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Thermal enhancement of parabolic trough collector with internally finned absorbers

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A B S T R A C T

Parabolic trough collector is one of the dominant emerging solar technologies for producing heat at high temperatures (usually 200–400 °C). The objective of this study is to investigate the thermal performance of internally finned absorbers. Twelve different fin geometries are examined and compared with the smooth absorber case for various operating scenarios. More specifically, the investigated internal fins have thicknesses 2 mm, 4 mm and 6 mm, while their lengths are 5 mm, 10 mm, 15 mm and 20 mm. The examined parameters for the evaluation of the internally finned absorbers are the thermal efficiency, the Nusselt number, the pressure losses, as well as the thermal enhancement index. According to the final results, higher fin thickness and length lead both to higher thermal performance and simultaneously to higher pressure losses. The impact of the length on the results is found to be more intense than the thickness. According to the thermal enhancement index, the case with 20 mm length and 4 mm thickness is found to be the optimum case. For this absorber, the increase in the thermal efficiency and the thermal enhancement index are found 1.27% and 1.483 respectively for 600 K inlet temperature, while the Nusselt number is proved to be 2.65 times greater than in the smooth case.

1. Introduction

Solar energy utilization is one of the most effective ways for facing the recent problems in the energy domain which are associated with the global warming, the fossil fuel depletion and the increasing rate of electricity price (Casati et al., 2015; Reddy et al., 2015). Solar energy is abundant energy source (Tripathi and Tiwari, 2016) which can either to be converted into useful heat and to electricity, the fact that makes it a suitable energy source for numerous applications from domestic hot water production to solar dryers and to electricity production in concentrating solar power plants (Qiu et al., 2017; Tiwari and Tiwari, 2016; Tzivanidis et al., 2016).

Concentrating solar collectors are the most suitable technology for operation in medium and high-temperature levels (over 150 °C) with high thermal efficiency (Fernández-García et al., 2010). Among the developed technologies, parabolic trough collector (PTC) is one among the most mature solar collector types which are used in many applications (Wang et al., 2016; Rovira et al., 2016). PTCs usually operate with thermal oils as Dowtherm, Therminol, Syltherm and Sandotherm (Buehler et al., 2016), while the last years' applications with molten salts (mainly nitrate salts) (Nunes et al., 2016) have been developed. Thermal oils can operate with safety up to 400 °C (Wadekar, 2017), while molten salts usually up to 550 °C (Myers and Goswami, 2016). For achieving higher temperature levels, liquid metals as liquid sodium and gas working fluids (air, carbon dioxide, nitrogen and helium) can be utilized (Bellos et al., 2017, 2016a). At this time, the majority of thermal applications with PTC uses thermal oils, as Therminol VP1 and Syltherm 800 because these are the most common and reliable solutions (Bellos et al., 2017).

In the literature, many techniques have been examined in order the thermal performance of parabolic trough collectors to be enhanced. The basic goal of these techniques is to improve the heat transfer conditions between absorber and fluid, increasing the heat transfer coefficient inside the flow. Moreover, the increase in the thermal efficiency leads to lower receiver temperature and to lower temperature gradients on it, a fact that reduces the possible deformation problems (Muñoz and Abánades, 2011; Wang et al., 2016). In the literature, there are many studies which have been focused on investigating alternative working fluids, as nanofluids for enhancing the thermal performance of PTCs (Mwesigye and Meyer, 2017; Mwesigye et al., 2016, 2015; Bellos et al., 2016b; Zadeh et al., 2015; Sokhansefat et al., 2014).

