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Efficiency of Photovoltaic Modules Using Different Cooling Methods: A Comparative Study

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Abstract

This paper presents an experimental investigation of the efficiency of a photovoltaic module using different cooling methods. The performance of the PV panels under different cooling techniques for the same operational conditions is explained. A special test rig was designed and installed in the Faculty of Engineering Technology, East Amman. All operating key variables such as solar radiation intensity, ambient and module temperatures using calibrated devices were measured and recorded as well as the electrical output. The present experiments results showed that the electrical efficiency of the tested PV panels is improved significantly when it was cooled. However, the best improvement obtained when a nanofluid (0.04% wt TiO_2/water) is used as a cooling medium, while the PV panel cooled by using Aluminum rectangular fins showed the lowest efficiency improvement. Such results including the comparative analysis (under local operating conditions prevailing in Jordan) are in agreement with literature and could be useful for researchers and developers of solar power generation.

Keywords

Cooling, Photovoltaic, Nanofluid, Fins, PV Efficiency

1. Introduction

Based on forecasts by researchers and concerned international agencies, the proven reserves of fossil fuels, e.g. oil and gas, at the current rate of world's consumption, will not be adequate to meet future demand for more than the coming five decades. What is equally important is the growing concern about environmental pollution that caused by burning conventional fuels. Thus, it is expected that the contribution of available renewable energy sources will increase significantly in the future to meet the growing energy demand world-wide. This is a true fact expressed by statistics published recently by specialized energy agencies such as IRENA and IEA. According to the International Renewable Energy Agency (IRENA), renewable electricity generation in 2015 was 191 TWh. This amount was higher than the prevailed rate in 2014 by about 3.5% [1]. Although solar energy is not consistent and has low intensity, the global installed capacity for solar-powered electricity has seen an exponential growth, reached around 227 GWe at the end of 2015, producing 1% of all consumed electricity in the world. The total capacity for solar heating and cooling in operation in 2015 was estimated at 406 GWth [2].

Locally, the Government of Jordan, GoJ, has taken necessary steps to promote renewable energy (RE) projects and enhance EE in all sectors of the economy. In order to attract the private sector participation in the development of RE, a new system of Direct Proposals has been approved and issued, this resulted in the awarding of about 1335 MWe of RE capacities in the 1st and 2nd rounds of direct proposals. Of which more than 400 MW are operational at the end of 2016, in addition to about 80 MW of small PV systems as roof tops [3]. The 3rd round, with a total capacity of 300 (200 PV and 100 Wind) MW, and the proposals, based on BOO basis for a 50 MW block in, by the qualified companies or investors are under evaluation. The GoJ, represented by the Ministry of Energy and Mineral Resources and Energy and Minerals commission, also has issued a well-developed and comprehensive technical codes and regulations for on-grid RE projects. This will lead to higher dependence on RE systems, in particular PV generation systems due to low cost of produced electricity from such systems compared with other alternatives [4]. The recent signed power purchase agreement with the GoJ to supply the national grid with generated electricity from a central PV system, connected to high voltage grid, achieved a very competitive price of about 0.05 USD per kWh delivered compared with about 0.16 USD per kWh for PV projects signed in 2014 [5]. Such low cost was also reported in other projects elsewhere [6], which are much cheaper than other conventional power generation systems. This is as a result of accelerated improvement due to intensive research and development in this field as well as increased mass production of PV modules world-wide which led to further reduction in prices of solar PV modules [2].

In addition to lower costs of PV modules and consequently generated power, the environmental dimension of solar energy is becoming an important advantage for such systems. Solar PV is clean and involves no direct-pollution. Therefore, it is believed widely that solar energy, and PV in particular, should be utilized instead of other existing conventional energy forms, even with slightly higher costs to generate electrical power. Solar energy has a wide spectrum of applications such as solar thermal utilization, photovoltaic power generation. However, photovoltaic technology (PV) is one of the most important promising renewable energy technologies [7] [8] [9]. However, photovoltaic final efficiency is still considered as one of most significant drives for development and industrial manufacturing of such conversion systems. Thus, developers and researches prime aim is to lower the cost, increase the efficiency, and develop new technologies related to PV cells, materials and solar tracking [10].

