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Optical features of linear Fresnel collectors with different secondary reflector technologies

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HIGHLIGHTS

- Different secondary reflector technologies for linear Fresnel collectors are compared.
- Optical annual performance is analyzed in selected ranges of the design variables.
- Efficiency, mean flux intensity and mean flux intensity uniformity are studied.
- Compound parabolic concentrators achieve more homogeneous fluxes.
- Adaptive design concentrators achieve higher efficiencies for vacuum absorbers.

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ABSTRACT

This paper is devoted to the analysis of different secondary reflector designs for linear Fresnel collectors. A number of authors have proposed alternative shapes of secondary reflectors in order to enhance the efficiency and the flux intensity at the absorber tube. In this work the primary mirrors layout has been maintained constant for all designs. Thus, only secondary concentrators that do not require a change in the primary mirrors field have been studied. In order to carry out the study a validated Monte Carlo ray trace code has been used, where three optical properties are considered: annual optical efficiency, mean flux intensity and circumferential flux intensity homogeneity. The maximum efficiency reached by each technology, for given optical flux specifications, is obtained. Finally, the optical performance of linear Fresnel collectors with secondary reflector is compared with that of state-of-the-art parabolic trough collectors. It is concluded that the efficiency of Fresnel collectors is around 23% than that of parabolic troughs, although with mean flux intensities around 46% higher and circumferential flux intensities notably more homogeneous (top to bottom flux intensity ratios five times higher).

1. Introduction and background

Linear Fresnel collectors (LFCs) are seen as a technology with a high potential for cost reduction in concentrating solar power (CSP). This is mainly due to the mirrors manufacturing simplicity, as they are nearly flat, the lighter structure, the lower negative effects of wind and the use of fixed receivers, which eliminates the need of rotating joints [1–3]. As a result, some published future trends conclude that potential capital cost of LFCs is the lowest of all CSP technologies [4] and that the expected levelized cost of energy (LCOE) is as low as for central towers [5–7].

However, LFC is still an immature technology compared to parabolic trough collectors (PTCs) and central tower. The number of design variables in LFC is very high, as it includes the number of mirrors, their location, their width, the receiver location and width, etc. There are many studies that analyse these variables and seek the solar field optimization, either by means of analytic studies [8–12] or with Monte Carlo ray trace (MCRT) methods [13–17].

Probably, the design choice that has a deeper impact on the Fresnel collector performance is the receiver technology. There are two main receiver technologies in LFCs: multitube receivers and secondary reflector receivers. Multitube receivers consist on a trapezoidal cavity with an array of parallel tubes where the fluid can flow either in parallel through the tubes or in series, entering by the outer tubes and exiting by the inner ones. This technology has been studied by many authors [18–21], and has been installed in Kimberlina (USA) and Dhursar (India) among others.

On the other hand, secondary reflector receivers only have one

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Nomenclature

D	relative outer tube diameter (–)
f	focal length (–)
H_r	distance from absorber tube center to secondary reflector extreme (–)
I	solar flux intensity at receiver surface (kW/m^2)
p_{sun}	probability of sunny day (–)
r_1	absorber tube radius (–)
r_2	distance from tube center to the closest point of the receiver (–)
w_r	aperture of the receiver (–)
w_t	relative total width of the reflecting surface (–)

Acronyms

ADC	Adaptive Design Concentrator
CPC	Compound Parabolic Concentrator
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiance
LCOE	Levelized cost of energy
LFC	Linear Fresnel collector
MCRT	Monte Carlo ray trace
NS	North–South
PTC	Parabolic trough collector
SPSC	Segmented Parabolic Secondary Concentrator
XX-SMS	Second-stage concentrator based on Simultaneous Multiple Surface

