# EXPERIMENTAL STUDY ABOUT UTILIZATION OF MWCNT AND GRAPHENE NANOPLATELETS WATER-BASED NANOFLUIDS IN FLAT NON-CONCENTRATING PVT SYSTEMS

by

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*Although the increment the performance of photovoltaic thermal (PVT) systems by using the nanofluids as working fluids have gained the attention of researchers during the last two decades, there is still, a lack in the literature study associated to this application. This study contributes to the investigations and researches of applying the nanofluids to increase the performance of PVT collectors. A flat non-concentrating PVT collector has been designed, constructed and, outdoor tested in Karabuk University, Turkey. The considered working fluids in this study are multiwall carbon nanotubes (MWCNT), and graphene nanoplatelets dispersed in water as a base fluid with a concentration of 0.5 wt.%. The experiments were run with a volume flow rate of 0.5 L per minute for the aforementioned nanofluids and distilled water (as a reference fluid). The study results have shown and revealed that the MWCNT-water nanofluid presented a better performance in terms of electrical energetic efficiency compared to graphene nanoplatelets-water nanofluid and distilled water, while graphene nanoplatelets-water nanofluid revealed the highest thermal energetic efficiency. Moreover adding thermal unit to photovoltaic module enhanced the total energetic efficiency by 53.4% for distilled water, 57.2% for MWCNT-water, and 63.1% for graphene-water.*

Key words: *PVT, energy analysis, graphene nanoplatelets, nanofluids, MWCNT*

## Introduction

Because of their enhanced thermophysical properties compared to the conventional working fluids (water, air, oil) [1], the usage of nanofluids as coolants in PVT has attracted a lot of interest during the last years. The PVT collector is a system, which can convert the solar energy simultaneously to electricity and thermal energy. This combination technology [2] has come out as a result of cooling PV panels to avoid the consequences of high cells temperature [3] and consequently to increase the PV panel efficiency [4, 5]. Utilization of water, which has the highest thermal conductivity among the used conventional fluids, as a coolant in PVT system [6-9] showed a higher electrical efficiency compared to PV modules. However, these enhancements were limited and restricted by the low thermal conductivity of the conventional

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coolants. Nanofluids, which was introduced by Choi and Estman [10] in 1995, are solid-liquid composite materials consisting of solid nanoparticles or nanofibers with sizes typically of 1 to 100 nm suspended in liquid [11]. A host of several investigations in the literature about utilizing nanofluids in PVT systems agreed that there is a valuable improvement in the performance of nanofluid cooled PVT systems compared to other conventional cooled PVT systems. Hosseinzadeh *et al.* [12] used ZnO/deionized water nanofluid with 0.2 wt.% concentration in their study work at a flow rate of 30 kg/h. The study indicated that reducing the coolant inlet temperature from 40 °C to 20 °C enhances the thermal efficiency of ZnO/water-cooled PVT system by 61.21%. In addition, among the considered parameters in the study (absorbed solar radiation, wind speed, ambient temperature, coolant inlet temperature, coolant mass-flow rate, and nanoparticles mass fraction), the coolant inlet temperature was the most effective parameter on the system efficiency, while for the electrical efficiency the considered parameters have a slight effect. Ebaid *et al.* [13], in their experimental study, used $T_iO_2$-water-cetyltrimethylammonium bromide mixture and $Al_2O_3$-water-polyethylene glycol mixture with the concentrations of 0.01, 0.05, 0.1 wt.% at 500-5000 mL per minute flow rates. The results indicated that $Al_2O_3$ nanofluid showed better performance than $TiO_2$ nanofluid and water. Moreover higher concentration of nanofluids produces a better cooling effect of the PV cell for all the studied range of volume flow rate. Most of the studies in the literature about using nanofluids in flat non-concentrating PVT collectors concentrated on using metals or metal oxides nanofluids and there is a lack in researches about utilization of carbon nanofluids in PVT collectors. Fayaz *et al.* [14] investigated numerically and experimentally the impact of utilizing MWCNT-water nanofluid on the performance of a PVT system at different flow rates. At nanofluid concentration of 0.75 wt.% and by fixing solar radiation at 1000 W/m$^2$, inlet temperature at 32 °C and ambient at 25 °C , the results showed that the electrical efficiency enhancement of PV was 10.72% numerically and 12.25% experimentally at nanofluid cooling flow rate of 120 L per hour, while the reduction in cell temperature was about 0.72 °C experimentally and 0.77 °C numerically per 10 L per hour. Abdallah *et al.* [15] conducted outdoor tests to investigate the utilization of the MWCNT-water nanofluid as heat storage/heat absorption agent in a PV/T system. The results showed that the best PVT system performance was obtained at 0.075 vol.% concentration, at which the reduction of PV panel temperature was 12 °C at noontime and 10.3 °C over the daytime, while the overall system efficiency at noon and experiment test day periods are 83.26% and 61.23%, respectively. Hassan *et al.* [16] conducted an outdoor experimental investigation to lower the PV temperature by using graphene/water nanofluid and phase change material –PCM (RT-35HC). In their set-up, they used three types of configurations, which are conventional PV module, PV module with back attached container contains PCM, and PVT collector with copper tubes for liquid flow embedded in back attached PCM container. The used coolants were water and graphene/water nanofluid with (0.05, 0.1, and 0.15) vol.% concentrations at different flow rates of 20, 30, and 40 L per minute. The best performance was achieved with 0.1 vol.% nanofluid concentration and at 40 L per minute. From results of the study, it was concluded that utilization of nanofluid with PCM provides better system performance than utilization of water with PCM and using PCM alone, respectively. The maximum enhancement in electrical efficiency was 23.9% for nanofluid-based PVT/PCM case, 22.7% for water-based PVT/PCM case, and 9.1% for PV/PCM case as compared to conventional PV. Hilo *et al.* [17] in their review about heat transfer enhancement using graphene nanofluid mentioned that the graphene nanofluid showed a significant effect on the heat transfer and thermal conductivity enhancement. Moreover, they concluded that there is limited studies in the literature have investigated the impact of graphene nanofluid in facing step or corrugated channel. They recommended conducting more experiments on the characteristics of graphene nanofluid in high temperatures in order to have better understanding of the behavior of graphene nanofluids and fill the gap in knowledge. In this paper, graphene nanoplatelets nanofluid was experimentally investigated for the first time to date, to the best of the author's knowledge, as a coolant in a flat non-concentrating PVT system and compared to MWCNT nanofluid. This investigation conducted under Turkish climate conditions with 0.5 wt.% nanofluid concentrations, at 0.5 L per minute working fluids-flow rate and compared with PV module and water-cooled PVT system from the energetic viewpoint.

