Energy Conversion and Management 117 (2016) 1–11

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental investigation of the solar FPC performance using graphene oxide nanofluid under forced circulation

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ARTICLE INFO

Article history:
Received 18 January 2016
Accepted 5 March 2016

Keywords:
Flat plate collector
Laminar flow
Collector efficiency
Graphene oxide nanofluid
Heat transfer coefficient

ABSTRACT

Experiments were conducted on a solar flat plate collector (FPC) with graphene oxide (GO) nanofluid as the working fluid, circulated forcibly with the aid of a pump. The FPC had a collector area of 2 m^2, a concentric tube heat exchanger (CTHX) and a storage tank. GO nanoparticles were synthesized from graphite by the modified Hummer's method. The morphology of the GO was estimated by XRD, UV–vis spectrometry and SEM imaging. The GO nanofluid was prepared by ultrasonication of the GO nanoparticles with de-ionized (DI) water as the base fluid, without adding any surfactant. Homogeneous and stable GO nanofluid for three different mass concentrations, (φ) = 0.005, 0.01 and 0.02, were prepared. The nanofluids were found to be stable for 60 days without any sedimentation issues. The thermo-physical properties of the GO nanofluids, such as the thermal conductivity, viscosity, density and specific heat, were estimated. For the flow supplied by the pump, the maximum value of the FPC inlet pipe and fluid property-based Reynolds number was found to be 430. The FPC's overall heat transfer co-efficient (h), friction factor and collector efficiency were investigated for GO nanofluids under laminar conditions. It was observed that for GO nanofluid with φ = 0.02 and a flow rate of 0.0167 kg/s, the enhancement in the collector efficiency was 7.3% over that of the base fluid (DI water). The collector efficiency was found to increase with increasing φ and flow rate. The increases in h for the GO nanofluid with φ = 0.005, 0.01 and 0.02 were 8.03%, 10.93% and 11.5%, respectively.

1. Introduction

Industries such as power generation, air conditioning, microelectronics and cooling systems use conventional fluids such as water, ethylene glycol (EG) and transformer oil as heat transfer fluids. The poor thermal conductivity (k) of these fluids greatly limits their heating and cooling role in heat exchangers [1]. Hence, it is essential to enhance or improve the heat transfer capabilities of the working fluids. The advances in nanotechnology have resulted in the development of a class of fluids termed nanofluids. Nanofluids, prepared by dispersing rods or tube-shaped nanoparticles in a base fluid, have gained attention because of their increased thermal conductivity [2–4], which translates to lower operating costs, higher energy efficiency and better performance [5–10].

Recently, significant research has been conducted on the use of carbon-based nanostructure materials to prepare nanofluids because of their super thermal conductivity properties. Carbon nanostructures have higher thermal conductivity than other nanoparticles because of their large intrinsic thermal conductivity and low density when compared to metals or metal oxides and also because of their strong C—C covalent bonds and phonon scattering [11]. A significant number of studies have been conducted on the use of carbon-based nanostructures such as carbon nanotubes [12], single-wall carbon nanotubes [13], multi-walled carbon nanotubes (MWCNT) [14], graphite [15], graphene oxide (GO) [16], and graphene [17] to prepare nanofluids. Graphene is a one-atom-thick planar sheet of sp^2-bond carbon atoms arranging itself in the form of a honeycomb lattice. Novoselov et al. [18] first discovered grapheme, which gained attention because of its unique chemical and physical properties and two-dimensional structure. The value of a single layer of graphene at room temperature is estimated to be in the range of 2000–5200 W/m K. Balandin et al. [19] reported a maximum thermal conductivity value of single layer graphene (SLG) as 5300 W/m K, which is notably higher than that of carbon nanotubes. Methods such as Hummer's method, the modified Hummer's method and chemical vapor deposition can be used for the synthesis of GO, and these authors adopted chemical methods to improve the yield.

The aqueous suspensions of stable homogeneous graphene nano platelet (GNP) nanofluids were normally prepared by high-power

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http://dx.doi.org/10.1016/j.enconman.2016.03.015
0196-8904/

Nomenclature

A_C	area of the solar collector (m^2)
C_p	specific heat (Jkg^{-1} K^{-1})
F'	collector efficiency factor
F_R	heat removal factor
G_T	global solar radiation (W m^{-2})
$\dot{m}$	mass flow rate (kg/s)
Q_u	rate of useful energy gained (W)
h	heat transfer coefficient (W m^{-2} K^{-1})
t	time (s)
T	temperature (K)
U_L	overall loss coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
Re	Reynolds number
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
f	fanning friction factor

Subscripts

a	ambient
bf	base fluid
i	inlet
np	nano particle
nf	nanofluid
o	outlet
tp	tube outlet side of the absorber
eff	effective

