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The impact of internal longitudinal fins in parabolic trough collectors operating with gases

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ABSTRACT

In this study, the use of internal fins in parabolic trough collectors operating with gas working fluids is examined. Air, helium and carbon dioxide are the investigated working fluids, while Eurotrough ET-150 is the examined solar collector. The design and the simulation of this solar collector are performed with the commercial software Solidworks Flow Simulation. The internal fins lead to higher thermal efficiency but also to higher pressure losses; something very important for the solar fields of Concentrated Power Plants. Thus, the collector is examined energetically and exergetically in order to take into account the increase in the useful output with the simultaneous greater need of pumping power. Various fin lengths are examined and finally the fin of 10 mm was proved to be the most appropriate exergetically. In working fluid comparison, helium is the most efficient working fluid exergetically for all the examined cases. In the thermal efficiency comparison, helium performs better up to 290 °C, while carbon dioxide is the best choice in higher temperature levels. Moreover, the optimum mass flow rate for the helium was proved to be 0.03 kg/s and for the other working fluids the value of 0.015 kg/s seems to lead to the most satisfying results.

1. Introduction

Solar energy utilization is a promising way for facing the present environmental problems, the fossil fuel depletion and the increasing price of electricity [1–3]. Solar energy is the most abundant and easily utilized technology with a low replenishment time [4]. Among the solar collectors, a parabolic trough collector is the most mature and well-established technology for producing heat in high temperature levels [5–7]. The majority of the concentrated solar power plants use parabolic trough collectors for producing electricity [8]. Moreover, these collectors are used for other proposes as industrial heat production and solar cooling applications [8,9]. The last years, many researchers have been focused on improving the thermal efficiency of the parabolic trough collectors; something that it is very important for establishing their use worldwide [10]. Two are the most usual field of research; working fluid investigation and enhancement of heat transfer between absorber and working fluid.

Many working fluids have been tested for operation in parabolic trough collectors. The most usual choice is the use of thermal oils as Therminol VP-1 [11], Therminol D-12 [12] and Dowtherm A [13], but these fluids can operate up to 400 °C creating constraints in the system efficiency in CSP Plants. An alternative solution is the use of nanoparticles as CuO and Al_2O_3 inside the fluid, creating the common nanofluids. Many studies [14–17] have investigated the use of nanofluids in solar collectors and the final results prove small increase in the efficiency up to 10% [18]. However, improvements in this technology have to be made in order to reduce the preparation cost and the instability problems [19]. Molten salts, usually nitrate salts, utilization is a promising way to improve the storage strategies in concentrating collector power plants. The solidification problems of this technology create obstacles in their application and for this reason a lot of research has been focused in this point [20,21].

The gas working fluids in parabolic trough collectors is a recent technique with many advantages. Using gases there is not constraint for the upper temperature operating level, from the working fluid point of view. Moreover, there is a great variety of gasses as air, nitrogen, carbon dioxide and helium which are non-toxic. Air for example has zero cost and it is abundant, contrary to other working fluids as thermal oil, nanofluids and molten salts. The thermal energy storage in this system can be achieved with many techniques as phase change materials [22] and concrete blocks [23,24]. However, the high pressure drop along the collector fields may lead to higher pumping power [25,26].

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Nomenclature

A	area (m^2)
C	concentration ratio (–)
c_p	specific heat capacity under constant pressure (kJ/kg K)
D	diameter (mm)
E	exergy flow (W)
f	focal length (mm)
G_b	solar direct beam irradiation (W/m^2)
h_{out}	convection coefficient between cover and ambient (W/m^2 K)
L	tube length (mm)
m	mass flow rate (kg/s)
Q	heat flux (W)
r	concentrator reflectance (–)
s	fin thickness (mm)
t	fin length (mm)
T	temperature (°C)
W	width (mm)

Greek symbols

α	absorber absorbance (–)
ε	emittance (–)
ΔP	pressure drop (kPa)
ΔS	specific entropy increase (kJ/kg K)
η	efficiency (–)
θ	solar incident angle (°)
ρ	density (kg/m^3)
τ	cover transmittance (–)