## Experimental set-up

As shown and revealed in fig. 1 the experimental set-up was fabricated and assembled in and on a movable box in the energy labs of Karabuk University, Turkey.

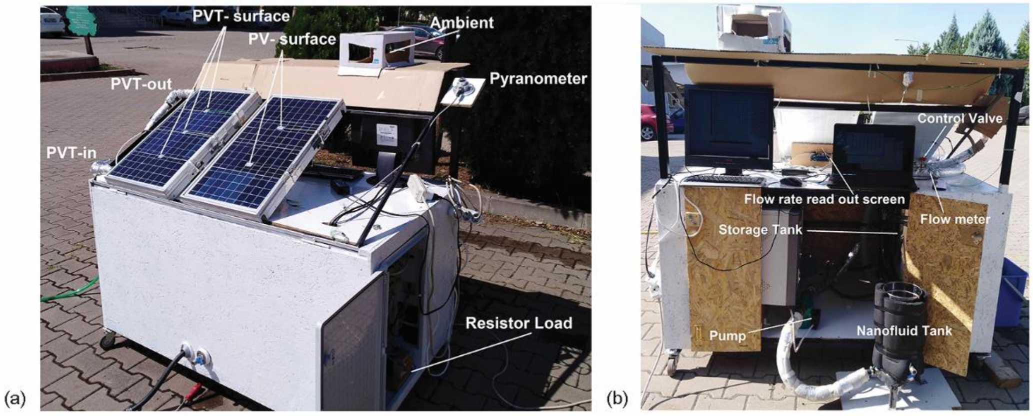


**Figure 1. View of experimental set-up; (a) thermocouples positions and (b) storage tanks and piping system**

The experimental set-up, fig. 2, consists of PV module (reference) and PVT collector mounted side by side facing to the south at a fixed tilt angle of 30°. The PVT collector was constructed by mechanically attaching a sheet and tube heat exchanger to the back of 40 W mono-crystalline silicon PV module, which is the same as PV reference module in specifications, with a thermal insulation layer beneath. The sheet and tube heat exchanger is serpentine copper tubing soldered to a thin copper plate. To ensure a good contact between the heat exchanger and the back surface of the PV panel, thermal conductive paste was spread between them. The PV module specifications are illustrated in tab. 1. Variable speed circulating pump (Nova company, model: RS25/4G-130) was used to run the working fluids throughout the PVT collector and the other components of the experimental set-up. A storage tank with coil heat exchanger was installed to remove gained heat from the coolants. A flow meter (Sea company, model: YF-S201) was used to measure and control the coolant flow rate at 0.5 L per minute. Temperatures of fluid inlet and outlet of PVT, surface temperatures of PV (two thermocouples) and PVT (three thermocouples) and ambient were measured by *K*-type thermocouples connected to eight channels data logger (Pico, USB TC-08 thermocouple data logger), which is connected to a laptop. Total incident solar radiation is measured by pyranometer (EKO Instruments, Model: MS-602, Japan) installed at the same incidence plane of PV and PVT panels. The pyranometer, PV and PVT were connected to a computer through a data collecting board, by which signals of radiation, currents and voltages are transferred to a

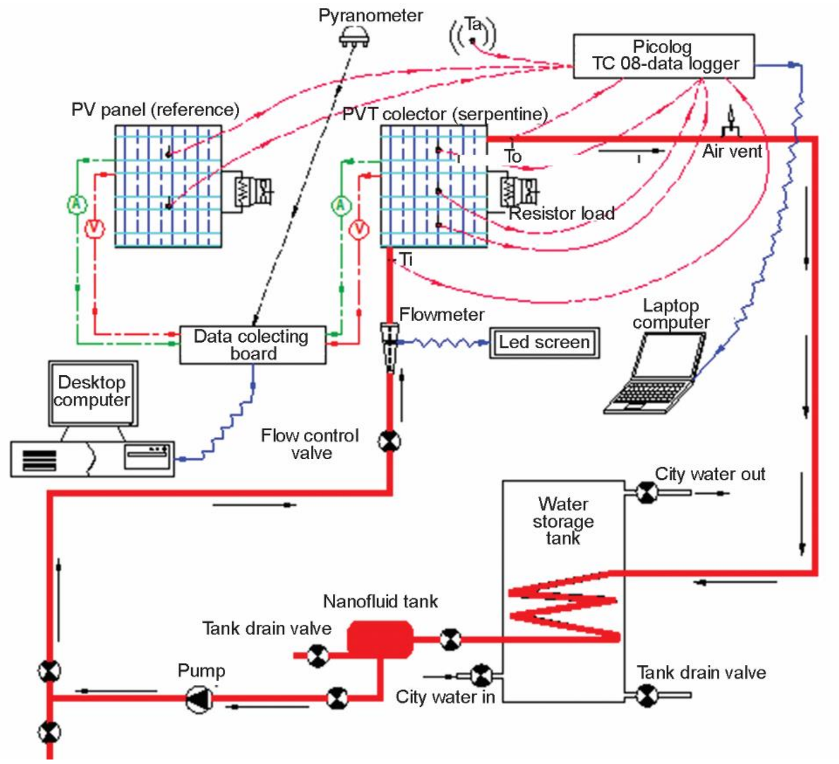


**Figure 2. Schematic diagram of the experimental set-up**

computer and processed by SIMULINK software to read, record, and gather the measured data of solar irradiance and the generated voltage and current for both PV panel and PVT collector. To obtain the maximum electrical power and ensure a continuous production of electricity from PV and PVT panels, constant resistor loads cooled by a fin-fan system were connected to PV and PVT panels. All parameters were measured simultaneously every 30 seconds.