One of the effective methods of improving efficiency of a photovoltaic (PV) module is by decreasing its operating surface temperature. A typical value for PV efficiency loss with increasing temperature is 0.5%˚C [11]. Lowering surface temperature can be achieved by cooling the PV module during operation which leads to higher heat dissipation rates from PV modules [12] [13] [14] [15]. As a result, most of the up to date research has tended to apply different methods to cool PV cells [16]-[22]. Therefore, adding an artificial cooling system to reduce the PV module surface temperature and increase its power output and efficiency is under investigation.

In this research paper, different cooling methods have been conducted: 1) using rectangular fins; 2) tap-water and/or; 3) nanofluids. Fins cooling of PV modules was studied by different researchers. Bryce *et al.* [23] have investigated cooling of a PV panel via fins and a duct attached to the rear surface of the panel. It was found that electrical output varies weakly with fin material and thickness, but strongly with fin length and air velocity in the duct. The impacted of tilted heat sinks was studied by Mittelman *et al.* [24] and Do *et al.* [25]. The latter proposed a correlation between the fin geometries, the tilt angles and the heat transfer coefficients. Other researchers used spray-water, on the back surface, to cool down PV modules in order to improve its efficiency [26] [27] [28]. It has been concluded that such system based on evaporative cooling could reduce modules' temperature by 10˚C when operated for 5 minutes. Although nanofluids was introduced by Chao in 1995, the use of such newly fluids still receiving high attention by researchers for different applications, including energy systems [29]. Recently nanofluids were used by different researchers to cool different thermal systems, including PVs [30]-[40]. The main conclusion was that an augmentation of particle concentration has produced a clear decrease of the junction temperature between the heated component and the cooling block. This is due to high thermal conductivity of solids with very small size in the order of few micrometers. For more details, readers could visit the following research [41].

In open literature, there are voluminous research works of theoretical and experimental studies for hybrid photovoltaic thermal systems [42] [43] [44] [45] [46]. For example, Agrawal and Tiwari [47] evaluated the performance of hybrid micro channel photovoltaic thermal system (MCPVT) used to produce electrical power and hot water simultaneously. Also Ibrahiem *et al.* [46] analyzed the performance of such system under conditions prevailed in Malaysia. From previous research papers, it was evident that key questions still linger concerning the best nanoparticle-and-liquid pairing and conditioning, reliable measurements of achievable thermal conductivity of employed nanofluid and sound simulation models that fully describe the particle dynamics and heat transfer of such nanofluids [48]. Mahian *et al.* [49] in their review paper they investigated nanofluids' applications in solar thermal engineering systems with the prime aim of enhancing efficiency and performance of such systems. Others [50] [51] [52] concentrated their efforts on the use of nanofluids in direct solar collectors for solar-thermal energy conversion. They reported that size reduction and cost savings are inevitable when nanofluids are used. Karami and Rahimi [53] [54] and Mittal *et al.* [55] studied possibilities of enhancing heat transfer in PV modules using different nanofluids. It was concluded that the average PV surface temperature could be decreased significantly by using nanofluids.

