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Beam-down linear Fresnel reflector: BDLFR

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ABSTRACT

This paper presents a novel linear solar concentrating system named BDLFR, acronym of Beam-Down Linear Fresnel Reflector. A BDLFR system consists of a primary LFR array reflecting sunlight into a secondary hyperbolic –or elliptic– cylinder mirror that beams-downs reflected rays to its secondary focal line at ground level, where the receiver is placed. A model based on vector notation –and validated against SolTrace– predicts the optical behavior of BDLFR and generates layouts to avoid blockings. The edge ray approach is utilized to determine receiver aperture widths. As a function of beam-down curvature ratio, the BDLFR configurations that maximize solar collection are found out. Concentration ratios about 80 are reached with a tertiary re-concentrator (CPC) coupled to the receiver aperture.

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1. Introduction

Linear Fresnel Reflector (LFR) systems consist of several, in parallel arranged, mirror strips that reflect and concentrate solar beam radiation into a common focal line. Compared to parabolic trough collectors (PTC) –the other CSP linear technology–, LFRs are receiving great attention in recent years because of its lower costs, while achieving similar concentration ratios [1–3].

Based on the original concept of LFR system, novel designs have been suggested to increase its functionality and performance. Mills and Morrison [4] proposed a Compact Linear Fresnel Reflector (CLFR) consisting in several receiver lines, so that significant spacing is saved between mirror rows alternatively aiming to the receivers while blockings are avoided. Using the CLFR concept, Collares-Pereira and Chaves [5,6] improved its optical efficiency by means of a wave-shaped trough with variable mirror widths. LFRs with variable mirror widths were also widely researched by Abbas and Martínez-Val [7]. Huang et al. [8] designed an azimuth tracking LFR system. Another configuration with changeable number of mirror rows, named Scalable Linear Fresnel Reflector (SLFR), was suggested in Ref. [9]. A novel low-cost system, where LFR mirrors float on a water basin, was recently presented in Ref. [10].

In LFR optical systems, the linear receiver is placed elevated from the ground, so as to minimize blockings between Fresnel mirror rows. This LFR configuration limits its applicability to small and lightweight receivers, usually consisting of a single tube or a few of them. When dealing with large and heavy linear receivers, such as thermochemical reactors or fluidized beds, placement on top is not feasible.

Gómez-Hernández et al. [11] recently proposed a new LFR coupled with a linear beam-down (BD) reflector to irradiate a particle receiver placed on the ground. Taking advantage of beam-down optics [12], a secondary linear reflector –aligned with the primary focus of the LFR– redirects concentrated beam rays into its secondary focus. The linear receiver aperture is situated along such secondary focal line, allowing the receiver to rest on the ground. The present work presents and analyzes this novel concentrating solar system named Beam-Down Linear Fresnel Reflector, BDLFR by its acronym.

Beam-down optical systems present some issues, as clearly pointed out by Vant-Hull [13]. Secondary reflectors magnify the reflected spot by a factor equal to the ratio of hyperbola heights, later defined as *f*. In other words, the greater the curvature of the beam-down reflector, the more the reflected flux is dispersed. For this reason, beam-down systems require a final concentrator, usually CPC, at ground level. Despite this issue, easy operation and maintenance of ground reactors, which may also lead to cost savings, has promoted the research and industrial use of BD systems

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[14].

The application of BDLFR systems is straightforward in power generation. The use of particles as heat transfer fluid is a promising approach for CSP cost reduction [15]. In this sense, a linear particle receiver at ground level solarized by a BDLFR system is being researched [11]. Such receiver consists of a multi-stage fluidized bed where gas and particles could both reach temperatures around 900 °C [16].

BDLFRs are also suited to many solar thermochemical processes [14] ranging from hydrogen production or biomass gasification to processing of metals like zinc or aluminum. Thermochemical processes tested in small-scale central beam-down systems, such as water splitting [17], can be favorably adapted to the proposed linear beam-down. Linear solar reactors for pyrolysis of biomass [18] or waste tyres [19] are also good candidates to be integrated in a linear beam-down optic system.

The preliminary objective of the present work is to provide full knowledge on this novel optical system. In this regard, the following section introduces the mathematical background on the optics of BDLFR systems, and is followed by the edge ray approach to determine the receiver aperture widths.

The provision of tools to properly size BDLFR systems is another research goal. Sections 4 and 5 respectively deal with the generation of BDLFR layouts and the selection of the optimal configurations, which are those leading to the narrower receiver apertures.

Results on flux concentrations by the optimal BDLFR configurations are provided in Section 6, along with the validation of the model against Monte-Carlo Ray-Tracing (MCRT) simulations. Then, the option of coupling a Compound Parabolic Concentrator (CPC) at the receiver entrance is researched. Last Section finally summarizes the conclusions from the whole study.

