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Energy and exergy analyses of a parabolic trough collector operated with nanofluids for medium and high temperature applications

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ABSTRACT

Thermal performance of parabolic trough collectors (PTCs) can be improved by suspending nanoparticles into the traditionally used heat transfer fluids. In this work, a one-dimensional mathematical model is proposed to investigate the effect of various nanoprticles suspended in the working fluid for medium and high temperature PTCs. The major finding of this work is that the nanofluid enhances the thermal efficiency of the PTC slightly. High operating temperatures are more suitable for using nanofluids and generate higher relative gains of energy delivered. It is also found that the exergetic efficiency improvement is more important than energetic efficiency. The peak exergy efficiency is achieved by the CuO based nanofluid and is about 9.05%. The maximum daily relative gain of thermal energy delivered is found to be 1.46% by using 5% of Al_2O_3 in the base fluid. Optimal control of the operating conditions can lead to maximum energetic and exergetic performances of the PTC.

1. Introduction

Concerns regarding climate change are growing and the world needs to take urgent measures to avoid further warming of the earth [1]. The damaging effects of climate change are accentuated with the use of fossil fuels that are up to now considered as the main energy source for power generation worldwide [2]. As a result, increasing efforts are deployed by the research community to propose efficient and reliable alternatives for power generation mainly based on renewable energy sources [3]. Among these renewable energy resources, it is strongly believed that solar energy has the most influential potential to achieve a sustainable global energy system because of many reasons. It is clean, abundant and becoming more and more cost-effective [4]. Solar energy is one of the sustainable and potential options to fulfill a wide range of the humankind daily needs, including natural lighting [5], space and water heating [6,7], cooling [8], water desalination [9] and power generation [10]. Electrical power can be generated using photovoltaic panels by converting solar energy or solar thermal systems driven by thermodynamic cycles. The main advantages of thermal power generation over the PV one rely on the easiness of storing heat compared to electricity and the capability of thermal systems to reach higher energy productions [11]. The current available technologies used in thermal energy plants include, parabolic trough collectors [12], solar towers [13], linear Fresnel lenses [14] and dish Stirling [15]. The use of parabolic trough collector technology has been successfully tested in many power generation stations worldwide due to its technological maturity and its economic competitiveness [16–18].

Recently, research related to PTCs has increased tremendously. Many researches proposed improvements in order to ameliorate the performance of PTCs. Some of them focused on proposing modifications in the absorber geometry and including objects inside the flow. Twisted tape inserts were used by Jaramillo et al. [19]. In the case of a twist ratio close to 1 and for low Reynolds numbers, their applications showed a positive effect on the performance of the collector via an enhancement of the heat transfer. Bortolato et al. [20] have studied experimentally a PTC with flat bar-and-plate absorber including an internal offset strip turbulator in the channel. The new design allowed a better efficiency (up to 64%) with low pressure drops. Other investigators tried to test innovative working fluids such as supercritical CO_2 [21] and nanofluids [22–28]. The literature review of the recently published research works has shown that there are only limited works investigating detailed analysis of PTC using nanofluids. Sokhansefat

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Nomenclature

Symbol	Signification Units
h	hour angle degree
δ	solar declination degree
θ	incidence angle degree
k_θ	incident angle modifier dimensionless
$\in$	emittance dimensionless
G_{bt}	solar beam radiation W/m^2
c	specific heat capacity J/kg K
h_f	convective heat transfer coefficient between the absorber and the HTF W/ m^2 K
h_w	convective heat transfer coefficient between the external surface of the glass cover and the ambient air W/ m^2 K
λ	thermal conductivity W/ m K
k_{eff}	effective conductive coefficient between the glass cover and absorber W/ m K
Nu	Nusselt number dimensionless
Pr	Prandtl number dimensionless
Pe	Peclet number dimensionless
Re	Reynolds number dimensionless
T	temperature K
v	velocity m/s
γ	intercept factor dimensionless
τ	transmittance dimensionless
α	absorbance coefficient dimensionless
r_m	reflectance of the mirror dimensionless
μ	dynamicviscosity kg/m s
ρ	density kg/m^3
σ	Stefan–Boltzman constant W/m^2 K^4
$\dot{m}$	fluid mass flow kg/s
W_a	width of the collector m
L	length of the collector m
D	diameter m
A	cross sectional area m^2
ϕ	fraction of nanoparticles dimensionless
η	energetic efficiency dimensionless
η_{ex}	exergetic efficiency dimensionless
Δe	relative energy gain dimensionless
FoM	figure of merit dimensionless

