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Experimental investigations of the performance of a flat-plate solar collector using carbon and metal oxides based nanofluids

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Abstract

Covalently functionalized carbon nanoplatelets and non-covalent functionalized metal oxides nanoparticles (surfactant-treated) have been used to synthesize water-based nanofluids in this paper. To prove nanofluid stability, ultraviolet-visible (UV-vis) spectroscopy is used, and the results show that nanofluid is stable for sixty days for carbon, and thirty days for metal oxides. The thermophysical properties are evaluated experimentally and validated with theoretical models. Thermal conductivities of f-GNPs, SiO₂, and ZnO nanofluids are enhanced with 25.68%, 11.49%, and 15.42%, respectively. Lu-Li and Bruggeman's thermal conductivity models are correctly matched with the experimental data. Similarly, the viscosity, density, and specific heat capacity of nanofluids are measured and compared with theoretical models. The enhancement in density, specific heat and viscosity of f-GNPs, ZnO, and SiO₂ nanofluids are 0.12%, 0.22%, and 0.12%; 1.54%, 0.96%, and 0.73%; 12%, 9.41%, and 24.05% respectively in comparison of distilled water. A flat-plate solar collector is installed, and its thermal performance is evaluated by using carbon and metal oxides based nanofluids, following the

ASHRAE standard 93-2003, at different heat flux intensities (597, 775, and 988 W/m²), mass flow rates (0.8, 1.2 and 1.6 kg/min), inlet fluid temperatures (30-50°C) and the weight concentrations (0.025- 0.2%). The thermal efficiency of the flat-plate solar collector is measured for distilled water and compared with the weight concentration (0.025- 0.2%) of functionalized carbon and metal oxide-based nanofluids. A comparison of 0.1wt% water-based nanofluids can be sequenced f-GNPs > ZnO > SiO₂ as a result of a percentage improvement of thermal efficiency of the flat-plate solar collector's obtained at a mass flow rate of 1.6 kg/min with values of 17.45% > 13.05% > 12.36%, respectively in comparison to water.

Keywords: Thermophysical; Heat Transfer; Nanofluids; Solar collector, efficiency

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Nomenclature			
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers ₁	A_c	Area of the solar collector (m ²)
AP	Absorber plate	C_p	Specific heat (J/kg K)
CTAB	Cetyltrimethylammonium bromide	F_R	Heat removal factor
EG	Ethylene glycol	G_T	Solar radiation available at surface (W/m ²)
FPSC	Flat-plate solar collector	k	Thermal conductivity (W/m K)
FeNPs	Iron nanoparticles	$\dot{m}$	Mass flux rate (kg/min)
SWCNT	Single-walled carbon nanotubes		
MWCNT	Multi-walled carbon nanotubes		
PEG 200	Polyethylene glycol 200		
P	Pressure (Pa)	Special Character	
SDS	Sodium dodecyl sulfate	α	Absorber plate absorbance
SDBS	Sodium dodecylbenzene sulfonate	η_c	Thermal efficiency of collector
TW	Tube wall	μ	Viscosity of fluid (Pa-s)
T_i	Fluid inlet temperature (K)	ρ	Density of fluid (kg/m ³)
T_o	Fluid outlet temperature (K)	τ	Glass cover Transmittance
T_a	Ambient temperature (K)	φ	Weight concentration

1. Introduction:

Worldwide growth of renewable energies is one of the main purpose by the governments to reduce the gas emissions [1]. Assets of renewable energy have shown their ability to fulfil sustainable energy requirements [2]. Both solar and wind energies are among the most important renewable energy sources [3]. Flat solar panels are simple, cost-efficient, and perhaps most widely used, but many researchers work on enhancing their performance due to their low efficiency [4, 5]. Using different techniques, flat-plate solar collectors (FPSCs) can improve their effectiveness [6, 7], e.g., applying different coating on the absorber plate [8-10], adjusting the flow rate [11], and taking into account different settings and tilting angle of collectors [12-14]. However, this technology requires improvements, for example, to increase the performance of FPSCs by adding a new fluid type as a conventional working fluid, known as “nanofluid”, for escalating the heat transfer rate from the absorber plate to the working fluid [15, 16]. Timofeeva et al. [17] reported that the thermal conductivity of Al_2O_3 was improved by 24% and 29% at a 10 vol.% concentration of 40 nm nanoparticles for water and ethylene glycol, respectively. Murshed et al. [18] an increase in thermal conductivity of the base fluid by almost 33% with 5 vol.% TiO_2 nanoparticles. The thermal conductivity of CuO nanofluid improved by 24% at a concentration of 0.05 mol/L [19]. Sarsam et al. [20] investigated the thermal conductivity of MWCNT with β -Alanine. The highest increment in the thermal conductivity was found at 12.2% and 14.74% for MWCNT with outer diameter 20-30 nm and less than 8 nm, respectively. Omer et al. [21] synthesized nanofluids using PEG-GNPs nanoparticles. The maximum enhancement in thermal conductivity was found 27.64% at 0.1% weight concentration.

A stable nanofluid is important for its use as an operating fluid in a heat transfer application [22-24]. The colloidal stability is not affected by buoyancy, gravity or any other body forces when nanoscale particles are dispersed in the base fluid. Nanofluid stability is then mainly governed by Brownian motion [25-27]. Covalent or non-covalent (surfactant) functionalization is used for improving long-term stability of the nanomaterial in base fluids. Solar flat plate collectors using covalently and non-covalently functionalized nanoparticles has not found in the literature [28-32]. Table 1 shows an overview of the effectiveness of flat-plate solar collectors using different nanofluids.

Table 1. Overview of documented studies utilizing nanofluid for improvement of thermal performance of FPSCs.

