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Optical design of compact linear fresnel reflector systems

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ABSTRACT

Compact linear Fresnel reflector (CLFR) system employing multiple receivers is promising with better optical performance and cost effectiveness compared to linear Fresnel reflector (LFR) system, especially for applications with limited ground availabilities. Nevertheless, only few researches have been conducted to evaluate optical design and performance of the CLFR system. In this study, geometrical models for the CLFR system with flat mirrors and receivers are developed on the basis of polar orientation. A comparative study of concentration characteristics among the LFR, CLFR-complete and CLFR-hybrid systems is conducted based on numerical, ray tracing simulation and experimental results. In addition, optical design analyses of the CLFR-hybrid system are carried out from various design aspects. It is noteworthy that the mirror arrangement and focal length should be optimized for the CLFR-hybrid system with considerations of the associated geometrical characteristic and optical performance. For a small-scale CLFR-hybrid system with a solar field width of 2100 mm and a focal length of 1500 mm, the geometrical concentration ratio of 15.14 and ground utilization ratio of 0.95 are achieved respectively. The findings demonstrate the feasibility of the CLFR-hybrid system with flat mirrors and polar orientation, which provide progress to the concentrated solar power technology.

1. Introduction

The supply shortage of conventional fossil fuels and environmental concern about climate changing lead to a great need to harness renewable energy for a sustainable future. Solar energy is regarded as the largest available carbon-neutral energy on the planet, which offers great potentials to be utilized by various technologies [1]. Besides direct conversion of the solar radiation into electricity with photovoltaic technology, the solar energy also can be transformed into thermal energy by solar collectors. Generally, solar collectors are categorized into non-concentrating and concentrating types. Non-concentrating solar collectors are commonly used in domestic hot water heating systems, whereas concentrating solar collectors are popular in thermal power generations with high efficiencies at medium to high operational temperatures, especially for locations receiving high solar beam radiation [2].

Based on the focus geometry, concentrating solar collectors are classified into parabolic tough concentrator (PTC), solar tower concentrator (STC), parabolic dish and linear Fresnel reflector (LFR) concentrator. Though PTC is a more mature and widely applied technology, its higher initial cost, complex manufacture process and serious challenge of wind resistance are noted [3]. Alternatively, the LFR system in a simple design is capable of harnessing the solar radiation efficiently with less land usage [4]. It has been proved to be a better choice for energy production where land availability is limited [5]. For the LFR system with a single centred receiver as illustrated in Fig. 1, each mirror element is suitably placed at a proposed tilt angle so that the incident solar radiation converges onto the receiver after reflection.

Optical designs of the LFR system have been investigated from different aspects, such as solar field layout and orientation, tracking algorithm and aiming strategy, reflector curvature and receiver configuration [6]. Among them, the solar field orientation influences significantly the other optical parameters. For instance, the complexity of a tracking mechanism depends on the orientation. Three common orientations are namely north-south, east-west and polar axis. Both north-south and east-west orientations are mostly preferred for applications, with which tracking schemes are based on the flat ground. In operation, reflectors follow the sun movement by varying their tilt angles under the control of a tracking system [7,8]. Consequently, end or lateral losses may occur when the reflected solar rays do not impinge on the receiver due to the longitudinal component of the solar radiation [9,10]. On the other hand, mirrors involved in the LFR system are commonly predefined with constant width and shift for the sake of simplicity. Such a simple optical design results in shading of the incoming solar radiation and blocking of the reflected solar radiation by adjacent mirror elements [11], which are illustrated in Fig. 2. Numerous researches have been conducted to minimize energy losses owing to the end, inter-row shading and blocking effects. For example,

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Nomenclature

Symbols

b_n	Half width of a mirror element [mm]
B	Half length of a receiver [mm]
d	Gap between two consecutive mirrors in central alternating array [mm]
D	Gap between the last mirror in common tilting array and the first adjacent alternating mirror [mm]
f	Focal length [mm]
k	Utilization ratio [dimensionless]
N	Total number of mirror elements [dimensionless]
W	Total solar field width of a CLFR system [mm]
W_n	Width of a mirror element [mm]
x_n	Centre reference position of a mirror element [mm]

