Solar Energy 150 (2017) 1–12

Contents lists available at ScienceDirect

Solar Energy

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

Optimization of solar linear Fresnel reflector system with secondary concentrator for uniform flux distribution over absorber tube

G.S. Chaitanya Prasad [a], K.S. Reddy [a,*], T. Sundararajan [b]

[a] Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Thermodynamics and Combustion Engineering Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 2 December 2016
Received in revised form 6 April 2017
Accepted 11 April 2017

Keywords:
Two-stage solar concentrator
Linear Fresnel reflector
Secondary concentrator
Uniform flux distribution
Variable aim line

ABSTRACT

Solar linear Fresnel reflectors (LFR) are attractive because of low cost and optimal utilization of land area. They provide high concentration ratio when used in conjunction with secondary concentrators. A pilot plant of LFR system with 154 m^2 of primary mirror field installed at Vallipuram, India has been considered for the present analysis. This type of collectors give rise to high variation of solar radiation flux in the circumferential direction of absorber for the cases with fixed aim line of primary mirrors. In the present work, the concept of variable aim lines for primary mirrors is introduced to defocus and spread the radiation flux in a more uniform manner over the absorber. In particular, both the tilt angles and the radii of curvature of the individual Fresnel mirrors are modified to obtain a better flux uniformity. In addition, a novel segmented parabolic secondary concentrator profile has also been developed, which in conjunction with the variable aim line concept leads to a high optical efficiency of 76.4% and a coefficient of flux variation value of 0.13. On the other hand, 74.9% and 70.9% of optical efficiencies along with 0.17 and 0.33 values of coefficient of variation are obtained with more commonly employed compound parabolic concentrator and trapezoidal concentrator profiles respectively.

1. Introduction

Solar thermal collectors have attracted wide attention among researchers due to their long sustainability and applicability at large scale (Kalogirou, 2004; Rabl, 1985). Concentrating collectors with line focus, such as parabolic troughs and linear Fresnel reflectors (LFR) allow the attainment of high temperatures with low heat loss, compared to conventional collectors. Linear Fresnel reflectors in particular, have a significant potential for sustainable market growth of solar thermal power plants, due to their better land utilization and lower manufacturing cost. LFR collector field primarily consists of slightly curved mirror strips which focus solar radiation onto a stationary receiver. The LFR mirrors can be provided with single axis tracking to concentrate the incident solar radiation onto a small aperture receiver, synchronized with the movement of solar disc. In order to provide higher concentration ratio and to increase the thermal efficiency of the collector system, secondary mirrors with smaller radius of curvature are employed to form receiver cavity around the absorber tube (Feuermann and Gordon, 1991).

Many authors have carried out experiments on several prototypes with innovative design concepts and studied the performance characteristics of LFR for different optical and geometric parameters (Barale et al., 2010; Beltagy et al., 2017; Bernhard et al., 2008; Häberle et al., 2001; Negi et al., 1989; Singh et al., 1999). Zhu et al. (2014) reviewed the technical features and challenges of different design concepts as well as the future outlook of linear Fresnel technology. The design and optimization of mirror field plays a vital role in developing a stable and cost-effective system. Many optical simulation tools such as SolTrace, Tonatiuh and Solfast as well as Monte-Carlo ray tracing codes (Cheng et al., 2014) have been developed predominantly to help optimize the mirror field design. Mills and Morrison (2000) introduced a new compact design of LFR that reflects the incident solar radiation onto two alternative linear receivers, thereby reducing the shading and blocking effects.

Linear Fresnel reflectors usually employ a secondary concentrator that enlarges the target area for primary mirrors, and also acts as protective cover to reduce convective losses. A number of authors have studied different types of receivers such as trapezoidal cavity with multiple absorber tubes (Facão and Oliveira, 2011), triangular, rectangular, arc-shaped and semi-circular cavity receivers (Lin et al., 2014), modified V-shaped cavity receiver (Lin et al., 2013), compound parabolic concentrator (CPC) with an evac-

* Corresponding author.
E-mail address: ksreddy@iitm.ac.in (K.S. Reddy).

http://dx.doi.org/10.1016/j.solener.2017.04.026
0038-092X/

Nomenclature

A_p	total aperture area of primary mirrors (m^2)
$d_{m,i}$	distance of *i*th mirror axis from central plane of the collector (m)
E_g	total solar power incident on ground area (W)
E_r	absorbed power (W)
$E_{c,L}$	transmission losses and uncaptured radiation (W)
E_{pm}	total radiation intercepted by primary mirrors (W)
$E_{r,d}$	radiation captured by receiver directly from primary mirrors (W)
$E_{r,sc}$	radiation captured by receiver after re-reflection (W)
$E_{g,L}$	power lost to the ground (W)
EM-i	*i*th mirror on the East side of collector
g	distance between the adjacent mirror axes (m)
h_{aim}	height of the aim line of primary mirrors (m)
h_r	height of receiver from axial plane of mirrors (m)
N_r	number of segments considered on the absorber tube
r_t	radius of absorber tube outer surface (m)
r_g	radius of glass envelope (m)
$R_{m,i}$	radius of curvature of *i*th mirror
$S_{r,i}$	solar flux distribution at *i*th position on absorber (W/m^2)