Ref.	Researcher	Nanoparticles			Surfactant	Base Fluid	Outcomes
		Type	Size (nm)	Volume or weight fraction			
[33]	Lee et al. (2020)	MWCNT/Fe ₃ O ₄	20/30 nm	0.003-0.005 0.01-0.015 vol%	without	H ₂ O	<ul style="list-style-type: none"> Maximum efficiency of 80.3% was noted for hybrid nanofluid, which was 17.6% higher than based fluid.
[34]	Ahmadi et al. (2016)	GNPs	< 100	0.01 and 0.02 wt%	without	H ₂ O	<ul style="list-style-type: none"> 18.87% improvement in the thermal efficiency of the solar collector was noted.
[35]	Akram et al. (2019)	GNPs	< 2 μm	0.025-0.1 wt%	without	H ₂ O	<ul style="list-style-type: none"> Efficiency of FPSC increased by 18.2% at mass flow rate of 0.0260 kg/m and 0.1 wt.% concentration
[36]	Hussein et al. (2020)	GNPs and MWCNT	N/A	0.05, 0.08, 0.1 wt%	Tween-80	H ₂ O	<ul style="list-style-type: none"> The thermal performance of the collector improves with 21.9% at 0.1 wt%.
[37]	Said et al. (2016)	Al ₂ O ₃	13	0.1 and 0.3 vol%	without	H ₂ O	<ul style="list-style-type: none"> Thermal performance of 83.5% reported at a concentration of 0.3 vol% and 1 mass flux rate of 1.5 kg/m
[38]	Kang et al. (2017)	Al ₂ O ₃	120, 50 and 1001	0.5, 1.0 and 1.5	without	H ₂ O	<ul style="list-style-type: none"> Thermal performance of 74.9% was reported for 20 nm particle with 0.1 wt% concentration, which was 14.8% higher than water.
[39]	Kim et al. (2017)	Al ₂ O ₃	120 to 501	10.5, 1.0 and 1.5 vol%	Without	H ₂ O	<ul style="list-style-type: none"> The maximum improvement in the performance of the solar collector was 24.1% The improvement in the thermal efficiency of the collector with a simple tube and twisted tube at 0.3 wt% concentration and 0.086 kg/s were 22% and 52.08% respectively
[40]	Sundar et al. (2018)	Al ₂ O ₃	< 20	10.1 and 0.3 vol%	SDBS	H ₂ O	<ul style="list-style-type: none"> The thermal efficiency of a blend is higher than individual and water
[41]	Farajzadeh et al. (2018)	Al ₂ O ₃ TiO ₂	20 and 15	0.1 wt%	CTAB	H ₂ O	<ul style="list-style-type: none"> Thermal performance with nanoparticles as compared to water
[42]	Noghrehabadi et al. (2016)	SiO ₂	12	1 wt%	Without	H ₂ O	<ul style="list-style-type: none"> 8.1% thermal performance enhancement noted with nanoparticles.
[43]	Jouybari et al. (2017)	SiO ₂	20 to 30	0.2, 0.4 and 0.6 vol%	Without	H ₂ O	<ul style="list-style-type: none"> 71.84% efficiency reported for concentration of 0.0066 vol% and flow rate 0.0195 kg/s
[44]	Sharafeldin and Gróf (2018)	CeO ₂	25	0.0167, 0.033 and 0.066 vol%	Without	H ₂ O	<ul style="list-style-type: none"> Thermal efficiency increased by 9.34% at a flow rate of 1.5 liter/m and 0.75 vol% concentration
[45]	Verma et al. (2016)	MgO	40	0.25 to 1.5 vol%	CTAB	H ₂ O	<ul style="list-style-type: none"> The maximum efficiency was 69.1%,
[46]	Choudhary et al. (2020)	MgO	40	0.08-0.2 vol%	CTAB	EG/DW	

[47]	Sharafeldin et al. (2017)	WO ₃	90	.0167, 0.0333 and 0.0666 vol%	Without	H ₂ O	<p>which is 16.7% higher than base fluid.1</p> <ul style="list-style-type: none"> • The highest efficiency of 71.87% was reported at a flow rate of 0.0195 kg/s.1 • Thermal conductivity was increased 6% at 0.3vol%.
[48]	Said et al. (2015)	TiO ₂	20 and 40	0.1 and 0.3 vol%	PEG200	H ₂ O	<ul style="list-style-type: none"> • Energy efficiency is increased by 76.6% at 0.1 vol.% and 0.5 kg/min • The maximum efficiency gains are 17.41%, 27.09%, and 33.54% for 1 wt%, 3 wt%, and 5 wt% nanoparticle concentration, respectively.
[49]	Moravej et al.(2020)	TiO ₂	--	1wt%,3wt%, and 5wt%	without	H ₂ O	

In this paper, nanofluids were synthesized using the covalent functionalization method for graphene nanoparticles, and the surfactant treated method for zinc oxide nanoparticles. Sodium hexametaphosphate (SHMP) was used as a surfactant for metal oxides, and the acid-treated covalent functionalization method was employed for GNPs. The stability of nanofluids was checked with ultraviolet-visible (UV-vis) spectroscopy. The thermophysical properties were evaluated and compared with theoretical models. The performances of functionalized carbon and metal oxides-based nanofluids, used as working fluids in FPSC, were evaluated in this paper to assess the synergetic compatibility. The thermal performance of FPSC was evaluated using three different heat flux intensities 597, 775 and 988 W/m² at a mass flow rates of 0.8, 1.2 and 1.6 kg/min. The fluid inlet temperatures were fixed at 30, 35, 40, 45 and 50°C. All experiments were performed according to ASHRAE Standard 93-2003 for indoor testing. The inaccuracies of thermal efficiencies were measured in this study from the collected experimental data on a flat plate solar collector using an uncertainty model.

2. Nanofluid synthesis and functionalization

2.1 Conventional (acid-treated) covalent functionalization of GNPs

Acidic treatment was done to introduce the carboxyl and hydroxyl group on the surface of GNPs (750 m²/g): in the first step, a solution of nitric acid (HNO₃) and sulfuric acid (H₂SO₄) with a 1:3 ratio were done; Then, 5 g GNPs (750 m²/g) was added in the strong acidic medium, and put the final solution under bath sonication for 3h at plus rate 3s ON 2s OFF; Then, the suspension solution is poured on the Teflon reaction vessel and placed in the industrial microwave for 15 min under 700W and 90°C (Milestone MicroSYNTH programmable

microwave system); The final suspension is cooled at room temperature and filtered through 45 μm polytetrafluoroethylene membrane, washed several times with distiller water (DI water) to attain neutral pH values (Figure 1). Finally, the resultant sample is dried overnight at 40°C in a vacuum oven [50].

2.2 Silicon dioxide (SiO₂) and Zinc Oxide (ZnO) nanoparticles

Silicon dioxide (SiO₂) nanopowder was obtained from Sigma-Aldrich Co., Selangor, Malaysia, with an assay of 99.5 % and particle sizes ranging from 10 to 20 nm. SiO₂ nanofluids were prepared through dispersion in the base fluid. Distilled water was used as a base fluid for SiO₂ nanofluid preparation. The nanofluids of specific SiO₂ nanoparticles and the base fluids are formed by an ultrasonic agitator. Throughout the preparation process, no surfactant was added. In this case, the stable suspension was obtained after 30 minutes of intense sonication.

Zinc oxide is a spherical nanopowder with an assay of 97%. It was purchased from Sigma-Aldrich Co., Selangor, Malaysia, being its particle size less than 50 nm. Within few minutes, the ZnO nanoparticles sediment because of the insolubility of zinc oxide between water and particle dissipation. Therefore, surfactant (non-covalent) is used for the aqueous dispersion of ZnO nanoparticles. The stability of ZnO nanofluids is enhanced with sodium hexametaphosphate (SHMP) surfactant. SHMP was obtained from Sigma-Aldrich Co. of Selangor, Malaysia, with a purity of 96%. After a 60-minute sonication cycle, the stable suspensions were obtained in line with ZnO weight concentrations (wt.%). The most stable suspension in the weight percentage was 1:10 (SHMP: ZnO).

