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Research Paper

Heat transfer analysis and the effect of CuO/Water nanofluid on direct absorption concentrating solar collector

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HIGHLIGHTS

- The effect of CuO/Water on a direct absorption parabolic collector is investigated.
- The power-law is used for simulating the turbulent flow into the receiver pipe.
- In this collector the solar irradiance is absorbed directly and converted to heat.
- Nanofluid as the working fluid improves the thermal efficiency of the collector.

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ABSTRACT

Direct absorption solar collectors (DASCs) form a new class of collectors that directly harvest sun beams via a working fluid. They offer several advantages over their conventional surface absorption counterparts such as reduced surface heat loss and increased solar irradiance absorption. The optical and thermo-physical properties of the working fluid may be improved and system efficiency may be enhanced in direct absorption solar collectors (DASCs) by introducing nanoparticles into the base fluid. The present study investigates, both analytically and experimentally, the effects of CuO/Water nanofluid on the efficiency of a direct absorption parabolic trough collector (DAPTC). The theoretical analysis of DAPTC is based on the power-law with the objective of simulating a turbulent flow into the receiver pipe. Comparison of the results obtained from the model and the experimental measurements reveals a good agreement between the two sets of data, indicating that they can be exploited to validate the numerical solution. Moreover, modeling results indicate that the average radial temperature and energy generation terms due to the solar irradiance absorbed and scattered by the nanoparticles decrease with increasing distance from the receiver pipe wall. It is also found that the solar irradiance is absorbed and converted into a significant amount of sensible heat along the length of the receiver pipe. Finally, the results of both the numerical and the experimental investigations of the DAPTC collector show that the thermal efficiency of the system improves as a result of increased nanoparticle volume fraction and nanofluid flow rate.

1. Introduction

Significant economic benefits and reliable supplies of energy have been achieved as a result of increasing applications of renewable energy resources and improved efficiency of the energy systems employed. Although renewable energy resources are available over wide geographical areas, applications of the solar energy by the industrial sector have remained scant. Solar energy can be directly converted into thermal energy using panels called solar-thermal collectors, which are indeed heat exchangers that transform solar radiation into the internal energy of the transport medium [1]. Moreover, recent advances in nanotechnology have led to the application of nanofluids in a vast variety of fields including solar collectors. A nanofluid is made by suspending nanoparticles in a base liquid; addition of even small amounts of nanoparticles to a base fluid brings about drastic changes in the thermal conductivity and optical (absorption and scattering) properties of the base fluid as well as its convective and boiling heat transfer coefficients. Most studies over the past decade have been focused on the thermal and physical properties of nanofluids to confirm the contribution of nanoparticles to the enhanced thermal conductivity of the fluid [2–8]. This has made nanofluids especially useful in direct absorption (or volumetric) solar thermal collectors

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Nomenclature

A	area (m^2)
a_n	coefficient obtained from Eq. (9)
b_n	coefficient obtained from Eq. (9)
C_0	speed of light in vacuum, 2.9979×10^8 ($m\,s^{-1}$)
c_p	specific heat ($J\,kg^{-1}\,k^{-1}$)
d_p	particle diameter (nm)
d_r	thickness of spatial node along r-direction (m)
d_x	thickness of spatial node along x-direction (m)
d_θ	thickness of spatial node along θ-direction
f_v	nanoparticle volume fraction in the base fluid
G	incident solar flux ($W\,m^{-2}$)
h	Planck's constant, 6.6256×10^{-34} J s
i'_λ	intensity of incident irradiance ($W\,m^{-2}$)
k	thermal conductivity ($W\,m^{-1}\,k^{-1}$)
k_B	Boltzmann constant, 1.38×10^{-23} ($J\,k^{-1}$)
n_f	refractive index of the base fluid
n_p	refractive index of nanoparticles
m	normalized refractive index of the nanoparticles with respect to the base fluid
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
q_r	energy generation ($W\,m^{-3}$)
Q_{ext}	extinction efficiency
Q_{scat}	scattering efficiency
r_1	radius of the receiver pipe (m)
r_2	radius of the cover pipe (m)
T	temperature (°C)
u	fluid velocity ($m\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stefan–Boltzman constant, 5.670367×10^{-8} ($kg\,s^{-3}\,k^{-4}$)
σ_{ext}	extinction coefficient
σ_{sca}	scattering coefficient
ε	emissivity
ε_H	eddy diffusivity for heat in a turbulent flow
ε_M	eddy diffusivity
λ	wavelength (nm)
ϕ	solid angle
ν	kinematic viscosity (m^2 s)
τ_w	wall shear stress ($kg\,m^{-1}\,s^{-2}$)
α	size parameter

