EXPERIMENTAL INVESTIGATION OF USING GRAPHENE NANOPLATELETS AND HYBRID NANOFLUID AS COOLANT IN PHOTOVOLTAIC PV/T SYSTEMS

Omran ALSHIKHI¹*, Muhammet KAYFECİ²

¹Department of Energy Systems Engineering, Institute of Graduate Studies, Karabük University, Karabük, Turkey
²Department of Energy Systems Engineering, Faculty of Technology, Karabük University, Karabük, Turkey

*Corresponding author; E-mail: oalshikhi@gmail.com

Abstract: It is a common observation that the photovoltaic (PV) panel shows a compromised performance when its temperature rises. To handle the performance reduction, most PV panels are equipped with a thermal absorber for removing the solar cells’ excessive heat with the help of a heat transfer fluid. The mentioned thermal absorber system is termed as PV thermal or simply PV/T. This study aims to experimentally investigate the effects of a graphene nano-platelets (GNP) nanofluid, distilled water, and hybrid nanofluid (HyNF) as transfer fluids in PV/T collectors. A hybrid nanofluid comprises aluminum oxide (Al₂O₃) and GNP. An outdoor experimental setup was installed and tested under the climatic conditions in Karabük (Turkey) to measure the inlet as well as outlet PV/T fluid temperatures, ambient temperature with solar radiation, and surface temperatures of both PV/T collector and the PV panel. The mass percentage of the coolant fluids was 0.5% (by weight) and their flow rate was 0.5L/m. Results show that the (GNP)nanofluid is the most effective fluid because it showed superior thermal efficiency among all the tested fluids. Adding a thermal unit to the PV/T unit increased the overall energy efficiency by 48.4%, 52%, and 56.1% using distilled water, hybrid nanofluid, and graphene nanofluid, respectively.

Keywords: photovoltaic thermal unit PV/T; energy performance; graphene nanofluid; hybrid nanofluid; nanofluids.

1. Introduction:

Energy systems rely on fossil fuels all over the world, which dramatically decrease when their consumption increases, and it requires focus on producing alternative energy sources. The issue of greenhouse gases emerged as a consequence of fossil fuel combustion. According to estimates, the global energy demands are expected to increase further 45% until 2030 (1.6% annually) [1]. Now, most developed nations are attempting to switch to common renewable energies to generate power, including wind, solar, and biofuels. The solar energy is received and used through thermal systems for power generation through photovoltaic effect. Generally, just 5-20% of incident solar radiation, which is
received using conventional PV modules, can actually be transformed into electricity while the leftover solar energy stores as heat in a PV[2]. Generally, silicon solar cells are used to convert some radiation into electricity while the residual solar radiation converts into thermal power.