Figure 1 Preparation methodology of nanofluids in this study

The colloidal stability can be measured by Ultraviolet visible (UV-vis) spectroscopy based on the principle of the measurement of light absorption of the suspension. Shimadzu UV-spectrometer was used in the 190-1100 nm range of wavelengths in the present study, UV-1800, Shimadzu Corporation, Kyoto, Japan. The light absorption data in all the samples were evaluated for a period of 60 days using unique quartz cuvettes suited for the UV region at certain distinct intervals. All specimens were water-diluted with a 1:20 proportion to allow the

correct propagation of light. In order to check the accuracy of the device, every read of absorbance was replicated twice, where the peak gaps of 0.08% were obtained.

Approximately 95% accurate KD2 Pro thermal properties analyzer (Decagon Geräte, Inc., USA) was used to measure the thermal conductivity of the water-based nanofluids prepared in this study. KS-1 probe, with a diameter of 1.3 mm and length 60 mm, was used as a needle sensor. The working principle of the needle sensor is based on the transient hot-wire method. The viscosities of the nanofluids were measured with an Anton Paar rotation rheometer (Anton Paar GmbH, Physica MCR 301). Shear rate range 20-200 1/s was selected for investigating the viscosity at different temperatures. The prepared nanofluids density was evaluated using a density meter Mettler Toledo (DM40) at different temperatures and weight concentrations. The measurement range for this device is 0.0-3.0 g/cm³, with an accuracy of 0.1 mg/cm³. The differential calorimetry scanning (DSC) was used to measure the specific heat through a thermal analysis process that controls the difference between the heat flow supplied to the reference and the sample as a temperature function. In this study, the specific heats of nanofluids prepared were evaluated using DSC-Q2000, TA Instruments, at distinct weight concentrations and temperatures.

2.3 Experimental setup

Figure 2 illustrates the schematic of the experimental setup used in this research to examine nanofluid-based solar collector's thermal performance. The main parts of the experimental setup are refrigerated water bath, flow loop, measurements and control devices, data logger, and flat-plate collector. The materials used in the FPSC section is: an aluminum stand with a T-slotted structure; A sheet frame of polypropylene (PP); Copper absorber plate of 2-mm thickness; riser; eader tubes (copper); glazing (glass); insulation, and; Base with adjustable angle. A ratio of Tin (Sn)/Silver (Ag) alloy (96.5/3.5) is used on both sides of each pipe to solder the copper absorber plate straight to the riser tubes (Figure 3). The choice of the copper absorber plate was 2 mm rather than 1 mm thick for the dimension of 91.44×50.8 cm, ensuring that after implementation of the heat needed for soldering between the copper absorber plate and riser pipes. The plate remains flat without corrugations. It is important to consider the flatness of the copper absorber plate for uniform distribution of heat flux along the surface during the installation of a flexible adhesive heater. The test configuration was described in two parts: the flow circuit and the FPSC section. The adhesive heater used to produce continuous heat flux, similar to solar radiation, comprises six distinct 30.48×25.4 cm flexible insulated heaters attached to a transformer of varying voltage. The heaters have been fitted with

an adhesive layer, which is a pressure-sensitive type (Omega USA, KH-1012/(2.5)-P). The insulation material used in this study was Isowool ceramic fiber, and it had 0.07 W/m K thermal conductivity at 400 °C. Table 2 shows the comprehensive specifications of the FPSC. PT-100 resistance temperature detectors (RTDs) were used to measure the entrance and exit fluid temperatures of the solar collector.

In contrast, ambient absorber plate and the riser tube temperatures at four different axial spots, i.e., 11.4, 34.3, 57.2, and 80.1 cm, were measured with T-type self-adhesive thermocouples (SA1XL-T-72, Omega, USA) with 2 m long fiberglass insulated cable. The supplier data revealed that the tolerances of RTDs and T-type thermocouples were $(0.15 + 0.002 |T|)$ and 0.75% °C, respectively. An eighteen-channel data logger (EC18) was used to connect the RTD, flow meter, and all the thermocouples and recorded the experimental data. Six universal cards were used in this data logger, where each of the cards contained three different channels. Moreover, an adjustable 0 – 60 ° angle base was used to regulate the FPSC tilt angle. In the present study, the angle was fixed at 30 °.

Figure 2 Schematic diagram of the test setup used in the present study

Figure 3. Pipe and fin type flat-plate collector

Table 2. Specifications of the solar collector and the components used in the present work

Specification	Dimension
Length of collector	1.135 m
Width of collector	0.6 m
Thickness	0.09 m
Collector area	0.6810 m ²
Absorber area	0.4645 m ²
Thickness of glass	0.005 m
Outer diameter of riser tube (do)	0.0127 m
Inner diameter of riser tube (di)	0.0116 m
Outer diameter of header tube (Do)	0.0222 m
Inner diameter of header tube (Di)	0.0209 m
Spacing between tubes	0.128 m
Emissivity of the glass cover	0.88
Coefficient of absorption	0.95
Back insulation	0.050 m
Thermal conductivity of the insulation	0.04 (W/mK)
Transmittance-Absorptance product	0.8772
Slope angle	30°

2.4 Testing method used for energy and exergy efficiency calculation

Indoor testing was carried out according to the ASHRAE Standard 93-2003 to assess the efficiency of the selected FPSC. The environmental factors heat flux (597,775,988 W/m²), ambient temperature, the effect of different weight concentrations (0.025-0.2wt%), mass flow rates (0.8,1.2,1.6 kg/min), and fluid inlet temperature range (30-50°C) were experimentally considered for the present investigation. Eq. 1 was employed to calculate the thermal efficiency of the FPSCs because it can be described as the value of useful heat gain Q_u divided by the total energy received by the absorber plate.

$$\eta_c = \frac{Q_u}{A_c G_T} \quad (1)$$

The useful heat gain energy was calculated using the Eq. 2, which is equal to the available thermal energy minus total energy losses by absorber plate as presented in Eq. 3 [51].

$$Q_u = \dot{m}C_p(T_o - T_i) = \rho VC_p(T_o - T_i) \quad (2)$$

Eq. (4) and Eq. (5) were used to calculate the thermal efficiency of the FPSC.

$$Q_u = A_c F_R [G_T(\tau\alpha) - U_L(T_i - T_a)] \quad (3)$$

$$\eta_C = \frac{\rho VC_p(T_o - T_i)}{A_c G_T} \quad (4)$$

$$\eta_C = \frac{A_c F_R [G_T(\tau\alpha) - U_L(T_i - T_a)]}{A_c G_T} \quad (5)$$

Eq. 5 is updated and rewritten as presented in the new Eq. 6, where F_R represents the value of the heat removal factor, and it was calculated by using Eq.7.

