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Multi-criteria evaluation of a nanofluid-based linear Fresnel solar collector

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ABSTRACT

Solar linear Fresnel reflector (LFR) is a promising concentrating technology, which presents important advantages such as the low investment cost, the reduced wind loads and the relatively low land utilization factor. The objective of this work is to investigate an innovative way for enhancing the thermal performance of LFR, especially at high temperatures. The utilization of nanofluid as heat transfer fluid is the investigated thermal enhancement method and more specifically the use of CuO nanoparticle dispersed on Syltherm 800 (6% volumetric concentration). The examined collector has total net aperture equal to 154 m^2 and concentration ratio of 58.36. The primary reflectors are curved mirrors, the secondary reflectors have compound parabolic shape and the receiver is an evacuated tube. The operation with nanofluid is compared to the operation with pure thermal oil for various inlet temperatures from 350 K up to 650 K and flow rate equal to 200 L/min. According to the final results, the maximum thermal efficiency enhancement with the nanofluid is close to 0.8%, while the pumping work demand is increased up to 50% with the nanofluid. Various criteria like the exergy efficiency, overall efficiency and entropy generation are applied in order to evaluate the nanofluid utilization properly. Finally, the operation with nanofluid is found to be beneficial, especially in high-temperature levels. The analysis is conducted with SolidWorks Flow Simulation with a validated model.

1. Introduction

Solar energy exploitation is one of the most promising techniques for facing numerous energy problems as the climate change, the global warming, the high energy demand and increasing electricity price (Rahou et al., 2016; Myers and Goswami, 2016; Abbas and Martínez-Val, 2017). The solar thermal energy can be utilized in low-temperature applications as space-heating and domestic hot water production with the conventional flat technologies or the evacuated tubes. Concentrating solar thermal energy is able to produce useful heat in medium and high-temperature levels, giving the possibility for the adoption of solar energy in various applications. In medium temperature levels, solar cooling with sorption machines, industrial heat production and desalination are examples of applications which can utilize the solar energy (Palomba et al., 2017; Zhou et al., 2017). Electricity production and chemical processes like methanol reforming are applications which need higher temperature levels (Loni et al., 2016). The most usual concentrating technologies are the parabolic trough collector, the linear Fresnel reflector, the solar dishes and the solar towers. Every concentrating technology presents different advantages and disadvantages and thus every application suits more with specific collector kinds.

The linear Fresnel reflector (LFR) is a developing concentrating solar technology which presents important advantages, compared to the linear parabolic trough collector (PTC) Zhu et al., 2014; Mathioulakis et al., 2017. More specifically, the LFR is a low-cost technology, with relatively low operational costs, while the wind loads are lower because the reflectors are located close to the ground. Moreover, the land utilization factor is low with LFR and it is easy to achieve high concentration ratios without mechanical difficulties. However, the LFR present greater optical losses compared to the parabolic trough collector and this is the most important drawback of this technology. In the literature, there are numerous configurations of Fresnel collectors and there is great variation in the reflector geometry as well as in the receiver type. The majority of the studies are focused on the optical and thermal analysis of the LFR.

The optimization of the geometrical characteristics of the Fresnel collector is a crucial issue because it directly effects on the optical efficiency. Boito and Grena (2016) optimized the LFR geometry by changing the reflector width, the focal point and the reflector distance. They finally found 12% performance enhancement with the suggested design modifications. Sharma et al. (2015) investigated the blocking and shading effects of the mirrors and they found them to be ranged from 6% up to 20%. Benyakhlef et al. (2016) carried out a detailed study about the impact of the mirror curvature of the collector performance. They found that maximum deflections up to 2 mm lead to

