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Study on optical and thermal performance of a linear Fresnel solar reflector using molten salt as HTF with MCRT and FVM methods

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HIGHLIGHTS

- A LFR which employs CPC, evacuated tubes and uses molten salt as HTF is designed.
- 3D optical and thermal models are developed with MCRT and FVM methods.
- The optical and thermal performance, the effects of key parameters are studied.
- The instantaneous optical efficiency of 65.0% is achieved at normal incidence.
- The collector efficiencies are above 46.0% under all the studied conditions.

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ABSTRACT

A novel linear Fresnel reflector which employs the evacuated tube, CPC secondary reflector, and uses molten salt as the heat transfer fluid (HTF) was designed and studied in this paper. A 3D optical model was developed to simulate the radiation transmission within the system with Monte Carlo Ray Tracing (MCRT) method. Based on the model, firstly, the optical performance of the systems using cylindrical and parabolic mirrors was compared. Then the local solar flux distribution on the absorber surface and the optical efficiency were computed. Then the effects of the slope error, time and location, etc. were investigated. Finally, the thermal performance was investigated by coupling the MCRT with the Finite Volume Method (FVM). The optical simulation results indicate that the system with optimized cylindrical mirrors can achieve nearly the same performance as the one with parabolic mirrors. The solar flux distribution on the absorber exhibits a non-uniform characteristic which can be improved by using mirrors with proper slope error. The instantaneous optical efficiency of 65.0% at normal incidence and the annual mean optical efficiency which ranges between 55.2% and 34.8% from the equator to N50° can be achieved. The numerical results indicate that the temperature profiles on the absorber follow the non-uniform solar flux. The collector efficiencies are all above 46.0% under the studied conditions. Both the thermal efficiency and the collector efficiency increase with decreasing salt temperature and with increasing radiation. These results suggest that the introduced system is a feasible choice for using molten salt as the HTF in Fresnel system.

1. Introduction

Linear Fresnel reflector (LFR) is a type of solar collector which collects sunlight by using long, narrow, flat or slightly curved mirrors to reflect the sun rays onto a fixed linear receiver mounted over a tower above and along the reflectors. The LFR technology which has been proposed as an attractive low-cost option for Concentrating Solar Power (CSP) generation presents important advantages when compared to the Parabolic Trough Collector (PTC) technology [1,2]. Particularly, the use of stationary receiver without rotating joints or high-temperature moving components makes LFRs safer and more cost effective than PTCs. In addition, LFRs use narrow primary mirrors which need no heavy supporting structures and thus lower the construction and operation costs. These two advantages make LFRs being considered as competitors of PTCs in medium–low temperature solar power generation.

LFRs have developed rapidly in the past 15 years. Especially two significant breakthroughs have been made at the turn of the century. One is the proposal of a novel design called Compact Linear Fresnel Reflector (CLFR) by Mills and Morrison [3]. The CLFR offers

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Nomenclature

A	solar azimuth (°)
c_μ, c_1, c_2	constants in turbulence model
DNI	Direct Normal Irradiance (W m^{-2})
d_m	distance between adjacent mirrors (m)
d_i	inner diameter of absorber
f	average friction factor coefficient
H_t	height of evacuated tube (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
I	turbulence intensity
IAM	incident angle modifier
$\boldsymbol{I}$, $\boldsymbol{N}$, $\boldsymbol{R}$	vector
k	turbulent kinetic energy (m^2 s^{-2})
k_m	inclination angle of mirror's tangent (°)
LCR	local concentration ratio on the absorber
L_m	length of the collector (m)
n_m	primary mirror number
n_p	the number of traced photons on a mirror
N_{day}	the number of the day in a year
Nu	average Nusselt number
$\boldsymbol{P}$	point on the reflector
Q	thermal power (W)
q	heat flux (W m^{-2})
r_1	outer radius of absorber (m)
R_g	outer radius of glass envelope (m)
t_s	solar time (h)
T	temperature (K)
W_p	average energy each photon carries
W_{field}	width of the field (m)
W_m	width of the mirror (m)
x, y, z	Cartesian coordinates (m)
u, v, w	x, y, z velocity components (m s^{-1})

