to optical and tracking errors, due to the larger distances between mirrors and receiver and to the fixed receiver configuration.

Fresnel systems, even from a purely geometric point of view, allow for a large variety of configurations, since the properties of the receiver and the positions, widths and focal distances of the mirrors can all be in principle changed independently. Usually, uniform configurations (with all the mirrors equal, and equally spaced, or not spaced at all) are employed, but this is not mandatory. Uniform configurations, while simpler in design, do not maximize efficiency. A number of quantities and effects change significantly with the distance from the midpoint of the solar field (the point directly under the receiver): the inclination of the

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[1] The *focal plane* is defined here as the vertical plane containing the receiver.

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mirrors, the distance from the receiver, the shape of the reflected beams, the shadowing and blocking among the mirror strips, and the shadowing from the receiver. In fact, solutions with varying widths or spacing among the mirrors have been proposed for fixed-frame linear Fresnel collectors[2] (Goswami et al., 1990). The no-blocking condition (total absence of blocking for normal incidence), usually imposed for such systems, can also be applied in the case of independent-mirror Fresnel systems, leading to nonuniformly spaced mirrors. Another possible criterion that has been suggested is the absence of shadowing up to a given incidence angle (Nixon and Davies, 2012). Mirrors with variable sizes and shapes (and even variable heights) are proposed in Chaves and Collares-Pereira (2010), following theoretical principles (etendue-matching). An analytical method to build a variable-size, variable-spacing solar field that reduces the degrees of freedom to three variables is described in Abbas and Martinez-Val (2015).

If we choose to remove all the uniformity conditions and other prescriptions, the efficiency of a Fresnel plant becomes dependent on a large amount of variables; so, there is space for refined – and nontrivial – optimization, which could potentially lead to significant gains. However, due to the large number of variables, only partial optimization approaches have been tried so far. Studies of the spacing factor for uniform systems, or of the optimal focal length of the mirrors, have been performed for specific systems (Grena and Tarquini, 2011); optimization of the exergy cost with respect to the no-shadowing maximal angle has been performed, in plants adopting the aforementioned no-shadowing criterium (Nixon and Davies, 2012). These studies consider a small number of parameters (3 at most), while no strategies for full optimization have been presented up to now.

In this paper we try to fill this void presenting a method for the full optimization of the configuration of a Fresnel collector. The target function (i.e. the function to minimize) is the ratio between the plant cost and the collected radiation. The collected radiation is computed considering the geometric optical collection of the system, averaged on the year. The optimized variables are all the listed parameters of a system, except the receiver properties (height and width), which are kept fixed, and the number of mirrors (this being a discrete quantity, it should be optimized separately, comparing the different cases).

The target function is proportional to the specific cost of the produced energy under two hypotheses (whose validity is discussed in the following): (i) the optical properties of the elements do not change too much with the radiation incidence angle and (ii) the thermal efficiency does not change too much in working conditions. Methods to refine the analysis removing these two hypotheses are discussed.

Unfortunately, too little data are available to build a general cost function for a Fresnel plant. Besides, such a function will also be strongly dependent on the design choices. Here a simple parametrization of the plant cost and an example with arbitrary but plausible cost parameters will be presented.

The optimization will proceed in several steps, in order to evaluate the gain due to different design choices; the gain is defined as the relative reduction of the target function. First, a simple optimization of a uniform system will be made, starting from an initial configuration with all the mirrors equal and adjacent; the optimized variables in this case are only three (width, spacing, focal length). Starting from the optimal uniform configuration, the uniform spacing condition can be removed, maintaining all the mirrors equal. Alternatively, the condition on the equal focal lengths can be removed, maintaining the mirrors uniformly spaced and with equal widths. These two special cases of optimization are of interest because they represent plausible engineering choices: mirrors can be mass produced, and then, in the latter case, mechanically bent. The final step is a full optimization, removing all the constraints on the solar field. The relative gains due to each type of optimization will be discussed and compared.

The mathematical technique used for optimization is mostly BFGS (Broyden–Fletcher–Goldfarb–Shanno), see e.g., Dennis and Schnabel (1983). With the exception of the uniform optimization, quite straightforward, in the other cases the method will be complemented with simulated annealing cycles (Kirkpatrick et al., 1983) in order to explore the configuration space in search of possible multiple local minima. It must be stressed that, from a practical point of view, the accuracy in finding the optimal configuration may not be very significant, as the reduction on the final cost is the only important aspect. In other words, if a very "flat" minimum is present, two distant configurations may exhibit a very small difference in the target function, and can be considered as equivalent.

Despite the necessary simplifications of the model, the presented methods are quite general and can be easily applied to practical cases, with known cost functions and considering also thermal efficiency.

The paper is organized as follows. In Section 2, the structure of the Fresnel system is described. Section 3 explains how to compute the target function: in particular, it presents the optical simulation of the system, and the method for the computation of the mean efficiency during the year. The model for the cost of the plant is also illustrated, thus defining a suitable target function. Section 4 is devoted to the optimization techniques used in this work. Section 5 shows the results of the optimization, and discusses possible further improvements of the methods to include other effects (more realistic cost functions, thermal efficiency, weather conditions).

2. Model of Fresnel system

The optimization only considers the geometric optical collection; for this reason, the only relevant aspects of the Fresnel plant are the geometric properties that determine the optical efficiency. In the model, the receiver is flat, horizontal, and placed at height h from the ground. The semi-width of the receiver opening will be indicated as l. The central axis of the receiver opening will be called (somewhat improperly) focal line. The quantities h and l are kept fixed (not involved in the optimization).

On the ground, a number N_m of cylindrical primary mirrors will be placed with rotation axis at ground level. The system is NS oriented. The mirrors will be placed symmetrically around the midline of the solar field (the line directly below the focal line); this means that, in the case of odd N_m, the central mirror will always be placed exactly below the receiver. This symmetry reduces the total number of degrees of freedom used in the optimization from $3N_m$ to $3N_m/2$ in the case of even N_m, and to $3(N_m+1)/2-2$ in the case of odd N_m. The position of the axis of the mirror n with respect to the midline will be indicated as x_n, and the semi-width of the mirror will be w_n. The mirror will have a focal length f_n. The scheme is shown in Fig. 1.

For convenience, the list of all the variables defining the system will be indicated as X_f in the following.

Some comments on the assumptions made here can be useful:

[2] In a fixed-frame (or "true") Fresnel collector, the mirror strips are blocked on a common flat frame that moves tracking the sun. Their properties and possible applications are completely different from the case of independent-mirrors Fresnel systems, such as the ones discussed in this work. In this paper, a Fresnel system will always be an independent-mirror system, unless otherwise specified.