Greek symbols

$\tau\alpha$	product of the absorbance and transmittance
η_i	instantaneous collector efficiency
φ	mass concentration of nanofluid
ρ	density (kg/m^3)
μ	viscosity (Pa s)

ultrasonication. The stability and the thermo-physical properties of GNPs have been reported previously by Mehrali et al. [20]. Jyothirmayee and Ramaprabhu [21] performed an experimental study on the enhanced convective heat transfer of graphene water nanofluids. For a 0.05% concentration, they reported 16% and 64% enhancements in thermal conductivity at 25 °C and 50 °C, respectively. Yarmand et al. [22] conducted experimental studies on thermal conductivity, the viscosity, the Nusselt number and the heat transfer coefficient (h) in the turbulent flow of GNP–Ag/water nanofluids in a pipe at a constant heat flux. Ahmad Ghozatloo et al. [23] experimentally studied the performance of h with graphene nanofluids in a shell and tube heat exchanger and found that the values increased by up to 35.6% at 38 °C with a concentration of 0.1 wt.% when compared to pure water. Mehrali et al. [24] also investigated the heat transfer and entropy generation for the laminar forced convection flow of GNP nanofluids in a horizontal tube and found that the thermal conductivity increases from 12% to 28% as the nanofluid temperature increases and the heat transfer co-efficient increases by 15%. Zanjani et al. [25] conducted experimental studies on the laminar forced convective heat transfer of a GO nanofluid inside a circular tube and obtained an increase in the values of thermal conductivity of 10.3% and h of 14.2% for a Reynolds number of 1850 with 0.02 volume concentration. Amiri et al. [26] conducted an experimental study on thermo-physical properties of graphene nano platelet-based water nanofluids and studied the covalent and non-covalent functionalization effects on the thermal conductivity, viscosity, and thermosyphon performance for various operating temperatures and concentrations. It was observed from the results that thermophysical property of covalent nanofluids (GNP–COOH/water) was more enhanced compared to those of non-covalent nanofluids (GNP-SDBS/water) and water. Overall heat transfer and thermal efficiency showed significant increases for covalent nanofluids at low concentrations. Sadeghinezhad et al. [27] reviewed the effective parameters on the thermal and rheological properties, forced convective heat transfer, pool boiling, critical heat flux and optical properties of graphene nanofluids. The results show that the thermal conductivity of graphene nanofluid is influenced by nanoparticle concentration, size, shape, base fluid, temperature, additives and acidity. A review of nanofluids on the applications of solar energy for different types of solar collectors [28–30], solar water heaters, solar still, solar photovoltaic systems were presented.

In addition to the literature being discussed here, it can be observed that a GO nanofluid has not been tested so far in a solar thermal energy device such as a flat plate collector (FPC). Few works were reported by researchers in the area of boiling [16,27], convective heat transfer coefficient [17,20] and heat exchangers [18,23] with a GO nanofluid. Hence, the objective of this work is to conduct performance studies on an FPC used for solar water heating with a GO nanofluid equipped with a concentric double pipe heat exchanger (CTHX) for utility water heating. As discussed earlier, the GO nanofluid was chosen for its high thermal and electrical properties. The GO particles were synthesized, and the thermo-physical properties of the GO nanofluid were found by suitable instruments. The GO nanofluid characterization was carried out using field emission scanning electron microscopy (*FESEM*), X-ray diffraction (XRD), FTIR spectra, Raman spectroscopy and UV–vis spectroscopy.

2. Experimental methods

The experiments were conducted on a solar thermal FPC fabricated with the identified GO nanofluid. The nanoparticle synthesis, preparation of the nanofluid and its characterization, experimental procedure adopted, uncertainty estimation in the measured parameters and estimation of the thermophysical properties of the nanofluid are discussed in this section.

2.1. Synthesis of graphene oxide nanoparticles

GO was prepared from graphite using the modified Hummer's method [31]. The reagents, including sulfuric acid, nitric acid, sodium nitrate, potassium permanganate and hydrogen peroxide, were of analytical grade. De-ionized (DI) water was used throughout the experiment. Briefly, 2 g of graphite was treated with 46 ml of sulfuric acid in an ice bath. One gram of sodium nitrate was added to the above solution slowly, followed by the addition of 6 g of potassium permanganate. At room temperature, a specific quantity of water was added to the above mixture. After 15 min, the suspension was further treated with hydrogen peroxide and filtered. Finally, the filter cake formed was washed with copious quantities of DI water.

The resultant graphite oxide aqueous dispersion was then diluted to 1.2 L, stirred for 6–8 h and later sonicated for 30 min