

The Influence of Al_2O_3 - ZnO - H_2O Nanofluid on the Thermodynamic Performance of Photovoltaic- Thermal Hybrid Solar Collector System

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Abstract

A thermodynamic analysis was conducted after alternatively testing different working fluids to particularly assess the effect of Nanofluid as heat transfer agent on improving thermal, electrical, and exergetic efficiencies of photovoltaic/thermal (PV/T) hybrid solar collector system under State of Qatar climate, using experimentally and computationally obtained data. The investigated fluids were water, and Al_2O_3 - ZnO - H_2O Nanofluid mixed with Ethylene Glycol as surfactant. Mass fractions of Nanoparticles were 0.05 wt.% Al_2O_3 with particle size of 5nm and 0.05 wt.% ZnO with particles size of 10-30 nm. The results showed that in comparison between water as absorption medium and the mentioned Nanofluid, an increase in thermal and hence total efficiency of the system was recorded for the latter absorption medium scenario, despite considering concentrations of the Nanoparticles relatively low. A very general trend of dramatic decrease in the positive effect of Nanofluid in consistency with the ambient temperature increase was also observed after fitting the data to segments of declining straight lines. For 0.05 wt.% mass fraction of Nanoparticles the averaged increment in total efficiency was 4.1%, and in total useable energy (exergy) efficiency was 4.6%.

Keywords: Solar hybrid collector system; Nano fluidic; Photovoltaic

General Introduction

Hybrid photovoltaic/thermal (PV/T) technology, through photovoltaic and photo thermal interaction, generates electricity and thermal power simultaneously from absorbed solar energy. Besides the higher overall energy performance, the merit of a PV/T system lies in the reduction of the demands on physical space and the equipment cost through the use of common frames and brackets as compared to the separated PV and solar thermal systems placed side-by-side. Its façade integration provides architectural uniformity and facilitates building thermal load reduction [1].

The assessment of solar photovoltaic/thermal (PV/T) hybrid collector system performance is commonly tackled from viewpoint of thermodynamics, as [1] conducted a study of appropriateness of glass cover on a thermo syphon heating PV/T system from the first law point of view and from the exergy analysis point of view. Ozgoren M, et al. [2] concluded that the conversion efficiency of the photovoltaic (PV) system with water cooling might be improved by an average of 10%, while Debbarma et al. [3] studied the thermal, electrical and exergetic characteristics of PV/T hybrid air collector system.

Nanofluids are skillfully prepared colloidal suspensions of nanoparticles (which is of size 1–100 nm) dispersed in a base fluid [4]. Many authors investigated the effect of Nanofluids on the performance of solar collectors, such as Yousefi et al. [5] who experimentally studied the effect of Al_2O_3 -water nanofluid on the efficiency of a flat-plate solar collector. Nagarajan et al. [6] prepared Nanofluids containing Al_2O_3 , ZnO , and MgO nanoparticles. The amount of forced convective heat transferred through the as-prepared nanofluids in tubular solar collector showed ZnO -water nanofluid with 0.2% concentration by volume as the optimal option for the collector. Other authors like Li et al. [7] reviewed the fields of application for solar collectors using nanofluids as the working fluid. The effect of Nano fluids on PV/T hybrid collector performance was studied by Cui and Zhu [8] who applied the Nano-solution on top of the PV module. Although the electrical efficiency of the PV/T system was lower than the bare PV module, the overall energy conversion efficiency of the PV/T system was higher.

The use of finite element simulation is of interest in this study, so to simulate the temperature distribution on top of the solar collector or on the PV panel surface and then evaluate its performance. Yang et al. [9] followed the same path of investigation by measuring and simulating the temperature distribution, and the resulting data of experiments and simulation were very consistent. Analysis of a conceptual photovoltaic thermal (PV/T) solar panel design was performed by Fontenault and Gutierrez-Miravete [10] using COMSOL Multiphysics software and combinations of water flow rates and reservoir thicknesses were analyzed to determine which one produced optimal PV/T total efficiency. The work of Elmir et al. [11] included studying by numerical simulation the cooling of a solar cell by forced convection in presence of a nano fluid, and concluded to an increase in the rate of heat transferred in comparison with absence of nanoparticles.

In the present work, the effect of Nanofluid in the performance of thermally biased solar PV/T hybrid collector system is analyzed in terms of the relevant efficiencies and in comparison, with the normal water as working fluid, taking advantage of the collected experimental data from an available set of PV/T collectors at GORD's Techno Hub research facility in Qatar and with the aid of finite element modeling COMSOL Multi physics software. It was of interest in this work to investigate a Nanofluid composed of two different nanoparticles with low mass fraction for each one dispersed by manual stirring in a mixture of distilled water and Ethylene Glycol serves as surfactant.

