Experimental investigation of the performance of a hybrid photovoltaic/thermal solar system using aluminium cooling plate with straight and helical channels

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ABSTRACT

This paper presents a field study for the performance of photovoltaic thermal (PVT) system that use aluminium cooling plate with straight and helical channels during July 2016. Three systems each of 0.37 m^2 commercial poly-crystalline PV panels have been installed at the faculty of engineering at Shoubra, Benha University, Cairo, Egypt (30.1°N Latitude). Two of the systems are cooled using straight and helical channels with dimensions of 10×10 mm^2 and compared with the uncooled panel. The results showed that an increase in average electrical efficiency of 17.7% to 38.4% with relative to uncooled panels for flow rate range of 0.25 to 1 L/min. The corresponding average thermal efficiency increases from 31.6% to 47.2% for straight channels and 34.6% to 57.9% for helical configuration. While the corresponding average exergy efficiency increases from 11.1% to 12.9% for straight channels and 11.5% to 13.5% for helical arrangement. The associated water pumping power in both configurations does not exceed 3.3% of the converted electrical power while the increase in the obtained electrical power is of 30% with relative uncooled cell power.

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1. Introduction

Photovoltaic (PV) system is one of highly electric energy quality and cleanness renewable energy in the world. On the other side, low efficiency and high cost of photovoltaic power generation restrict the development of solar photovoltaic industry. Commercial PV electrical conversion efficiency is of 6∼15% and this output power decreases by 0.2∼0.5% per 1 K increase in temperature module (Huang et al., 2013). Enhancing the overall efficiency or utility of solar energy collection by developing a hybrid photovoltaic/thermal solar collector has been investigated by many researchers (Singh and Othman, 2009; Hovel, 1977; Vorobiev, 2006; Mittelman et al., 2007; Coventry, 2005; Najafi and Woodbury, 2013; Ma et al., 2015; Eicker, 2003). Ma et al. (2015) showed that the thermal regulation of a PV system is of great role. The absorbed heat that elevates cell temperature can be removed using passive and active approaches. Active is also referred to photovoltaic/thermal collector, PV/T, and it utilizes both electrical and heat energies of the system. Eicker (2003) presented that most PV facades are built these days as certain walls in front of thermally insulated buildings with air ducts behind PV cells to decrease building cooling loads. This approach enhances heat dissipation rates, leading to higher PV performance rates. Active ventilation with PV facades allows a reduction of cell operating temperatures of 18 K, resulting in an increase of 8% in electrical energy output at air velocity of about 2 m/s (Krauter, 2004). van Helden et al. (2004) showed that total efficiency of PVT modules is higher than the sum of the efficiencies of separate PV and solar thermal systems. Also, through the higher combined yield PVT can contribute to the reduction in the consumption of fossil fuels in the built environment in a more cost-effective way. Helmers et al. (2014) presented an energy balance model for concentrating photovoltaic and thermal (CPVT) systems. The influence of the operating temperature and concentration ratio on the electrical and thermal performances of the CPVT system are discussed. It is shown that high concentration reduces the thermal losses considerably and increases the electrical efficiency. At concentration ratios above 300, the system operates with an overall efficiency of 75% at temperatures up to 160 °C.

The air-type product design provides a simple and economical solution to PV cooling, and the air can be heated to different temperature levels through forced or natural flow. Forced circulation is more efficient than natural circulation owing to better convective and conductive heat transfer, but the required fan power reduces the net electricity gain. Inducing airflow in underneath cavity

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Nomenclature

$\dot{m}$	mass flow rate, kg/s		ctp	conversion of thermal power plant
P_{el}	electric power, W		el	electrical
Q_{in}	incident solar radiation rate, W		i	inlet
Q_{th}	thermal heat transfer rate, W		in	incident
A	area, m^2		MP	maximum point
Cp	specific heat, J/kg °C		o	outlet
G	incident solar intensity (W/m^2)		oc	open circuit
I	electrical current, A		sc	short circuit
T	temperature, K		th	thermal
t	time, s		w	water
V	electrical voltage, V			

Greek letters

Δ	differential
η	efficiency

Subscripts

a	ambient

Acronyms and abbreviations

CPVT	concentrating photovoltaic and thermal
MCSCT	micro-channel solar cell thermal
PV	photovoltaic
PVT	photovoltaic thermal

located in the back of the PV modules is proposed as an effective strategy to reduce frontal surface temperatures. Computational fluid dynamics has been applied as a powerful methodology to study the cavity ventilation potential (Gan, 2009; Corbin and Zhai, 2010; Yoo and Manz, 2011). Mei et al. (2009) performed an experiment to test PV modules under various climate conditions. Back-ventilation was performed by installing a fan behind the cavity while different ventilation rates were applied. Mirzaei and Carmeliet (2015) carried out an experimental setup consists of a complete simulator for building prototype and solar radiation. The experimental setup placed inside an atmospheric wind tunnel to control wind velocity. Thermography is measured using an infrared camera to record the surface temperature of the BIPV. The effect of an underneath cavity with various cavity heights and PV arrangement is further studied. The results would be eventually useful in the development of practical guidelines for BIPV installation. Hegazy (2000) carried out an extensive investigation of the thermal, electrical, hydraulic and overall performance of four types of flat-plate PVT/air collectors. The four modes are: channel above PV, channel-below PV, single-pass channels with PV in-between, and finally the double-pass design. The numerical analysis illustrated that while channel above PV mode has the lowest performance, the other three have comparable energy yields. Also, single-pass channels with PV in-between consume the least fan power.