On the other hand, many studies have been focused on geometrical improvements of the absorber in order to increase the heat transfer rate to the fluid. More specifically, the basic idea is to create higher turbulence degree inside the flow, fact that increases the heat transfer coefficient and leads to higher mixing inside the flow. Many techniques

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Nomenclature

A	area, m^2
C	concentration ratio, –
c_p	specific heat capacity under constant pressure, J/kg K
D	diameter, m
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
L_c	characteristic length, m
m	mass flow rate, kg/s
N	number of fins, –
Nu	Nusselt number
Q	heat flux, W
Re	Reynolds number
r	concentrator reflectance, –
t	fin thickness, mm
PER	wet perimeter, m
P_{out}	outlet pressure, kPa
p	fin length, mm
T	temperature, K
T_{sky}	sky temperature, K
u	fluid velocity, m/s
V	volumetric flow rate, L/min
V_{wind}	ambient air velocity, m/s
W	width, m

Greek symbols

α	absorber absorbance, –
ε	emittance, –
ΔP	pressure drop, kPa
η	efficiency enhancement index, –
η_{opt}	optical efficiency, –
η_{th}	thermal efficiency, –
θ	solar incident angle, °
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
τ	cover transmittance, –
φ	peripheral absorber angle, °

Subscripts and superscripts

a	aperture
am	ambient
c	cover
ci	inner cover
co	outer cover
core	core area without fins
fin	fin area
fm	mean fluid
in	inlet
loss	thermal loss
out	outlet
r	receiver
real	real fluid area of the finned absorber
ri	inner receiver
ro	outer receiver
s	solar
u	useful
0	smooth absorber case – reference case

Abbreviations

CFD	computational fluid dynamics
LCR	local concentration ratio
PTC	parabolic trough collector

have been examined, such as the use of inserts in the flow and the modification of the absorber surface with fins or dimples which act as passive vortexes inside the flow.

Many kinds of object inserts have been examined in PTCs. A great number of these studies use the thermal enhancement index (η) for evaluation the examined heat transfer techniques compared to the respective reference case. Practically this index takes into account the increase in the Nusselt number and the simultaneous increase in the friction factor, compared to the respective reference case. Values over 1 for this index indicates thermal enhancement and when this index takes higher values than the thermal enhancement is higher. More details about this index are given in Section 2.2.

Zhu et al. (2016) examined the use of a wavy-tape insert inside a PTC and they found the maximum thermal enhancement index close to 1.82 for laminar flow conditions with water as working fluid. Song et al. (2014) examined the use of a helical screw-tape insert under non-uniform heat flux conditions. They used Dowtherm thermal oil and their results indicated that the use of the helical screw-tape insert can improve the thermal efficiency of the solar collector. Mwesigye et al. (2014) examined the use of perforated plate inserts in LS-2 PTC operating with Syltherm 800 and they found thermal efficiency increase from 1.2% up to 8% for various operating conditions compared to the respective reference case. Ghadirijafarbeigloo et al. (2014) examined the use of louvered twisted-tape inserts with thermal oil and they found the thermal enhancement index to be 2.67 for Reynolds number equal to 5000 and to be close to 1.4 for Reynolds number equal to 25,000. The use of twisted tape inserts has been investigated by many researchers. Mwesigye et al. (2016) found that with this technique the heat transfer rate inside the PTC absorber can be increased up to 169%, the circumferential temperature difference can be reduced up to 68% and the thermal efficiency can be increased up to 10%. The previous values are compared with the respective cases with the reference absorber. Jaramillo et al. (2016) determined the operating condition that the twisted tape inserts can lead to higher performance. More specifically, they stated the use of these objects in low flow rates and for twist ratio close to 1. Moreover, many studies have been focused on the use of metal foams inside the flow. Wang et al. (2013) examined the use of metal foams in PTC for steam generation and they found the thermal enhancement index to be ranged from 1.1 to 1.5. Reddy et al. (2015) examined experimentally the use of various metallic foams in PTC under ASHRAE 93-1986 test procedure and they found high thermal performance which indicates that the use of this kind of inserts is preferable. Kumar and Reddy (2009) examined the use of a PTC with porous disc receiver and they found 64.3% enhancement in Nusselt, while they stated significant penalty in the pressure drop. Too and Benito (2013) performed a comparative analysis among helical coil/wire insert, twisted tape insert, dimpled tube and porous foam inside a PTC for operation with air, carbon dioxide and helium. They finally found that the dimpled absorber is the best solution among the examined.

Many other studies have been focused on the utilization of internal fins in the absorber, as well as in modifications over the internal absorber side. Huang et al. (2017) examined a dimpled PTC for turbulent flow conditions. They finally found that the deeper dimples lead to

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