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Materials and Set up

Experimental investigations were conducted on two working fluids: water and Al₂O₃-ZnO- distilled water (H₂O) Nanofluid mixed with Ethylene Glycol. The Nanofluid composition is 0.05 wt.% ZnO 99+% purify nearly spherical Nanoparticles (particle size 10-30 nm), 0.05 wt.% Al₂O₃ 99.99% purify nearly spherical Nanoparticles (particle size 5 nm) [12], ethylene glycol as natural surfactant for dispersion of Nano-powders, and a distilled water as the base fluid. Gentle stirring was applied to reassure dispersion of Nanoparticles in the base fluid. Figure 1 shows the prepared mixture.

The following Table 1 [13] summarizes thermo-physical properties and quantities of Nanofluid structural components.

Experiments were conducted on a ready setup consists of: an outdoor set of five solar PV/T hybrid collectors tilted 25°S and connected in series within a closed hydronic circuit in where the volumetric flow rate is maintained constant at 3.25 L/min, indoor 500 Liter storage tank with integrated heat exchangers in where the collectors' hydronic circuit is connected, variable speed circulating pump, electromagnetic flow meter, and a simple ball valve to control the flow. The ball valve is connected to the inlet (downstream) of the collectors' set. Two K-type Thermocouples and their data loggers were attached to the inlet and outlet pipes of the collectors' set to record the relevant temperatures. The local weather data of ambient temperature and wind speed was provided by Vantage Pro 2 weather station model manufactured by Davis' weather monitoring. The solar irradiation at the plane of the PV/T collectors was measured using an ISO 9060 first class complaint Kipp & Zonen CMP 6 pyranometer. The following Figure 2 shows a schematic diagram of the full setup and Figure 3 shows the Photographic view of solar PV/T hybrid collector system.

The following Table 2 presents specifications of VOLTHERM POWER THERM hybrid PV/T collector as provided by the manufacturer.

Test Procedure and Condition

The closed hydronic circuit of the solar PV/T hybrid collector was firstly injected with the Nanofluid, and a static pressure of 0.4 bar and flow rate of 3.25 L/min was maintained. Figure 4 shows a photographic view of Nanofluid insertion process. The experimental tests took place in March 2017, solar irradiation, wind speed, inlet, outlet, and ambient temperatures were all recorded on hourly basis starting from 9:00 AM till 15:00 PM. The experiments have been repeatedly conducted so to obtain nearly matching or fixed surrounding atmospheric conditions and hence the comparison analysis becomes as realistic and accurate

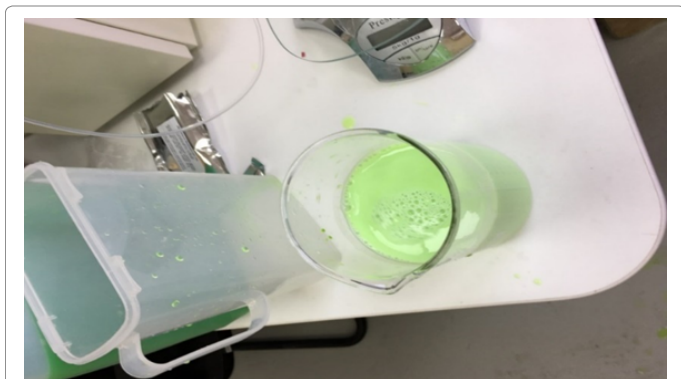


Figure 1: Al₂O₃-ZnO distilled water with Ethylene Glycol Nanofluid.

as possible. Selected two days data representing each different heat carrier fluid scenario were used for the analysis. The following Figure 5 compares solar irradiation, wind speed, and ambient temperatures for the two days of interest climatic conditions.

Methods

Thermo-physical properties of nano-fluid

The following available in the literature set of equations were utilized to quantify the thermo-physical properties of the resulting Nano-solution. Pak and Cho [14] mentioned in their work the well-known equation of density which will represent the nano fluid as:

$$\rho_{nf} = (1 - \phi)\rho_{bf} + \phi\rho_{np} \quad (1)$$

Where ρ_{nf} is density of nanofluid, ϕ is mass fraction of Nanoparticles, ρ_{bf} and ρ_{np} are densities of base fluid and Nanoparticles respectively. Density of the base fluid ρ_{bf} represents the mixture of distilled water and Ethylene Glycol and is computed using the same Eqn (1).

For the heat capacity of the Nanofluid, Chow et al. [1] has quoted the following equation:

$$C_{p_{nf}} = (1 - \phi)C_{p_{bf}} + \phi C_{p_{np}} \quad (2)$$

Where $C_{p_{nf}}$ is heat capacity of the Nanofluid, $C_{p_{bf}}$ and $C_{p_{np}}$ are heat capacities of base fluid and Nanoparticles respectively. Heat capacity of the base fluid $C_{p_{bf}}$ represents the mixture of distilled water and Ethylene Glycol and is computed using the same Eqn (2).