**Table 1. The PV panel specifications at standard test conditions**

| Type | Mono-crystalline silicon | Type | Mono-crystalline silicon |
|---|---|---|---|
| Rated maximum power, $P_{max}$ | 40 W | Maximum power current, $I_{mp}$ | 2.22 A |
| Open circuit voltage, $V_{oc}$ | 22.10 V | Aperture area | 355×652 mm |
| Maximum power voltage, $V_{mp}$ | 18.00 V | Dimensions | 380×675×20 mm |
| Short circuit current, $I_{sc}$ | 2.58 A | | |

## Nanofluids used in the study

Single layer graphene nanoplatelets aqueous dispersion (0.55-1.2 nm thickness, 1-12 μm diameter, 500-1200 m²/g specific surface area, and more than 99.3 wt.% purity) and MWCNT-water dispersion (18-28 nm outside diameter, 8-35 μm in length, and more than 96% purity) were purchased from NANOGRAFI Co. Ltd. The nanofluids were prepared with

0.5% concentrations. The thermophysical properties of nanoparticles and water are presented in tab. 2. These properties of water [18], MWCNT nanoparticles [19], and graphene nanoplatelets nanoparticles [20] were taken from the literature. Transmission electron microscopy (TEM) image for MWCNT and graphene nanoplatelets nanoparticles are shown in fig 3. No sedimentation was observed during the experiments period and after four months of preparation.

**Table 2. Thermophysical properties of water and nanoparticles**

| Material | $\rho$ [kgm$^{-3}$] | $k$ [Wm$^{-1}$K$^{-1}$] | $C_p$ [kJkg$^{-1}$K$^{-1}$] |
|---|---|---|---|
| Water | 997 | 0.607 | 4.180 |
| MWCNT | 1600 | 3000 | 0.796 |
| Graphene | 2100 | 5000 | 0.710 |

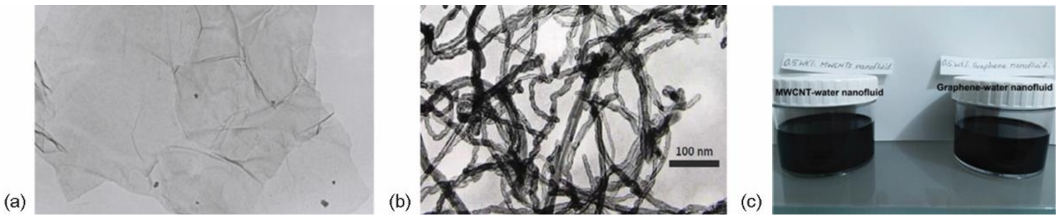


**Figure 3. (a) The TEM image for graphene nanoplatelets, (b) TEM image for MWCNT nanoparicles, and (c) nanofluids after four months of preparation**

## Parameters used in the calculations

The thermal properties of the prepared nanofluids are calculated by using Pak and Cho [21] model for density, Xuan and Roetzel [22] model for heat capacity, and Maxwell-Garnet [23] model for thermal conductivity as follows:

$$\rho_{\mathrm{nf}} = \phi\rho_{\mathrm{n}} + (1-\phi)\rho_{\mathrm{f}} \tag{1}$$

$$(\rho_{\mathrm{nf}} C_{p,\mathrm{nf}}) = \phi(\rho_{\mathrm{n}} C_{p,\mathrm{n}}) + (1-\phi)(\rho_{\mathrm{f}} C_{p,\mathrm{f}}) \tag{2}$$

$$k_{\mathrm{nf}} = k_{\mathrm{f}} \frac{k_{\mathrm{n}} + 2k_{\mathrm{f}} - 2\phi(k_{\mathrm{f}} - k_{\mathrm{n}})}{k_{\mathrm{n}} + 2k_{\mathrm{f}} + \phi(k_{\mathrm{f}} - k_{\mathrm{n}})} \tag{3}$$

$$\phi = \frac{\dfrac{m_{\mathrm{n}}}{\rho_{\mathrm{n}}}}{\dfrac{m_{\mathrm{n}}}{\rho_{\mathrm{n}}} + \dfrac{m_{\mathrm{f}}}{\rho_{\mathrm{f}}}} \tag{4}$$

where $\rho$ [kgm$^{-3}$] is the density, $C_p$ [kJkg$^{-1}$K$^{-1}$] – the specific heat, $k$ [Wm$^{-1}$K$^{-1}$] – the thermal conductivity, and $\phi$ – the volumetric ratio of nanoparticles in a suspension solution of the base fluid. The subscripts n, f, and nf stand for, nanoparticles, base fluid, and nanofluid, respectively. The useful thermal power $Q_{\mathrm{u}}$ [W] gained by the coolant in the PVT collector is given by:

$$Q_{\mathrm{u}} = \dot{m} C_p (T_{\mathrm{o}} - T_{\mathrm{i}}) \tag{5}$$

where $\dot{m}$ [kgs$^{-1}$] is the coolant mass-flow rate, $C_p$ [kJkg$^{-1}$K$^{-1}$] – the coolant specific heat, $T_i$ and $T_o$ [°C] – the coolant inlet and outlet temperatures, respectively. The electrical power $P$ [W] generated from the PV module and PVT collector is given by:

$$P = I_{\rm opt} V_{\rm opt} \tag{6}$$

where $I_{\rm opt}$ [A] is the optimum generated current and $V_{\rm opt}$ [V] – the optimum generated voltage. Energetic efficiency (First law of thermodynamic efficiency) of PVT represents the amount of energy (electrical and thermal) that PVT collector extracted from the solar radiation. The thermal, $\eta_{\rm th}$, and electrical, $\eta_{\rm el}$, efficiencies are expressed:

