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A numerical and experimental investigation on the performance of a low-flux direct absorption solar collector (DASC) using graphite, magnetite and silver nanofluids

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ABSTRACT

Application of nanofluids as a potential working fluid in solar-to-thermal energy conversion systems has shown remarkable improvements in solar power systems. Herein, a combined numerical and experimental study has been conducted on a nanofluid direct absorption collector utilizing three types of nanoparticles (i.e., graphite, magnetite, and silver) dispersed in deionized water as the absorbing medium. To increase the dispersion stability, surface modification was performed on the nanoparticles prior to the preparation of nanofluids via the two-step method and the optical characteristics of nanofluids were experimentally evaluated prior to their use in the DASC. A two-dimensional computational fluid dynamics simulation model was developed to solve the radiative transfer in particulate media and heat transfer equations. Considering the absorption and scattering within the nanofluid medium, the nanofluid temperature distribution within the collector was evaluated. Simultaneously, experiments were performed on a direct absorption collector to validate the numerical model and to investigate the effect of solar flux intensity, nanoparticle concentration and flow rate on the collector thermal performance. According to the results, nanofluids promoted the thermal and exergy efficiencies by 33–57% and 13–20%, respectively than the base fluid.

1. Introduction

With free availability and least environmental impact, solar energy utilization offers a promising sustainable solution to the energy crisis. Solar thermal systems, as one of the most common and effective ways of harvesting solar energy, are based on solar to thermal energy conversion. The most commonly used type of solar thermal collectors is the conventional surface-based absorber in which solar radiation is absorbed through a black or spectrally selective surface and then transferred to a working fluid through conduction and convection heat transfer. Due to the presence of inherent convection and conduction resistances between the solid absorber and the working fluid, solar to thermal energy conversion of these systems is not a very efficient process.

Direct absorption solar collector (DASC) was initially introduced in 1970s, as an alternative to conventional surface-based collectors (Minardi and Chuang, 1975; Huang et al., 1979). In this type of collector, solar radiation was directly absorbed by a black liquid transport medium (i.e. India ink or black dye) flowing in transparent tubes rather than in a very thin layer at a solid surface. Compared with surface-based absorbers, lower heat losses and higher efficiency results were reported. It was also demonstrated that seeding the fluid medium with black and gray micron-sized particles such as graphite and silicon carbide more improved the absorption ability of the semi-transparent medium than using white particles such as silicon dioxide (Arai et al., 1984). However, application of micro-particles in the first generation of DASCs resulted in several practical drawbacks such as clogging, erosion and abrasion of pipes and pumps due to inherent stability and rapid settling of micro-particles. As the particle size becomes smaller in a fluid medium, the Brownian agitation overcomes the gravitational settling and makes the suspension more stable.

With the development of nanotechnology in the recent years, these problems can be solved by mixing very low particle loadings of nanoparticles ($\ll 1\%$ volume fraction) in transparent base fluids. Besides, several studies have shown the working fluid absorption properties can dramatically improve by utilizing these engineered colloid suspensions known as nanofluids (Sani et al., 2010, 2011; Mercatelli et al., 2011; Han et al., 2011; Kameya and Hanamura, 2011; Taylor et al., 2011; Meng et al., 2012; Otanicar et al., 2013;

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Nomenclature

A	total surface area exposed to solar radiation (m^2)
a	nanofluid absorptance (–)
Abs	absorption coefficient (cm^{-1})
c_p	specific heat at constant pressure (J/kg K)
F_R	collector heat removal factor (–)
G_T	total incident radiative flux (W/m^2)
h	specific enthalpy (J/kg)
H	height (cm)
I_λ	spectral radiative intensity (W/m^2 μm)
k	thermal conductivity (W/m K)
$K_{e\lambda}$	extinction coefficient (1/cm)
$K_{a\lambda}$	absorption coefficient (1/cm)
$K_{s\lambda}$	scattering coefficient (1/cm)
L	length (cm)
$\dot{m}$	mass flow rate (kg/s)
m	relative refractive index (–)
n	real component of refractive index (–)
N	complex refractive index $n + i\kappa$ (–)
p	Pressure (Pa)
q	heat flux (W/m^2)
Q	volumetric flow rate (ml/h)
s	entropy (J/kg K)
T	temperature (K)
u, v	u and v components of velocity (m/s)
U_L	overall heat loss coefficient (W/m^2 K)
W	width (cm)
x	size parameter (–)