Thermal conductivity of the Nanofluid k_{nf} is calculated from the empirical correlation derived by Corcione [15]

$$\frac{k_{nf}}{k_{bf}} = 1 + 4.4 \text{Re}^{0.4} \text{Pr}^{0.66} \left(\frac{T_{nf}}{T_{fr}} \right)^{10} \left(\frac{k_{np}}{k_{bf}} \right) \quad (3)$$

Where thermal conductivity of the base fluid k_{bf} represents the mixture of distilled water and Ethylene Glycol and is computed by Jamieson et al. [16]:

$$k_{bf} = k_w \phi_w + k_{Eth} \phi_{Eth} - (k_w - k_{Eth})(1 - \sqrt{\phi_w})\phi_w, k_w > k_{Eth} \quad (4)$$

Where k_w and k_{Eth} are thermal conductivities of water and Ethylene Glycol, ϕ_w and ϕ_{Eth} are mass fractions of water and Ethylene Glycol respectively.

Re is the Nanoparticles Reynold's number and is defined by Corcione [15] as

$$\text{Re} = \frac{2\rho_{bf}K_bT_{nf}}{\Pi\mu_b^2d_p} \quad (5)$$

Where $K_b = 1.38066 \times 10^{-23} \text{J} \cdot \text{K}^{-1}$ is Boltzman constant, T_{nf} is the Nanofluid temperature, d_p is the Nanoparticle diameter, and dynamic viscosity of the base fluid μ_b represents the mixture of distilled water and Ethylene Glycol and is computed by Papaioannou et al. [17]:

$$\ln\mu_{bf} = \sum_i x_i \ln\mu_i \quad (6)$$

Where x_i and μ_i are the component respective mole fraction and dynamic viscosity.

Pr is the base fluid Prandtl number $\text{Pr} = C_{p_{bf}}\mu_{bf}/k_{bf}$, T_{fr} is freezing point of the base fluid which is -3.2°C for the 10 wt.% of Ethylene Glycol aqueous solution [18], and k_{np} , x_{np} are the thermal conductivity and volume fraction of the Nanoparticles respectively.

Eqn (3) strictly represents a Nanofluid that contains solely

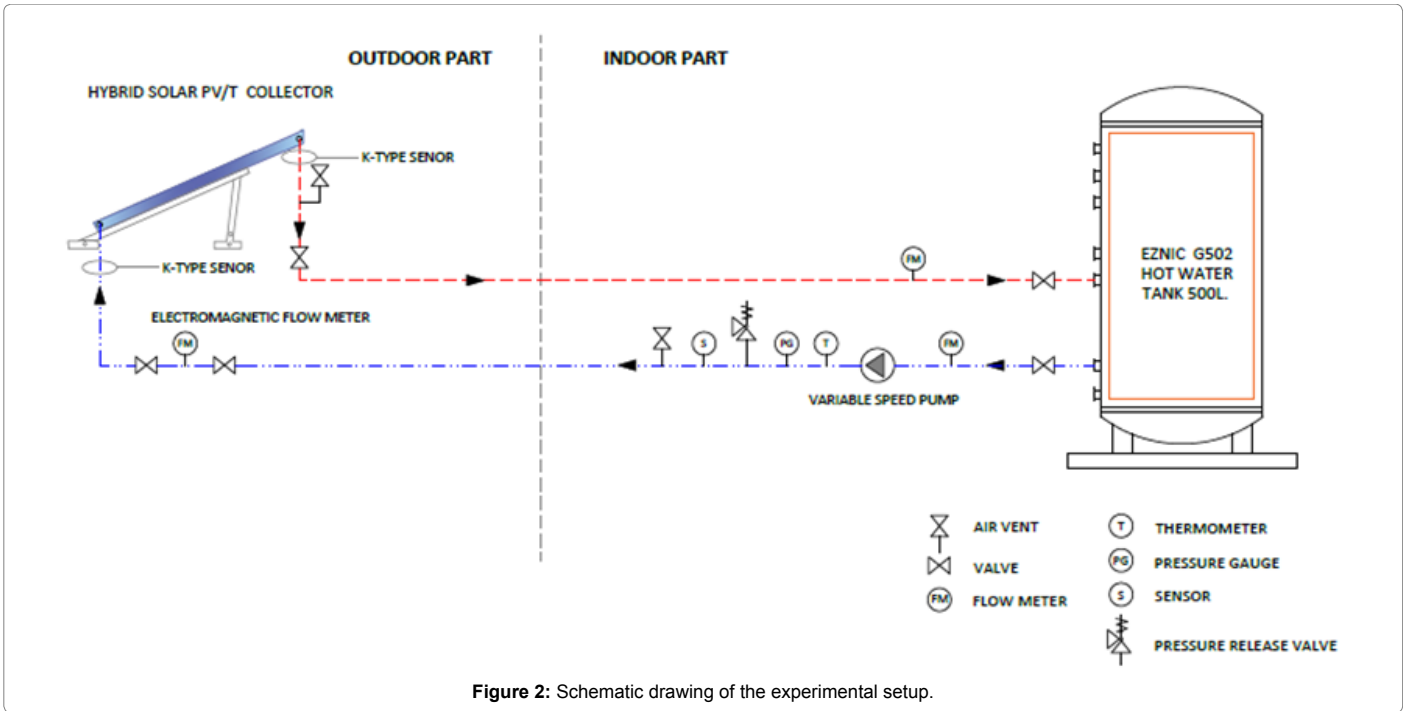


Figure 2: Schematic drawing of the experimental setup.

