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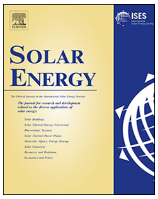

Experimental investigation of the daily performance of an integrated linear Fresnel reflector system

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ABSTRACT

The objective of this work is to investigate the daily and the instantaneous performance of a linear Fresnel reflector (LFR) experimentally and numerically. The examined LFR has an inverted flat plate receiver with a 36 m^2 total collecting aperture area and is coupled to a storage tank of 1 m^3 volume. This system is investigated experimentally for daily operation in the period from May to October for the climate conditions of Athens (Greece), using water as the working fluid (temperature levels up to 100 °C). Moreover, a detailed mathematical model for the prediction of the instantaneous and of the daily performance is developed. This model is validated with the experimental results for 52 operating days and it estimates the daily useful energy production with a mean error of 3%. This modeling is based on the energy balance on the collector loop and the storage tank. The emphasis is given on the determination of the optical losses of the collector, which are associated with the sun position during the day. It is found that the maximum useful heat production is about 8.4 kW, while the maximum daily heat production is about 260 MJ. The results of this work can be exploited for the evaluation of integrated solar concentrating systems and especially of linear Fresnel reflectors.

1. Introduction

Solar energy is one of the most promising renewable energy sources and its exploitation is important in order to face the modern energy problems such as the fossil fuel depletion (Reddy et al., 2015), the increasing electricity price, the high energy demand worldwide and the greenhouse emissions (Sait et al., 2015). Concentrating solar power is able to produce high amounts of useful heat at medium and high-temperature levels and it is able to totally or partially meet the energy needs in various applications such as industrial processes, drying (Tiwari and Tiwari, 2016), electricity production systems (Moghimi et al., 2015), trigeneration systems, sorption cooling machines and desalination systems (Loni et al., 2016).

The most well-established concentrating technologies are the parabolic trough collector (PTC), linear Fresnel reflector (LFR), solar dish and central towers. Among them, the most common systems for heat production from 200 to 400 °C are the linear concentrating technologies which are the PTC and the LFR (Zhu et al., 2014). The PTC and the LFR have the same operating principle; a moving linear concentrator reflects the incident solar beam irradiation to a linear receiver. However, these technologies have many differences and they are competing technologies, with the LFR being a developing technology while the PTC a more mature one.

The LFR presents significant advantages compared to the PTC. The LFR is a low-cost technology because of the small number of movable parts and of the reduced operation and maintenance costs. The receiver is located some meters above the ground (about 3–5 m usually) and does not move during its operation. Moreover, the primary reflectors of the LFR are close to the ground, a fact that leads to reduced wind loads and mechanical difficulties during the operation. On the other hand, the PTC suffers from high wind loads especially at high concentration ratios (PTC aperture over 4 m). An increase in the concentration ratio of the LFR is also possible, by adding extra reflectors on the ground if the absorber area is kept constant. However, the higher concentration ratio in the LFR is associated with reduced optical efficiency. The spaces between the primary mirrors of the LFR and the need for a secondary reflector (usually of trapezoidal or parabolic shape) maybe add extra optical losses (Nixon et al., 2013). Moreover, the end losses are usually more intense in the LFR, because of the higher focal distance compared to the PTC and also of the shading losses.

In the literature, there are various LFR designs which present variation in the reflectors (primary or secondary) and in the receiver design. Many studies have optimized the LFR design by setting different optimization variables. Boito and Grena (2016) performed an optimization procedure of an LFR, by examining different field widths, focal distances and mirror distances. Abbas and Martínez-Val (2015)

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Nomenclature

A_a	aperture of the linear Fresnel reflector, m^2
C	concentration ratio, –
c_p	specific heat capacity, J/kg K
E_{st}	daily stored energy, MJ
F_1	first parameter of the input/output method, m^2
F_2	second parameter of the input/output method, MJ/K
H	collector height, m
H_b	daily amount of the direct beam solar irradiation, MJ/m^2
G_b	direct beam solar irradiation, W/m^2
K	incident angle modifier, –
K_{mean}	daily mean incident angle modifier, –
L	collector length, m
$(MC)_c$	total thermal capacity of the collector, J/K
$(MC)_{st}$	storage tank thermal capacity, J/K
N	day duration, s
p_0	zero order parameter of Eq. (10), W/K
p_1	first order parameter of Eq. (10), –
p_2	second order parameter of Eq. (10), J s/K
Q	heat, W
q	effective day fraction, –
T	temperature, °C
T_{stN}	storage tank temperature at the end of the day, °C
T_{st0}	storage tank temperature at the start of the day, °C
$(UA)_c$	collector overall heat loss coefficient, W/K
$(UA)_{ex}$	overall heat transfer coefficient of the heat exchanger, W/K
$(UA)_{st}$	storage tank overall heat loss coefficient, W/K
V	storage tank volume, m^3
W	reflector field width, m

