Solar Energy 173 (2018) 769–779

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Development of analytical expressions for the incident angle modifiers of a linear Fresnel reflector

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ARTICLE INFO

Keywords:
Linear Fresnel reflector
Optical analysis
Incident angle modifier
Optimization

ABSTRACT

Linear Fresnel reflector is one promising solar concentrating technology for medium and high temperatures (200–400 °C) because of its simple design and its low cost. However, the greatest drawback of this collector is the increased optical losses and thus the emphasis is usually given to this issue. In this direction, the objective of this work is the development of analytical expressions for the incident angle modifiers of a linear Fresnel reflector for the longitudinal and the transversal directions. The goal is to create a simple and accurate formula for all the possible solar angles ranges. The developed equations are based on reasonable assumptions and on the geometric analysis of a simple collector with flat primary mirrors. The developed equations are tested with literature data from other studies and from commercial collectors. It is found that the developed equations lead to accurate results with mean deviations up to 5%. The developed analytical expressions can be used for the quick calculation of the optical performance of a linear Fresnel reflector, as well as they can be used for the geometry optimization of the collector.

1. Introduction

Solar energy utilization is an important weapon for facing numerous tremendous problems as the global warming, the fossil fuel depletion and the increasing worldwide energy demand (Myers and Goswami, 2016; Tiwari and Tiwari, 2016; Sahota and Tiwari, 2017). The concentrating solar thermal technologies are able to provide heat production at medium and high temperatures with significant efficiencies. So, they can be used in numerous applications as industrial processes, solar cooling, chemical processes and electricity production (Zhou et al., 2017; Loni et al., 2016).

The linear Fresnel reflector (LFR) is a concentrating technology which is competitive with the other linear collector, the parabolic trough collector (PTC). These linear technologies have many similarities; they have linear absorber, there is always one-axis tracking system and usually tubular absorbers are used in both technologies. The LFR presents important advantages compared to the PTC which are (Zhu et al., 2014; Morin et al., 2015; Montes et al., 2017; Bellos and Tzivanidis, 2018):

- Lower installation cost.
- There is a lower number of movable parts because the receiver does not move.
- There are low wind loads because the primary mirrors are close to the ground.
- High concentration ratios can be achieved with low mechanical difficulties.

However, the LFR presents lower optical efficiency compared to the PTC and this is an important limitation which has to be faced in order the LFR to be more common in the future. There are many reasons for the reduced optical efficiency of the LFR which are given below (Nixon et al., 2013; Hongn et al., 2015; Bellos et al., 2018; Sharma et al., 2015):

- There is a need for a secondary concentrator which adds an extra optical loss. More specifically, the secondary reflector can add shading losses and also there are optical losses because the secondary reflector reflectance is lower than 100%.
- There are spaces between the primary mirrors and so there are increased optical losses. More specifically, the primary mirrors have to rotate in order to follow the sun path and thus they are not so close to each other.
- During the tracking of the sun, the primary mirrors move and so their relative position change. The result of this movement is the existence of shading and blocking effects among the mirrors.
- The receiver of LFR is located some meters over the primary

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https://doi.org/10.1016/j.solener.2018.08.019
Received 19 April 2018; Received in revised form 31 July 2018; Accepted 7 August 2018
0038-092X/

Nomenclature

D_W	distance between reflectors, m
F	focal length, m
K	total incident angle modifier, –
K_L	longitudinal incident angle modifier, –
K_T	transversal incident angle modifier, –
L	collector length, m
M	total number of primary reflectors, –
N	number of primary reflectors on the one side, –
N_{day}	number of the examined day, –
t_{hours}	solar time, h
W	width between the centers of the first and the last mirror, m
W_{tot}	total width, m
W_0	mirror width, m
X	x-direction, m
Y	y-direction, m
Z	z-direction, m

Greek symbols

γ_s	solar azimuth angle, °
δ	solar declination angle, °
η	efficiency, –
ζ	angle in Fig. 5, °
θ	solar incident angle, °
θ_L	longitude solar incident angle, °
θ_T	transversal solar incident angle, °
λ	ratio of the mirror width to the mirrors distance, –
ξ	angle in Fig. 5, °
φ	position angle of the mirror, °
φ_{lat}	latitude of the examined location, °
φ_m	mean position angle of the mirror, °
ψ	mirror slope angle, °
ω	angle in Fig. 5, °
ω_{time}	solar hour angle, °