Substance	Density (kg/m ³)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Dynamic viscosity (Pa.s)	Quantity (g or liter)
Aluminum oxide nanopowder Al ₂ O ₃ ("Aluminum Oxide Nanopowder / Nanoparticles (Al ₂ O ₃ , gamma, 99.99%, 5nm, Hydrophilic)," n.d.)	3890	880	36.96 at 27°C ("Weblet Importer," n.d.)	---	25g
Zinc oxide nanopowder ZnO ("Zinc Oxide Nanoparticles / Nanopowder (ZnO, 99+%, 10-30 nm)," n.d.)	5610	504.7	54 at 27°C (Madelung et al., 1999)	---	25g
Water	998	4186	0.58	0.7255×10 ⁻³	50 liters
Ethylene Glycol(Sigmund, 2009)	1117	2470	0.25145 at 27°C	0.0214	5 liters

Table 1: Summary of thermo-physical properties and quantities of Nanofluid components.



Figure 3: Photographic view of solar PV/T hybrid collector system set connected in series within a closed hydronic circuit at the Techno Hub facility, Gulf organization for research and development, Qatar (latitude 25.3548° N).

Glazing	Low iron tempered glass,
Cell type	Monocrystalline silicon
PV module efficiency	12
Module area	1.28 m ²
PV cell efficiency	15.24
Number of Cells	12 × 6(72)
Cell Dimensions LW	125 × 125 mm
Cell thickness	200 μm
Nominal operating cell temperature (NOCT)	37°C
Copper sheet thickness	0.12 mm
Absorber material	Copper
Absorber tube external diameter	8 mm
Absorber tube thickness	0.45 mm
Thermal insulation	50 mm (glasswool), 40 mm (EPS)

Table 2: Specifications of the hybrid PV/T collector.

Dynamic viscosity of the Nanofluid μ_{nf} is calculated from the empirical correlation derived by Corcione [15]:

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{1 - 34.87(d_{np} / d_{bf})^{-0.3} x_{np}^{1.03}} \quad (7)$$

d_{bf} is the equivalent diameter of the base fluid molecule given by

one Nanoparticle substance in its mixture, hence the effective thermal conductivity of the Nanofluid will be the averaged thermal conductivities calculated for each Nanoparticles substance.



Figure 4: Insertion of Nanofluid in the PV/T closed hydronic circuit.

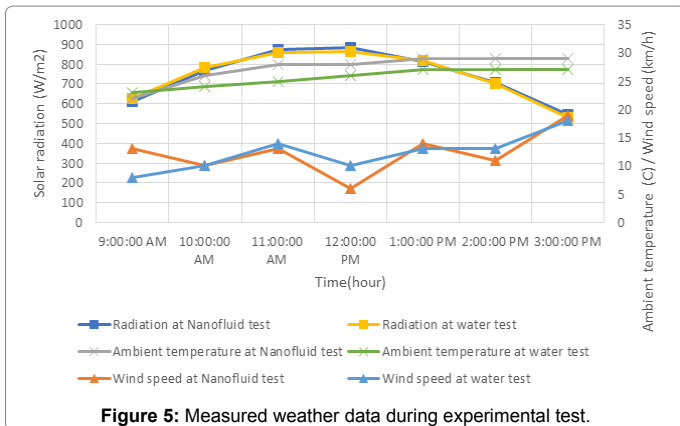


Figure 5: Measured weather data during experimental test.

Corcione [15]

$$d_{bf} = 0.1 \left(\frac{6M}{N\pi\rho_{bfo}} \right)^{1/3} \quad (8)$$

Where M is the molecular weight of the base fluid, $N = 6.022 \times 10^{23} \text{ mol}^{-1}$ is Avogadro number, and ρ_{bfo} is the density of the base fluid calculated at $T_c = 293\text{K}$.

Eqn (7) strictly represents a Nanofluid that contains solely one Nanoparticle substance in its mixture, hence the effective dynamic viscosity of the Nanofluid will be the averaged dynamic viscosities calculated for each Nanoparticles substance.

