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Thermal, hydraulic and exergetic evaluation of a parabolic trough collector operating with thermal oil and molten salt based nanofluids

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ABSTRACT

The use of nanofluids in parabolic trough collectors is a promising technique for enhancing their performance. This study investigates the dispersion of CuO nanoparticles in Syltherm 800 (thermal oil) and in nitrate molten salt (60% $NaNO_3$ – 40% KNO_3). The objective of this work is to examine the thermal efficiency enhancement margin of the utilization of nanofluids for two usual working fluids (thermal oil and molten salt) as base fluids. Moreover, this work includes hydraulic analysis about the pressure losses and exergetic analysis in order to evaluate the total performance of the collector. The module of LS-2 parabolic trough collector is examined with a computational fluid dynamics program developed in SolidWorks Flow Simulation. The model accuracy is checked with thermal efficiency and flow criteria using literature results. The simulations are conducted for temperatures up to 650 K for oil cases and up to 850 K for molten salt cases. According to the final results, the use of oil-based nanofluids leads to thermal efficiency enhancement up to 0.76%, while the use of molten salt-based nanofluid up to 0.26% thermal efficiency enhancement. The Nusselt number enhancement is found up to 40% for Syltherm 800-CuO and up to 13% for molten salt-CuO.

1. Introduction

Solar energy utilization is one of the most sustainable ways for facing the modern problems as fossil fuel depletion, climate change, and increasing energy demand [1–3]. Solar energy is the most promising energy source among the renewables because it can be converted to electricity or to useful heat. Moreover, it is an abundant and easily exploited energy source [4,5].

Solar energy is exploited in numerous applications, such as hot water, space heating, solar cooling, industrial heat production, chemical processes, methanol reforming, desalination and electricity production [6,7]. Especially in electricity production applications, photovoltaic panels can be used for direct electricity production or the concentrating solar collector can be used for electricity production through a thermodynamic cycle (Rankine, ORC or Brayton) [8,9]. In these applications, there are many kinds of solar collectors that can be utilized with flat plate technologies to be ideal for temperatures up to 100–150 °C (flat plate collector and evacuated tube collector) [10], while concentrating technologies are better at higher temperatures. The most mature concentrating technology is the parabolic trough collector (PTC) which is ideal for temperature levels from 150 to 400 °C [11].

PTCs operate with numerous working fluids and a lot of research has been focused on this domain. Water/steam is conventional working fluid and there are applications that include operation with water at low temperature, as well as with water/steam in direct steam production systems. The use of thermal oils as Syltherm 800, Therminol VP-1, Therminol D12, Marlotherm TH, Dowtherm A and Sandotherm 59 is usual in indirect systems with heat exchangers for the heat production [12]. However, the utilization of the thermal oils set upper limits up to 400 °C [13]. The next generation of working fluids is focused on the molten salts (especially nitrate salts) because these can operate up to 550–600 °C giving higher margin in the solar energy to electricity conversion [14]. These working fluids can be exploited as working fluids in PTCs, as well as a storage medium for concentrating solar power plants. However, the molten salts have to be kept upper to a lower limit close to 200 °C due to solidification danger [12]. Other solutions are liquid metals as sodium and gas working fluids (air, helium, nitrogen and carbon dioxide) for operation at higher temperatures but their operation is not well-established yet.

Many techniques have been examined in the literature in order to increase the thermal efficiency of PTC and to make them a more sustainable solution [15]. Generally, these techniques aim to increase the effective thermal conductivity in the flow and to increase the heat transfer coefficient between the absorber and the working fluid. Moreover, the circumferential temperature deviation is getting lower with these techniques, the fact that leads to lower thermal stresses and

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Nomenclature

A_a	aperture 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
f	friction factor, –
G_b	solar direct beam irradiation, W/m^2
h	heat transfer coefficient, W/m^2 K
h_{out}	convection coefficient between cover and ambient, W/m^2 K
k	thermal conductivity, W/m K
L	tube length, m
m	mass flow rate, kg/s
Nu	Nusselt number, –
Pr	Prandtl, –
Q	heat flux, W
Re	Reynolds number, -
r	concentrator reflectance, –
T	temperature, K
T_{sky}	sky temperature, K
u	fluid velocity, m/s
U_L	thermal loss coefficient, W/m^2 K
V	volumetric flow rate, L/min
V_{wind}	ambient air velocity, m/s
W	width, m
W_p	pumping work, W