Subscripts and superscripts

crit	critical
eff	effective
i	counter of the primary mirrors (i = 1…N)
max	maximum
opt	optical
rot	rotation
shL	shading factor included in K_L
shT	shading factor included in K_T

Abbreviations

CPC	Compound Parabolic Concentrator
IAM	Incident Angle Modifier
LFR	Linear Fresnel Reflector
PTC	Parabolic Trough Collector

reflectors (usually 3–4 m) while in the PTC it is located about 1 m to 2 m over the parabola. So, the optical losses due to the sun elevation (end losses) are more intense, especially in collectors with low length and during the winter period.

It is obvious that there are important reasons for the lower optical performance of the LFR. Thus, there are numerous ideas in the literature which have been applied in order to enhance the optical performance of the LFR. These ideas try to eliminate one or more reasons for the optical losses of the LFR in order to achieve higher optical efficiency on the nominal case (zero incident angle of the sun) or for various operating scenarios (for instance daily performance).

Boito and Grena (2016) optimized an LFR with the objective function to be the maximum optical efficiency and the optimization variables to be the primary reflector width, the distance between the primary reflectors and the focal distance as optimization parameters. Recently, Yang et al. (2018) suggested a two-axis tracking system for the reduction of the end losses of the LFR. In this system, the primary reflector field is able to be moved in an axis parallel to the receiver axis in order to concentrate suitable the incident direct beam irradiation on the receiver. They found that the annual optical efficiency can be improved from 8% up to 50%. Ma and Chang (2018) suggested the titled reflector (or adjusted) in order to concentrate all the incident solar irradiation on the absorber. This idea reduces the optical end losses of the collector and it is able to enhance the performance up to 50%. This idea has been also suggested for PTC in Refs Xu et al. (2014), Li et al. (2015). Manikumar et al. (2015) examined an elevated LFR with a trapezoidal cavity in order to reduce the optical end losses. Huang et al. (2014) suggested the use of an azimuth tracking system in an LFR in order to achieve high optical efficiency. They calculated the yearly mean optical efficiency close to 61% and they stated that it is competitive to the PTC and maybe higher. Zhu et al. (2016) suggested the use of a stretched parabolic linear Fresnel reflector in order to reduce the gap between the primary mirrors and they found higher optical performance compared to other similar configurations.

The next part of the literature includes studies for the optical analysis of the LFR. These studies investigate different geometries and they use simple models or more complex models. One of the first studies had been performed by Singh et al. (1980) who investigate an LFR with the flat receiver. They examined various parameters as the tilt and the width of the mirrors in order to achieve a uniform heat flux over the flat absorber. More detailed studies have been performed by Negi et al. (1990) for flat absorber and Goswami et al. (1990) for the triangular absorber. The calculation of the heat flux over the absorber tube was the main scope of these papers. Zhu (2013) suggested an optical method for the calculation of the intercept factor of the LFR which is based on the vector analysis. Canavarro et al. (2014) developed a multiple surface method for the optimization of the secondary reflector of an LFR. Sharma et al. (2015) studied the impact of various geometric parameters on the blocking optical losses of an LFR. According to their results, the blocking optical losses can reach up to 20% on a yearly basis. Barbón et al. (2016) set the theoretical elements for designing a small LFR with flat primary mirrors and one tubular absorber.

The calculation of the optical performance of the LFR for various solar angles is usually performed using the incident angle modifiers (IAM) in the longitudinal and the transversal directions. Hertel et al. (2015) developed analytical equations for the biaxial factor of the IAM. This model includes the basic dimensions of the LFR. Hongn et al. (2015) developed a least square method for the end losses factor of an LFR which have to be multiplied with the IAM. Mathioulakis et al. (2018) found that every mirror of the LFR can be modeled with its own IAM.

Moreover, there are important studies in the literature which investigates both optically and thermal the LFRs. Qiu et al. (2015) investigated an LFR with a compound parabolic concentrator (CPC) as the secondary reflector in the tubular absorber. They used Monte Carlo ray tracing method and finite volume method for their simulation. They found maximum optical efficiency, while the yearly thermal performance was over 46% for a location with latitude at 35°. Craig et al. (2016) studied an LFR with trapezoidal cavity receiver using a code in