$$\eta_{\rm th} = \frac{Q_{\rm u}}{I_{\rm R} A_{\rm th}} \tag{7}$$

$$\eta_{\rm el} = \frac{P}{I_{\rm R} A_{\rm PV}} \tag{8}$$

where $I_{\rm R}$ [Wm$^{-2}$] is the total incident solar radiation on the PV and PVT surfaces and $A_{\rm PV}$ and $A_{\rm th}$ [m$^2$] are the areas of PV cells and PVT collector, respectively. The total energetic efficiency of PVT collector, $\eta_{\rm tot}$, can be defined as [24]:

$$\eta_{\rm tot} = \eta_{\rm th} + r\eta_{\rm el} \tag{9}$$

where $r = A_{\rm PV}/A_{\rm th}$ is the packing factor.

## Results and discussion

The measurements were collected simultaneously and continuously in every other 30 seconds from a time period from; 9:00 a. m. to 5:00 p. m., at 0.5 L per minute for all the coolants under investigation, during the selected days in the month of August and September. As an example for the experimental parameters measured during the testing days, fig. 4 shows every 30 seconds daily measured parameters for the selected testing day of graphene nanoplatelets-water nanofluid. The collected data is averaged and illustrated at the middle of each half an hour for further calculations and analysis. The weather conditions, solar radiation, and ambient temperature, of the testing days, were averaged and depicted in fig 5. According to this figure, the distribution of daily average incident solar radiation throughout the experiments period is a bell shape, whereas the average maximum value is 940 W/m² at 13:00 p. m. and average minimum values are 320 W/m² at 9:00 a. m. and 540 W/m² at 17:00 p. m.. The daily average ambient temperature trend is gradually raised from 20 °C at 9:00 a. m. to 32 °C at 17:00 p. m.. The average incident solar radiation and the ambient temperature were 739 ± 39 W/m² and 27.3 ± 2.4 °C during the testing period. Thermal properties for the nanofluids under investigation are estimated by eqs. (1)-(4) and demonstrated in tab. 3.

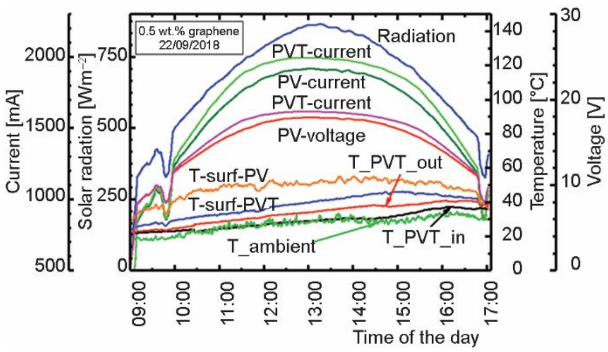


**Figure 4. Daily every 30 seconds measured parameters**

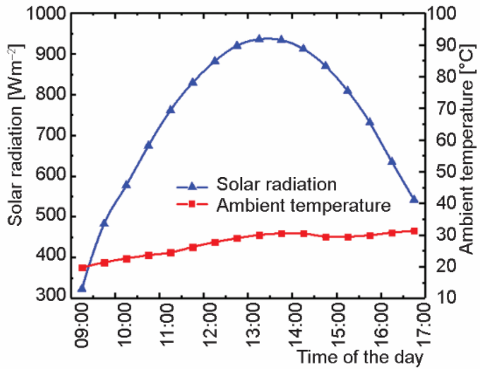


**Figure 5. Daily variations of solar irradiance and ambient temperature during days of experiments**

**Table 3. Thermophysical properties of nanofluids**

| Nanofluid | wt. [%] | $\rho$ [kgm$^{-3}$] | $k$ [Wm$^{-1}$K$^{-1}$] | $C_p$ [kJkg$^{-1}$K$^{-1}$] | $(\rho C_p)$ [kJm$^{-3}$K$^{-1}$] |
|---|---|---|---|---|---|
| MWCNT-water | 0.5 | 1185.3 | 1.4328 | 2.7538 | 3264.1 |
| Graphene-water | 0.5 | 1259.5 | 1.1755 | 2.8030 | 3530.4 |

### *Electrical energetic efficiency and temperature evaluation*

The daily average variation of weather, electrical performance, and temperatures for both PVT collector with the investigated coolants and PV module are depicted in figs. 6-8.

The measured surface temperatures for both PVT collector and PV panel were averaged and drawn throughout the time of experiment. In all figs. 6-8, the variation of electrical power generated by both PV panel and PVT collector follow the same trend of solar radiation along the experiment period, in which the maximum electrical power generated at maximum solar radiation. The surface temperature of PVT collector was reduced, as a result of adding cooling system, and consequently, the electrical power generated by PVT collector (cooled PV module) higher than that generated by PV module. For the distilled water case fig. 6, the

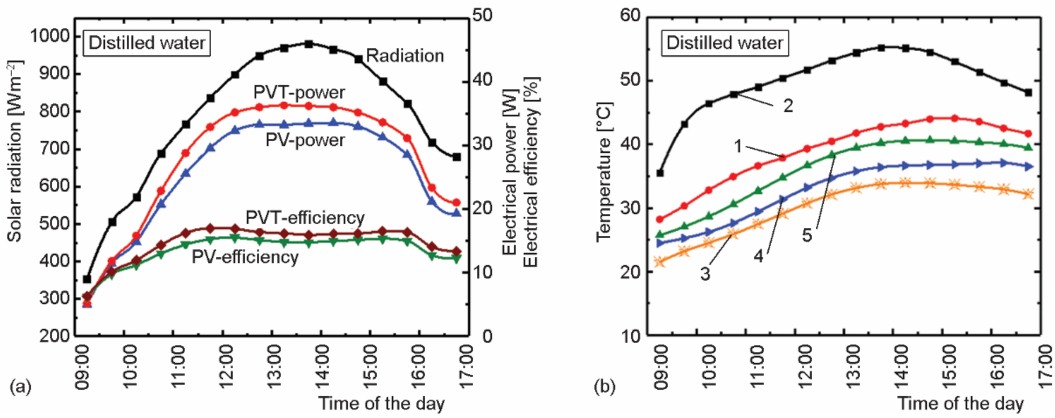


**Figure 6. Daily variations of measured and calculated parameters for cooling with distilled water;** *1 – PVT-surface, 2 – PV-surface, 3 – ambient, 4 – PVT-inlet, 5 – PVT-outlet*