$$\eta_C = F_R(\tau\alpha) - F_R U_L \left(\frac{T_i - T_a}{G_T} \right) \quad (6)$$

$$F_R = \frac{\dot{m}C_p(T_o - T_i)}{A_c [G_T(\tau\alpha) - U_L(T_i - T_a)]} \quad (7)$$

where, $\dot{m}$, T_i , T_o , T_a represents the mass flow rate, inlet, outlet, and the ambient temperatures, respectively, of the collector. C_p , A_c , G_T , $\tau\alpha$, and U_L are represented by the specific heat capacity, area of the solar collector, solar radiation (heat flux), transmittance - absorption product, and overall heat losses, respectively. The thermal efficiency η_c of the solar collector versus the reduced temperature parameter $\left(\frac{T_i - T_a}{G_T} \right)$ produced a straight line. Along the y-axis, the thermal performance line intersects at $F_R(\tau\alpha)$. The collector inlet fluid temperature was the same as the ambient temperature at that point, where the collector thermal output achieved a maximum value. The efficiency at that point is maximum and considered the zero-loss point. If the straight line crosses the horizontal axis (reduced temperature line), then the thermal efficiency becomes zero. $F_R(\tau\alpha)$ was considered as the parameter of absorption, while $F_R U_L$ was referred as the parameter of deletion.

Exergy is the highest possible output relative to the ambient temperature. The general equation of the exergy equilibrium is shown in Eq. (8) [52, 53]:

$$\dot{E}_{xheat} - \dot{E}_{xwork} - \dot{E}_{xmass,in} - \dot{E}_{xmass,out} = \dot{E}_{xdest} \quad (8)$$

where,

$$\dot{E}_{xheat} = \left(1 - \frac{T_a}{T_{sur}} \right) \dot{Q}_s \quad (9)$$

being $\dot{Q}_s$ the total rate of energy absorbed by the absorber plate area, and equal to the product of collector area and solar irradiance, given by Eq. (10).

$$\dot{Q}_s = I_t(\tau.\alpha) = G_s A_c \quad (10)$$

The exergy flow at the inlet and outlet of the collector can be expressed by Eq. (11) and (12).

$$\dot{E}_{xmass,in} = \dot{m}[(h_{in} - h_a) - T_a(S_{in} - S_a)] \quad (11)$$

$$\dot{E}_{xmass,out} = \dot{m}[(h_{out} - h_a) - T_a(S_{out} - S_a)] \quad (12)$$

where h_{in} is the inlet enthalpy, h_{out} is the outlet enthalpy, h_a is the surrounding enthalpy, S_{in} is the inlet entropy, S_{out} is the outlet entropy, S_a is the surrounding entropy, and T_a is the ambient temperature.

Substituting these equations into Eq. 8 is obtained Eq. (13)

$$\left(1 - \frac{T_a}{T_{sur}}\right) \dot{Q}_s - \dot{m}C_p(T_{out} - T_{in}) - \dot{m}(h_{out} - h_{in}) - T_a(S_{out} - S_{in}) = \dot{E}_{xdest} \quad (13)$$

Eq. (14) and (15) presents the transition in the output of enthalpy and entropy via nanofluid to the solar collector.

$$\Delta h = h_{out} - h_{in} = C_{p,nf}(T_{f,out} - T_{f,in}) \quad (14)$$

$$\Delta S = S_{out} - S_{in} = \dot{m}C_{p,nf} \ln \frac{T_{f,out}}{T_{f,in}} - \frac{\dot{m}}{T_a} \frac{T_a}{T_{f,in}} \frac{\Delta p}{\rho} \quad (15)$$

Substituting Eq. (14) and (15) in Eq. (13), then the expression for exergy loss is given by Eq. (16),

$$\dot{E}_{xdest} = \left(1 - \frac{T_a}{T_{sur}}\right) I_t(\tau \cdot \alpha) A_c - \dot{m}C_{p,nf}(T_{f,out} - T_{f,in}) + \dot{m}C_{p,nf}T_a \times \ln \frac{T_{f,out}}{T_{f,in}} - \dot{m} \frac{T_a}{T_{f,in}} \frac{\Delta p}{\rho} \quad (16)$$

where $\dot{E}_{xdest}$ is the exergy loss rate and calculated by Eq. (17) in terms of temperature and entropy.

$$\dot{E}_{xdest} = T_a \cdot S_{gen} \quad (17)$$

where S_{gen} is represented by Eq. (18).

$$S_{gen} = \dot{m}C_{p,nf} \ln \frac{T_{f,out}}{T_{f,in}} - \frac{\dot{m}}{T_a} \frac{T_a}{T_{f,in}} \frac{\Delta p}{\rho} - \frac{G_t A_c}{T_a} \left\{ 1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right\} + \frac{(\tau \cdot \alpha) G_t A_c}{T_a} \left\{ 1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right\} \quad (18)$$

Exergy efficiency η_{ex} is represented by Eq. (19).

$$\eta_{ex} = 1 - \frac{T_a S_{gen}}{\left(1 - \frac{T_a}{T_{sur}}\right) \dot{Q}_s} \quad (19)$$

Finally, the exergy efficiency equation of the solar collector can be analyzed in accordance with the above expression.

$$\eta_{ex} = \frac{\dot{m}C_{p,nf} \left(T_{f,out} - T_{f,in} - T_a \times \ln \frac{T_{f,out}}{T_{f,in}} \right) - \frac{\Delta p}{\rho}}{\left(1 - \frac{T_a}{T_{sur}}\right) \dot{Q}_s} \quad (20)$$

Eq.(20) is modified for the present study as Eq.(21).

$$\eta_{ex} = \frac{\dot{m}C_{p,nf} \left(T_{f,out} - T_{f,in} - T_a \times \ln \frac{T_{f,out}}{T_{f,in}} \right)}{\left(1 - \frac{T_a}{T_{sur}} \right) \dot{Q}_s} \quad (21)$$

where T_{sur} and T_a are sun temperature and ambient temperature, which were taken as 5770K and 298.15K, respectively.