Computational model

Finite Element Modeling (FEM) and simulation was introduced in this work to help computing magnitudes of PV module surface temperature, structural part in the hybrid PV/T collector system, in accordance with day hours so to eventually evaluate thermodynamic and electrical efficiencies. Figure 6 illustrates a section drawing of Power Therm PV/T collector various components that are of interest in the computational analysis.

The conjugate heat transfer, laminar flow interface built in COMSOL Multiphysics' FEM software allows analysis of the phenomenon of forced convection between a heat carrier fluid and the high-temperature PV cells as a heat source. The governing heat transfer equation for every previous and subsequent layer of the PV cells needs to be considered so to conclude to a model when entered and solved computationally by the software will accurately predict the PV cells temperature. Figure 7 shows the geometry considered for deriving the computational model and the major corresponding heat transfer modes in different directions.

The general heat energy balance equation would be:

$$Q_{SUN} - Q_{RAD} - Q_{CONV} - Q_T = 0 \quad (9)$$

$$Q_{COND} = Q_T \quad (10)$$

Heat transferred downwards in direction of thermal insulation layer $Q = 0$. The inward steady state heat transferred from the Sun is:

$$Q_{SUN} = GA_c \quad (11)$$

Where G is the solar irradiation and A_c is the PV/T collector surface area. The glazing radiated heat out of the system is formulated by [1] as:

$$Q_{RAD,g-a} = h_{RAD,g-a} (T_a - T_g) \quad (12)$$

Where $Q_{RAD,g-a}$ is the heat transferred by radiation from the glazing surface to the surroundings, $h_{RAD,g-a} = 4\sigma T_a^3$ (Ingersoll, 1986) is the radiative coefficient from the glazing, where $\sigma = 5.775 \times 10^{-8} \text{ W / m}^2 \text{ K}^4$ is the Stefan-Boltzman constant, T_a is the ambient temperature, and T_g is the glazing temperature.

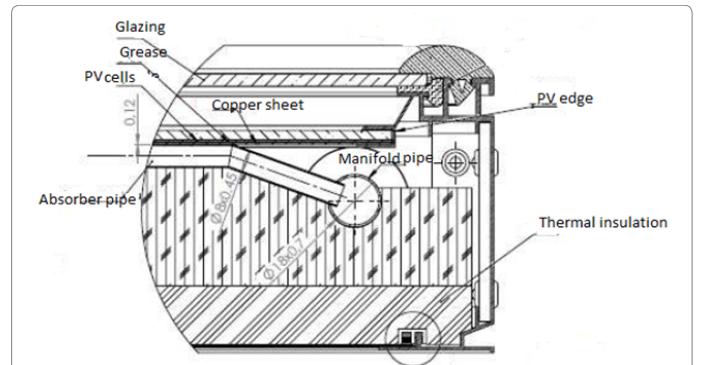


Figure 6: Power Therm Hybrid PV/T collector section drawing shows different layers used in the computational analysis.

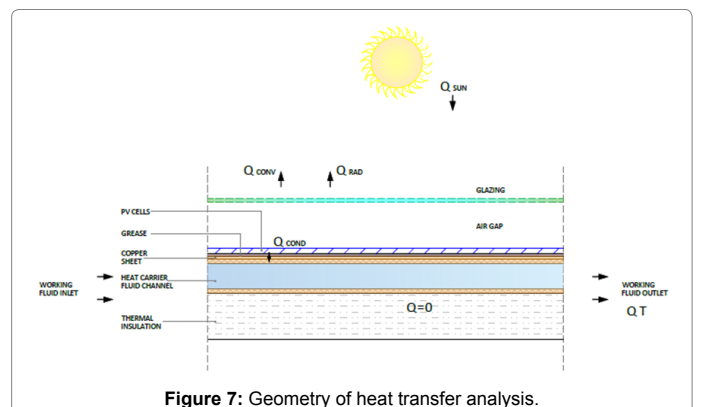


Figure 7: Geometry of heat transfer analysis.

The glazing will also radiate heat inside the system and towards the PV cells again according to the formula [1]:

$$Q_{RAD,g-c} = h_{RAD,g-c} (T_c - T_g) \quad (13)$$

Where $Q_{RAD,g-c}$ is the heat transferred by radiation from the glazing surface to the PV cell surface, and T_g is the PV cells surface temperature.

PV cells surface will by its turn radiate heat in the upwards direction, represented by the equation (Oruc et al., 2016):

$$Q_{RAD,pv} = \epsilon \sigma (T_c^4 - T_g^4) \quad (14)$$

Where $Q_{RAD,pv}$ is the upward heat transferred by radiation from the PV cells, and $\epsilon=0.85$ is the average surface emissivity of silicon.

Summation of $Q_{RAD,g-a}$, $Q_{RAD,g-c}$, and $Q_{RAD,pv}$ will give the total heat transfer by radiation of the system Q_{RAD} .