testing day was in August, in which the time of daylight is longer and solar radiation and ambient temperature are higher. At noon, the PV average surface temperature was 55 ° C, while for PVT-distilled water collector was 43 °C at 981 W/m² maximum solar radiation and ambient temperature of 34 °C. For the graphene nanoplatelets. nanofluid case fig. 7, at noon, the average measured PV surface temperature was 49 °C whereas the solar radiation was 879 W/m², the ambient temperature was 30 °C and the PVT-graphene nanoplatelets nanofluid surface temperature was 38 °C. For MWCNT nanofluid fig. 8, at noon, the average measured PV surface temperature was 53 °C whereas the solar radiation was 939 W/m², the ambient temperature was 29 °C and the PVT-MWCNT nanofluid surface temperature was 38 °C.

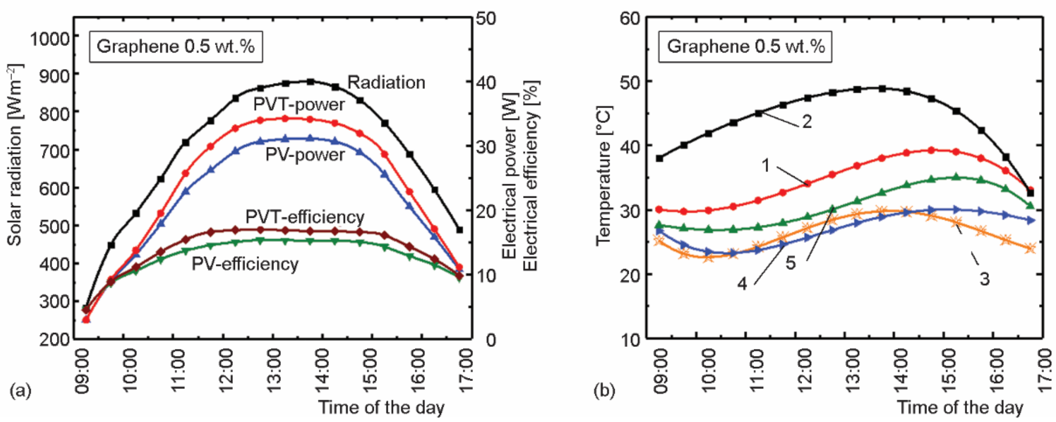


**Figure 7. Daily variations of measured and calculated parameters for cooling with graphene nanoplatelets-water nanofluid;** *1 – PVT-surface, 2 – PV-surface, 3 – ambient, 4 – PVT-inlet, 5 – PVT-outlet*

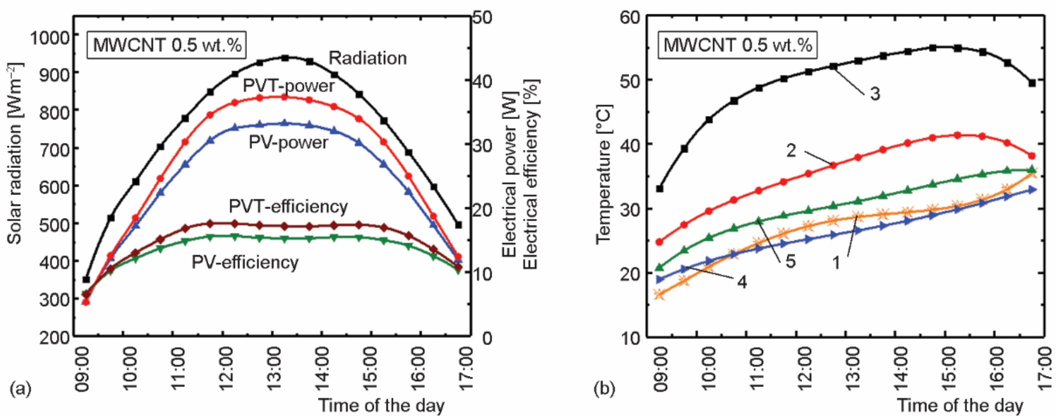


**Figure 8. Daily variations of measured and calculated parameters for cooling with MWCNT-water nanofluid;** *1 – ambient, 2 – PVT-surface, 3 – PV-surface, 4 – PVT-inlet, 5 – PVT-outlet*

The maximum measured difference in surface temperature between PV panel and PVT with distilled water, graphene nanoplatelets nanofluid and MWCNT nanofluid are 14 °C, 14 °C, and 16 °C, respectively.

At first glance, it might be understood that the thermal performance of distilled water and graphene nanoplatelets nanofluid are the same and lower than MWCNT nanofluid, however, the weather conditions, especially solar radiation, have an influence on the PV surface temperature reduction. The average daily solar radiation during the experiment periods for distilled water, graphene nanoplatelets nanofluid, and MWCNT nanofluid were 783, 704, and 737 W/m², respectively. In order to get a clear comparison between the used coolants, the collected data of weather conditions (radiation and ambient temperature), PV surface temperature, $T_{S,PV}$, surface temperature difference between PV and PVT, $\Delta T_S$, calculated electrical efficiencies of PV ($\eta_{PV,EL}$) and PVT ($\eta_{PVT,EL}$), and electrical efficiency enhancement, $\Delta\eta_{EL}$, were averaged for the experiment period (9:00-17:00) and for the peak period of radiation (11:15-5:45) and summarized in tabs. 4 and 5, respectively.