Normally, it is possible to convert 7% radiation into electricity when amorphous silicon is used while 16% radiation can be converted into electricity when cadmium telluride is used. Some radiation mediates and transforms into heat, which raises the cell temperature and diminishes both efficiency and output of a cell. Thermal collectors can collect this heat for heating water and air[3] using photovoltaic thermal PV/T units rather than using just PVs. It reduces the two separate systems’ position areas, materials, and costs besides improving the overall efficiency. Typically, a PV cell’s heat recovers when a cooling medium is applied that can be air, liquid, or a mix of both. PV/T systems simultaneously generate both electric and thermal energies using the same surface area. Several researchers have used air[4], water[5-8] and nanofluids to cool down PVs or reduce their surface temperatures by using a number of ways, including spraying water[9] and running a water film on the back surface of a PV with the help of nozzles [10]. Nanofluids are mixtures of phase-solid nanoparticles and deionized water, which are different as compared to conventional cooling fluids[11]. Nowadays, nanofluids have widespread applications and they have unique heat transfer characteristics, substantial thermal conductivity, and enhanced heat transfer mechanisms. Moreover, they have the ability to decrease the temperature in PV/T collectors and a number of devices. Nanofluids have two varieties: Single nanofluid that is made using a single type of nanoparticles and a hybrid nanofluid, which is a mixture of various nanoparticles and base liquids. Bhattacharjee et al. [12] performed experimental investigations using three different designs of solar photovoltaic panel (circular spiral, circular spiral semi-flattened, and semi-oval serpentine) to absorb heat on the back surface. The results showed that a circular spiral semi-flattened absorber most optimally performed among all the investigated types because it showed highest efficiency (4.32%) and fill factor (19.80%). In a recent indoor study, Al-Waeli et al. [13] tested Al2O3, CuO, and SiC-based nanofluids for performance enhancement of PV/T systems at 4.0% concentration by volume. They attached a 110-watt PV panel to a solar collector to construct their PV/T. They cooled their working fluid by passing it through a storage tank. According to the results, SiC nanoparticles showed superior stability and thermal conductivity, which can improve the PV/T system performance as compared to the other two nanofluids. In another study, Al-Waeli et al. [14] used three different types of nanoparticles in water-based fluid with different volumes to determine the nanoparticles’ best concentration, which is appropriate to cool down an indoor PV/T system. They selected CuO, SiC, and Al2O3 nanoparticles and added them to water by volume (0.5, 1, 2, 3, and 4%). Results showed that adding nanoparticles improved the thermal conductivity of the fluid that slightly increased the density and viscosity as compared to water. A suspension with SiC nanoparticles showed higher stability and thermal conductivity when it was compared to the suspensions with other nanoparticles. The fluid containing CuO had the next best thermal conductivity while Al2O3 showed the least thermal conductivity but the fluid’s output stability was lower. The results showed stabilizing properties of the three selected materials.

In another study, Vakili et al. [15] conducted experiments on de-ionized water and GNP in a solar collector. Until then, (GNP) nanofluid was not used as a working fluid in any volumetric solar collector.
Their results showed an ideal mass flow rate (0.015 kg/s) with zero-loss efficiency while weight fractions at 0.0005, 0.001 and 0.005 were 83.50%, 89.70%, and 93.20% respectively. It was 70% when a base fluid was used. Ebaid et al. [16] conducted experiments to investigate a couple of nanofluids and water as coolants at volumetric flow rate 0.5-5 L/min (0.01%, 0.05% and 0.1% wt. concentrations). They used TiO₂ in a water-cetyltri-methylammonium bromide mixture (pH 9.7), Al₂O₃ in a water-polyethylene glycol mixture (pH 5.7), and concluded that both types of nanofluid cooling substantially reduced the average PV cell temperature after comparing the results of using water as a coolant. They declared that the Al₂O₃ nanofluid outperformed as compared to the TiO₂ nanofluid while higher nanofluid concentrations produced a better cooling effect on the PV cell. Moreover, the electrical power and efficiency analyses revealed that the TiO₂ nanofluid performed better than water. Another experimental investigation by Iranmanesh et al. [17] analyzed the effect of using a graphene nano-platelet-distilled water nanofluid on the thermal performance of a tube solar collector water heater. The flow rates of 0.5, 1, and 2 L/min were selected for different nanofluid concentrations (0.025, 0.5, 0.75 and 0.1% wt.). They reported that the mentioned nanofluid improved the thermal efficiency of the solar collector by up to 90.7% at 1.5 L/min when it was used as an absorption medium. A mathematical model was proposed by Al-Waeli et al. [18] that discussed a new nanofluid/nano-PCM PV/T system. This model was tested by conducting experiments using silicon carbide-water nanofluid and silicon carbide-PCM in the PV/T system. The comparison proved effectiveness of the proposed mathematical model. Sangeetha et al. [19] showed the effects outdoors of nanofluids (Al₂O₃, CuO and MWCNT) mixed with water at 0, 0.5, 1, 2.5 and 5% vol. on PV/T systems. They showed that MWCNT and CuO reduced cell temperatures by nearly 19%. MWCNT, Al₂O₃ and CuO respectively produced electrical efficiency improvement by approximately 60%, 55%, and 52% greater than the conventional PVs. Moreover, Al₂O₃, CuO, and MWCNT on PV/T systems produced a greater exergy efficiency than the conventional PVs. Alousetal. [20] studied the performances of graphene nano-platelets mixed in water as a base fluid (flow rate: 0.5 L/min; wt. concentration: 0.5%) and PV/T systems of multi-walled carbon nanotubes (MWCNT). The MWCNT-water mixture performed better for photovoltaic energetic conversion as compared to graphene and distilled water. They reported that the graphene-water nanoplatelets have shown the highest thermal energetic efficiency. Furthermore, the total energy efficiency increased by 63.1% for graphene-water, 57.2% for MWCNT water, and 53.4% for distilled water. The total exergy efficiency increased by 12.1%, 20.6%, and 11.2% for the PV/T collector when it was cooled using MWCNT-water nanofluid, graphene nanoplatelet-water nanofluid, and distilled water, respectively.