2.5 Uncertainty Analysis

The obtained data contains few errors and inaccuracies, which cannot be prevented in any experimental investigation that generates uncertainty in the experimental results. Therefore, the inaccuracies of thermal efficiencies were measured from the collected experimental data on a flat plate solar collector in this study using an uncertainty model. This analysis will explain the efficiency of the flat plate solar collector proportionally, as presented by Eq. (22) and (23).

$$\eta_c \propto \frac{\text{useful energy collected available}}{\text{heat stream obtained on the collector surface}} \propto \frac{\rho V C_p (T_o - T_i)}{G_T} \quad (22)$$

$$\Rightarrow \eta_c \propto \rho V C_p G_T^{-1} (T_o - T_i) \propto \rho V C_p G_T^{-1} \Delta T \quad (23)$$

According to Holman [54] and Kline & McClintock's [55] relationship, the uncertainty (ω) in the value of R can be expressed as shown by Eq. (24).

$$\frac{\omega_R}{R} = \left[\sum_{i=1}^n \left(\frac{a_i \omega_{x_i}}{x_i} \right)^2 \right]^{0.5} \quad (24)$$

Eq.25 is used to calculate the uncertainties in the estimated values of the collector's efficiencies.

$$\frac{\omega_{\eta_c}}{\eta_c} = \left[\left(\frac{\omega_\rho}{\rho} \right)^2 + \left(\frac{\omega_V}{V} \right)^2 + \left(\frac{\omega_{C_p}}{C_p} \right)^2 + \left(\frac{\omega_{G_T}}{G_T} \right)^2 + \left(\frac{\omega_{\Delta T}}{\Delta T} \right)^2 \right]^{0.5} \quad (25)$$

The estimated values 0.04%, 1.67%, 2.75%, 1.75%, and 0.67% are the uncertainty data of the five independent variables. Therefore, the evaluated FPSC efficiencies remained within the accuracy of 3.75%. The maximum variation in ambient temperature, inlet temperature, and radioactive flux in each test period were $\pm 0.5^\circ\text{C}$, $\pm 0.1^\circ\text{C}$, and $\pm 25 \text{ W m}^{-2}$, respectively.

3. Results and Discussion

3.1 Stability of nanofluids

The sonication cycle was conducted at a power output of 80% amplitude using a sequential mechanism of three seconds. In order to ensure that the visible UV-vis spectrometer wavelengths could move through the samples, the sample was diluted with DI water at a 1:20 dilution rate. Then, pour the samples into quartz cuvettes, which were particularly used to

transmit UV wavelengths, and measured the absorption of the samples over 58 days at wavelengths of 265 nm at specified intervals (Figure 6). The photometric analysis has been used to monitor the weight concentration of all samples at varying periods over 58 days (Figure 4). Figure 5 represents the photographic representation of samples before and after be used in FPSC. The sample weight concentrations decreased at different rates with time, see Figures 7-8, due to sedimentation and agglomerations. For all of the samples after sixty days, the remaining concentrations of weight were (0.0217 for 0.025wt%), (0.0461 for 0.05wt%), (0.062 for 0.075wt%), and (0.092 for 0.1wt%), respectively (Figure 7a). Therefore, the rate of sedimentation, among the samples, changed at different weight concentrations. The results of previous researchers are presented in Table 3, which are well-matched with the trend [20, 56].

Table 3. Summary of selected experimental investigations on the stability and thermal conductivity enhancement of water-based nanofluids using carbon materials as nanoparticles.

Author	Material with Concentration	Surfactant Functionalization method	Stability	Maximum enhancement in Thermal conductivity
Farbod et al.[57]	MWCNT 0.1–0.5 vol%	Acid oxidation mixture of 3:1 sulfuric and nitric acids	80 days	17%
Nasiri et al. [58]	SWCNT DWCNT FWCNT 0.25 wt%	Treated with hydrochloric and nitric acid	< 2 months	36.5%
Sadri et al.[59]	FWCNT, MWCNT 0.5 wt%	GA, SDBS, SDS	>28 days	22.31%
Yang et al.[60]	GO 0–1.5 wt% –	Hummers method	>1 month	48.1%
Ding et al.[61]	GO 0–1 wt%	GA	– Months	80%
Sharaf et al.[62]	CIT-AuNPs, PEG-AuNPs	CIT-reduction method	16 months	-
Fazeli et al. [63]	SiO ₂	ultrasonication	3 days	-
Present study	SiO ₂ , ZnO, F-GNPS	Ultrasonication + Acid oxidation	30,30, and 58 days	11.49%, 15.42% and 25.68%

Figure 4 Photograph of the synthesized (a) SiO₂, (b) ZnO, and (c) f-GNP nanofluids for all concentrations

Figure 5 Photograph of the synthesized nanofluids before and after use in FPSC

Figure 6. UV–Vis absorption spectra of (a) f-GNP, (b), ZnO, and SiO₂ nanofluids for all concentrations.

The relative concentration will assist in deciding the maximum stability of the sample from all synthesized samples. The relative concentration of the nanofluids declined by increasing the number of days following the preparation of the sample. After fifty-eight days, in the corresponding estimates, the relative sample concentrations were 0.9195, 0.9078, 0.8960 and 0.8821, for 0.025wt%, 0.05 wt%, 0.075wt% and 0.1wt%, respectively (Figure 7b). From these findings, the 0.025-wt% f-GNP assay with a relative concentration of 0.9195 was attained to the maximum colloidal stability, indicating 8.05% sedimentation after fifty-eight days.

Figure 7. Weight concentration and (b) relative concentration of f-GNP nanofluid against no. of days at different concentrations

Eight different nanofluid samples were synthesized by following the two-step method and using ZnO and SiO₂, each material with four different concentrations of 0.015%, 0.1%, 0.15%, and 0.2%. A sequential three-second system was used for the sonication process at an amplitude of 70%, and 30 minutes of ultrasonication time was selected to prepare nanofluids. The concentrations for ZnO and SiO₂ nanofluids were different from the carbon-based nanofluids because the stabilities and thermophysical properties of lower concentrations were

low. After the detailed study of different concentrations, the optimal concentrations were selected with a common concentration of 0.05% and 0.1% with carbon-based nanofluids. UV-vis spectroscopy was used to analyze the weight concentration of ZnO and SiO₂ nanofluids as a function of time for more than 30 days. The relative concentration was used to select the sample with maximum and minimum stability from the available samples. Figure 8 shows the relative concentrations of ZnO and SiO₂ with different concentrations. The results indicate that, after 30 days, the relative concentrations of 0.05wt%, 0.1wt%, 0.15wt%, and 0.2wt% fresh sample were (87.04, 86.660, 86.425 and 85.665) and (87.42, 86.66, 86.19 and 85.14) for ZnO and SiO₂, respectively. The maximum colloidal stability for both materials was found at 0.05wt%, i.e., 87.04 and 87.42, which means that the rate of sedimentation and agglomeration of particles was 12.96% and 12.56% for ZnO and SiO₂, respectively.

