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Thermal performance analysis of a parabolic trough collector using water-based green-synthesized nanofluids

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ABSTRACT

The parabolic trough collector (PTC) is one of the most advanced solar concentrating technology available. The study employed experimental synthesis and numerical modeling to present possible solutions to the challenges of nanofluids application in solar collectors. A green alternative of using nanoparticles synthesized from green biomatter (Olive leaf extract OLE) and agricultural waste (barley husk BH) is proposed. The synthesized nanoparticles were characterized using analytical and morphological techniques and were found to be efficient corrosion inhibitor, non-toxic and cheap to produce when compared to the conventional ones. The study presents an innovative thermal performance evaluation of a parabolic trough collector operating with green-synthesized nanofluids: water/BH-SiO_2 and water/OLE-TiO_2. The model of the PTC was developed on the engineering equation solver (EES) and validated using the experimental results of the Sandia National Laboratory (SNL), AZTRAK platform LS-2 test. The results of the analysis show that a 0.073% mean enhancement in the thermal efficiency is observed with the use of water/BH-SiO_2 nanofluids and 0.077% mean enhancement with the use of water/OLE-TiO_2 nanofluids. The heat transfer performance of the nanofluids shows a mean enhancement in heat transfer coefficient of 128% and 138% for water/OLE-TiO_2 and water/BH-SiO_2 nanofluids respectively. The mean variation in pressure losses between the nanofluids and base fluid was also observed to be less than 14.85% at a 3% volumetric fraction of nanoparticles.

1. Introduction

The growing demand for renewable and sustainable energy resources has lead energy scientist into investigations on alternative and possible improvements of renewable energy technologies. Solar energy technologies still remain one of the most deployed renewable systems in the world. The parabolic trough collector (PTC) is one of such solar technology which is gaining much attention due to its cost, ease of deployability and wide temperature applications ranging from 50 to 400 °C (Kalogirou, 2004; Bellos et al., 2016).

The thermal performance enhancement of the PTC has gained attention in the past decade. One of the main suggestion to its improvement is to enhance the rate of heat transfer in the receiver tube. To this aim, the use of various working fluids has been suggested, modeled and experimental studies performed for better thermal performance. The synthetic thermal oil is the most commonly used heat transfer fluid (HTF). Bellos et al. (2016a, 2016b), considered the use of pressurized water and gas-based working fluids in the PTC. The use of nanoparticles dispersed in water (Subramani et al., 2018), nanoparticles dispersed in oil (Bellos et al., 2016; Mwesigye and Meyer, 2017) and nanoparticles dispersed in brines (Cabaleiro et al., 2017) has also been studied. The use of modified receiver tube has also been proposed (Bellos et al., 2016, 2017; Muñoz and Abánades, 2011; Gong et al., 2017). The results of these studies have shown significant improvements in the performance of the PTC. Manufacturers have also made progress in improving the optical properties of the collector as a way of improving the overall collector efficiency.

The issues of irreversibility in the flow due to a rise in temperature and pressure losses in a solar collector was discussed by Mahian et al. (2014, 2015). They addressed the impact of tube roughness and nanoparticle size on the thermophysical model. A comparison of a mini-channel solar collector using different water-based nanofluids was also performed by Mahian et al. (2014). They compared the performance of Cu/water, Al_2O_3/water, TiO_2/water, and SiO_2/water. Their results

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Nomenclature

A	area (m^2)
C_p	specific heat capacity (J/kg·K)
D	diameter (m)
E	exergy (W)
f	friction factor
G_b	direct normal irradiance (W/m^2)
h	heat transfer coefficient (W/m^2·K)
K	incident angle modifier
k	thermal conductivity (W/m·K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
M	mole
Nu	Nusselt number
P	pressure (kPa)
Pr	Prandtl number
$\dot{Q}$	heat transfer rate (W)
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
V_f	volumetric flow rate (L/min)
Greek symbols	
α	absorber absorbance respectively
γ	intercept factor
ε	emissivity
η	efficiency (%)
θ	incident angle
μ	dynamic viscosity (Pa s)
ρ	density (m^3)
ρ_{opt}	concentrator reflectance
ρ_c	reference reflectance
ρ_1	shadow effect
ρ_2	twisting error
ρ_3	geometric error
ρ_4	mirror clearness
ρ_5	receiver clearness
ρ_6	other possible errors
σ	Stefan-Boltzmann constant
τ	cover transmittance
φ	volumetric fraction of nanoparticles (%)
ΔP	pressure drop (kPa)