Our study aims to divert the research community’s attention towards using HyNF as coolants in PV/T collectors, which is still rare in the literature. This study, to the best of our knowledge, is the first attempt to conduct experimental investigations on using a hybrid nanofluid of aluminum oxide and GNP as a coolant in PV/T collectors. The hybrid nanofluid is made of two types of nanofluids (GNP and Al₂O₃), which has an equal quantity and concentration. Water and GNP were also used to achieve the same aim. The concentration for the coolants used were 0.5 wt%, at coolants’ flow rate 0.5 L/min. Moreover, a PV/T collector is designed using a rectangular tube heat exchanger and a sheet. The experiment was designed, and both PV/T and PV were installed at the same level and direction, and they were exposed to the same factors. Also, all experiments have been conducted outdoor at the University of Karabuk, Turkey, at
different experimental days. The analysis of the obtained results was conducted from energetic perspective and they were compared with water-cooled PV/T system and PV module results. The thermal and electrical energy efficiencies were calculated and compared with the other research results cited above.

2. Experimental set-up

An experimental test rig was constructed at the Karabük University (Turkey) between August and October, 2019. It used a two 20-watt polycrystalline PV module; one of them was used to construct a PV/T collector, which can be seen in Figure. 1. The photovoltaic module specifications have been listed in Table 1. A 1mm thick copper plate was installed on the PV unit’s bottom surface and soldered with a copper tube as a singleunit. The tube was square in shape with 10mm outer dimension and 8mm inner dimension. Also, it was installed below the thermal barrier insulation to maintain the effectiveness of heat exchange. Thermal paste was used to ensure the perfect contact between the copper plate and the surface behind the PV module.

Moreover, there were extra components in the system, which are shown in Figure 2. We used a Nova RS25/4G-130 pump to run the fluids through the nanofluid storage tank, PV/T collector, and heat exchanger for cooling down the warm fluid. We used a Sea YF-S201 flow meter for measuring and controlling the coolant flow rate at 0.5 L/m. We connected the K-type thermocouples to a computer and eight channel data loggers (Pico, USB TC-08 thermocouple data logger) for measuring the inlet and outlet fluid temperatures besides measuring ambient and surface temperatures.

Solar radiation was measured by using an EKO MS-602 (Japan) pyranometer, which was connected to a data collecting board with a 4.2-inch screen Arduino and SD card. PV/T collector and PV module were inclined at a constant 30° angle of inclination towards south and tested under identical conditions. All data were simultaneously collected every 12seconds.

![Figure 1. Picture of the experimental setup](image)

<table>
<thead>
<tr>
<th>Table 1. Specifications of typical PV/T panel.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Type</strong></td>
</tr>
<tr>
<td><strong>Brand Name</strong></td>
</tr>
<tr>
<td><strong>Electrical Characteristics</strong></td>
</tr>
<tr>
<td>Rated Max. Power (Pmax)</td>
</tr>
<tr>
<td>Power Tolerance Range</td>
</tr>
<tr>
<td>Open Circuit Voltage (Voc)</td>
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<tr>
<td>Max Power Voltage (Vmp)</td>
</tr>
<tr>
<td>Short Circuit Current (Isc)</td>
</tr>
<tr>
<td>Max Power Current / (Imp)</td>
</tr>
<tr>
<td>Max. System Voltage</td>
</tr>
<tr>
<td>Max. Sense Fuse Rating</td>
</tr>
<tr>
<td>Dimension</td>
</tr>
</tbody>
</table>
3. Testing procedure

