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Thermal analysis of parabolic trough collector operating with mono and hybrid nanofluids

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ABSTRACT

In this paper, the use of mono and hybrid nanofluids in parabolic trough collectors is investigated. The LS-2 PTC module is studied for operation with Syltherm 800 as the base fluid, while the examined nanofluids are the following: 3% Al_2O_3/Oil, 3% TiO_2/Oil and 1.5% Al_2O_3-1.5% TiO_2/Oil. As it is obvious, in all the cases the total volumetric nanoparticle concertation has the same value in order to perform a suitable comparison. The analysis is conducted for turbulent flow conditions with a flow rate equal to 150 l/min, a value which leads to sufficient thermal performance results. The solar collector is investigated for inlet temperatures from 300 K to 650 K in order to cover a great range of possible operating temperature levels. According to the final results, the thermal efficiency enhancement for the hybrid nanofluid reaches up to 1.8%, while it is up to 0.7% with for mono nanofluids. This higher thermal efficiency enhancement is based on the great Nusselt number enhancement for the hybrid nanofluid case which is about 2.2 higher than the respective for operation with pure oil. The analysis is conducted with a developed thermal model in EES (Engineering Equation Solver) which is validated with literature results.

Introduction

Solar energy utilization is vital for achieving the sustainability and facing a series of problems as the global warming, the fossil fuel depletion, the increased CO_2 emissions and the increasing rate of electricity [1–3]. Solar energy is an abundant renewable energy source [4] can be exploited in many applications as the useful heat production, the electricity production and various chemical processes [5,6]. Especially with the use of concentrating collectors, high temperatures (400–500 °C) can be easily obtained [7,8]. Parabolic trough collector (PTC) is the most mature technology among the concentrating collectors and thus a lot of research has been focused on it [9,10].

Many techniques have been tested in order the thermal performance of solar collectors and especially of PTCs to be enhanced. The use of nanofluids as working fluids is one of the most promising techniques. Nanofluids can be prepared by dispersing and stably suspending nanometer sized solid particles in usual base fluids, as water or thermal oil, and this term was suggested by Cho in 1995 [11]. The nanofluids present improved thermal properties compared the respective base fluids and thus they are ideal for heat transfer applications. More specifically, these fluids present higher thermal conductivity and higher density, while it has proved that there is a significant increase in the heat transfer coefficient [12]. The most usual nanoparticles are the following: TiO_2, SiO_2, Al, Al_2O_3, Cu, CuO, Au, ZnO, Fe and Fe_2O_3 [13,14]. Generally, the greatest amount of the literature includes studies with mono nanofluids which include only one dispersed nanoparticle.

Literature includes numerous studies which investigated the use of nanofluids in PTCs under various operating conditions. The first part of these studies includes papers with water-based nanofluids. Ghasemi et al. [15] examined the utilization of Al_2O_3 and CuO nanoparticles dispersed in water for PTCs. They proved enhancement in the heat transfer coefficient close to 28% for Al_2O_3 and to 35% for CuO. Coccia et al. [16] examined experimentally the use of various nanoparticles in water for various concentrations and they finally did not found significant enhancement in the thermal efficiency. Mwesigye et al. [17] studied the use of Al_2O_3 nanoparticle dispersed on water for volumetric concentrations up to 6%. They found that there is a maximum limit for the Reynolds number in order to achieve thermal efficiency enhancement with nanofluids.

On the other hand, there are more studies in the literature with oil-based nanofluids in PTCs because thermal oils are more usually utilized in them. Bellos et al. [18] found that the utilization of Al_2O_3 nanoparticles in thermal oil enhances the thermal efficiency close to 4.25% for the IST-PTC. Mwesigye et al. [19] investigated the use of Al_2O_3 in Syltherm 800 for volumetric concentrations up to 8% and they found

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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, W
f	focal length, m
G_b	solar beam radiation, W/m^2
h	convection coefficient, W/m^2K
h_{out}	convection coefficient between cover and ambient, W/m^2K
k	thermal conductivity, W/m K
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
V	volumetric flow rate, l/min
Vair	ambient air velocity, m/s
W	width, m