2. BDLFR basics

This section puts forward the mathematical background of the proposed beam-down linear Fresnel reflector system. Firstly, the BDLFR geometry is introduced. Using vector notation, relevant tracking formulae are later stated. Finally, the calculation of optical losses is outlined.

2.1. Geometry

The beam-down linear Fresnel reflector system consists of a primary stage of linear Fresnel reflector and a beam-down secondary. Taking advantage of the optical properties of conics, sunrays reflected by the mirror Fresnel array towards the focal line of a cylinder, whose transversal section is hyperbolic or elliptical, are redirected to the other focal line.

Previous research in point-focus beam-down systems showed better optical performance of hyperboloid compared to ellipsoid reflectors [12]. Hence, such favorable geometry results into a hyperbolic cylinder for a linear system, as herein considered.

Regarding the orientation of the LFR system, investigations such as that in Ref. [20], have shown preference of North-South over East-West. Thus, the system herein studied is oriented in the North-South direction axis, about which symmetry exists in the position of mirror rows. Each mirror is focused, having a slight curvature of radius equal to twice the distance to the primary focus [21]; i.e. on-axis alignment. Additionally, in the present study all the mirror rows have the same width, W_m.

The system of coordinates has origin in the secondary focus with X-axis pointing to the East, Y-axis aligned with the secondary focal line and Z-axis pointing to the zenith. According to this convention, YZ and XZ planes are respectively the longitudinal and transversal planes. The height of the primary focus, H, is then the distance between both focal lines. For the sake of convenience, the secondary focus is at the same height as the mirrors axes.

In the transversal plane, LFR systems have scaling properties over a point; say the origin of coordinates (Y-axis). All length parameters in the transversal plane can be expressed as non-dimensional parameters as a function of a scaling factor [6]. Mirror width, W_m, is herein taken as the scaling factor. This means that for $W_m = 1\ m$, the remaining length parameters (i.e.: focal height, distance between mirror rows …) are also in meters. The notation throughout this document uses uppercase Latin symbols to represent dimensional parameters, and lowercase for the non-dimensional ones. For instance, non-dimensional focal height is represented with h, as defined as: $h = \frac{H}{W_m}$.

The beam-down reflector is a hyperbolic cylinder along the Y-axis. The geometric parameters of the hyperbola, as represented in Fig. 1, are: a main semiaxis, b secondary semiaxis, c linear eccentricity, and h focal distance, so that $h = 2c$. All the hyperbola parameters are correlated according to the following equation:

$$c = \sqrt{a^2 + b^2} = h//2 \tag{1}$$

The top hyperbola branch is considered as the single beam-down reflector. Since independent on y-coordinate −direction of cylinder axis−, the equation of the hyperbolic cylinder can be written in terms of the z-coordinate as a function of the x-coordinate as follows:

$$z_{hyp} = \frac{a}{b}\sqrt{x_{hyp}^2 + b^2} + \frac{h}{2} \tag{2}$$

To consider the whole bundle of hyperbolas, f is defined as the ratio of height of the hyperbola vertex to the total height h (Eq. (3)), just like Segal and Epstein's Ref. [12]. f gives an idea on the openness or closeness of the hyperbola, so that *curvature fraction* of the hyperbola is used interchangeably to name it. This f parameter ranges between 0.5 (flat horizontal) and 1.0 (infinite curvature, flat vertical). Fig. 2 represents the whole family of hyperbolas.

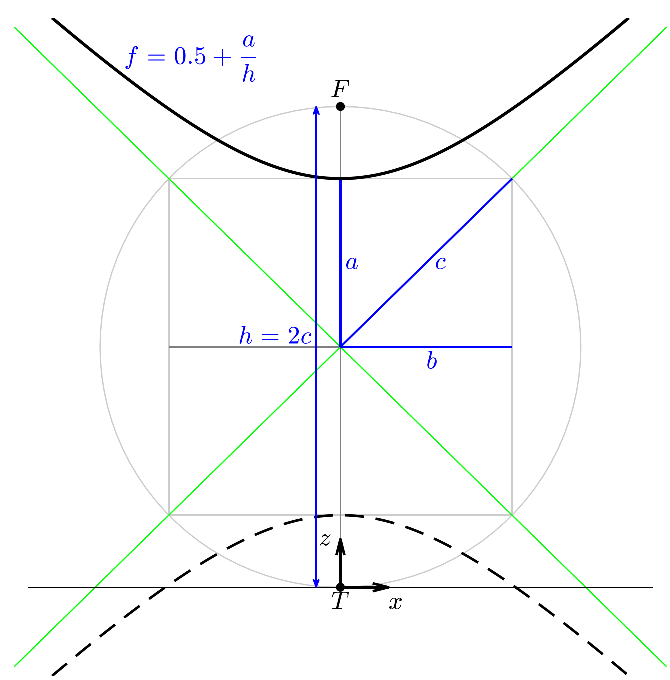

Fig. 1. Geometric parameters of hyperbolas.

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