We conducted numerous experiments in August, September and October 2019 under consistent weather conditions, and noted the measurements. The experimental duration was 09:30-17:00 for tests pertaining to the GNP, distilled water, HyNF, and PV/T coolant inlet and outlet temperatures. We also measured solar irradiance, PV and PV/T surface temperatures, and generated current and voltage for PV and PV/T simultaneously every 12 seconds with a regular flow rate (0.5L/min) during the experiment. Then, the datacollection during the selected days was used to compute averages and for further calculations. We also studied and compared the performances of the PV/T water-cooled, PV/T nanofluid-cooled, and PV modules.

4. Preparation of nanofluids

The hydrous dispersion of the GNP(1-12μm diameter, 0.55-1.2nm thickness, more than 99.3% wt. purity, and 500-1200 m²/g specific surface area), HyNF consisting of 1:1 0.5 GNP,0.5Al₂O₃ concentrations, and Al₂O₃ nanofluids with particle sizes of 30-40nm and 99.9% purity were obtained from NANOGRAFI Co. Ltd. in Turkey. Table 2 shows the thermal properties of both nanoparticles. Figure 3 shows scanning electron microscopy (SEM) image of GNP and Al₂O₃ nanofluids It could be observed that all the particles are almost sheet and spherical in shape Figure 3a and b and nano sized in the range of 10–30 nm with small agglomeration. Figure 4 shows the nanofluid samples after finishing the nanofluid preparation while sedimentation was not observed when experiments were conducted.

Table 3 shows thermo-physical properties of nanofluids and water, which were taken from the literature [21] and the (GNP) nanofluid[22].

Figure 2. Schematic diagram of the experimental setup

Figure 3: Scanning electron microscopy (SEM) image of the nanoparticles: a)GNP, b) Aluminum oxide (Al₂O₃)
Figure 4: Samples of nanofluids: a) Graphene nanoplatelets (GNP) b) Aluminum oxide (Al₂O₃) c) Hybrid nanofluid (HyNF).

Table 2. Thermo-physical properties of water and nanoparticles [20, 21]

<table>
<thead>
<tr>
<th>Property</th>
<th>Water</th>
<th>Al₂O₃</th>
<th>GNP</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho , (kg/m^3) )</td>
<td>997.1</td>
<td>3970</td>
<td>2100</td>
</tr>
<tr>
<td>( C_p , (kJ/kgK) )</td>
<td>4179</td>
<td>765</td>
<td>5000</td>
</tr>
<tr>
<td>( k , (W/mK) )</td>
<td>0.613</td>
<td>40</td>
<td>0.710</td>
</tr>
</tbody>
</table>

5. Analysis

The density of nanofluids is obtained from (Pak and Cho [23]):

\[
\rho_{nf} = \varphi \cdot \rho_{np} + (1 - \varphi) \rho_{bf}
\]

(1)

Where \( \rho_{bf} \) is the base fluid density, \( \varphi \) is the volume concentration of the dispersed fluid, and \( \rho_{np} \) is the nanoparticles’ density; otherwise, the density of the hybrid nanofluid is obtained using the following alternative formula (Al-Oran et al. [24]):

\[
\rho_{hnf} = \varphi_{np1} \cdot \rho_{np1} + \varphi_{np2} \cdot \rho_{np2} + (1 - \varphi_{tot}) \cdot \rho_{bf}
\]

(2)

The volume fraction of nanofluid can be calculated through the following formula (Xuan et al. [25]):

\[
\varphi = \frac{m_p}{\rho_p + \frac{m_f}{\rho_f}}
\]

(3)

