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Experimental and numerical investigation of a linear Fresnel solar collector with flat plate receiver

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ABSTRACT

In this study a linear Fresnel solar collector with flat plate receiver is investigated experimentally and numerically with Solidworks Flow Simulation. The developed model combines optical, thermal and flow analysis; something innovative and demanding which leads to accurate results. The main objective of this study is to determine the thermal, the optical and the exergetic performance of this collector in various operating conditions. For these reasons, the developed model is validated with the respective experimental data and after this step, the solar collector model is examined parametrically for various fluid temperature levels and solar incident angles. The use of thermal oil is also analyzed with the simulation tool in order to examine the collector performance in medium temperature levels. The experiments are performed with water as working fluid and for low temperature levels up to 100 °C. The final results proved that this solar collector is able to produce about 8.5 kW useful heat in summer, 5.3 kW in spring and 2.9 kW in winter. Moreover, the operation of this collector with thermal oil can lead to satisfying results up to 250 °C.

1. Introduction

The energy production and supply are crucial problems for our society with economic, environmental and social effects. The increasing global energy demand, the fossil fuel depletion, the increasing rate of the electricity price and the environmental problems due to carbon dioxide emissions, create the need for using renewable and alternative energy resources [1–4]. Solar energy utilization is a promising and clean way for covering a great variety of the human beings energy needs with low cost [5,6].

Solar thermal collectors are the devices which capture the solar energy and convert it to useful heat. In low temperature level applications up to 100 °C, flat plate collectors (FPC) and evacuated tube collectors (ETC) are usually used [7]. In medium temperature levels (100–300 °C), usually concentrated solar collectors are preferred [8,9]. The ETC can be also used up to 150 °C, while for higher temperature levels compound parabolic collectors (CPC), linear Fresnel collectors (LFC) and parabolic trough collectors (PTC) are selected. For high temperature levels, PTC is the most mature technology [10] with the solar dish collectors to be a promising solution especially in extremely high temperature levels over 500 °C [11].

The majority of the applications need medium temperature levels and LFC is the most appropriate solar collector, as it has been stated from many researchers [12–14]. Lin et al. [12] characterized LFC as the most appropriate technology for industrial heat production and a promising technology for concentrating solar power (CSP) domain because of its simplicity in structural design and the relative low construction cost. Lancereau et al. [13] also added the low land utilization and the low material utilization as extra advantages of this technology. The LFC is consisted of three basic parts; the mirrors close to the ground, the receiver mounted in a linear tower and the tracking system [12,15]. Usually, the Fresnel solar collectors are compared with parabolic trough collectors, especially for medium-high temperature applications. Extra advantages of LFC are the elimination of thermal dilation and moving junction problems which are usual in PTC [16]. However, the thermal efficiency of the LFC is lower than the efficiency in PTC, due to higher optical losses [17]. Shading and blocking problems are the main causes for the relative low optical efficiency of the LFC [14].

In this direction, many studies have been made and many ideas have been investigated. Zhu and Huang [14] designed a

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Nomenclature

A	area, m^2
C	concentration ratio, –
C_L	local concentration ratio, –
c_p	specific heat capacity under constant pressure, kJ/kg K
E	exergy flow, W
G_b	solar direct beam radiation, W/m^2
$G_{b,hor}$	solar beam radiation in horizontal surface, W/m^2
h	heat transfer coefficient, W/m^2 K
H	collector height, m
k	thermal conductivity, W/mK
K	optical efficiency modifier, –
L	collector length, mm
m	mass flow rate, kg/s
n	number of the day during the year, –
Q	heat flux, W
R	final mirror reflectance, –
s	insulation layer thickness, mm
t	time, hours
T	temperature, °C
W	width, mm
x_1	longitudinal position in absorber 1 (cold), m
x_2	longitudinal position in absorber 2 (hot), m
Z	position in the width direction of the absorber, cm