Greek letters

α^{ab}	Absorber acceptance angle from a point of the secondary reflector (rad)
β	Aperture half-acceptance angle from a primary mirror point
Δt	time step (min)
η_{en}	energy efficiency (%)
θ	parabola rim angle (rad)
θ_a	half-acceptance angle of the incident radiation (rad)
ρ	solar flux ratio (–)
σ	circumferential flux standard deviation (kW/m^2)
ϕ	parabola rotation angle (rad)

Subscripts

$m-m$	minimum to maximum
min	minimum
p	parabola
$t-b$	top to bottom
use	useful

absorber tube covered by a secondary reflector that redirects sun beams towards the tube. They have been also studied by many authors [22–24] and they have been installed in commercial plants such as Puerto Errado (Spain). This technology is able to achieve higher mean flux intensities at the absorber tube [25], which leads to a lower absorber surface and, thus, to a reduction of thermal losses and an increase in thermal efficiency. However, there is a slight decrease in optical efficiency due to the use of secondary reflector receivers [25].

It must be noted that the secondary reflector shape has been under research during the last years. As a result, different shapes have been proposed by a number authors. One of the first proposals was the compound parabolic concentrator (CPC), which is under research since 1974 [26]. However, it was not initially proposed for LFC but for horizontal non-tracking collectors. Nowadays, it is the secondary reflector shape assumed by many authors [27,22].

Grena and Tarquini 2011 [28] used a parabolic double wing secondary concentrator, where some of the primary mirrors aim one wing and others the second wing. The authors sought a more homogeneous circumferential flux intensity. However, to the authors' knowledge this design has not been used in later articles.

Canavarro et al. 2014 [29] suggest a second-stage concentrator based on simultaneous multiple surface (XX-SMS) method for linear Fresnel collector. This methodology had been proposed previously for parabolic trough collectors [30] and for fixed receiver troughs [31]. However, the design of the XX-SMS for linear Fresnel collectors is carried out together with the etendue-matched design of the primary mirror field [32].

Other authors have compared simpler designs such as parabolic and involute concentrators [33]. Later, an evolution from the parabolic concentrator was developed [34], with a double parabola that changes its tilt at a given point.

Finally, Zhu 2017 [35] has developed a new design of secondary reflector by means of an adaptive method. This concentrator has been compared with a compound parabolic collector in terms of incidence angle modifier and efficiency [36], but no information is given on the design variables used for the comparison.

From the literature review one can conclude that there is a large number of different designs of secondary reflector shapes. Although some of the previous studies compare two different shapes [33,36], none of them has conducted a comprehensive comparison that includes not only one design for each technology, but its whole design area. This is an important point to be considered, as a bad design can reduce the performance for any technology. In addition, the above mentioned comparisons do not include all the optical key performance parameters: efficiency, mean flux intensity and circumferential homogeneity.

The present study is devoted to analyse the optical performance of different secondary reflector technologies for a given primary mirror layout and for a given location. The work includes the whole design range for the analysed technologies, which ensures that all possible optimum designs are included. The simulations consider all the optical key performance parameters previously identified. In order to carry out this analysis the studied secondary reflector shape have been implemented on a validated Monte Carlo ray trace code and their design area has been simulated. The definition of the primary mirror layout, the secondary reflector technologies used and the implemented outputs of the code are presented in Section 2. In Section 3 the efficiency, mean flux intensity and circumferential flux homogeneity achieved by different technologies are included and the achieved optical performance is compared to that of parabolic troughs. Finally, conclusions are given in Section 4.

2. A MCRT model for linear Fresnel collectors: optimization parameters and selected technologies

This section presents first the Monte Carlo ray trace code used, together with the assumptions and the code outputs required in the analysis. Then, the solar field layout and the secondary reflector designs studied are defined by means of their design variables. Finally a validation of the secondary reflector MCRT code is carried out.

2.1. MCRT assumptions and outputs

A Monte Carlo Ray Trace method has been developed specifically for linear collectors [9,21,25,37,38]. This model has been validated with Soltrace [25] and includes the possibility to simulate linear Fresnel collectors with secondary reflector. The following assumptions are