Where \( \varphi \) is the volumetric ratio of nanoparticles in a base fluid, and \( \rho \) is the density in kg/m³. We used the following formula to calculate the volume fraction of a hybrid nanofluid (Nadooshan et al. [26]):

\[
\varphi = \left[ \frac{\frac{m}{\rho} \cdot Al_{2}O_{3} + \frac{m}{\rho} \cdot GNP}{\frac{m}{\rho} \cdot Al_{2}O_{3} + \frac{m}{\rho} \cdot GNP + \frac{m}{\rho} \cdot EG} \right] \times 100
\]

(4)

The following equation is used to obtain the heat capacity of nanofluids (Khanjari et al. [5]):

\[
(\rho C_p)_{nf} = (1 - \varphi)(\rho C_p)_{f} + \varphi(\rho C_p)_{p}
\]

(5)

Here, \( \rho \) denotes the density in kg/m³, \( C_p \) represents the specific heat in kJ/kgK, and \( \varphi \) shows the volumetric ratio of nanoparticles in a base fluid. The subscripts f, n, and nf respectively represent base fluid, nanoparticles, and nanofluid. The heat capacity of HyNF is obtained using the following main formula (Al-Oran et al. [24]):
Maxwell-Garnet model is used to calculate the nanofluids’ thermal conductivity by using the following model [27]:

$$\frac{C_{p,hnf}}{\rho_{hnf}} = \frac{\varphi_{np1} \cdot \rho_{np1} \cdot C_{p,np1} + \varphi_{np2} \cdot \rho_{np2} \cdot C_{p,np2} + (1 - \varphi_{tot}) \cdot \rho_{bf} \cdot C_{p,bf}}{\rho_{hnf}}$$  \tag{6}

Also, the thermal conductivity of HyNF was represented by the following equation (Al-Oran et al. [24]).

$$k_{hnf} = k_{bf} \left[ \frac{\varphi_{np1} \cdot k_{np1} + \varphi_{np2} \cdot k_{np2}}{\varphi_{tot}} + 2 \cdot k_{bf} + 2 \cdot (\varphi_{np1} \cdot k_{np1} + \varphi_{np2} \cdot k_{np2}) - 2 \cdot \varphi_{tot} \cdot k_{bf} \right]$$  \tag{7}

Here $\varphi$ is the volumetric ratio of nanoparticles in a base fluid and $k$ represents the thermal conductivity in [Wm$^{-1}$K$^{-1}$].

For performance evaluation of a nanofluid-based PV/T collector, we obtained the thermal variable $Q_u$:

$$Q_u = \dot{m}C_p(T_o - T_i)$$  \tag{8}

Here, $\dot{m}$ is the coolant mass flow rate in kgs$^{-1}$, $T_i$ and $T_o$ are coolant inlet and outlet temperatures, and $C_p$ is the coolant specific heat in [kJ kg$^{-1}$K$^{-1}$].

The PV and PV/T model’s electrical power output is obtained from the following equation:

$$P = I \times V$$  \tag{9}

In this equation, $V$ is the output voltage (V) and $I$ is the output current (A).

The PV/T collector extracts thermal efficiency from solar radiation. The electrical ($\eta_{el}$) and thermal ($\eta_{th}$) efficiencies are expressed below:

$$\eta_{th} = \frac{Q_u}{I_R \times A_{th}}$$  \tag{10}

$$\eta_{el} = \frac{P}{I_R \times A_{PV}}$$  \tag{11}

In this equation, $A_{PV}$ and $A_{th}$ are the area (m$^2$) of PV cells and PV/T collector and $I_R$ shows the total incident solar radiation on the PV and PV/T surfaces (W/m$^2$).

The thermal and electrical efficiencies to assess the overall energetic efficiency of a PV/T collector ($\eta_{ov}$) is as follows (Chow et al. [28]):

$$\eta_{ov} = \eta_{th} + r \cdot \eta_{el}$$  \tag{12}

Where $r = r = A_{PV}/A_{th}$ is the packing factor.

The electrical efficiency increment $\Delta_{el}$ was obtained by Eq. 14.

$$\Delta_{el} = \frac{\eta_{PV,el} - \eta_{PV,el}}{\eta_{PV,el}} \times 100$$  \tag{13}
Table 3. Thermo-physical properties of the studied nanofluids.