Figure 8 Relative concentration of nanofluid as a function of time (a) ZnO (b) SiO₂

3.2 Thermal conductivity of f-GNPs, SiO₂ and ZnO nanofluids

The thermal conductivity of water-based f-GNPs nanofluid at four different weight concentrations (0.025% - 0.1%) from 20 to 45°C in comparison to water is shown in Figure 9. The percentage improvements of nanofluids in thermal conductivity in comparison with water was from 5.29% to 8.02%, 7.9% to 11.91%, 11.13% to 18.45%, 15.1% to 25.68% at weight concentration of 0.025% 0.05%, 0.075% and 0.1%, respectively. From these results, it is possible to conclude that the rise in weight concentration and temperature will result in an increase in the thermal conductivity of nanofluids, and the maximum improvement was found by 25.68% at 0.1wt%. The experimental results obtained for f-GNP nanofluids from the KD2 Pro unit at various concentrations and temperature ranges were compared to the current

Maxwell (1881), Bruggeman, Hamilton & Crosser (1962), and Lu-Lin (1996) thermal conductivity models. Figure 10 shows that at a low concentration of 0.025wt% Maxwell (1881), Lu-Li (1996), and Bruggeman Model, being correctly matched with the experimental data taken from KD2 Pro for f-GNPs nanofluid. As concentration increases from 0.05wt% to 0.1wt%, only Lu-Li (1996) model was well-matched with experimental data taken from KD2 Pro. The three other models underestimate the experimental data for high concentration.

Figure 9 Thermal conductivity of f-GNPs nanofluid and water at different temperatures and concentrations.

Figure 10 Comparison of thermal conductivity of f-GNPs nanofluid measured with KD2 Pro at different concentrations with the available models (Maxwell[64] , Buggeman[65], Lu-Lin[66], and Hamilton & Crosser[67]) of thermal conductivity

The measured values of thermal conductivity of SiO₂ and ZnO in comparison to water are shown in Figure 11 at different weight concentrations (0.05%,0.1%,0.15%,0.2%) and temperatures (20-40 °C). The general trend of increment of thermal conductivities of SiO₂ and ZnO samples were matched with the carbon-based nanofluids, i.e., an increase in thermal conductivity with an increase in weight concentration and temperature. The range of weight concentrations selected in this study were 0.05%,0.1%,0.15%, and 0.2% for SiO₂ and ZnO, which were different from the range of weight concentration of carbon-based nanofluids (0.025%,0.05%,0.075%,0.1%). The main reason behind this difference is the low thermal conductivities behavior of SiO₂ and ZnO nanofluids at low concentrations. In order to compare the effect of all materials on thermophysical properties and thermal performance of FPSC, 0.05 wt% and 0.1wt% were chosen as common concentrations. It was observed in Figure 11(a) that thermal conductivity of SiO₂ improved from 0.613 to 0.640, 0.620 to 0.657, 0.638 to 0.661, and 0.644 to 0.678 W/m K for weight concentration of 0.05%,0.1%,0.15%, and 0.2%, respectively. Similarly, this enhancement for the ZnO nanofluid was from 0.617 to 0.648, 0.625 to 0.660, 0.648 to 0.675 and 0.671 to 0.702 W/m K at weight concentrations of 0.05%, 0.1%, 0.15%, and 0.2%, respectively, as shown in Figure 11(b). The percentage enhancements of SiO₂ and ZnO nanofluids in comparison with water for the temperature range of 20 to 40 °C were 4.63% to 5.73%, 6.71% to 8.16%, 8.01% to 10.11%, 10.40% to 11.49%; and 5.93% to 6.36%, 7.53% to 9.09%, 10.32% to 12.58%, 13.40% to 15.42% at of weight concentration of 0.05%, 0.1%, 0.15%, and 0.2%, respectively.

Figure 11. Thermal conductivity values at different temperatures and concentrations for (a) SiO₂ (b) ZnO

3.3 The viscosity of f-GNPs, SiO₂ and ZnO nanofluids

A comparison of the dynamic viscosity was done against shear rate (20-200 1/s) of water-based f-GNPs at a weight concentration of 0.025%, 0.05%, 0.075% and 0.1%, and temperature range of 25 - 40 °C. As far as the shear rate increases, the value of viscosity remains almost the same at a specific temperature for f-GNPs nanofluid, proving that the nanofluid behaves as a Newtonian fluid. However, the value of viscosity decreases with an increase in temperature, and rises with an increase in concentration, see Figure 13. The dynamic viscosity of f-GNPs nanofluid is higher than DI water at every concentration. The percentage enhancement in viscosity of f-GNPs nanofluids was analysed in comparison of water at weight concentrations of 0.025%, 0.05%, 0.075% and 0.1% and temperature range of 20 - 40 °C were (6.3% - 6.5%), (6.9% - 7.6%), (10.1% - 13.7%) and (11.6% - 12%), respectively. The maximum percentage enhancement was found at a weight concentration of 0.1% f-GNPs nanofluid. Furthermore, the dynamic viscosity of nanofluid was compared with three different classical models of viscosity at two different temperatures (30 and 40 degrees), shown in Figure 12.

Figure 12. Viscosities for f-GNPs with the classical models (Brinkman[68], Batchelor[69], and Einstein[70]) at (a) 30°C and (b) 40°C

Figure 13 Viscosities of f-GNPs against the shear rate at a weight concentration of 0.025%,0.05%,0.075%, and 0.1%.

The viscosities of SiO₂ and ZnO nanofluids at a shear rate of 200-1/s, different temperatures, and weight concentrations are presented in Figure 14(a-b). Figure 14a shows that the viscosity of SiO₂ nanofluids with a weight concentration of 0.05%, 0.1%, 0.15%, and 0.2% in the temperature range of 20 - 40°C decreases as temperature increased and rises as concentration increased. The percentage enhancement in viscosity of SiO₂ nanofluids in comparison of water was (5.39% - 7.63%), (7.20% - 12.66%), (13.4% - 20.41%) and (18.23% - 24.05%) for weight concentration of 0.05%, 0.1%, 0.15% and 0.2% in temperature range of 20 - 40 °C, respectively. Similarly, Figure 14b represents the viscosity of ZnO nanofluids with weight concentration of 0.05%, 0.1%, 0.15%, and 0.2% in temperature range of 20 - 40 °C. The percentage enhancements in viscosity of ZnO nanofluids in comparison of water at weight concentration of 0.05%, 0.1%, 0.15%, and 0.2% at the said temperature ranges were (2.25% - 1.27%), (5.58% - 7.35%), (5.69% - 8.48%) and (7.44% - 9.41%), respectively. The viscosity enhancement of ZnO is less as compared to SiO₂ nanofluids. It may be because there was no need for surfactant required for the SiO₂ nanofluids synthesis and particles of may aggregate soon.

Figure 14 Viscosities against temperature at a shear rate of 200-1/s for water and different concentration of (a) SiO₂ (b) ZnO

3.4 Density of f-GNPs and metal oxides (SiO₂, ZnO) based nanofluids

Figure 15 shows the measured value of the density of f-GNPs at different weight concentrations and temperatures compared to the measured density of water. In Figure 15a, the density of f-GNPs nanofluid increases slightly with weight concentration, while it decreases as the temperature of nanofluid increases. The maximum increment was found when the density of nanofluid was 0.08% in comparison to water. The experimental values of nanofluid densities were compared with the calculated values of the Pak & Cho (1998) equation, as represented in Figure 15b. The maximum difference of 0.12% was observed at a weight concentration of

0.1wt%. Thus, the Pak & Cho (1998) equation can be considered to be highly accurate for measuring the density values of water-based f-GNPs nanofluid.