Subscripts and superscripts

a	aperture
am	ambient
c	cover
ci	inner cover
co	outer cover
ex	exergetic
fm	mean fluid
in	inlet
opt	optical
optim	optimum operating conditions
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
s	solar
sun	sun
th	thermal
u	useful

Abbreviations

CSP	concentrated solar power
PTC	parabolic trough collector

Many researches have been focused in the study of gases in solar power plants with parabolic trough collectors. Air and carbon dioxide were compared by Cipollone et al. [27] in a discrete Ericsson cycle and finally the second was proved to be the most efficient. Islam et al. [28], examined ammonia, carbon dioxide and nitrogen in a CSP Plant and they also concluded that carbon dioxide is the best choice with nitrogen to be the second one. They also proved that the difference among them is getting greater in higher temperature levels. Muñoz-Anton et al. [29] studied experimentally the use of nitrogen and carbon dioxide in parabolic collectors up to 500 °C and the final results were competitive to the other conventional technologies. Moreover, they stated that the use of helium has to be studied because this fluid is a very promising solution for these temperature levels. Biencinto et al. [30] compared nitrogen and thermal oil for a solar power plant in Almeria (Spain).They concluded that thermal oil lead to a slight increase in yearly energy production which can be balanced by the flammability and the environmental toxicity of thermal oil. Furthermore, they stated that other gas working fluids may lead to better performance than nitrogen. From the above studies, nitrogen is proved not to be a sustainable and feasible solution for parabolic trough collectors, while carbon dioxide and helium seem to have advantages, especially in high temperature levels.

The other technique for improving the efficiency of PTC is the geometry improvements of the absorber in order to increase the heat transfer rate. Usually, these geometry changes aim to create passive vortexes inside the flow [31] or to increase the mixing rate in order to increase the turbulence degree; fact that lead to higher heat transfer coefficient between fluid and absorber. The result of this technique is the decrease in the absorber temperature level and consequently the increase in thermal efficiency. On the other hand, the increase in turbulence leads to higher pressure losses and to greater pressure drop along the absorber tube; something with negative impact in pumping power [32].

A usual technique is to design a dimpled geometry in order to create passive vortexes and to create higher heat transfer levels. Chen et al. [33] investigated dimpled and smooth absorber tubes and finally they proved that the dimples lead to higher heat transfer rate inside the tube. Moreover, Kalinin et al. [34] examined annular turbulizers in the flow and they conclude to great thermal enhancements.

The use of objects inside the flow is another way for enhancing the thermal efficiency with geometrical interventions. Mwesigye et al. [35–38] investigated the use of centrally placed perforated plate inserts [35,36] and of wall-detached twisted tape inserts [37]. The first idea lead to thermal enhancement up to 8%, while the second up to 10%. Different kind of inserts as V-nozzles, screw-tapes, conical nozzles and conical-rings can be used in order to increase the thermal efficiency of the collector [38,39]. Moreover, Hong et al. [40], after an interesting study, concluded that the geometrical changes have to be made carefully because other geometric combinations increase the efficiency and others lead to lower efficiency.

In a recent study, it is proved that the geometry modifications can lead to similar enhancement with the working fluid enhancement [41]. For this reason, it is interesting to examine simultaneously the impact of new absorber geometries with alternative working fluids. Bader et al. [42] investigated a parabolic trough collector with a tubular cavity operating with air and they concluded to satisfying results. Moreover, Kasperski and Nems [43] examined multiple-fin arrays in order to enhance the thermal efficiency of a PTC operating with air. The final results proved about 14% increase in thermo-hydraulic performance. Too and Benito [44] compared air, helium and carbon dioxide in tubular absorbers with dimples and inserts. They concluded that helium and carbon dioxide performs better that air, leading to lower pressure drop in the absorber.

In this study, the use of air, helium and carbon dioxide are investigated energetically and exergetically as working fluids is a