In a previous paper by Al-Busoul *et al.* [56], the performance of a cooled PV module by using Al_2O_3 and TiO_2 nanofluids with different concentrations was studied under local conditions. It has been found that there is a significant increase in both of output power and final efficiency of all tested modules when nanofluids employed to cool down the PV module. The highest possible enhancement, under the local testing conditions, was observed for a nanofluid based on Al_2O_3 with a concentration of 0.02% by wt. In this new experimental investigation and despite numerous works done in this field, the main objective of the present work is to determine the most appropriate cooling method that may be employed to improve the performance, output power and efficiency of the PV module under local operating conditions prevailing in Jordan. It is important to stress here that there is still a gap in available information related to comparison between different cooling methods of PV modules. Such missing info could be useful and help all stakeholders to understand the effect of increasing the temperature of PV module which drastically decrease its efficiency and consequently the generated power. Bearing in mind that at present in the Middle East and North Africa (MENA) region, which enjoys high solar radiation and relatively high atmospheric temperature as well as dry climate, there is a growing trend to install PV modules in both distributed and central systems.

2. Experimental Apparatus and Procedure

In this research work a tailor-made test rig was fabricated and assembled based on available resources and materials in the local market. The experimental system is shown in **Figure 1**. As can be seen from this figure, there are four PV modules 1) that are connected in parallel and all of these modules are working under same operating conditions (*i.e.* solar irradiation intensity, atmospheric temperature, wind speed, and dust content in the atmosphere). The first and second PV modules are cooled using water and a nanofluid, respectively, flowing inside copper tubes with the diameter of 6 mm attached to the back surface of the module, with a total length of 3 meters.

The third PV module is cooled by using 24 vertical Aluminum rectangular fins (length = 395 mm, height = 20 mm, thickness = 2 mm) attached to the back

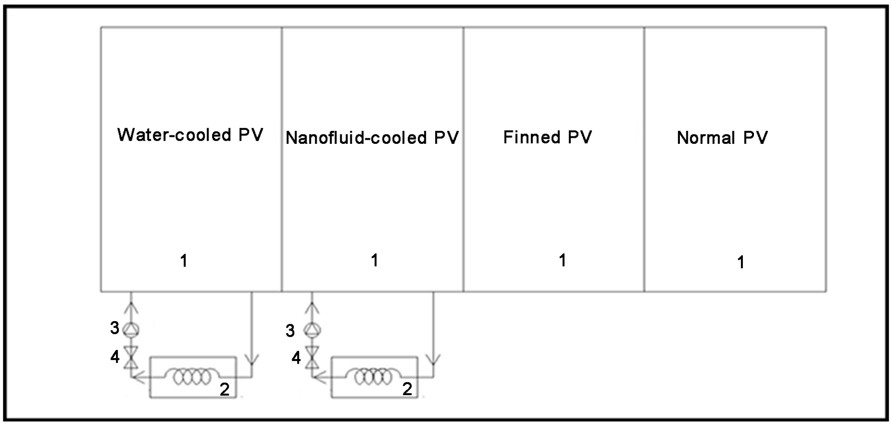

Figure 1. Cooling system for PV module. 1) PV module; 2) Coolant heat exchanger; 3) Pump and; 4) Throttling valve.

surface of the module. The back surface of the first, second and third modules are shown in Figure 2, while the fourth PV module is left without any cooling, *i.e.* plain with natural cooling. A special tube-heat exchanger 2) was designed to reject heat to the sink, which is a large tank filled with cold water. This tube coil is made of 6 mm copper tube, with a total length of about 2 meters, and connected to a small circulating pump 3) that used to drive the cooling fluid through heat exchangers. A throttling valve 4) was used to control the flow rate in the circuit.

3. Preparation of Nanofluid

In this study a nanofluid (metal oxide) with water as base fluid was used. TiO_2 nanoparticles with an average grain size of about (30 - 50) nm were utilized. This was grinded and separated in a specialized laboratory, *i.e.* Royal Scientific Society (RSS), in Jordan. The used nanofluid also was made by an expert in RSS laboratory with the desired specs. In order to prepare the nanofluid, deionized water (the basis of the nanofluid) was mixed with the required mass grinded solid material, *i.e.* nanoparticles, to attain the required concentration (*i.e.* 0.04% by weight). Then, the nanoparticles were dispersed in the deionized water and the solution was sonicated by an ultrasonic device for a minimum time of 90 minutes in order to obtain a uniformly dispersed solution. The obtained properties of the yielded nanofluid are summarized in Table 1.