Heat transferred due to convection out of the system is [1]:

$$Q_{CONV,g-a} = h_{wind} (T_a - T_g) \quad (15)$$

Where $Q_{CONV,g-a}$ is the heat transferred by convection from the

glazing surface to the surroundings, $h_w = 0.6 + 6.64 \sqrt{v_w} W / m^2 \cdot ^\circ C$ [19] where v_w is the wind speed.

Heat transferred due to convection towards the PV cells surface [1]

$$Q_{CONV,g-c} = h_{g-c} (T_c - T_g) \quad (16)$$

Where $Q_{CONV,g-c}$ is the heat transferred by convection from the glazing surface to the PV cells surface.

Summation of $Q_{CONV,g-a}$, and $Q_{CONV,g-c}$ will give the total convection heat of the system Q_{CONV} .

The general equation for steady state heat transfer within heat carrier fluid layer is stated by Yousefi et al.:

$$Q = m C_p (T_o - T_i) \quad (17)$$

Where m is the mass flow rate of the working fluid, C_p is the heat capacity of the working fluid, T_o and T_i are the inlet and outlet temperatures, respectively.

The forced convection is described using the continuity and momentum equations for laminar and incompressible fluid flow as follows [20]:

$$\nabla \cdot (\rho u) = 0$$

$$\rho u \cdot \nabla u = \nabla p + \nabla \cdot (\mu (\nabla u + (\nabla u)^T)) \quad (18)$$

The initial temperature of the PV cells was assumed to be derived from the equation [21]:

$$T_c = T_a + (NOCT - 20^\circ C) \frac{G}{800} \quad (19)$$

So, to reduce number of iteration carried out by the software and to increase the accuracy of the resulting temperature.

Thermo-physical properties of each layer material and used in the COMSOL software are listed in Table 3.

Thermodynamic analysis

The conventional first law of thermodynamics thermal efficiency η_t as mentioned by Yousefi et al. [5] is:

$$\eta = \frac{m C_p (T_o - T_i)}{G A_c} \quad (20)$$

Where G is the solar irradiance and A_c is the collector's surface area.

The electrical efficiency of the PV module mounted at the upper part of the PV/T hybrid collector can be represented by the simplified equation [22]:

$$\eta_e = \eta_{e,ref} \times (1 - \beta \times (T_c - T_{ref})) \quad (21)$$

Where $\eta_{e,ref}$ is the PV module electrical efficiency at standard testing condition (STC), β temperature coefficient for cell efficiency and equals $0.0045^\circ C^{-1}$ [23], and T_{ref} is reference temperature at STC which is $25^\circ C$.

The total or overall efficiency of the PV/T hybrid collector $\eta_{PV/T}$ then is the automatic linear combination of the thermal and electrical efficiencies of the collector system according to Fujisawa and Tani [24]:

$$\eta_{PV/T} = \eta_e + \eta_t \quad (22)$$

The exergy term represents the convertible amount of low grade energy into useful one, and hence the exergetic efficiency (second law of thermodynamics efficiency) equation for the predefined quasi-static process would be [1]:

$$\epsilon_t = \frac{Q_{t,exergy}}{Q_{SUN,exergy}} = \frac{Q \left(1 - \frac{T_a}{T_o} \right)}{\left[1 - \frac{T_a}{T_{SUN}} \right] G} \quad (23)$$

Where T_a is the ambient temperature, T_o is outlet temperature of the fluid medium, and T_{SUN} is the solar radiation temperature at 6000K.

For the electrical exergetic efficiency ϵ_e of the PV part in the PV/T hybrid collector system the following equation is inclusive [1]:

Layer	Material	Density (kg/m ³)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Dynamic viscosity (Pa.s)
Glazing	Low iron tempered glass(ABRISA Technologies, 2014)	2530	879.2	0.937	---
PV cells	Monocrystalline silicon(Yang et al., 2012)	2330	700	130	---
Copper sheet and absorber pipe	Copper (Yang et al., 2012)	8940	390	401	---
Nanofluid (at 35°C)	ZnO+Al ₂ O ₃ +water+Ethylene Glycol	1013	4005.7	1.8312	8.1021 × 10 ⁻⁴
Water (at 35°C)	-----	993.95	4186	0.58	0.7255 × 10 ⁻³
Thermal insulation	GLASSWOOL +EPS	---	---	---	---

Table 3: Properties of solar PV/T hybrid collector layers used in COMSOL simulation.

$$\varepsilon_e = \frac{Q_{e,exergy}}{Q_{SUN,exergy}} = \frac{\eta_e}{\left[1 - \frac{T_a}{T_{SUN}}\right]} \quad (24)$$

And the total exergetic efficiency is:

$$\varepsilon_{PV/T} = \varepsilon_e + \varepsilon_t \quad (25)$$

Results

The following Figure 8 demonstrates magnitudes of PV cells temperature for each of the two heat transfer fluids obtained from the computational analysis.