Greek symbols

α	absorbance, –
γ	intercept factor, –
γ_s	solar azimuth angle, °
δ	solar declination angle, °
ε	emittance, –
ΔT_f	fluid temperature increase, K
η	efficiency, –
θ	solar incident angle, °
θ_L	solar incident angle in longitudinal direction, °
θ_T	solar incident angle in transversal direction, °
λ	mirror clearness factor, –
ρ	primary mirror reflectance, –
τ	transmittance, –
$(\tau\alpha)$	transmittance-absorbance product, –
φ	local latitude, °
ω	solar time angle, °

Subscripts and superscripts

a	aperture
abs	absorbed
air	air
am	ambient
c	cover
ex	exergetic
fm	mean fluid
in	inlet
loss	thermal losses
max	maximum
o	zero incident angle
opt	optical
out	outlet
r	receiver
s	solar
sun	sun
tube	fluid tube
th	thermal
u	useful

Abbreviations

CPC	Compound parabolic collector
CSP	Concentrated solar power
ETC	Evacuated tube collectors
FPC	Flat plate collector
LFC	Linear Fresnel collector
LFR	Linear Fresnel reflector
PTC	Parabolic trough collector

semi-parabolic linear Fresnel reflector which is the combination of PTC and LFC. In this system, there are numerous small reflectors with parabolic shape which are located in the ground, simulating the parabolic shape. The final results proved that this system performs as the respective parabolic collector and it has advantages from the LFC as the lower wind loads. Benyakhlef et al. [18] investigated the impact of mirror curvature to the system dimensions and they proved with the proper curvature, the collector height can be reduced without effect on the performance. This design is able to reduce the cost and the land utilization. Sharma et al. [19] investigated the cosine losses, the shading and the blocking in a LFC parametrically. They proved that the blocking losses are lower than the shading losses and also they stated that the south-north orientation is better than the east-west orientation. Montes et al. [20] investigated the idea of Mills and Morrison [21] by comparing a hybrid and a complete Compact LFR to the conventional LFC (FRESDEMO prototype). They proved that both Compact LFR lead to lower shading and the blocking losses. In the literature, many tools can be used in order to calculate the solar energy delivered to the collector as HELIOS [22], SOLTRACE [23], DELSOL [24], MIRVAL [25] and HFLCAL [26].

In the literature, many configuration of the linear Fresnel collector has been proposed. The most adopted configuration is the use of cavity receivers [27] and many companies have been designed their collectors in this direction (Novatec Solar [28], Areva Solar [29], Solar Power Group [30] and Industrial Solar [31]). The trapezoidal cavity receiver was examined by Qiu et al. [32] by coupling Monte Carlo Ray Tracing and Finite Volume Method. The examined collector had 25 mirrors and 8 fluid tubes inside the cavity. The simulation was performed in ANSYS and the final results proved annual optical efficiency from 45% to 60%. Mokhtar et al. [33] analyzed a small scale LFC with 10 mirrors and 4 tubes in a trapezoidal cavity. They developed a mathematical model for the evaluation of their system which was validated with experimentally results. Their experiments were carried out for low temperature levels up to 80 °C and the maximum thermal efficiency of the collector was about 29%. Facão and Oliveira [34] investigated a trapezoidal cavity LFC with 10 mirrors and 6 tubes. They analyzed parametrically the cavity depth and the insulation thickness and finally the proved that the values of 45 mm and 35 mm are the optimum respectively. Sahoo et al. [35] investigated a LFC with the commercial software RELAP. They made thermal hydraulic modelling and simulation of a LFC with 8 mirrors and 8 tubes, while their results were validated by literature experimental data. They focused on the steam quality production and on the pressure drop inside the tube, by changing various parameters as the tube length and the mass flow rate. Other researchers has been analyzed the natural convection inside the trapezoidal cavity with many details. Reddy and Ravi Kumar [8] developed a 2-D mathematical modelling for calculating the heat losses of a trapezoidal receiver by using the non-Boussinesq approximation. They analyzed their cavity for various depths and receiver temperature levels and compared their