<table>
<thead>
<tr>
<th>Property</th>
<th>GNP</th>
<th>HyNF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho (kg m^{-3})$</td>
<td>1259.5</td>
<td>1315</td>
</tr>
<tr>
<td>$C_p (kJ kg^{-1} K^{-1})$</td>
<td>2803</td>
<td>2873</td>
</tr>
<tr>
<td>$k (W m^{-1} K^{-1})$</td>
<td>1.1755</td>
<td>1.0110</td>
</tr>
</tbody>
</table>

Thermal physical properties for the nanofluids are obtained by Eq.1to8.

6. Results and Discussion

For this study, several experiments were conducted on the cooling operations of PV/T modules. All the measurements were collected after every 12 seconds in Figure.5 from 09:30 to 17:00 at flow rate 0.5L/m and it is calculated for two time periods. The first was the all-day period from 09:30 to 17:00 and the second was the peak period from 11:15 to 15:15 for all the coolants under investigation. Firstly, the distilled water experiment was performed on 27 August 2019 at flow rate 0.5L/m under stable weather conditions. Secondly, the same experiment was conducted for the GNP on 18 September 2019 at flow rate 0.5L/m. Finally, the experiment using HyNF was conducted on 1 October 2019 at flow rate 0.5L/m. Because of unstable weather conditions on other days, we ignored the results of several experiments of unstable results.

6.1 Solar Irradiance and Ambient Temperature

The experimental module was tilted about 30° and directed towards south, which is an inappropriate direction to receive solar radiation. As we can see in Figure 6, the highest ambient temperature reached its peak at around 15:15; after which, it started to decrease to 30°C by the end of the experiments at 17:00. Moreover, the solar radiation reached its peak at about 908 Wm$^{-2}$ at 13:45, which gradually decreased to 530 Wm$^{-2}$ by 17:00. All data taken from the experiments are presented in Figure 6.
Figure 6: Ambient temperature on the experiment day and daily average solar radiation intensity

6.2 The surface temperature measurements

Figure 7 shows the PV/T and PV collectors’ surface temperatures during the cooling times for both water and nanofluids from 09:30 to 17:00. The PV/T collector’s surface temperature reduced more quickly when a coolant was used. The first experiment was conducted on 27 August 2019 from 09:30 to 17:00 and distilled water was used for cooling when the ambient temperature and solar radiation were high, and the daylight duration was longer. Moreover, at 09:30, the PV/T and PV surface temperatures were 30°C and 46°C, respectively, and reached a high temperature (38°C) for the PV/T at 14:15 and 56°C for the PV at 13:00. After the middle of the day, the radiation was lower, which decreased the PV surface temperature; however, the inlet, outlet, and PV/T surface temperatures were not affected due to the heat gained by the coolant and to insufficient time to respond and they progressively decreased until the end of the test, which is shown in Figure 7a.

The second experiment was conducted on 18 September 2019 from 09:30 to 17:00 using GNP fluid for cooling. As shown in Figure 7b, the weather was steady most of the day and the surface temperatures for the PV/T and PV increased gradually from 27°C and 39.5°C at 09:30 to 38°C and 54.8°C at 14:45, respectively, which progressively decreased until 17:00. The third experiment was conducted on 1 October 2019 from 09:30 to 17:00 using HyNF for cooling. The solar radiation and ambient temperature were lower than the previous experiments and they were stable most of the test day Figure 7c. The respective surface temperatures (PV/T and PV) were 26.8°C and 39.8°C at 9:30, which gradually increased to 37°C and 52°C, respectively, at 14:15. As a result, when the solar radiation increased, the PV and PV/T surface temperatures increased as well, and the coolant fluid temperatures also increased. The maximum surface temperature values for PV/T and PV collectors using distilled water, GNP, and HyNF were 14.2°C, 14.4°C, and 14°C, respectively.
Figure 7: Daily average variations in surface temperature for PV, PV/T: a) Distilled water, b) GNP, and c) HyNF.