Greek symbols

α	absorber absorbance, –
β	nanolayer thickness ratio, –
γ	Intercept factor, –
ΔP	Pressure drop, Pa
ε	Emittance, –
η	Efficiency, –
η_{ovr}	Overall heat transfer performance factor, –
θ	solar incident angle, °
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
τ	cover transmittance, –
φ	volumetric nanoparticle concertation, –
ω	peripheral absorber angle, °

Subscripts and superscripts

am	ambient
bf	base fluid
c	cover
ci	inner cover
co	outer cover
d	destruction
ex	exergetic
fm	mean fluid
in	inlet
loss	thermal loss
nf	nanofluid
np	nanoparticle
opt	optical
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
r-f	receiver-fluid
s	solar
s-r	solar-receiver
th	thermal
u	useful

Abbreviations

CFD	computational fluid dynamics
EES	Engineering Equation Solver
LCR	local concentration ratio
MCNT	multiwall carbon nanotube
ORC	organic rankine cycle
PTC	parabolic trough collector

to lower deformation danger [16]. The first category of these techniques is focused on geometrical modifications as the use of dimpled absorbers [17], the use of internal fins [18] and vortex generators [19]. Moreover, use of inserts in the flow as twisted tape inserts [20], porous disks [21] and metallic foams [22] are usually found in the literature, as well as the use of alternative receiver geometries [23].

Another great part of the literature examines the dispersion of nanoparticles in the working fluid in order to enhance the thermal properties (mainly the thermal conductivity) of the working fluids. These fluids are called nanofluids, a term which was introduced by Choi in 1995 [24]. The most usual nanoparticles are the following: Al, Al_2O_3, Cu, CuO, TiO_2, SiO_2, Fe, Fe_2O_3, ZnO and Au [25,26]. The volumetric fraction of nanoparticles in the nanofluid is usually low, close to 0.1–6%, while there are literature studies with examined concentrations up to 10%. Nanofluids have higher thermal conductivity and density compared to the pure respective base fluids. However, they present lower specific heat capacity and higher dynamic viscosity; two negative factors which reduce the possible enhancement. The final result of the utilization of nanofluids is the increase of heat transfer coefficient in the flow which leads to lower thermal losses and to higher thermal efficiency [27,28].

In literature, there are plenty of studies which examine various combinations of base fluids and nanoparticles. These studies are presented below in details. Firstly, studies with water as base fluid are presented and after them, the studies with thermal oil are given. Mwesigye et al. [29] examined the use of Al_2O_3 nanoparticle dispersed on water for concentrations up to 6%. They performed an interesting analysis for operation in low-temperature levels based on the entropy generation criterion. According to their results, there is a maximum limit for the Reynolds number, and consequently for the flow rate, for achieving flow enhancement with the nanofluids. Ghasemi et al. [30] investigated the use of Al_2O_3 and CuO nanoparticles in water for PTCs. They found enhancement in the heat transfer coefficient about 28% with Al_2O_3 and 35% with CuO. Coccia et al. [31] examined experimentally the use of various nanoparticles in water for various concentrations. More specifically they examined the use of Fe_2O_3, SiO_2, TiO_2, ZnO, Al_2O_3 and Au. According to their results, they did not find significant enhancement with the use of these nanoparticles.

The next part of literature studies examines the use of oil-based nanofluids. The majority of the studies investigate the dispersion of Al_2O_3 nanoparticles in the oils operating in PTCs. Sokhansefat et al. [32] proved that higher nanoparticle concentration ratio leads to higher heat transfer coefficient enhancement, and they found that the enhancement is greater at lower temperatures. Mwesigye et al. [33] examined the use of Al_2O_3 in Syltherm 800 for concentrations up to 8% and they found that there is an optimum Reynolds number for