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Nomenclature

A_α	collector net area, m^2
Be	Bejan number, –
C	concentration ratio, –
c_p	specific heat capacity under constant pressure, J/kg K
D	diameter, m
D_m	distance between reflectors
F	focal length, m
f	friction factor, –
G_b	solar direct beam irradiation, W/m^2
h	heat transfer coefficient, $W/m^2 K$
h_{out}	convection coefficient between cover and ambient, $W/m^2 K$
k	thermal conductivity, W/m K
L	tube length, m
m	mass flow rate, kg/s
N_s	entropy generation ratio, –
Nu	Nusselt number, –
P	pressure, Pa
Pr	Prandtl number, –
Q	heat flux, W
Re	Reynolds number, –
T	temperature, K
T_{am}	ambient temperature, K
T_{sky}	sky temperature, K
T_0	reference temperature, K
u	fluid velocity, m/s
V	volumetric flow rate, L/min
V_{wind}	ambient air velocity, m/s
W	total width, m
W_p	pumping work, W
W_0	mirror width, m

Greek symbols

α	absorber absorbance, –
β	ratio of the nanolayer thickness, –
ΔS	total entropy generation, J/K
ΔS_P	total entropy generation due to the fluid friction, J/K
ΔS_T	entropy generation due to heat transfer, J/K
ΔP	pressure drop, kPa
ε	emittance, –
η_{el}	equivalent electrical efficiency, –
η_{ex}	exergy efficiency, –
η_{ovr}	overall efficiency, –
η_{th}	thermal efficiency, –
η_I	performance evaluation criterion for the same pumping work, –
η_{II}	performance evaluation criterion for the same pressure drop, –
η_{II}	performance evaluation criterion for the same volumetric flow rate, –
θ	solar incident angle, °
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
ρ_1	primary concentrator reflectance, –
ρ_2	secondary concentrator reflectance, –
τ	cover transmittance, –
φ	volumetric nanoparticle concentration, %
ω	peripheral absorber angle, °

Subscripts and superscripts

bf	base fluid
c	cover
ci	inner cover
co	outer cover
fm	mean fluid
in	inlet
loss	thermal loss
m	logistic temperature for exergy
nf	nanofluid
np	nanoparticle
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
s	solar
th	theoretical
u	useful
0	reference case with pure thermal oil

Abbreviations

LFR	Linear Fresnel Reflector
MWCNT	Multi-wall carbon nanotubes
PEC	Performance evaluation criterion
PTC	Parabolic Trough Collector

high optical performance and they recommended the use of curved mirrors. The impact of the wind loads on the Fresnel structure has been studied by Lancereau et al. (2015). They found extremely low wind loads compared to the linear parabolic collectors and thus they indicated low stresses in the metallic structure.

The receiver shape of the LFR is a crucial issue and various designs exist. The most usual receivers have a trapezoidal cavity or a secondary parabolic/compound-parabolic concentrator. Moghimi et al. (2015, 2017) optimized the trapezoidal cavity of an LFR and they indicated that the thermal losses play a significant role in the optimization procedure. Sahoo et al. (2012, 2013, 2016) examined the thermal losses of the trapezoidal cavity (Sahoo et al., 2012) and they performed hydraulic simulations of the absorber tubes (Sahoo et al., 2013, 2016). Their studies indicate that the convection thermal losses are high and they have to be taken into account during the design procedure. Qiu et al. (2016) examined an LFR with the trapezoidal cavity and they achieved high optical efficiency close to 75%. Other interesting studies about trapezoidal cavities have been performed by Facão and Oliveira (2011), Reddy and Kumar (2014), Mokhtar et al. (2016), Nixon and Davies, 2016.

The use of an evacuated tube receiver with a secondary parabolic or compound parabolic reflector is also very usual in the literature. Important studies for the optimization of the secondary reflector have been performed by Canavarro et al. (2013, 2014) and Zhu (2017). Chaitanya Prasad et al. (2017) examined different secondary reflectors in order to achieve uniform heat flux distribution in the absorber periphery. Canavarro et al. (2016) suggested an elliptical secondary reflector in order to reduce the cost of the LFR and to create a higher concentrating ratio. Yanqing et al. (2016) studied a stretched parabolic linear Fresnel reflector and they found maximum thermal efficiency close to 66%. Balaji et al. (2016) compared two secondary reflectors, one with parabolic shape and one with involute geometry. They finally found the parabolic shape to be better with 83.33% secondary reflector performance, while the involute has 78.33%. Qiu et al. (2015) examined an LFR with compound parabolic cavity operating with molten salt. The optical efficiency of the investigated collector for zero incident