Subscript/superscript

a	aperture
amb	ambient
bf	base fluid
c	collector
co	cover outside
ci	cover inside
ex	exergetic
f	fluid
fm	mean fluid
g	glass cover
in	inlet
nf	nanofluids
np	nanoparticles
o	outlet
r	receiver
ri	inner receiver
s	solar
sun	sun
th	thermal
u	useful
w	wind

Abbreviations

BH	barley husk
EES	engineering equation solver
HCl	hydrochloric acid
HTF	heat transfer fluid
NP	nanoparticles
NREL	National Renewable Energy Laboratory
OLE	olive leaf extract
PTC	parabolic trough collector
SiO_2	silicon dioxide
SNL	Sandia National Laboratory
Ti	titanium
TiO_2	titanium dioxide
XRD	X-ray diffraction

show that Al_2O_3/water provided the highest heat transfer coefficient while the highest outlet temperature was obtained from Cu/water nanofluids. On the bases of the second law analysis, Cu/water produced the lowest entropy generation amongst the examined nanofluids.

The use of the engineering equation solver (EES) in the modeling of the PTC has also been performed in a number of studies. Forristall (2003); presented an EES model of the PTC for the National Renewable Energy Laboratory (NREL), LS-2 test in Sandia. Kalogirou (2012); also presented a detailed thermal model of the PTC using EES. Bellos et al. (2016); performed an analysis on the use of various gaseous working fluids for PTC using EES. Subsequently, they also performed another study on the use of various working fluids using the EES (Bellos et al., 2017). A 2-dimensional study of the PTC for possible installation in Cameroon was performed by Keou et al. (2017) while Bellos and Tzivanidis (2017) also performed an exergetic investigation of the PTC using EES. Most the aforementioned studies presented detailed mathematical equations of the thermal, energetic and exergetic modeling of the PTC using EES software.

The dispersion of nanoparticles like metal, non-metal, metallic carbide, oxide-ceramic (Amina et al., 2016) to improve the thermal conductivity of the working fluid has been studied (Chamkha et al., 2017; Sokhansefat, 2014). Most of the results from literature so far proved that the addition of nanoparticles improves the heat transfer performance of the fluid. The application of nanofluids in solar collectors has suffered many limitations such as sedimentation, corrosion of components, the high cost of preparation, the toxicity of the nanoparticles, pressure drop and additional pumping power (Sunil et al., 2014). These limitations have hindered the deployment of nanofluids as HTF in solar collectors.

Various nanoparticles have been synthesized, mediated by various materials using many techniques (Nasrollahzadeh and Sajadi, 2015; Zulfiqar et al., 2016; Fazlzadeh et al., 2017). Kavaz et al. (2012), stated that the material used for synthesis depends on the intended end use. Kavaz et al. (2017) and Mittal et al. (2013), have synthesized nanoparticles from plant biomass because plant-mediated materials are nontoxic and inexpensive. Plant-based nanoparticles have been applied in various areas, and recently as oilfield chemicals (Rasheed et al., 2017; Lau et al., 2017). Oilfield chemicals are employed in the industry for drilling, completions, and production of hydrocarbons. Some nanomaterials have been reported to be effective in inhibiting corrosion in many environments (Sharmila et al., 2013; Johnson et al., 2014). Despite that, plant biomass is rich in various phyto-compounds that contain many potential adsorption sites; few plant materials have been green-synthesized into nanoparticles for application as corrosion