6.3 Electrical Efficiency and electrical power

As mentioned previously, we measured the surface temperature and its effect on the PV/T and PV surfaces and how to use the coolant to reduce the temperature to improve the electrical and the overall energy performance. Furthermore, the electrical energy and the power generated by the panels in relation to PV and PV/T collectors always follow solar radiation, and it was noted that the maximum electric power was generated when the solar radiation was maximum. Table 4 and 5 present the results of the solar radiation, electric efficiency of the PV and PV/T, surface temperature differences, and electrical efficiency increments for both time periods (all day and peak periods).
Table 4. The average daily weather conditions, electrical increment, and cell temperature during the day-long experiment.

<table>
<thead>
<tr>
<th>Type of coolant</th>
<th>$I_R$ (Wm$^{-2}$)</th>
<th>$T_{amb}$ (°C)</th>
<th>$T_{S,PV}$ (°C)</th>
<th>$T_{S,PVT}$ (°C)</th>
<th>$\eta_{PV,el}$ (%)</th>
<th>$\eta_{PVT,el}$ (%)</th>
<th>$\Delta_{eL,in}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>803</td>
<td>28.4</td>
<td>49.4</td>
<td>35.2</td>
<td>8.8</td>
<td>9.6</td>
<td>8.7</td>
</tr>
<tr>
<td>Graphene</td>
<td>794</td>
<td>26.0</td>
<td>48.4</td>
<td>34.0</td>
<td>9.2</td>
<td>10.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Hybrid</td>
<td>742</td>
<td>24.5</td>
<td>48.0</td>
<td>34.0</td>
<td>8.9</td>
<td>9.8</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Figure 8 clearly indicates that the electrical power increases when solar intensity rises; however, during the experimental periods, the average daily solar radiation values using GNP nanofluid, HyNF, and distilled water were 803, 794 and 742 Wm$^{-2}$, respectively. Moreover, all data taken from the experiments in terms of ambient temperature, radiation and electrical efficiency increments were averaged and divided into two times, namely the day-long periods and peak periods, while we compared the performances of the coolants. Every coolant showed significant output electrical energy at 9.6%, 9.8%, and 10.2% for distilled water, HyNF, and GNP, respectively.

Figure 8. Electrical efficiencies and power production using PV/T and PV collectors for the selected coolants: distilled water, HyNF and GNP
Table 5. Average daily weather conditions, electrical increment, and cell temperature during the peak period

<table>
<thead>
<tr>
<th>Type of coolant</th>
<th>$I_R$ (Wm$^{-2}$)</th>
<th>$T_{amb}$ (°C)</th>
<th>$T_{S,PV}$ (°C)</th>
<th>$T_{S,PVT}$ (°C)</th>
<th>$\eta_{PV,el}$ (%)</th>
<th>$\eta_{PVT,el}$ (%)</th>
<th>$\Delta_{el,in}$ (%)</th>
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<tbody>
<tr>
<td>Water</td>
<td>893</td>
<td>29.6</td>
<td>51.0</td>
<td>37.0</td>
<td>10.2</td>
<td>11.4</td>
<td>10.5</td>
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<tr>
<td>Graphene</td>
<td>880</td>
<td>26.7</td>
<td>51.0</td>
<td>36.0</td>
<td>10.8</td>
<td>12.3</td>
<td>12.9</td>
</tr>
<tr>
<td>Hybrid</td>
<td>831</td>
<td>25.0</td>
<td>49.4</td>
<td>35.5</td>
<td>10.5</td>
<td>11.7</td>
<td>11.0</td>
</tr>
</tbody>
</table>

6.4 Electrical Efficiency Increment

As mentioned previously, the PV/T and PV surface temperatures increased when the solar radiation increased from the beginning to the end of the experiments, which decreased the electric efficiency of PV/T. In such cases, the heat is gradually extracted with the coolant fluid at a high temperature, which increases the electrical efficiency. As shown in Figure 9, GNP is the most electrically efficient fluid coolant as compared to rest of the coolants. This indicates that the GNP have higher thermal conductivity as compared to other coolants, which results in faster heat disposal, which is obtained by Eq. 14. Table 4 and Table 5 summarize the average daily electrical increments for the day-long and peak durations.