Greek letters

α	Tilt angle of a mirror element [°]
β	Inclination angle of a receiver [°]
Ω_1	Subtended angle by the sun [′]
θ	Angle between the reflected extreme outer solar ray impinging on the lower edge of receiver and proposed horizontal plane [°]

Subscripts

c	Central alternating mirror array of a CLFR-hybrid system
co	Mirror array of a CLFR-complete system
l	Common tilting mirror array on the left side of a CLFR-hybrid system
r	Common tilting mirror array on the right side of a CLFR-hybrid system

Abbreviations

CLFR	Compact linear Fresnel reflector
CR	Geometrical concentration ratio
LFR	Linear Fresnel reflector
PTC	Parabolic trough collector
STC	Solar tower concentrator

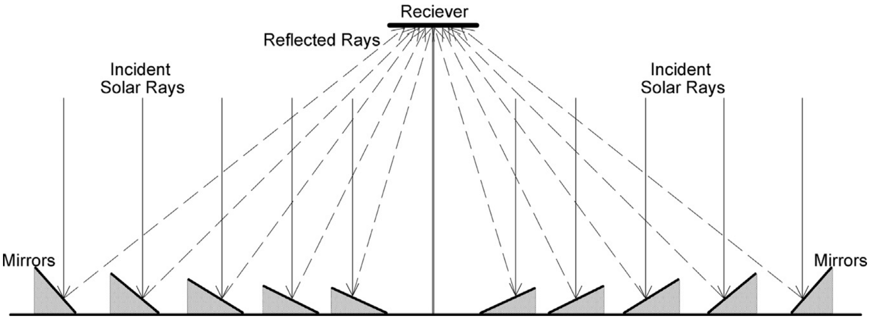

Fig. 1. Schematic diagram of LFR system.

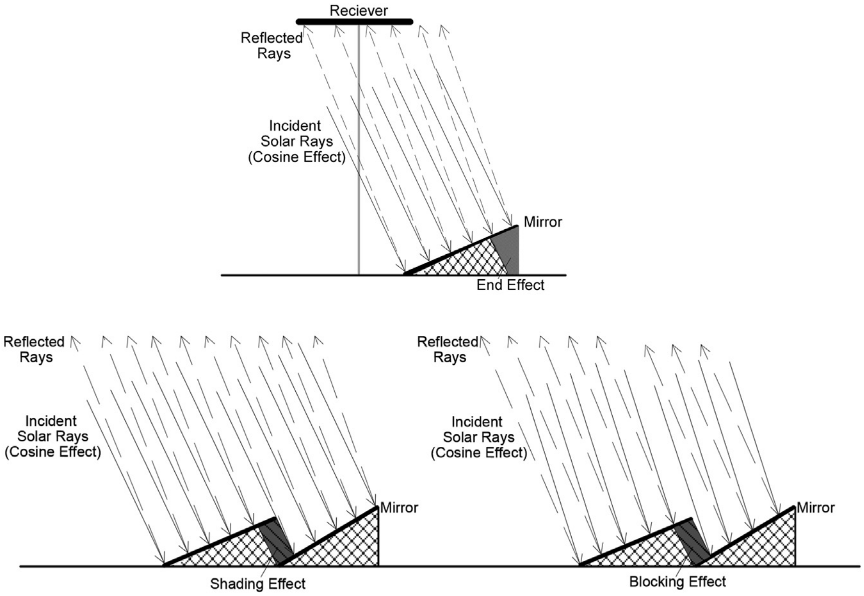

Fig. 2. Cosine, end, shading and blocking effects in LFR system.

optical variables such as the width and position of each mirror element, gap between consecutive mirrors and receiver height have been considered in literatures [9,10,12,13]. Abbas and Martínez-Val [13] observed an evident increase in the annual energy efficiency for a LFR system with mirrors of variable widths and shifts, but more complicated optical modelling and additional installation cost are required accordingly. On the other hand, the receiver has remarkable impacts on optical and thermal performances of the LFR system as well, which can be assembled horizontally, vertically or in triangular configuration [14]. To address the drawbacks of shading and blocking of the LFR system, Barlev, Vidu and Stroeve [1] suggested increasing receiver height, but the spacing between two adjacent mirror elements causes