The thermal conductivity of nanofluid k_{eff} was calculated using the following equation [13]:

$$k_{eff} = k_f + 3\psi^{-1} v_p \frac{k_p - k_f}{\left(3\psi^{-1} - 1\right) k_f + k_p - v_p \left(k_p - k_f\right)} k_f \tag{1}$$

where:

k_{eff}: Thermal conductivity of nanofluid,

k_f: Thermal conductivity of based fluid,

k_p: Thermal conductivity of particles,

(a) (b)

Figure 2. (a) Back surface of PV module cooled by water and nanofluids; (b) Back surface of PV module cooled by rectangular fins.

Table 1. Physical properties of 0.04% by weight TiO_2 nanofluid.

M_{TiO_2}	V_{water}	ρ_{water}	ρ_{TiO_2}	ρ_{NF}	k_{water}	k_{TiO_2}	k_{eff}	By weight
kg	Lit	kg/m^3	kg/m^3	kg/m^3	W/m.K	W/m.K	W/m.K	%
0.004	10	999	4230	1029.7	0.613	11.8	0.628	0.04

v_p: Volume fraction of nanoparticles,

ψ: Sphericity of the particles ($\psi = 1$ for spherical and 0.5 for cylindrical).

It is necessary to mention that the volume flow rate of water and nanofluid in this work remained unchanged (0.1313 L/s) in all experiments in order to be able to evaluate effects of other key parameters. The performance of the modules was monitored through the measurement of 1) PV back surface temperature by using type T-thermocouple; 2) solar radiation intensity (W/m^2) by using a calibrated solar power meter; and 3) the yielded output power by using AVO meter to measure open circuit voltage and short circuit current. Measurement devices with their main specification are shown in **Figure 3**.

In all experiments, measuring devices were reset and tested before conducting any measurement to ensure validity of all readings. The experimental rig was run by same group in order to minimize differences and personal error. The test procedure was started by cleaning PV modules, checking all connections and examining the tilt angle and direction facing the south. Then recording measured variables for short intervals of 5 minutes for all modules. It is important to mention here that experiments were repeated three times in order to make sure that the effect of other factors such as dis-uniformity and externalities has no influence on obtained results. Same procedure was followed in all experiments to reduce uncertainty and have sound representative results.

		
Digital Multi-meter UT33D	Digital Thermometer Fluke 87V	Solar Power Meter TENMARS TM-207
DC Voltage: 200 mV to 500V Accuracy: ±(0.5% + 2 digits) DC current:2000μA to 10 A Accuracy: ±(1% + 2 digits)	Range: -200 to 1090°C Accuracy: ±(1% + 10)	Range: 0 - 2000 W/m^2 Accuracy: ±(10W/m^2) Sample time: 0.25 sec

Figure 3. Measuring devices used to monitor the performance of PV modules.

4. Results and Discussion

The effect of different cooling methods (free-cooling by using fins, water and nanofluid of 0.04% wt TIO_2/water) on efficiencies of silicon PV modules was analyzed. The effectiveness of cooling of different cooling methods was evaluated and compared with obtained results for normal free-cooling PV module under same operating conditions. The fact that solar irradiation varies on daily basis was considered by taking an average for a testing period of five days. The standard performance, e.g. output and efficiency, of a PV module was calculated and analyzed by employing specialized commercial software, *i.e.* PV_{SYS} 6.0, which is available freely on the web [57]. It is worth to be mentioned that all data presented in the following figures are an average of the results of five continuous days (1st to 5th of July, 2015).

Figure 4 shows the average solar radiation intensity during the experiment period and as can be seen from this figure that solar irradiation varies daily with peak recorded at solar noon. The max measured value was 846 W/m^2, which is in good agreement with published data of nearest weather station based in Amman Airport [58].