Greek symbols

α_s	solar altitude angle (Degree)
η_o	optical efficiency (%)
θ_a	acceptance angle (Degree)
θ_i	incidence angle (Degree)
θ_o	parametric arc angle on absorber (Degree)
μ_r	mean value of the circumferential flux distribution (W/m^2)
σ_r	standard deviation of the circumferential flux distribution
σ_{TE}	tracking error (Degree)
σ_{SE}	slope error (Degree)
$\phi_{m,i}$	tilt angle of *i*th mirror (Degree)

Abbreviations

CPC	Compound Parabolic Concentrator
DNI	Direct Normal Irradiance (W/m^2)
LFR	Linear Fresnel reflector
SPC	Segmented Parabolic Concentrator
TC	Trapezoidal Concentrator
VSC	Vallipuram Secondary Concentrator

uated absorber (Beltagy et al., 2017; Qiu et al., 2015), parabolic and involute concentrators (Balaji et al., 2016), etc., to improve the collection efficiency of a Fresnel system. Zhu (2017) proposed a new approach to optimize the secondary concentrator profile for intercepting maximum amount of energy at the absorber surface. This adaptive method resulted in 90% optical efficiency with a derived secondary concentrator profile when used on a test case. Evacuated receiver tubes are widely used for high temperature solar energy applications at present. Many authors have studied the circumferential flux distribution over the absorber tube, for different diameters and angles of incidence (Balaji et al., 2016; Eck et al., 2007).

In a LFR system, the radiation incident on the absorber surface from different primary mirrors overlap, leading to high concentration of solar flux. The amount of energy concentrated on the upper half of absorber tube is in general, lower than that on the lower half. Such a non-uniform flux distribution in turn, can lead to a large circumferential temperature difference as well as significant deflection of the tube structure. In extreme circumstances, the outer glass envelope can break if the deformed absorber touches it, thereby resulting in total loss of vacuum.

Direct steam generation (DSG) exhibits many advantages over the use of thermic oil as the working fluid. In DSG plants, high temperatures and efficiencies can be achieved. Also, heat exchangers and oil pumping equipment can be eliminated, resulting in low capital cost. The main disadvantage of a DSG system is the occurrence of two phase flow which can give rise to hot spots and associated tube failure, due to the poor heat transfer in the vapor region (Almanza et al., 1997).

Grena and Tarquini (2011) attempted to overcome the non-uniform circumferential flux distribution by replacing the traditional secondary concentrator with an open parabolic wing-like structure. They succeeded in increasing the solar flux on the upper half from 10% to 20% to a value of about 37%. A similar approach was extended to trough collectors by Wang et al. (2014). These authors varied the shape and position of a homogenizing reflector in the focal region of collector and also moved the absorber tube towards the collector aperture to achieve a uniform flux distribution. It has been noted that the flux homogenization is accompanied by a slight reduction in collector efficiency.

Qiu et al. (2015) investigated the thermal performance of LFR that employs a compound parabolic concentrator (CPC) with an evacuated absorber. Monte-Carlo ray tracing and finite volume methods were used together to estimate the circumferential temperature distribution and the effect of slope errors on optical efficiency. They concluded that uniformity of flux distribution can be improved by choosing a proper slope error, but with a small sacrifice in the optical efficiency.

The present work attempts to develop a LFR with secondary concentrator for a direct steam generation solar plant. Although the LFR system coupled with secondary mirrors can provide a high concentration ratio, it may also give rise to highly non-uniform circumferential flux distribution over the absorber. In turn, non-uniform thermal stresses and different thermal expansion occur, often resulting in structural failure, especially in the high-quality regions of two-phase flow. Therefore, an attempt has been made here to overcome the above challenges and achieve a nearly uniform circumferential solar flux distribution by modifying the orientation and focal length of LFR primary mirrors as well as the secondary concentrator profile. The ray tracing method has been used to optimize the collector system configuration.

2. Description of present LFR system with primary and secondary concentrators

A schematic of the linear Fresnel reflector based DSG pilot plant recently installed by the authors at Vallipuram, India (12°34′19.0″N, 79°59′23.4″E) is shown in Fig. 1 and its pictorial view is shown in Fig. 2. The collector field consists 12 rows of Fresnel mirrors with a receiver fixed at 7.9 m above the axial plane of mirrors. The width of each mirror element is equal to 1.07 m and the distance between the axes of adjacent mirrors is 1.5 m. The receiver assembly is a combination of an evacuated absorber and a compound parabolic secondary concentrator, whose aperture plane is fixed at 7.8 m above the axial plane of primary mirrors. The selectively coated absorber tube is placed near to the focal line of the Fresnel mirrors, inside an evacuated borosilicate glass envelope. The collector parameters are listed in Table 1.