Greek symbols

α	absorbance, –
γ	intercept factor, –
δ	solar declination angle, °
ΔT	temperature difference in the collector, °C
η_{opt}	optical efficiency, –
$\eta_{opt,0}$	optical efficiency for zero incident angle, –
θ	solar irradiation incident angle, °
ρ_{mir}	mirror reflectance, –
ρ_{cl}	clearness factor, –
τ	cover transmittance, –
φ	location latitude, °
ω	hour angle, °
ω_s	hour angle at sunset, °

Subscripts and superscripts

abs	absorbed
am	ambient
c	collector
cal	calculated
exp	experimental
exploit	exploited part of the solar irradiation
f	mean fluid
in	inlet
out	outlet
sol	solar
st	storage tank
stand	standard's equation for I/O method
u	useful

Abbreviations

I/O	input/output method
LFR	linear Fresnel reflector
PTC	parabolic trough collector

developed a mathematical model for optimizing an LFR. They investigated the distance between the mirrors and the mirror curvature as the optimization parameters and they found that the optimization is vital for designing a high-efficiency collector. Moreover, there are other studies which have investigated various parameters of LFRs. Benyakhlef et al. (2016) found that a small curvature in the mirrors (about 2 mm) is able to enhance the optical performance of the collector. Sharma et al. (2015) stated that the optical losses due to the blocking effects can be up to 20% in LFR. Hertel et al. (2016) examined optically and thermally an LFR and they found that the thermal losses have not to be taken into account in the incident angle modifier modeling. Furthermore, Huang et al. (2014) examined an LFR with azimuth tracking and they found 61% mean thermal efficiency performance with the fluid temperature levels close to 400 °C. This is a high value of mean thermal efficiency but the suggested system is a complex and high-cost configuration.

The next part of the literature studies is focused on the receiver design. The first collector type has trapezoidal cavity receivers where there are fluid tubes inside the cavity. Abbas et al. (2012) investigated a trapezoidal cavity with a flat absorber which has many tubes on its backside. Singh et al. (2010) studied four different LFRs with the trapezoidal cavity and they found that the selective round pipe absorber is the best design. The convective thermal losses of the trapezoidal cavity have been examined by many researchers as Facão and Oliveira (2011). Saxena et al. (2016) suggested correlations for the Nusselt number calculation in a trapezoidal receiver for modeling the thermal losses. Natarajan et al. (2012) investigated the thermal losses of a trapezoidal cavity receiver. According to their results, the minimization of the thermal losses can be achieved with an aspect ratio over 2.5. Reddy and Kumar (2014) conducted a detailed work about the determination of the thermal losses in different kind of trapezoidal receivers. Sahoo et al. (2013) studied an LFR with a trapezoidal cavity which has 8 fluid tubes and they determined the optimum tube length with hydrodynamic criteria. Mokhtar et al. (2016) examined experimentally a trapezoidal cavity LFR without cover and they found a relatively low thermal efficiency (~30%) for water temperatures close to 70 °C. Moghimi et al. (2017) performed a detailed analysis and optimization of an LFR with a trapezoidal cavity and two fluid tubes. In another interesting study, Qiu et al. (2016) investigated an LFR with 8 tubes in the trapezoidal cavity. The optical efficiency of the suggested configuration has a maximum optical efficiency close to 75%; a high value which is competitive to the PTC. Furthermore, Qiu et al. (2017) proposed a methodology for designing trapezoidal cavity receivers with uniform heat flux distribution over the tubes. The uniform heat flux reduces the temperature peaks, which in turn reduces the thermal losses and especially those due to radiation.

Other literature studies study LFR with evacuated tube receivers and parabolic shape secondary reflectors, usually with a compound parabolic shape. There are studies which are focused on the optical optimization of the secondary reflector (Canavarro et al., 2014; Zhu, 2017). Moreover, Canavarro et al. (2016) suggested an elliptical secondary reflector in order to reduce the manufacturing cost. Balaji et al. (2016) found that the secondary reflector with a parabolic shape is more efficient than the respective one with an involute geometry. The secondary reflector with a typical compound parabolic shape is optimized by Prasad et al. (2017) in order to achieve uniform heat flux over the absorber. Qiu et al. (2015) investigated an LFR with compound