Improvements in the cooling of PV cells due to use of Nanofluid is barely exists according to Figure 8 by an averaged reduction in temperature of 0.65°C. Figure 9 presents the electrical, thermal, and total efficiencies of the PV/T hybrid system for the heat transfer fluids used in this study.

Figure 10 presents the electrical, thermal, and total exergetic efficiencies of the PV/T hybrid system for each of the two heat transfer fluids used in this study.

Figures 9 and 10 illustrates the variation in different efficiencies between the two heat transfer fluids. The effect of Nanofluid in the electrical efficiency is trivial when compared with the effect in the thermal efficiency, which complies with the general benefit of Nanofluid utilization which is the increase of thermal capability of the system at the first place. The following Table 4 summarizes the averaged increment in the relevant efficiencies.

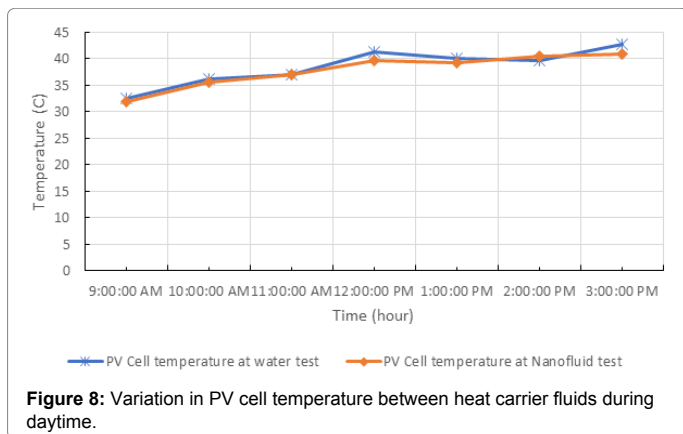


Figure 8: Variation in PV cell temperature between heat carrier fluids during daytime.

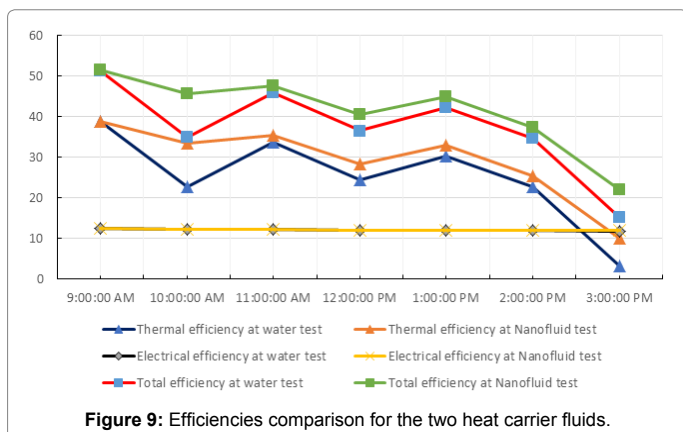


Figure 9: Efficiencies comparison for the two heat carrier fluids.

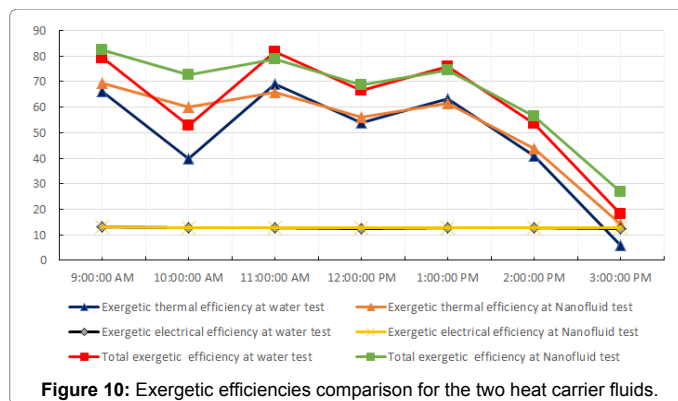


Figure 10: Exergetic efficiencies comparison for the two heat carrier fluids.

Efficiency	Averaged increment
Thermal	4.053604873
Electrical	0.038064214
Total	4.091669087
Thermal exergetic	4.588498137
Electrical exergetic	0.04388059
Total exergetic	4.632378727
Efficiency	Averaged increment (%)
Thermal	4.054
Electrical	0.038
Total	4.092
Thermal exergetic	4.588
Electrical exergetic	0.044
Total exergetic	4.632

Table 4: Averaged increment while using the Nanofluid.

Curve fitting was applied over the obtained data range to define the behavior of Nanofluid in compliance with the ambient temperature. Fig. 11 plots PV cells temperature difference between the two working fluids against the averaged ambient temperature during daytime testing. The points were splitted into two regions of interest and connected in form of descending lines.