The measured hourly surface temperature of four PV modules and ambient temperature are shown in **Figure 5**. It can be noticed that the surface temperature of the PV modules has reached its maximum at 12:00 noon and the maximum temperature difference between back surface of PV module and dry air temperature (T_s - $T_{ambient}$) was about 19.2˚C for the normal cooled PV module and occurred between 11:00 am and 12:00, while the maximum temperature difference recorded for the module cooled with TiO_2 nanofluid was about 8.1˚C at same time. For the other two modules, water and fins-cooled, it was observed that such difference was 9.5˚C and 12.19˚C, respectively. It is clear that the nanofluid-cooled module has the lowest temperature difference which means that an effective cooling has achieved. It is clearly shown in **Figure 5** that such temperature difference, in the case of using nanofluid, is much less in the morning (about 4˚C) and in late afternoon dropped further (−6˚C). This could be attributed to different factors, but the most important being the lower ambient

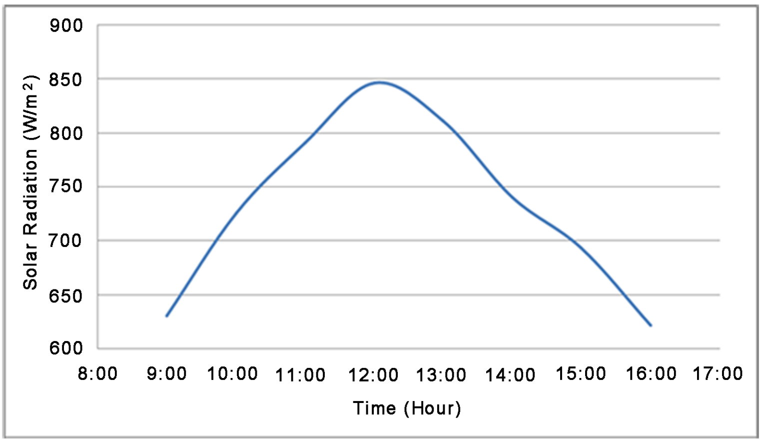

Figure 4. Solar radiation intensity during July 2015.

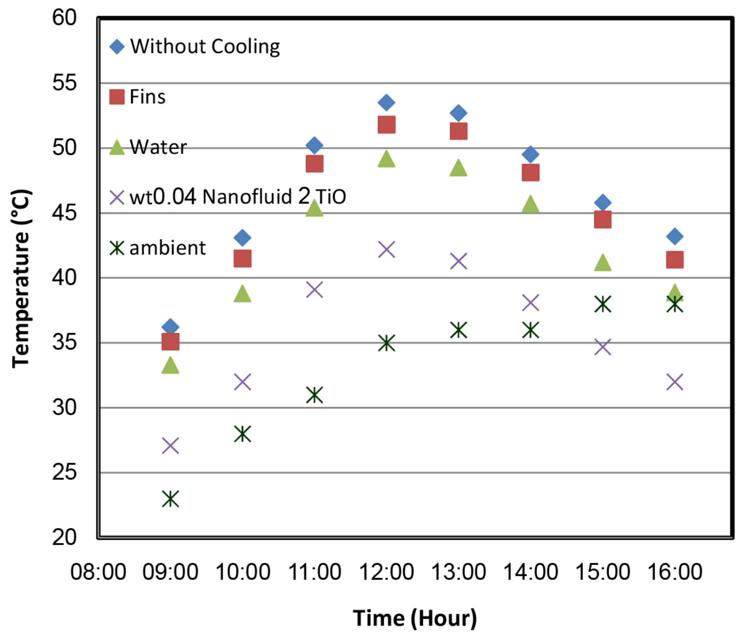

Figure 5. Average surface module temperature during the experiment (1st to 5th of July, 2015).

temperature in early morning and late evening, reduced incoming solar radiation and the fact that the back surface temperature of tested PV module was lower than the ambient temperature as a result of continuous cooling without altering the flow rate.

