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A detailed exergetic analysis of parabolic trough collectors

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ABSTRACT

The objective of this study is to present a detailed exergetic analysis of the commercial parabolic trough collector LS-2. A complete thermal model is developed in EES (Engineering Equation Solver) and it is validated with literature results. The solar collector is examined for operation with Therminol VP1 and air in order to examine the most representative liquid and gas working fluids. In the exergetic analysis, detailed presentation of the exergetic losses and the exergy destruction is given for various operation cases. More specifically, different combinations of flow rates and inlet temperature levels are tested for both working fluids and the results indicate the reasons for the exergetic reduction in every case. According to the final results, the global maximum exergetic efficiency for operation with air is 25.62% for an inlet temperature of 500 K and flow rate of 10,000 l/min, while for Therminol VP1 is 31.67% for 500 K and 100 l/min. Moreover, it is proved that the exergy destruction is more intense in the thermal oil case, while the exergetic losses are more important in the air case. The final results and conclusions clearly present the exergetic analysis of parabolic trough collector for a great range of operating conditions.

1. Introduction

Solar energy utilization is one of the most promising ways for facing global problems as the climate change, the increased CO_2 emissions, the fossil fuel depletion and the increasing energy demand due to the new lifestyle trends [1–3]. In this direction, solar energy is more and more often used in power plants in order to supply totally or partially the thermal input [4–5]. The sustainability and the development of these plants are depended on the suitable design which leads to sizing the plants properly [6].

The best thermodynamic tool for investigating power production applications is the exergetic analysis because with this technique emphasis is given in the evaluation of the system design. The exergetic analysis in solar collectors is applied the last decades with an increasing rate. One of the first preliminary studies was performed by Marschall and Adams [7] in 1978 for the evaluation of a flat plate collector with thermal and energetic terms. The next years, more studies for the exergetic evaluation of the systems have been found in the literature, as Madrifa in 1985 [8] for flat plate collectors and Altfred et al. [9] in 1988 for air heaters.

Moreover, it is essential to state that a lot of scientific discussions have been made the last decades about the exergetic potential of the solar energy. Many models have been proposed with the most widespread to be by Petela [10], Spanner [11], Jeter [12], Parrot [13] and Badescu [14]. For the exergy potential of the undiluted solar irradiation, the suggested model by Petela [15] is the one that is used in the majority of the literature studies up today.

In the recent literature, all the kinds of solar collectors have been examined exergetically with solar air heaters [16–19] and hybrid PV [20–23] to be the most usually exergetically examined collectors. Moreover, some recent reviews about the exergetic analysis of solar collectors are found in the literature [24–27]. According to these studies, the exergetic analysis has to be applied more in concentrating collectors which are used more often in solar power plants.

Parabolic trough collector is the most mature technology for power production [28] and many CSP plants use them as the most cost-effective and developed solution. However, there are not many studies which examined and interpret the exergetic performance of parabolic trough collectors. Petela [29] performed a detailed analysis about a parabolic trough solar cooker and finally proved that the exergetic performance is very low (<1%) due to the high thermal losses of the examined configuration. Similar results are taken from the study of Ozturk [30] for parabolic trough solar cooker. On the other hand, Ozturk et al. [31] examined the exergetic efficiency of a parabolic trough collector and he found it close to 25%; a satisfying value due to the low thermal losses of the examined collector. Padilla et al. [32] examined a parabolic trough collector (LS-3) operating with thermal oil for various mass flow rates and inlet temperatures with a detailed analysis. They found that higher inlet temperatures lead to higher exergetic efficiency

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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
E	exergy flow stream, W
f	focal distance, m
f_r	friction factor, –
G_b	solar beam radiation, W/m^2
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/mK
K	incident angle modifier, -
L	tube length, m
m	mass flow rate, kg/s
Nu	mean Nusselt number, –
Pr	Prandtl number, –
Q	heat flux, W
Re	Reynolds number, –
T	temperature, K
u	velocity, m/s
V	volumetric flow rate, l/min
W	collector width, m

Greek symbols

α	absorbance, –
γ	intercept factor, –
ΔP	pressure drop, Pa
ε	emittance, –
η	efficiency, –
θ	incident angle, °
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ_{fluid}	density, kg/m^3
ρ	final reflectance, –
ρ_0	reference reflectance, –
ρ_1	shadowing optical losses, –
ρ_2	twisting tracking error, –
ρ_3	geometric errors, –
ρ_4	mirror clearness, –
ρ_5	receiver clearness, –
ρ_6	miscellaneous optical losses, –
σ	Stefan–Boltzmann constant [=$5.67 \cdot 10^{-8}$ $W/m^2 K^4$]
τ	transmittance, –

Subscripts and superscripts

a	aperture
abs	absorbed
air	ambient air
am	ambient
c	cover
ci	inner cover
co	outer cover
c-a	cover-ambient
d	destruction
d, s-r	destruction from sun to receiver
d, r-f	destruction from receiver to fluid
ex	exergetic
fluid	working fluid
in	inlet
in, opt	inlet optimum
loss	losses
loss, opt	exergetic optical losses
loss, th	thermal exergetic losses
opt	optical
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
s	solar
sky	sky
sun	sun outer layer
th	thermal
u	useful

Abbreviations

CSP	Concentrating Solar Power
EES	Engineer Equator Solver
PTC	Parabolic trough collector
SNL	Sandia National Laboratories

which is up to 37% for all the examined cases. Moreover, they stated that the exergy destruction during the heating of the fluid from the absorber is relatively low and up to 0.5% to the total exergy input. Bellos et al. [33] examined exergetically two techniques for improving the performance of the IST-PTC collector; the use of nanoparticles inside the thermal oil and the use of a converging-diverging inner absorber surface. Finally, they proved that there is great enhancement with the utilization of the nanofluid compared to the pure thermal oil and the converging-diverging also increases the exergetic performance of the collector. Guo et al. [34] performed a parametric analysis of a PTC operating with Dowtherm A for various receiver diameters, inlet temperatures, ambient temperatures, incident angles and wind velocities. In every analysis, only one parameter was examined parametrically, while all the others had been kept constant. According to their results, there is optimum mass flow rate exergetically in every case and they stated the need of reducing the high optical losses as a way for improving the PTC exergetically.

The last years, parabolic trough collectors have been also examined for innovative CSP which operate with gas working fluid in order to exceed the temperature limitations of the thermal oils and of the molten salts. For example, PTCs operating with air have been examined in Brayton cycles by Ferraro et al. [35–36]. Moreover, a lot of research has been focused on the utilization of supercritical carbon dioxide in solar parabolic trough collectors in order to feed Brayton or Rankine Power cycles [37].

However, the parabolic trough collectors operating with gases are seldom examined exergetically in the literature. Hernández-Román et al. [38] examined experimentally a PTC operating with air and they evaluated it in energetic and exergetic terms. According to their results, the optimum mass flow rate for air was 0.03 kg/s for receiver diameter between 10 mm and 30 mm with the total aperture to be 3 m^2. Bellos et al. [39] examined thermally and exergetically six different working fluids in the Eurotrough PTC module. Air, nitrogen, carbon dioxide, helium argon and neon are examined and it is proved that the mass flow rate plays a significant role in the results due to the high-pressure drop in operation with gases. The same authors examined the use of internal longitudinal fins in the Eurotrough module for operation with air, carbon dioxide and helium [40]. According to their results, the intermediate fin length of 10 mm is the optimum length exergetically because it combines significant heat transfer enhancement from absorber to fluid and