**Table 4. Average daily measured weather conditions, cells temperature, and electrical enhancement during the experiment period (9:00-17:00)**

| Coolant | $I_R$ [Wm$^{-2}$) | $T_{amb}$ [°C] | $T_{S,PV}$ [°C] | $\Delta T_S$ [°C] | $\eta_{PV,EL}$ [%] | $\eta_{PVT,EL}$ [%] | $\Delta\eta_{EL}$ [%] |
|---|---|---|---|---|---|---|---|
| Water | 783.3 | 30.1 | 50.0 | 10.9 | 13.5 | 14.6 | 8.5 |
| Graphene | 703.6 | 27.2 | 48.3 | 10.1 | 14.4 | 15.7 | 9.0 |
| MWCNT | 736.7 | 27.0 | 49.6 | 13.9 | 13.6 | 15.0 | 10.6 |

**Table 5. Average daily measured weather conditions, cells temperature, and electrical enhancement during the peak period (11:15-15:45)**

| Coolant | $I_R$ [W/m²] | $T_{amb}$ [°C] | $T_{S,PV}$ [°C] | $\Delta T_S$ [°C] | $\eta_{PV,EL}$ [%] | $\eta_{PVT,EL}$ [%] | $\Delta\eta_{EL}$ [%] |
|---|---|---|---|---|---|---|---|
| Water | 901.7 | 32.1 | 52.8 | 11.5 | 15.0 | 16.4 | 8.9 |
| Graphene | 822.2 | 28.9 | 51.6 | 10.7 | 16.2 | 17.8 | 10.0 |
| MWCNT | 851.5 | 28.5 | 52.8 | 14.8 | 15.2 | 17.1 | 12.4 |

As demonstrated in tabs. 4 and 5, some observations can be made. Firstly, there is an agreement in the results of daily average electrical efficiency enhancement for water-PVT collector with that obtained by Sardarabadi [25] for pure water. Secondly, cooling PV module with liquid working fluid reduced the maximum cell temperature and consequently increased the electrical efficiency. The MWCNT nanofluid showed a better electrical performance compared to that of graphene nanoplatelets nanofluid and distilled water. As the solar radiation increases, during the peak period, PVT surface temperature increases and consequently the coolant extracts more heat and its temperature also increases. This causes a reduction in PVT electrical efficiency as seen in fig. 9, in which MWCNT nanofluid showed better stability in electrical efficiency enhancement than graphene nanoplatelets nanofluid and water. This stability attributed to the higher thermal conductivity of MWCNT nanofluid, which gives it the ability to dissipate heat faster than the other coolants.

### *Total and thermal energetic efficiencies*

Equation (9) is used to estimate the total energetic efficiency of PVT collector with the coolants under investigation. Since the collector area covers the entire PV cells with an assumption of perfect surfaces contact, the packing factor, *r*, equals one. Figure 10 shows the calculated total energetic efficiency for PV panel and PVT collector. Total energetic efficiency is affected by thermal efficiency more than electrical efficiency. The variation of thermal efficiency, during the test period, does not follow a specific trend, as a result of experimental conditions variations such as ambient temperature, wind speed, humidity, and solar radiation amount. Table 6 summarizes the average daily thermal and total energetic efficiencies for PVT. Because of its relatively higher heat capacitance, $\rho C_p$, graphene nanoplatelets nanofluid showed better thermal and consequently total energetic performance than MWCNT nanofluid and water.

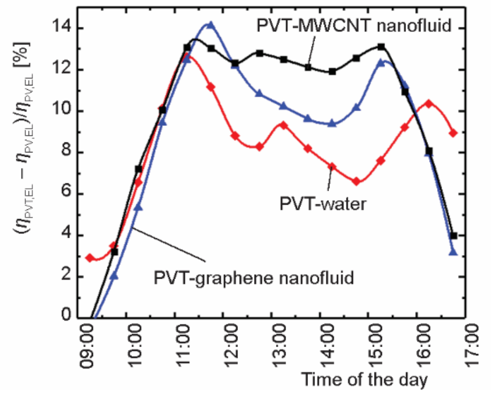


**Figure 9. Daily variation of electrical efficiency enhancements relative to the PV module**

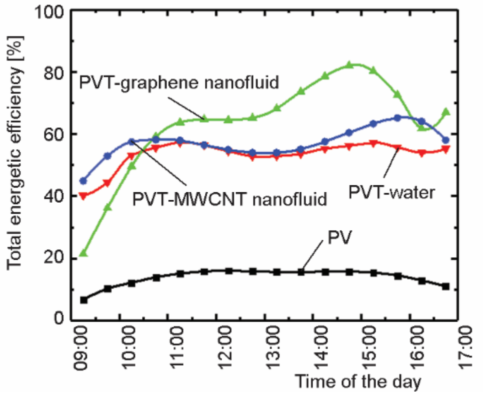


**Figure 10. Daily variation of PV and PVT total energetic efficiencies**

A comparison summary of energetic efficiencies enhancements of MWCNT nanofluid-cooled PVT system reported in present study and that reported in the literature is presented in the tab. 7. Based on this table, there is an acceptable convergence in experimental results of this study and the literature. The difference in the results is related to the experimenting procedure (outdoor or indoor), nanoparticle size, mixing methods, and nanofluid concentrations.