The hourly electrical output power is given in **Figure 6**. The values of the electrical power varied slightly following changes in solar radiation intensity and PV surface temperature. It has been found that this output was the max for the PV cooled by TiO_2 nanofluid, since it has the lowest surface temperature and the maximum yielded electricity values at 12:00 noon were (15.7, 15.3, 15.1 and 14.9 W) for 0.04% wt-TiO_2, water, fins cooled PV modules and normal PV module, respectively.

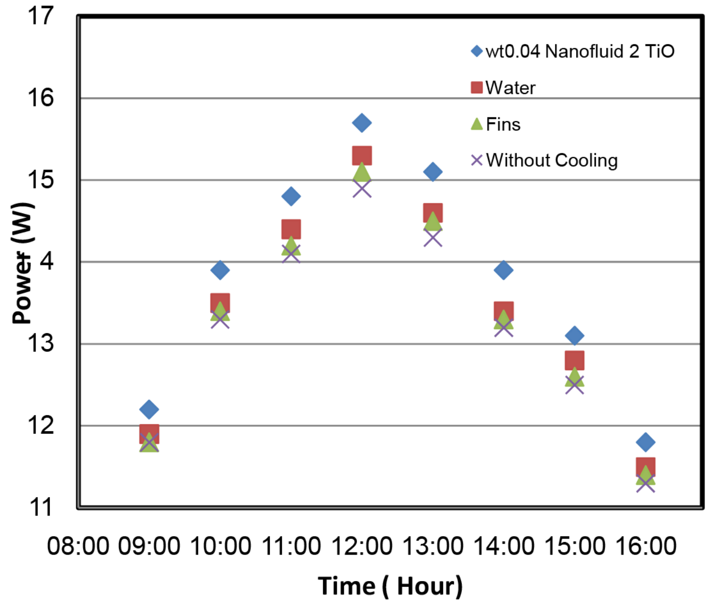

Figure 6. Hourly output electrical power of the tested PV modules.

The final efficiency of the tested PV modules is illustrated in **Figure 7**. Efficiency varied during the test period due to changes in solar radiation intensity and PV surface temperature. But it is witnessed that all cooling methods follow same pattern: high efficiency in early morning and late afternoon, while the lowest efficiency occurred during mid of the day. Moreover, it has been observed that PV efficiency for cooled module by TiO_2 nanofluid is higher than the other modules (13.39%, 12.99%, 12.88% and 12.71% for 0.04% wt-TiO_2 nanoflids, water, fins cooled and normal PV module, respectively). The explanation for such behavior is that the obtained efficiency is inversely related with surface temperature, while the power output is directly proportional to solar radiation intensity. Bearing in mind that the output power is also proportional to the module short circuit current, which slightly increases with temperature, while inversely proportional to the module open circuit voltage. It is important to mention here that results of this research work are in good agreement with those reported in previous similar work by other researchers [49]-[54].

The hourly relative efficiency (ratio between cooled and normal PV modules) is shown in **Figure 8**. The maximum improvement in energy conversion was about 6.5% when using nanofluid, while this was much lower for other cooling methods, *i.e.* 2.7% and 1.46% for water and fins, respectively.

To sum up, the obtained results in this research work proved that PV module efficiency could be improved when applying cooling on the back surface of the module. Higher efficiency could be achieved when nanofluid was used to cool down the PV module. In the future a research work to investigate the possibility of integrating water desalination and power generation using PV modules for residential applications will be conducted to examine the feasibility of such system.