Subscripts

a	ambient
ab	absorber
bf	base fluid
f	working fluid
g	glass cover
i	inner
in	inlet
nf	nanofluid
np	nanoparticle
o	outer
out	outlet
s	solid nanoparticle

Abbreviations

HTF	heat transfer fluid
PTC	parabolic trough collector

et al. [22] were the first authors to study the possibility of improving heat transfer in PTCs by selecting Al_2O_3/synthetic oil nanofluid as a working fluid. A 3-D numerical model based on Navier-Stokes mass, momentum and energy equations were proposed to characterize a fully developed turbulent mixed convection heat transfer through the receiver tube. Authors reported that increasing the concentration of Al_2O_3 nanoparticles up to 5% may increase the heat transfer coefficient by 14%. Ghesemi and Ranjbar [23] simulated the thermal behavior of a PTC using CuO-water and Al_2O_3-water nanofluids. The numerical model is based on the finite volume approach and solved by a CFD commercial code. It is shown that the tested nanofluids gave better performances compared to pure water. For a volume fraction of 3%, they reported an increase in the heat transfer coefficient of about 28% and 35% for CuO-water and Al_2O_3-water nanofluids, respectively. Mwesigye et al. [24] investigated numerically the thermal and thermodynamic performance of a high concentration ratio PTC employing Cu-Therminol VP-1 nanofluid as the working fluid. The conclusion given by the authors is that the collectors' thermal efficiency increased to 12.5% when the nanoparticle concentration varied between 0 to 6%. They have also shown that by using the entropy generation method, the nanofluids can enhance thermodynamic efficiency for the certain range of Reynolds numbers. Bellos et al. [25] analyzed theoretically two options for enhancing thermal efficiency of PTCs. The first option consists of considering a dimpled receiver with a sine form. For the second option, they compared three working fluids and nanofluid was one of them. They argued that both approaches can improve the efficiency by around 4%. An optic-thermal-stress coupling model was suggested by Wang et al. [26] in order to evaluate the influence of using Al_2O_3/synthetic oil nanofluid as a working fluid in PTCs. The authors indicated that nanofluids enhance heat transfer, avoid high temperature gradients and minimize thermal stress receiver's deformation. Simulations were carried out by Coccia et al. [27] to analyze the energy yields of low-enthalpy parabolic trough collectors utilizing six water-based nanofluids. The authors concluded that adding low concentrations of some nanofluids lead only to minor improvements in the PTC efficiencies while high concentrations do not induce an advantage compared to water. This result originates from the fact that the dynamic viscosity increases with the weight concentration. They have therefore recommended that evaluating nanofluids (as working fluids in PTCs) at high temperatures (characterized by lower dynamic viscosities and higher thermal conductivities) could be interesting.

Based on literature survey, it was found that there are only limited investigations studying the thermal behavior of PTCs operating with nanofluids. More works with detailed analysis are therefore required for a good understanding of the best conditions of using nanofluids in PTC applications. Moreover, the assessment of their benefits seems to be of a particular interest, especially for medium and high temperature applications as emphasized by [27]. Another key contribution of this paper is the discussion of the effect of nanofluids on the exergetic performance of PTCs. Very limited studies were carried out on this aspect as well. In this sense, the present work presents a thermal analysis and performance assessment of PTC using three types of nanofluids as heat transfer fluids for medium and high temperature applications. The proposed mathematical model is one-dimensional and takes into account real varying external conditions in terms of incident radiation and ambient temperature for the Moroccan city "Ouarzazate". A parametric study was also conducted to show the effect of mass flow rate, inlet temperature and nanoparticle concentration on the output energy. Detailed energetic and exergetic analyses are carried out as well to identify the best conditions of nanofluid utilization in PTCs.

2. Mathematical formalism

2.1. Tested fluids

The mathematical model attempts to study heat transfer and