**Table 6. Average daily thermal and total energetic efficiencies for PVT with coolants under investigation**

| Coolant | (9:00-17:00) period | | (11:15-15:45) period | |
|---|---|---|---|---|
| | Thermal efficiency [%] | Total efficiency [%] | Thermal efficiency [%] | Total efficiency [%] |
| Water | 38.8 | 53.4 | 38.9 | 55.2 |
| Graphene | 47.4 | 63.1 | 53.6 | 71.4 |
| MWCNT | 42.2 | 57.2 | 40.8 | 57.9 |

There is no investigation work in the literature of using graphene nanoplatelets nanofluid in flat non-concentrating PVT systems to date, to the best of author's knowledge. The results of this study can be compared, from thermal viewpoint, with Vakili *et al.* [26] study, who used graphene nanoplatelets-deionized-water as a working fluid in a volumetric solar collector. The results showed that at the optimum mass-flow rate of 0.015 kg/s the zero-loss efficiency using graphene nanoplatelets nanofluid with weight fraction of 0.005 was 93.2%, whereas it was 70% using deionized water. In this study, the average daily thermal efficiency of PVT used graphene nanoplatelets nanofluid-distilled water with 0.5 wt.% concentration at

**Table 7. Energetic performance comparison with different studies**

| Reference | Test conditions | Coolant | Electrical efficiency enhancement relative to PV | Thermal and total efficiency enhancement relative to PVT-water |
|---|---|---|---|---|
| [19] | **Indoor.** Flow rate: 0.5 L per min., 1000 W/m², 32 °C inlet temp., 25 °C ambient temp. | Water | 9.2% | – |
| | | MWCNT-water 1.0 wt.% | 0.14 % higher than PVT-water | Thermal efficiency higher by 4% numerically and 3.67% experimentally. Total efficiency by 3.81% numerically and 4.11% experimentally |
| [14] | **Indoor.** Flow rate: 120 L per hour, 32 °C inlet temp., 25 °C ambient temp. | Water | – | – |
| | | MWCNT-water 0.75 wt.% | 10.72% numerically. 12.25% experimentally | Thermal efficiency increased by 5.62% numerically and 5.13% experimentally |
| Present study | **Outdoor.** Flow rate: 0.5 L per min. | Water | 8.5% | – |
| | | MWCNT-water 0.5 wt.% | 10.6% | Thermal efficiency higher by 3.4%. Total efficiency higher by 3.8% |
| | | Graphene-water 0.5 wt.% | 9.0% | Thermal efficiency higher by 8.6%. Total efficiency higher by 9.7% |

0.5 L per minute is 47.4% and the maximum thermal efficiency is 64.1%, whereas for distilled water it was 38.8% and 42.0%, respectively. Volumetric solar collector has higher thermal efficiency, since it converts the solar radiation to a thermal energy, while PVT collector converts a significant part of solar energy to thermal energy and the rest to electricity. Using graphene nanoplatelets nanofluids increased the zero-loss efficiency of volumetric solar collector, which is the maximum value on the efficiency line, by 23.2%, while for PVT collector the maximum thermal efficiency increased by 22.1% compared to the base fluid. The results of maximum thermal efficiency of this study and that of Vakili's study, to a certain extent, are in close agreement.

## Conclusions

In this experimental study, performance evaluation of a flat non-concentrating PVT system operated by distilled water, MWCNTS-water nanofluid and graphene nanoplatelets-water nanofluid with 0.5 wt.% concentration was performed at a fixed coolant flow rate of 0.5 L per minute and compared to a conventional PV system. The following findings can be summarized from the experimental results as follows.

- By adding cooling system to a conventional PV module it reduces the PV surface temperature by 14 °C with distilled water, 14 °C with graphene nanoplatelets nanofluid, and 16 °C with MWCNT nanofluid at average daily solar radiation of 783, 704, and 737 W/m², respectively.

- Through the usage of the distilled water, it increases the average daily electrical energetic efficiency by 8.5%. The average daily total energetic efficiency for the PVT collector becomes 53.4% when it is 13.5% for the PV module.
- The usage of the nanofluids increases the electrical energetic efficiency by 10.6% and 9.0% for MWCNT-water and graphene nanoplatelets-water nanofluids, respectively compared to PV system.
- In terms of the electrical energetic efficiency enhancement, MWCNT-water nanofluids showed better stability than graphene nanoplatelets-water nanofluids and distilled water during the peak period of solar radiation and high cell temperature.
- Compared to PVT-distilled water, the average daily total energetic efficiency for the graphene nanoplatelets-water nanofluid case increased by 18.0%, while for the MWCNT-water nanofluid, It is increased by 7.0%. The average daily thermal energetic efficiency of graphene nanoplatelets-water and MWCNT-water nanofluids improved by 22.1% and 8.6%, respectively.

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## Nomenclature

$A_{PV}$ – PV surface area, [m²]
$A_{th}$ – PVT collector surface area, [m²]
$C_p$ – specific heat, [kJkg$^{-1}$K$^{-1}$]
$I_{opt}$ – optimum generated current, [A]
$I_R$ – total incident solar radiation, [Wm$^{-2}$]
$k$ – thermal conductivity, [Wm$^{-1}$K$^{-1}$]
$m$ – mass, [kg]
$\dot{m}$ – mass-flow rate of working fluid, [kgs$^{-1}$]
$P$ – electrical generated power, [W]
$Q_u$ – useful thermal power collected by working fluid in PVT, [W]
$r$ – packing factor of the PV cells
$T$ – temperature, [°C]
$\Delta T_S$ – surface temperature difference between PV and PVT, [°C]
$V_{opt}$ – optimum generated voltage, [V]

*Greek symbols*

$\eta_{el}$ – electrical efficiency, [%]
$\eta_{th}$ – thermal energetic efficiency, [%]
$\eta_{tot}$ – total energetic efficiency, [%]
$\eta_{PV,EL}$ – PV electrical efficiency, [%]
$\eta_{PVT,EL}$ – PVT electrical efficiency, [%]
$\Delta\eta_{EL}$ – electrical efficiency enhancement, [%]
$\phi$ – volumetric ratio of the nanofluid, [–]
$\rho$ – density, [kgm$^{-3}$]

*Subscripts*

amb – ambient
f – base fluid
i – inlet
n – nanoparticles
nf – nanofluid
o – outlet
S,PV – PV surface