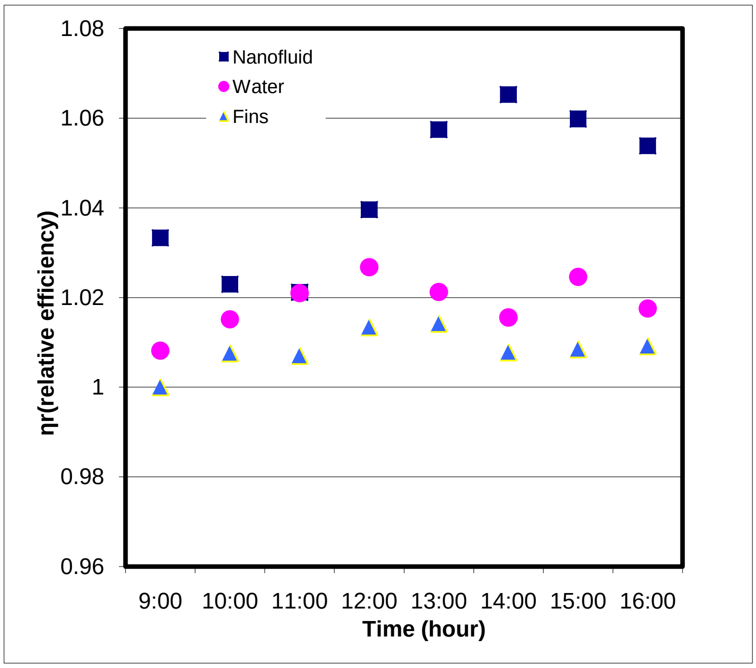

Figure 7. Hourly electrical efficiency of the tested PV modules.

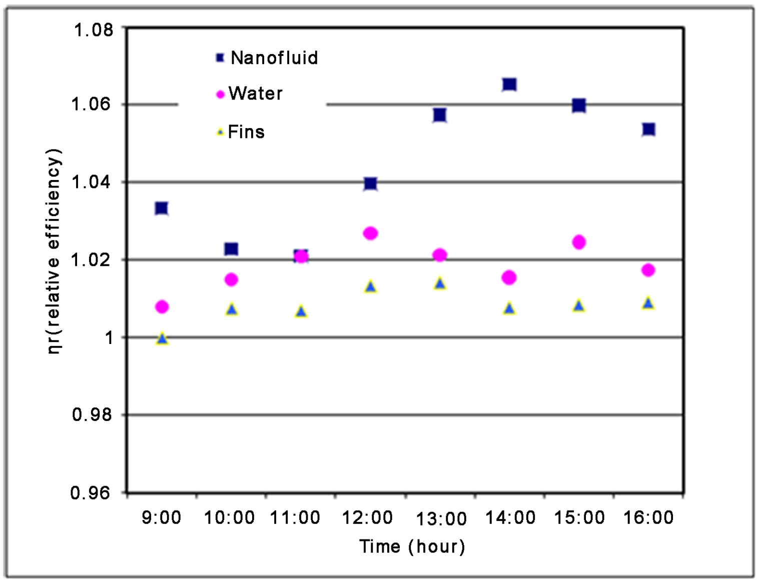

Figure 8. Hourly relative efficiency (ratio between cooled and uncooled) of tested PV modules.

5. Conclusion

This experimental study aimed to assess the performance of PV modules when applying different cooling methods: nanofluid, tap water and fins. The obtained results are compared with a standard uncooled PV module. The measured key variables, under same operating conditions, were reported and analyzed and compared with the base case-scenario. The obtained results clearly demonstrate that cooling the PV module enhanced heat transfer and thus achieving higher electrical efficiency. The main conclusion of the paper in hand is that the electricity yield of the PV module cooled by 0.04% wt TiO_2, water and fins compared with uncooled PV was higher by 5.37%, 2.62% and 1.34%, respectively. As expected in all cases, same pattern noticed following solar radiation intensity and ambient temperature. Based on the obtained results, it is strongly believed that PV cooling is most effective during mid-day period. Future research work will address the integration of PV based power generation and water desalination. This is extremely important for a country like Jordan, which ranked as 2nd in the world in terms of water resources poverty.

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