Greek symbols

α	thermal diffusivity (m^2/s)
ε	dielectric constant $\varepsilon_1 + i\varepsilon_2$ (–)
η	efficiency (–)
κ	complex component of refractive index (–)
λ	wavelength (μm)
ρ	density (kg/m^3)
τ	transmittance (–)
μ	dynamic viscosity (Ns/m^2)
υ	kinematic viscosity (m^2/s)
ϕ	volume fraction (–)
Φ	scattering phase function
Ω	direction unit vector

Subscripts

amb	ambient
b	blackbody
bf	base fluid
c	collector
ex	exergy
g	glass
in	inlet
nf	nanofluid
np	nanoparticle
out	outlet
r	radiative
s	steel
sol	solar
stag	stagnation
th	thermal
opt	optical

Constants

h	$6.62606957 \times 10^{-34}$ m^2 kg/s
c_0	299,792,458 m/s
k_B	1.38×10^{-23} J/K

He et al., 2013; Karami et al., 2014; Hordy et al., 2014; L. Zhang, et al., 2014; H. Zhang, et al., 2014; Gorji et al., 2015). Spectral transmittance and extinction coefficients of aqueous and ethylene glycol suspensions of carbon nanohorns (Sani et al., 2010, 2011; Mercatelli et al., 2011); carbon black aqueous suspensions (Han et al., 2011); alkyl naphthalene suspensions of Ni nanoparticles (Kameya and Hanamura, 2011); graphite, Ag, Cu, Au, Al and TiO_2 nanoparticles dispersed in water and Therminol® VP-1 (Taylor et al., 2011); multi-walled carbon nanotubes (MWCNT) glycol suspensions (Meng et al., 2012); silver and silica–gold core–shell nanoparticles dispersed in water and ethylene glycol (Otanicar et al., 2013); aqueous Cu nanoparticle suspensions (He et al., 2013); base treated functionalized MWCNT aqueous suspensions (Karami et al., 2014); plasma functionalized MWCNTs dispersed in water, glycol and Therminol® VP-1 (Hordy et al., 2014); Ni, Cu and carbon-coated Ni (Ni/C) nanoparticles dispersed in ionic liquid [HMIM][NTf_2] (L. Zhang, et al., 2014); aqueous gold nanoparticle nanofluids (H. Zhang, et al., 2014); acid treated single-walled carbon nanotubes (SWCNT) aqueous dispersions (Gorji et al., 2015) have shown that the absorption capability of nanofluid suspensions with very low nanoparticle concentrations is much higher than that of the base liquids over the majority of the solar spectrum. These investigations imply the potential of utilizing nanofluids for increasing the overall efficiency of a new generation of direct absorption sunlight exploiting devices.

The feasibility of particle-laden direct absorption solar receiver was firstly numerically assessed by Kumar and Tien (1990). Tyagi et al. (2009) laid the groundwork for a numerical model of a nanofluid-based DASC utilizing Aluminum nanoparticles dispersed in water. They reported up to a 10% efficiency enhancement over a conventional flat-plate collector by using 0.1% volume fraction nanofluid. In the past 5 years or so, numerous experimental and numerical research efforts that have been devoted to nanofluid-based DASCs and several prototype collectors have been built and tested (Otanicar et al., 2010; Taylor et al., 2011; Lenert and Wang, 2012; Parvin et al., 2014; Bandarra Filho et al., 2014; Khullar et al., 2014; Luo et al., 2014; Liu et al., 2015; Gupta et al., 2015; Karami et al., 2015; Delfani et al., 2016). These studies have shown that dispersing trace amounts of nanoparticles in conventional heat transfer fluids could significantly enhance the thermal performance of such solar systems. In general, these researches could be categorized into low- and high-flux DASCs. Experimental studies on low flux solar collector include evaluation of a DASC system based on carbon nanotubes, graphite, and silver nanoparticles dispersed in water nanofluids (Otanicar et al., 2010); performance study on a volumetric absorption system utilizing aqueous dispersions of multi-walled carbon nanotubes (Khullar et al., 2014); investigation of photothermal conversion capability of aqueous dispersions of silver nanoparticles (Bandarra Filho et al., 2014); study on a direct absorber using Al_2O_3 in water nanofluids (Gupta et al., 2015); investigation of a DASC using CuO nanoparticles (Karami et al., 2015) and MWCNTs (Delfani et al., 2016) in a water and ethylene glycol mixture, graphene nanoplatelets in water nanofluids (Vakili et al., 2016) and water based blended plasmonic nanofluids (Jeon et al., 2016). In a numerical study, Parvin et al. (2014) simulated the heat transfer performance and entropy generation of forced convection of Cu nanofluid flow through a low-flux direct absorption solar collector and reported that both heat transfer and entropy generation