Figure 15 (a) Experimental density values of DI water and f-GNPs nanofluid at different weight concentrations and temperatures (b) Comparison of experimental density values of f-GNPs with Pak & Cho (1998) [71].

The densities of SiO₂ and ZnO nanofluids at a weight concentration of 0.05% - 0.2% and temperature range 20-40 °C compared to water are presented in Figure 16(a-b). The weight concentration ranges for SiO₂ and ZnO nanofluids were higher than that of f-GNPs nanofluids. However, the measured density values were high for SiO₂ and ZnO in comparison to other nanofluids. The maximum difference noticed between the densities of DI water to SiO₂ and ZnO nanofluids were 0.12% and 0.22%, respectively. Furthermore, the measured values were compared with the densities for SiO₂ and ZnO nanofluids. Pak & Cho (1998) equation was used to calculate the densities of SiO₂ and ZnO nanofluids (Figure17a-b). The highest difference between the measured and calculated densities of SiO₂ and ZnO nanofluids were 0.11% and 0.12%, respectively. It can be observed that the density of nanofluids increased with weight concentration, and decreases as temperature increases, but the difference between measured and calculated values of all nanofluids increase equally. Accordingly, it was decided that Pak and Cho equation is suitable for calculating the density of nanofluid.

Figure 16 Comparison of experimental density values at different weight concentrations and temperatures of (a) SiO₂ (b) ZnO nanofluids with DI water.

Figure 17 Comparison of measured density values of (a) SiO₂ (b) ZnO with Pak & Cho (1998) [71]

3.5 Specific heat of f-GNPs and metal oxides (SiO₂, ZnO) based nanofluids

The calculated specific heat capacity of f-GNPs at various weight concentrations and temperatures is presented in Figure 18a together with the standard values of NIST and measured values of DI water. It can be seen from Figure 18a that the specific heat values decrease as the temperature of the nanofluid increases. In comparison to water, the measured values of specific heat decrease as weight concentration increases. The maximum difference between the measured values of specific heat capacity of 0.025wt%, 0.05wt%, 0.075wt%, 0.1wt% f-GNPs nanofluids and DI water were 0.55%, 0.96%, 1.23% and 1.54%, respectively. This reduction may be attributed to the fact that solid nanomaterials typically have a lower specific heat value than liquids.

The calculated values of specific heat using Pak & Cho (1998) and Xuan & Roetzel (2000) equations were compared with the experimental values of f-GNPs nanofluid at various temperatures and weight concentrations. A comparison is shown in Figure 18b for the 0.1wt% f-GNPs, which clearly shows that the experimental results are well matched with Xuan & Roetzel's (2000) equation while equation Pak & Cho (1998) [71, 72] underestimate the experimentally measured values. The maximum differences found for 0.1wt% f-GNPs nanofluids were 0.19% and 1.24% for Xuan & Roetzel (2000) and Pak & Cho (1998), respectively.

Figure 18 (a) Specific heat values of f-GNPs nanofluid at different weight concentrations and temperature in comparison to DI water and NIST values (b) Comparison of specific heat capacity of f-GNPs with an available correlation of Pak & Cho (1998) [71] and Xuan & Roetzel (2000) [72] at 0.1wt%

The measured specific heat values of SiO₂ and ZnO at weight concentrations of 0.05%, 0.1%, 0.15%, 0.2%, and temperatures range 20-40°C were presented in Figure 19(a-b) with the

standard values of NIST and measured values of DI water. Compared to the water and the standard values of NIST, the experimental values of specific heat reduced as weight concentration increased. The maximum differences between the experimental specific heat capacities of SiO₂ and ZnO nanofluids at weight concentrations of 0.05%, 0.1%, 0.15% and 0.2% in comparison to DI water and NIST values were 0.55%, 0.96%, 1.23% and 1.54%, and 0.35%, 0.73%, 1.08% and 1.43%, respectively. When the experimental specific heat values of metal oxides-based nanofluid were compared with graphene nanofluids, decrement in specific heat values were higher for metal oxides than graphene compared to DI water. This may be attributed to the that the weight concentration was higher for metal oxides nanofluids.

Figure 19 Specific heat values of (a) SiO₂ and (b) ZnO nanofluid at different weight concentrations and temperature in comparison to NIST values[73]

4. Thermal efficiency of FPSC using water as operating fluid

The experiments were performed at Mechanical Engineering Department, University of Malaya, Malaysia, and the time frame was 8:00 to 15:00 hours for conducting the tests. To track the repeatability and integrity of the reported results, all of the tests conducted for DI water were under the ASHRAE Standard 93-2003. All the investigations at different heat flux intensities (597,775,988 W/m²), mass flow rates (0.8, 1.2, 1.6 kg/min), inlet fluid temperatures (30-50°C) and the weight concentrations (0.025- 0.2%) were repeated several times, and the best data were selected for graphical representation. Table 4 shows the heat absorption parameters $F_R(\tau\alpha)$, and the heat removal parameters $F_R U_L$. Figure 20 shows the thermal efficiency of the FPSC versus the reduced temperature parameter for the DI water. When the mass flux rate increased from 0.8 to 1.6 kg/min, the values of $F_R(\tau\alpha)$ and $F_R U_L$ were also increased, which improved the thermal efficiencies of the FPSC. The data shown in Figure 20

are based on the precise linear Equation, and R^2 is the root mean square error for these data points

Table 4 $F_R(\tau\alpha)$ and $F_R U_L$ factors for DI water at different flow rates.

Mass flow rate (kg/min)	$F_R(\tau\alpha)$	$F_R U_L$	R^2
0.8	0.6120	4.8261	0.9539
1.2	0.6640	5.2561	0.9584
1.6	0.6829	5.2945	0.9573

Figure 20 The experimental efficiency of FPC against reduced temperature parameter at various flow rate using DI water

4.1 Thermal efficiency of nanofluids as working fluids in FPSC

Table 5 provides $F_R(\tau\alpha)$ and $F_R U_L$ values for f-GNP and H_2O at various mass flow rates and weight concentrations. This shows that nanofluids have higher values of heat reduction factor than water, and continues to rise as the rate of flow increases. As previously discussed, that nanofluid thermal conductivity is greater than water. For f-GNP, the coefficient of convective heat transfer was greater than for water. Therefore, using f-GNP/water nanofluid, the thermal efficiency of a solar collection can be improved. The sharp rise in the heat transfer coefficient is primarily attributed to the thin thermal boundary layer on the riser tube walls due to the increased thermal conductivity of the f-GNP / water nanofluid and the decrease of thermal resistance between the nanofluid and the inner wall in the riser tube. Also, thinner thermal boundary thicknesses arise from carbon nanomaterials such as graphene and CNT. Specific surface area and Brownian movement of nanoparticles often play a role in improving the

convection heat transfer coefficient [74]. When the Re is enhanced for nanofluids and DI water, then the convective heat transfer coefficient can be strengthened.