The observed trend of Fig. 11 generally states a segmental decrease in the Nanofluid effect. The following possibilities were suggested to explain the illustrated behavior:

Either a discontinuous function correlates the independent variables (PV cells temperature difference and ambient temperature) together, which splits around 12:00 PM to recontinue its dramatic descending direction, therefore the effect of Nanofluid is fluctuating with the increase in ambient temperature while keeps its declining manner.

Or it is a linear descending function, with some outliers which caused that noise in the graph.

Conclusions

The averaged PV surface temperature was obtained by means of finite element modeling software COMSOL Multiphysics for each working fluid scenario. The average increase in the electrical efficiency was less than 0.1% which is rational as it complies with the low concentrations of the Nanoparticles and it may considered neglectable. The traceable effect of Nanoparticles appeared in the averaged increase of thermal efficiency, which was around 4.1%. The increase in total exergy efficiency was also detectable by 4.6%, which presents a typical increase in the use of low grade energy.

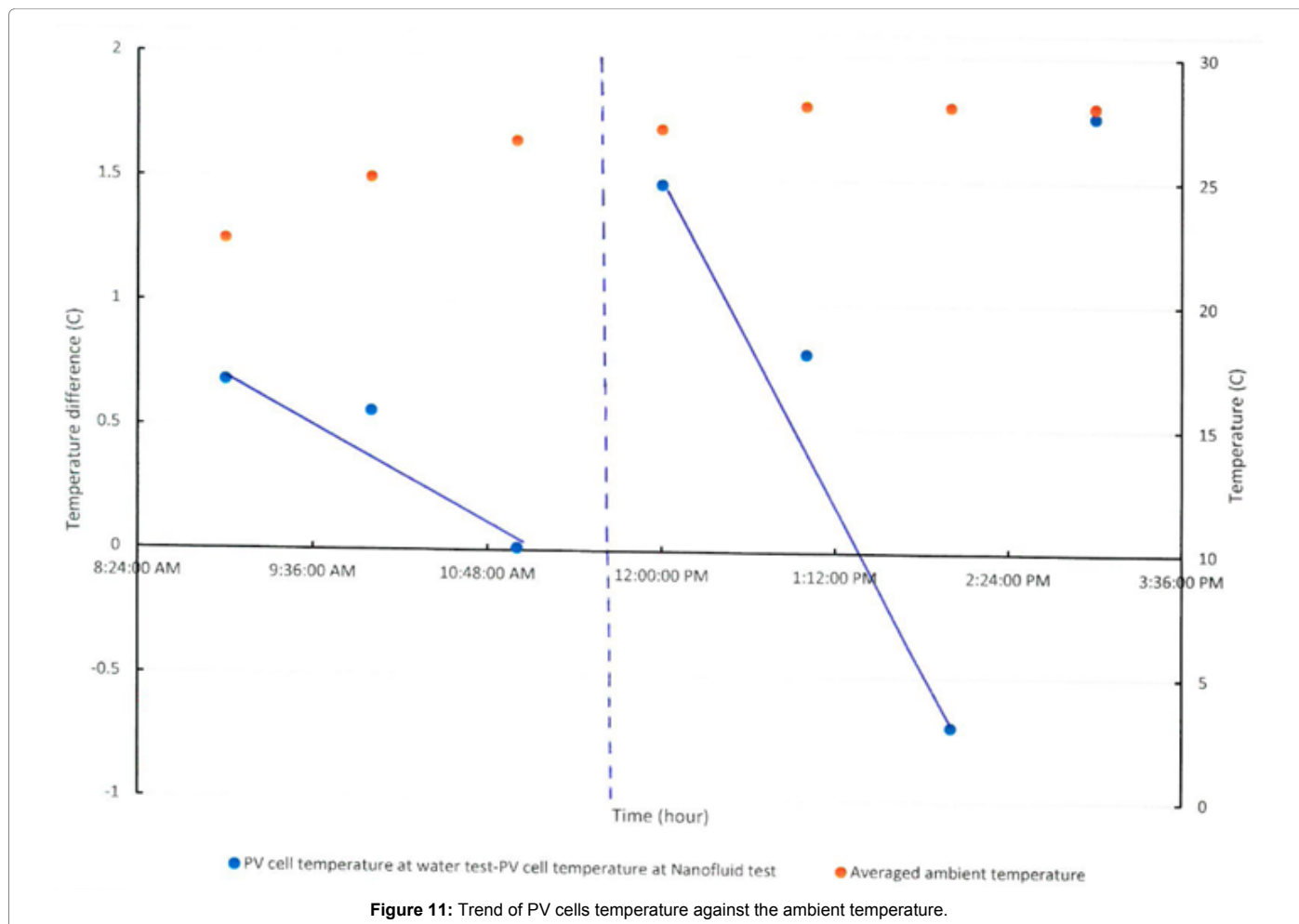


Figure 11: Trend of PV cells temperature against the ambient temperature.

Abstractly, it is concluded that the effect of Nanofluid in hot climates might be subjected to declination in accordance with ambient temperature increase.

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