Greek symbols

α	absorbance, –
γ	intercept factor, –
ε	emittance, –
η	efficiency, –
θ	incident angle, °
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
ρ_m	mirror reflectance, –
σ	Stefan–Boltzmann constant $[=5.67\cdot10^{-8}\ W/m^2\ K^4]$
τ	transmittance, –
φ	total volumetric concentration
φ_1	volumetric concentration of Al_2O_3
φ_2	volumetric concentration of TiO_2

Subscripts and superscripts

a	aperture
am	ambient
bs	base fluid
c	cover
ci	inner cover
co	outer cover
ex	exergetic
fm	mean fluid
in	inlet
loss	thermal losses
nf	nanofluid
np	nanoparticle
np-1	Al_2O_3 nanoparticle
np-2	TiO_2 nanoparticle
oil	Thermal oil
opt	optical
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
s	solar
sky	sky
sun	sun
th	thermal
u	useful
0	reference conditions

Abbreviations

EES	Engineer Equator Solver
PTC	Parabolic trough collector

that there is an optimum Reynolds number close to 10^5 for minimizing the entropy generation. Sokhansefat et al. [20] found that the higher nanoparticle concentration ratio leads to higher heat transfer coefficient enhancement, especially in lower temperatures. Ferraro et al. [21] found that the use of Al_2O_3 in synthetic oil leads to thermal enhancements when the operating temperature is up to 500 K. Kaloudis et al. [22] conducted an interesting study by using a two-phase model for the simulation of nanofluid in PTC. According to their results, the thermal efficiency enhancement was found up to 8%. Zadeh et al. [23] performed an optimization method for determining the optimum operating and design conditions for a PTC with nanofluids and the finally found significant enhancement. Moreover, it is important to state that Wang et al. [9] found that use of nanofluids reduces the deformation of the absorber.

The previous studies have examined the use of Al_2O_3 in thermal oil. However, there are also other examined nanoparticles in PTCs. Bellos et al. [13] investigated the use of Al_2O_3 and CuO nanoparticles dispersed on Syltherm 800 for various operating conditions and concertation ratios. They proved that the use of CuO leads to 1.26% thermal efficiency enhancement and the use of Al_2O_3 to 1.13%. Mwesigye et al. [24] investigated the use of Al_2O_3, Cu and Ag in a PTC for various concentration ratios. According to their results, the use of Ag is the best solution. Benabderrahmane et al. [25] studied the use of Al_2O_3, C, Cu and SiC dispersed on Dowtherm A for a PTC with fin inserts. Their results indicate the use of Cu nanoparticle. Kasaeian et al. [26] carried out an experimental study for the use of MCNT in an oil-based nanofluid, and they found a significant increase in the thermal efficiency up to 11%. Mwesigye et al. [27] studied the use of Cu - Therminol VP-1 nanofluid and they found thermal enhancement up to 12.5%. Moreover, they found that the CuO-Syltherm 800 nanofluid enhances the performance up to 15% [28].

The last years, the use of hybrid nanofluids gain more and more attention. These fluids are created by dispersing two kinds of nanoparticles inside the base fluid [29]. The hybrid nanofluid is a homogenous mixture which presents new physical and chemical bonds [30], the fact that makes it extremely interesting a promising solution for achieving better heat transfer characteristics. Moreover, it is important to state that the hybrid nanofluids present different hydrodynamic and heat transfer properties, compared to the mono nanofluids due to synergetic effects [31]. For the preparation of these nanofluids, there are numerous techniques as thermochemical synthesis technique, ball milling, mechanical alloying method, solvothermal process and chemical vapor deposition technique [32]. Except for the different chemical bonds and properties, the utilization of hybrid nanofluids presents extra advantages. Nanoparticles with different favorable thermal properties can be used in order the final fluid to be an improved heat transfer fluid [31]. Moreover, they give the possibility to utilize cheap nanofluids with more expensive in order to achieve good thermal properties with a reasonable cost [33,34].

As it is obvious from the previous paragraph, the utilization of hybrid nanofluids presents many advantages and thus it has to be investigated. In the literature, the studies with hybrid nanofluids in solar