Table 5 f-GNP heat absorption and heat removal factor at various weight concentrations and flow rates when compared to DI water

Mass flow rate (kg/min)	Weight concentration (wt. %)	$F_R(\tau\alpha)$	$F_R U_L$	R^2
0.8	0.1	0.7437	6.0000	0.9918
	0.075	0.7324	5.5638	0.9795
	0.05	0.6778	5.5449	0.9858
	0.025	0.6452	5.4050	0.9621
	DI Water	0.6120	4.8261	0.9539
1.2	0.1	0.8134	6.3832	0.9825
	0.075	0.7873	6.2325	0.9726
	0.05	0.7233	5.9923	0.9611
	0.025	0.6929	5.9528	0.9669
	DI Water	0.6640	5.2561	0.9584
1.6	0.1	0.8131	7.0011	0.9582
	0.075	0.8095	6.6030	0.9684
	0.05	0.7555	6.4501	0.9661
	0.025	0.7017	6.2011	0.9723
	DI water	0.6729	5.2945	0.9573

Figure 21(a-b) shows the experimental thermal efficiency of FPSC against reduced temperature parameter at mass flow rate 1.60 kg/min and weight concentration range (0.05 - 0.2 wt%) for SiO₂ and ZnO nanofluids in comparison to DI water. Therefore, thermal efficiency of FPSC increases with the loading of nanoparticles in the base fluid. When it is compared with water, maximum increase in thermal efficiencies of SiO₂ and ZnO nanofluids at 1.60 kg/min mass flow rate and weight concentrations of (0.05%, 0.1%, 0.15%, 0.2%) were (8.0%, 10.7%, 12.96%, 13.21%), and (9.30%, 11.14%, 13.75%, 14.21%), respectively. The specific heat capacity (C_p) of nanofluid is a smaller than base fluid (water), while the temperature difference (ΔT) for nanofluids was significantly higher than the base-fluid, which attributes the enhancement in the thermal efficiency of the solar collector. The main reason for this increment

in temperature difference is the improved thermal conductivity of nanofluids, see references [35, 36, 75, 76].

Figure 21 The thermal efficiency of FPC using (a) SiO₂ and (b) ZnO nanofluid at different weight concentration and 1.60 kg/min mass flow rates in comparison to DI water

Figure 22 Experimentally measured values of TW and AP at the different mass flow rate, fluid inlet temperature 30°C and heat flux intensity 998 W/m² for DI water and 0.1 wt.% (a-b) SiO₂ and (c-d) ZnO nanofluids

Figure 22 shows the variations of the calculated values of AP and TW against axial distance along the direction of flow in the collector for water and 0.1 wt.% water-based SiO₂ and ZnO nanofluids are shown at 998 W/m² heat flux strength and 30 °C fluid inlet temperature. It can be seen that the calculated values of TW and AP decline as the flow rate increases, and their values for water-based SiO₂ and ZnO nanofluids are lower than their corresponding water values, down to 4.46% and 3.75%, and 6.53% and 6.14% at 0.8 kg/min, respectively. This decrease will result in an increment in the heat transfer coefficient in the material due to the improvement in the thermal conductivities of SiO₂ and ZnO nanoparticles. In view of the fact that nanofluids with a greater thermal conductivity than their base fluids often have higher convective heat transfer coefficients in previous work as well as in laminar and turbulent regimes [77]. Figure 23 shows the exergy efficiency of flat plate collectors at a different flow rate for materials such as functionalized carbon and metal oxides-based nanofluids. Figure 23

shows that if the mass flow rate increases, then exergy efficiency improved. Also, exergy efficiency enhanced for all nanofluids used in the present study in comparison to DI water.

Figure 23 Exergy efficiency at different values of mass flow rate for 0.1wt% metal-oxides and carbon-based nanofluids

4.2 Comparison of metal oxides-based and carbon-based aqueous nanofluids

The experimental thermal efficiency of FPSC against reduced temperature parameters at a weight concentration of 0.1% and different mass flow rates compared to DI water is presented in Figure 24a-c. In contrast to that of water, water-based GNP nanofluids are again superior to all other nanofluids prepared in the present study. It shows the highest thermal performance of FPSC, up to 17.45% at a 1.6 kg/min mass flow rate. The 0.1wt% water-based nanofluids can be sequenced as f-GNPs > ZnO > SiO₂ a result of a percentage improvement in FPSC's thermal efficiency obtained at a flow rate of 0.8 kg/min with values of 14.0% > 10.2% > 9.2%, respectively, in comparison to water. Similar sequence was observed for the 1.2 kg/min and 1.6 kg/min mass flow rates but with the corresponding thermal efficiency values of 15.21% > 11.6% > 10.3% and 17.45% > 13.05% > 12.36%, respectively, in comparison to water.

Figure 24 Comparison of the calculated thermal efficiency of FPSC for DI water and metal-based & carbon-based nanofluids at 0.1wt% concentration and mass flow rates of (a) 0.8 kg/min (b) 1.2 kg/min (c) 1.6 kg/min

5. Conclusions

The thermal performance of solar flat plate collector has been analysed for the first time in this paper according to the state of the art by using functionalized graphene and metal oxides nanofluids. The main conclusions are summarised as follow:

- Covalent functionalization method for carbon-based GNPs and Non-covalent functionalization (Surfactant) method for metal oxides based ZnO have been used to synthesize stable dispersible nanofluids as operational fluids.
- The thermal conductivity of any nanofluid is an essential parameter for convective heat transfer. KD2-pro has been used for measuring the thermal conductivity of nanofluids and water, obtaining about 25.68%, 11.49%, and 15.42% of improvements for f-GNPs, SiO₂, and ZnO, respectively, in comparison to DI water. The enhancements in density, specific heat and viscosity of f-GNPs, ZnO, and SiO₂ nanofluids were noticed about (0.12%, 0.22%, 0.12%) (1.54%, 0.96%, 0.73%) and (12%, 9.41%, 24.05%), respectively.
- The thermal efficiency of FPSC has been enhanced by increasing the mass flow rate from 0.8 to 1.6 kg/min. The percentage increments of $F_R(\tau\alpha)$ and $F_R U_L$ for the carbon-based nanofluid compared to DI water at a flow rate of 1.6 kg/min, a weight concentration of 0.1wt% were 20.83% and 32.23%, respectively.
- The thermal performance of the flat plate solar collector has been measured for 0.1wt% water-based all nanofluids and compared with DI water. The percentage improvement in thermal efficiency at a mass flow rate of 1.6 kg/min was 17.45% for f-GNPs compared to DI water. It is concluded that all nanofluids improved the thermal performance of FPSC as compared to DI water, and these nanofluids can be used as an alternative operational fluid.

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