Greek symbols

α	solar altitude (°)
α_c	absorber coating absorptivity
α_i	Angle between $\boldsymbol{I}$ and Y_g (°)
ε	turbulent dissipation rate (m^2 s^{-3})
$\eta_{\mathrm{i,opt}}$	instantaneous optical efficiency (%)
$\eta_{\mathrm{d,opt}}$, $\eta_{\mathrm{y,opt}}$	daily and yearly mean optical efficiencies (%)
η_t, η_c	thermal and collector efficiencies (%)
θ	angle on the absorber (°)
θ_o	angle variable (°)
θ_a	half acceptance angle of CPC (°)
θ_{omax}	design parameter (rad)
θ'_m, θ_m	ideal tracking angle/tracking angle with error (°)
θ_i	incident angle on mirror (°)
λ_m	radial angle of $\boldsymbol{N}$ (rad)
ξ	random number
ρ	density (kg m^{-3})
ρ_o	variable (m)
ρ_1, ρ_2	reflectivity of primary mirror/CPC
σ_{te}, σ_{se}	tracking error, slope error (mrad)
σ_q	nonuniformity index of solar flux
σ_k, σ_ε	turbulent Prandtl numbers for diffusion of k/ε
σ_T	turbulent Prandtl number
τ	glass envelope transmissivity
φ	local latitude (°)
ψ_m	tangential angle of $\boldsymbol{N}$ (rad)

Subscripts

in	inlet parameter
o	outlet parameter
test	experiment result
num	numerical result
w	at the wall condition
ave	average value

two alternative receivers for each mirror, thus less land being needed than the traditional one. A CLFR prototype has also been built to generate saturated steam for a coal plant in Australia [4,5]. The other is the construction of the Solarmundo collector with a secondary reflector in Belgium, and the collector shows the optical efficiency of 61% at normal incidence [6].

Furthermore, more prototypes and commercial plants have been built in recent years. In Spain, a prototype called Fresdemo based on the Solarmundo technology has been built to prove the technological feasibility for the commercial use of LFRs [7]. Other plants, such as the 1.4 MW PE1 and 30 MW PE2 plants in Spain, the 5 MW prototype in California, have also been built [8,9].

However, there are also some disadvantages of LFRs including lower optical efficiency than PTCs and the important change of the collected energy during a day which has bad effects on the operating stability of the plant. The first defect could be minimized by optimizing the geometric parameters, but it is helpless for the second one which is determined by the system structure. To eliminate the second defect, a molten-salt thermal storage system could be coupled with LFRs [10]. In this way, the thermal output could be kept relatively stable within a day. The thermal storage system could also be used to drive the system at night with no solar radiation so that the LFRs could work around the clock.

The system could be greatly simplified if the salt was used as the heat transfer fluid (HTF) in the receiver in a CSP system with molten-salt storage. In recent years, the molten salt has been used mainly as storage material and as HTF in tower plants such as Solar Two [11] and Gemasolar [12]. However, in 2010, a 5 MW trough plant called Archimede Plant [13] using molten salt as the HTF and storage material has also been built and tested. These facts have encouraged an important research on the use of the molten salt as the HTF and storage material in LFRs.

Linear trapezoidal, triangular and CPC cavity receivers which can lower the cost are usually used in LFRs. The performances of these receivers have been widely investigated [14–18]. However, the use of evacuated tubes which can achieve higher thermal efficiency and work at the higher temperature is another trend in LFRs. In 2010, Grena and Tarquini [19] have proposed a system using a large evacuated tube which has a diameter of 10 cm but is not commercially available up to now. They found the use of evacuated tubes can achieve higher efficiency in LFRs. The aim of this paper is to study the optical and thermal performance of a LFR with commercial evacuated tubes, a Compound Parabolic Collector (CPC) and using molten salt as the HTF. The system is designed, and a 3D optical model is fully developed with Monte Carlo Ray Tracing (MCRT) method in order to simulate the radiation transmission within the system. The MCRT method has been utilized successfully to investigate the performance of PTCs [20–22], Parabolic Dish System [23–25], and Solar Power Tower System [26–31]. Based on the model, firstly, the local solar flux distribution on the absorber surface and the optical efficiency are computed. Then the performance of the systems with parabolic mirrors and cylindrical mirrors is compared. Then the effects of the reflector slope error, tracking error, time and location are also investigated. Finally, the thermal performance of the system is studied by coupling the MCRT and the Finite Volume Method (FVM) methods.