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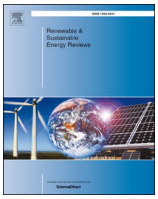

Enhancing the performance of parabolic trough collectors using nanofluids and turbulators

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ABSTRACT

Parabolic trough collector is one of the most usual solar collectors for applications up to 400 °C. The thermal enhancement of this collector concentrates a lot of interest and various techniques are tested in order for the thermal efficiency to be maximized with a reasonable penalty in the pressure drop. The use of nanofluids as working fluids, as well as the use of flow turbulators, mainly inserts and internal fins or tube dimples are the main techniques which are examined. The objective of this work is to give a complete literature review of the existing studies on this domain and to present a numerical comparative analysis between the most usual thermal enhancement techniques. More specifically, the use of oil-based nanofluids with 6% CuO is compared with the use of internal rectangular fins in the absorber, while the combination of these techniques is also examined. The analysis is conducted with a validated CFD model in SolidWorks Flow Simulation for various fluid temperature levels. According to the final results, the use of nanofluids leads to 0.76% thermal efficiency enhancement, the use of internal fins to 1.10% and the combination of these techniques to 1.54%. Moreover, emphasis is given in the pressure drop of the examined cases and in the evaluation criteria which are used in every case.

1. Introduction

1.1. Parabolic trough collectors – General description

Solar energy utilization is one of the most important ways for facing the numerous problems in the energy domain, as the global warming, the fossil fuel depletion, the climate change, the increasing energy demand and the high electricity price [1–5]. Solar concentrating technologies are able to cover a great number of energy needs such as heating (domestic and industrial), cooling, refrigeration, electricity production and chemical processes (methanol reforming, desalination, etc) [6,7].

The most usual concentrating technologies are parabolic trough collectors (PTCs), Fresnel reflectors, solar dishes and central receivers. Among these technologies, parabolic trough collector is the oldest technology which has been used in a great variety of applications. Especially for temperature levels up to 400 °C, PTCs are able to supply the useful heat with high thermal efficiency with a reasonable investment cost (~200 €/m^2) and they are characterized as cost-effective and mature technologies [6–8].

The latest trends in commercial PTCs are collectors with high concentration ratios (up to 40), evacuated tube receivers and selective coating [1]. This design leads to high thermal efficiency by minimizing the thermal losses. The thermal losses of the PTCs are generally low, especially in low-temperature levels. However, in high-temperature levels, close to 400 °C for instance, their performance is getting lower and this is a limitation for establishing them as a competitive technology to the conventional fossil fuel electricity production technologies. Thus, there is a need for further thermal efficiency enhancement of PTCs in order to reduce the thermal losses at high-temperature levels.

1.2. Working fluids

The most usual working fluids in PTCs are water/steam, thermal oils, molten salts and more seldom gas working fluids as air or carbon dioxide. Water/steam power plants present important advantages as safety operation, simple storage system and non-toxic working fluid. A characteristic example of this technology is the CSP Plant “Abengoa Solar” at the Solucar Platform [9]. The limitations of the direct steam generation power plants are based on the need for sophisticated control strategies, as well as on the need for high operating temperatures [7].

The next category is the applications which use thermal oil as heat transfer fluid. The most usual thermal oils are the following: Syltherm 800, Therminol VP1, Therminol 66, Therminol D-12, Sandotherm, Dowtherm A and Behran oil. Generally, the thermal oils can operate up to 400 °C [2] with a reasonable pressure level (generally close to 15

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Nomenclature

A	Criterion for the multi-objective optimization, -
A_a	Collecting area, m^2
B	Criterion for the multi-objective optimization, -
Be	Bejan number,-
c_p	Specific heat capacity under constant pressure, J/kg K
D	Diameter, m
F	Focal length, m
f	Friction factor, -
F_o	Objective function, -
G_b	Solar direct beam irradiation, W/m^2
h	Heat transfer coefficient, W/m^2K
h_{out}	Convection coefficient between cover and ambient, W/m^2K
k	Thermal conductivity, W/mK
L	Tube length, m
m	Mass flow rate, kg/s
N_s	Entropy generation ratio, -
Nu	Nusselt number, -
Q	Heat flux, W
Re	Reynolds number, -
T	Temperature, K
T_{sky}	Sky temperature, K
T_{sun}	Sun 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	Width, m
W_p	Pumping work, W

Greek symbols

β	Ratio of the nanolayer thickness, -
ε	Emittance, -
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
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, -
η_{el}	equivalent electrical efficiency, -
η_{ex}	Exergy efficiency, -
η_{ovr}	Overall efficiency, -
η_{th}	Thermal efficiency, -
μ	Dynamic viscosity, Pa s
ρ	Density, kg/m^3
φ	Volumetric nanoparticle concentration, %
ω	Peripheral absorber angle, °

Subscripts and superscripts

am	ambient
bf	base fluid
co	outer cover
fm	mean fluid
in	inlet
m	logistic exergy parameter
max	maximum
min	minimum
nf	nanofluid
np	nanoparticle
out	outlet
r	receiver
ri	inner receiver
s	solar
u	useful
0	reference CASE

Abbreviations

CFD	Computational fluid dynamics
CSP	Concentrating power plant
EXP	Experimental
MCNT	Multi-walled nanotubes
PEC	Performance evaluation criterion
PTC	Parabolic trough collector

bars). However, the use of thermal oils leads to relatively low thermal performance, compared to other working fluids, as well as there is increased maintenance cost.

The new trends in the CSP plants with PTC are to use working fluid in higher temperature levels, as molten salts and pressurized gases [7]. Molten salts are usually nitrate salts, for instance (60% $NaNO_3$ − 40% KNO_3), which can easily operate up to 550 °C, giving possibilities for higher thermal efficiency [10]. However, there is a need for high safety in the operation due to the freezing danger which can be occurred in temperature levels from 100 °C to 230 °C [11]. The use of pressurized gases gives the possibility to work in high-temperature levels without fluid temperature limitation. Air, nitrogen, helium and carbon dioxide are the main representative of the gas working fluids [12]. Especially, a lot of research has been focused on the supercritical carbon dioxide [13] due to its superior thermophysical properties close to the critical point.

1.3. Why to use heat transfer augmentation techniques

The last years, many techniques have been tested in PTCs in order for their thermal efficiency to be enhanced. These techniques are mainly applied for operation with thermal oil or water. The main goal is to increase the heat transfer rate from the tube to the working fluid in order to reduce the receiver temperature. The result of the lower receiver temperature is the lower thermal losses and consequently the higher thermal efficiency. Moreover, it has been proved that the reduction of the receiver temperature leads also to more uniform temperature distribution in its periphery, the fact that reduces the thermal strains. The thermal strains are associated with the high-temperature gradients and with deformation problems [7]. So, the heat augmentation techniques not only increase the thermal efficiency, but also reduce the danger of deformation problems.

The solar irradiation is concentrated on the absorber with a non-uniform way and this is the reason which makes the lower part to be the hotter one. The heat augmentation techniques try to create a more uniform temperature distribution by enhancing the heat transfer coefficient and creating paths to the incoming heat from the hot absorber to the cold center of the working fluid. Two usual heat augmentation techniques are the use of nanofluids as working fluids and the use of turbulators in the flow. At this point, it is important to state that in the direct steam generation PTC, the deformations are more intense and usually operation strategy techniques are used for the reduction of the deformation problems [14,15].

In the literature, the number of studies with heat transfer