## References

[1] Vandrangi, S. K., *et al.*, Friction Factor Analysis of $SiO_2$ and $Al_2O_3$ Nanofluids Dispersed in 60 EGW and 40 EGW Base Fluids, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *51* (2018), 1, pp. 61-70
[2] Michael, J. J., *et al.*, Flat Plate Solar Photovoltaic-Thermal (PV/T) Systems: A Reference Guide, *Renewable and Sustainable Energy Reviews*, *51* (2015), Nov., pp. 62-88
[3] Chow, T. T., A Review on Photovoltaic/Thermal Hybrid Solar Technology, *Applied energy*, *87* (2010), 2, pp. 365-379
[4] Ma, T., *et al.*, Using Phase Change Materials in Photovoltaic Systems for Thermal Regulation and Electrical Efficiency Improvement: A Review and Outlook, *Renewable and Sustainable Energy Reviews*, *43* (2015), Mar., pp. 1273-1284,

[5] Armstrong, S., Hurley, W. G., A Thermal Model for Photovoltaic Panels Under Varying Atmospheric Conditions, *Applied Thermal Engineering*, *30* (2010), 11, pp. 1488-1495
[6] Hazami, M., *et al.*, Energetic and Exergetic Performances Analysis of a PV/T (Photovoltaic Thermal) Solar System Tested and Simulated Under to TUNISIAN (North Africa) Climatic Conditions, *Energy*, *107* (2016), July, pp. 78-94
[7] Yazdanifard, F., *et al.*, Investigating the Performance of a Water-Based Photovoltaic/Thermal (PV/T) Collector in Laminar and Turbulent Flow Regime, *Renewable Energy*, *99* (2016), Dec., pp. 295-306, DOI No. https://doi.org/10.1016/j.renene.2016.07.004
[8] Haddad, S., *et al.* Investigation of the Electrical and Thermal Performance of a PV/T Hybrid System, *Proceedings,* 10$^{th}$ International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte Carlo, Monaco, 2015, pp. 1-6
[9] Ceylan, İ., Gürel, A. E., Exergetic Analysis of a New Design Photovoltaic and Thermal (PV/T) System, *Environmental Progress & Sustainable Energy*, *34* (2015), 4, pp. 1249-1253
[10] Chol, S., Estman, J., Enhancing Thermal Conductivity of Fluids with Nanoparticles, *ASME-Publications-Fed*, *231* (1995), Jan., pp. 99-106
[11] Sridhara, V., Satapathy, L. N., $Al_2O_3$-Based Nanofluids: A Review, *Nanoscale Research Letters*, *6*. (2011), 1, p. 456
[12] Hosseinzadeh, M., *et al.*, Optimization and Parametric Analysis of a Nanofluid Based Photovoltaic Thermal System: 3D Numerical Model with Experimental Validation, *Energy Conversion and Management*, *160* (2018), Mar., pp. 93-108
[13] Ebaid, M. S., *et al.*, Experimental Investigation of Cooling Photovoltaic (PV) Panels Using ($T_iO_2$) Nanofluid in Water-Polyethylene Glycol Mixture and ($Al_2O_3$) Nanofluid in Water-Cetyltrimethylammonium Bromide Mixture, *Energy Conversion and Management*, *155* (2018), Jan., pp. 324-343
[14] Fayaz, H., *et al.*, Energy and Exergy Analysis of the PVT System: Effect of Nanofluid Flow Rate, *Solar Energy*, *169* (2018), July, pp. 217-230
[15] Abdallah, S. R., *et al.*, Performance Analysis for Hybrid PV/T System Using Low Concentration MWCNT (Water-Based) Nanofluid, *Solar Energy*, *181* (2019), Mar., pp. 108-115
[16] Hassan, A., *et al.*, Thermal Management and Uniform Temperature Regulation of Photovoltaic Modules Using Hybrid Phase Change Materials-Nanofluids System, *Renewable Energy*, *145* (2020), Jan., pp. 282-293
[17] Hilo, A., *et al.*, Heat Transfer and Thermal Conductivity Enhancement using Graphene Nanofluid: A Review, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *55* (2019), 1, pp. 74-87
[18] Sengers, J., Watson, J. T. R., Improved International Formulations for the Viscosity and Thermal Conductivity of Water Substance, *Journal of Physical and Chemical Reference Data*, *15* (1986), 4, pp. 1291-1314
[19] Nasrin, R., *et al.*, Water/MWCNT Nanofluid Based Cooling System of PVT: Experimental and Numerical Research, *Renewable Energy*, *121* (2018), June, pp. 286-300
[20] Contreras, E. M. C., *et al.*, Experimental Analysis of the Thermohydraulic Performance of Graphene and Silver Nanofluids in Automotive Cooling Systems, *International Journal of Heat and Mass Transfer*, *132* (2019), Apr., pp. 375-387
[21] Pak, B .C., Cho, Y. I., Hydrodynamic and Heat Transfer Study of Dispersed Fluids with Submicron Metallic Oxide Particles, *Experimental Heat Transfer an International Journal*, *11* (1998), 2, pp. 151-170
[22] Xuan, Y., Roetzel, W., Conceptions for Heat Transfer Correlation of Nanofluids, *International Journal of heat and Mass transfer*, *43* (2000), 19, pp. 3701-3707
[23] Maxwell-Garnett, J. C., Colours in Metal Glasses and in Metallic Films, *Phil. Trans.*, *203* (1904), A, pp. 385-420
[24] Chow, T. T., *et al.*, Energy and Exergy Analysis of Photovoltaic-Thermal Collector with and without Glass Cover, *Applied Energy*, *86* (2009), 3, pp. 310-316
[25] Sardarabadi, M., *et al.*, Experimental Investigation of the Effects of Silica/Water Nanofluid on PV/T (Photovoltaic Thermal Units), *Energy*, *66* (2014), Mar., pp. 264-272
[26] Vakili, M., *et al.*, Experimental Investigation of Graphene Nanoplatelets Nanofluid-Based Volumetric Solar Collector for Domestic Hot Water Systems, *Solar Energy*, *131* (2016), Aug., pp. 119-130

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