Index

abs	absorption
aper	aperture
ave	average
ext	extinction
in	inlet
max	maximum
nf	nanofluid
np	nanoparticle
out	outlet
scat	scattering

[9–11], in which the sun beams are directly absorbed by the working fluid. As most working base fluids (e.g., water or ethylene glycol) used in direct absorption solar thermal collectors have low absorption coefficients, it follows that introducing nanoparticles into them should enhance their optical properties and improve their efficiency [12–19]. Otanicar et al. [15] introduced a nanofluid-based direct absorption solar collector and investigated the effects of a variety of nanoparticles such as carbon nanotubes, graphite, and silver on its efficiency. Taylor et al. [16] devoted their research to spectroscopic measurements of extinction coefficients of nanofluids. Menbari et al. [20–22] conducted an experimental and analytical study of the optical properties of binary nanofluids for direct absorption in solar systems. Luo et al. [23] studied the performance of a nanofluid solar collector based on direct absorption collection to show that solar collector efficiency could be improved by up to about 2–25% as a result of the use of nanofluids. Lenert et al. [24] presented a combined theoretical and experimental work to improve the thermal efficiency of high-flux direct solar receivers by using carbon-coated cobalt nanoparticles. Khullar et al. [25] conducted a theoretical study of solar energy harvesting using nanofluid-based concentrating solar collectors. Their theoretical results indicated that the efficiency of a concentrating solar collector based on a nanofluid (Al_2O_3/Water) could be higher by about 5–10% than a conventional parabolic solar collector. Karami et al. [26] conducted an experimental study to investigate the CuO nanofluid-based direct absorption solar collector for residential applications. Their results showed that the thermal efficiency of the flat plate collector using nanofluids could be improved by 9–17% relative to the base fluid.

The review of previous studies indicates that no rigorously convincing investigation has been carried out on DAPTCs. The current experimental and numerical study was, therefore, designed and implemented to evaluate the effects of the CuO/Water nanofluid used in DAPTCs on their thermal efficiency. In this study, a theoretical descriptive model is initially developed and later extended to the coupling of radiative transfer and energy equations (according to which, the working fluid absorbs solar radiation directly by its suspended nanoparticles to convert it into heat energy). In a later stage of the study, the numerical and experimental results obtained are compared to evaluate the performance of the DAPTCs.

2. Experimental details

2.1. Experimental setup

The experimental system (a solar parabolic collector) consists of a parabolic section, a reflector, and an absorber tube installed on the focal axis of the surface reflector. The parabolic section supported on a wooden structure is a reflector (steel mirror) 1 m long with an aperture width of 0.8 m. The focal distance of the parabolic reflector is 0.22 m. The following equation captures the parabolic concentrator described:

$$y = 1.13x^2 \tag{1}$$

The absorber tube is the most important part of the parabolic trough collector. The receiver pipe, 20 mm in diameter, together with the glass envelope (36 mm in diameter), is made of glass (quartz) for high transmission and mounted on the focal axis of the reflector. The clearance between the receiver pipe and the glass envelope is vacuumed both to enhance heat absorption and to avoid convection heat losses. The two ends of the receiver tube are coated with two bushings with screws on both to adjust the angle of the collector and to hold it in place. Standard wheels with the ability to lock in a fixed position are employed in the structure of the base–collector that will allow rotation around the vertical axis. Thus, the collector is designed on a movable structure that