![Image of Figure 9: Daily average variation in electric efficiency](image)

Table 6: Average daily thermal and overall energy efficiencies for PV/T with different coolants

<table>
<thead>
<tr>
<th>Type of Coolant</th>
<th>All day period</th>
<th>Peak period</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\eta_{th}$ (%)</td>
<td>$\eta_{ov}$ (%)</td>
</tr>
<tr>
<td>Water</td>
<td>38.4</td>
<td>48.1</td>
</tr>
<tr>
<td>GNP</td>
<td>45.7</td>
<td>55.8</td>
</tr>
<tr>
<td>HyNF</td>
<td>43.7</td>
<td>53.5</td>
</tr>
</tbody>
</table>
6.5 Thermal and Overall Energetic Efficiency

In this study, the overall energy efficiency was calculated using Eq. 13 as shown in Figure.11. Since the collector area covers all the photovoltaic cells and the collector while the PV cells have a perfect contact, the packing factor is equal to 1. The results showed that GNP are better than HyNFs and distilled water because they have better thermal as well as overall energy efficiency. Moreover, the overall energy efficiency increased during the day when the thermal efficiency increased and the PV/T collector’s energy extracted from solar energy is too close to the GNP and water values mentioned by Alousetal.[20] and distilled water values indicated by Sardarabadietal.[29]; however, there are several factors, such as wind speed, change in solar radiation, and humidity, and all of them affect the thermal energy efficiency and make the thermal efficiency curve does not follow a specific trend as shown in Figure.10. As a result, the averages of the daily overall energy efficiency for the day-long periods were 48.1%, 53.5% and 55.8% for distilled water, HyNFs and GNP, respectively, and 50.1%, 58.9% and 64.4% respectively for distilled water, HyNF and GNP during the peak period. The reference PV system showed 9.4% average overall efficiency when there was no collector (day-long period) and 10.7% for the peak period. This confirms that thermal cooling units should be used to improve the overall energy efficiency of a PV. We used Eq.11 to obtain the average daily thermal efficiency, which was 38.4% and 45.7% with PV/T for distilled water and GNP, respectively. These results are comparable to the values obtained in a study conducted by Alous et al. [20], who found respective values 38.8% and 47.4% for distilled water and GNP, which are compatible with the values given in Table 6. The result for every experiment depended on different conditions such as ambient temperature, type of cooling, and intensity of solar radiation.

Figure.10: Average daily variation in thermal efficiencies for PV and PV/T
7. Conclusion

In this study, the effects of GNP and HyNF as coolants were experimentally investigated for evaluating the thermal and electrical efficiencies of PV/T systems. The mentioned coolants include GNP, distilled water, and a HyNF (concentration: 0.5% wt.; flow rate: 0.5L/m). The experiments were carried out when all the PV and PV/T had a tilt angle of nearly 30° to compare a conventional PV system with a PV/T system. The results from this study revealed the following:

- Nanofluids and distilled water work as coolants through a cooling module, which reduces the maximum cell temperature for a PV/T system by approximately 14.2°C, 14.4°C and 14°C for distilled water, HyNF and GNP, respectively.
- The overall energy efficiency enhanced by 5.4% and 7.7% for the HyNF and GNP nanofluid as compared to the distilled water.
- The highest electrical energy generation level was observed when GNP nanofluid was used as a coolant.
- For a PV/T system, the thermal efficiency increased by nearly 5.3% and 7.3% more than the distilled water for HyNF and GNP nanofluids, respectively.
- The nanotechnology used in PV/T systems in the form of nanoparticles is more effective for hybrid system efficiency as a coolant as compared to distilled water.
8. References


[10] Abdolzadeh, M., M. Ameri, Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells, Renewable energy, 34.(2009), 1, pp. 91-96