Tripanagnostopoulos et al. (2002) carried out outdoors measurements on PVT with air and water collectors of different configurations. They found that 5% and 8% higher than the PV modules in production costs for PVT/air and PVT/water, respectively. Their measurements gave a range of thermal efficiency from 38% to 75% for PVT/air designs. The corresponding values are and 55% to 80% for PVT/water system. The tests are performed at steady state noon-hour measurements in the University of Patra (at 38.2°N) in Greece. Nualboonrueng et al. (2013) focused on the performance of photovoltaic-thermal (PVT) systems working in Bangkok for residential applications. The results show that effect of water flow can improve the cell efficiency of PV cells. Moreover, the total energy output from the PVT collectors, which had glass covers is very significantly higher than those without design. Vivar et al. (2013) carried out the first prototype of the hybrid CPVT micro-concentrator. The prototype has been installed at the Australian National University, Canberra, Australia. The results show that

the combined efficiency of the system can exceed 70%. The full day performance shows that the average electrical efficiency was 8%. The corresponding average thermal efficiency was 50%. Vivar and Everett (2014) performed a review study on actively cooled solar concentrators. The most suitable candidate fluids available in the market are assessed according to their properties and applications, with a special emphasis on fluid toxicity and long-term performance. Yamada and Hirai (2016) investigated experimentally the maximization of module electrical efficiency based on global normal irradiance (GNI) rather than direct normal irradiance (DNI). The results of outdoor tests showed that the low-cost cell enhanced the generated power by factors of 1.39 and 1.63 for high-DNI and midrange-DNI conditions, respectively. Tiwari et al. (2006) estimated the overall efficiency of an unglazed PVT/air collector in India. In that study, the optimal air flow rate, duct dimensions were concluded. Also, Raman and Tiwari (2008, 2009) investigated the annual thermal and exergy efficiencies of the hybrid PVT/air system for five different Indian climate conditions. It was noticed that the exergy efficiency is 40–45% lower than the thermal efficiency under strong solar radiation. Also, the double-pass system illustrated better performance than the single-pass option. These results are similar to the findings of Sopian et al. (1996). On the other hand, Joshi and Tiwari (2007) provided an exergy analysis of an unglazed PVT/air collector for the cold climate region of India. The instantaneous energy and exergy efficiencies were found in the ranges of 55–65% and 12–15%, respectively.

Sandnes and Rekstad (2002) studied the energy performance of a PVT/water collector with c-Si solar cells pasted on polymer thermal absorber. The absorption coefficient is of 0.94 for normal incidence. The analysis found that the presence of PV cells reduces the heat absorption by about 10% of the incident radiation. Also, the glass cover decreases the optical efficiency by around 5%, and its application to low-temperature water-heating system is promising. Chow (2003) introduced an explicit dynamic model for analysing single-glazed sheet-and-tube collector performance. Through the multi-nodal finite different scheme, the exact influences of fluctuating irradiance and dynamic auto-control device operation can be readily analysed. The steady–state energy flow analysis also reveals the importance of having good thermal contact between the encapsulated solar cells and the absorber plate, as well as between the absorber plate and the water tubing. Abdolzadeh

and Ameri (2009) investigated the performance of the photovoltaic water pumping system by spraying water over the front of the photovoltaic cell. They concluded that the PV electrical efficiency increased by 3.26% at 16 m head due to spraying water over the cell. Agrawal (2011) experimentally examined two cases of micro-channel solar cell thermal (MCSCT) tiles; single MCSCT (case-I) and similarly, two MCSCT tiles, which are connected in series (case- II). Fabricated MCSCT tile consisted of single solar cell, micro-channel and fan for extraction of heat from bottom of solar cell. Comparing the two cases, results showed that the electrical efficiency is higher in case-I, while the thermal output is higher in case-II on same intensity and mass flow rate. Additionally, the average electrical and thermal efficiency of newly designed and fabricated MCSCT tile is 12.4% and 35.7% respectively. Bahaidarah et al. (2013) experimentally examined the performance of photovoltaic cell by integrating a heat exchanger (cooling panel) at its back surface, using water as a cooling medium. The results indicated that the cell electrical efficiency improved by 9%. Chen et al. (2014) experimentally studied the performance of PV panel with and without fin cooling to investigate the effect of PV panel inclination, ambient temperature, and solar radiation and wind velocity on the electrical efficiency and power output. The study displayed that the average power output of the PV panel with fin increased by 1.8%–11.8% than without fin.

Alzaabi et al. (2014) proposed a design to improve the electrical efficiency of PV panels using water hybrid PVT system. The system is composed of a polycrystalline PV panel with a solar thermal collector adhered to its backside. The results showed that the electrical power output for the PVT system increased by 15–20% when compared to PV panel. The thermal efficiency of the system was calculated from measured data and obtained values close to 60%–70% were achieved. Karami and Rahimi (2014) conducted experiments to investigate the cooling performance of channels by water-based nanofluids containing small concentrations of Boehmite for the PV cell. Results showed that the nanofluid perform better than water and caused higher decrease in the average PV cell temperature. The obtained maximum increase in the electrical efficiency was 37.67%. Agrawal and Tiwari (2015) analysed the performance of glazed hybrid photovoltaic thermal air collector in terms of effect of carbon credit earned on annualized uniform cost on the basis of annual thermal energy and exergy for New Delhi climatic conditions. They evaluated the effect of interest rates on annualized uniform cost. Results revealed that there is significant decrease in annualized uniform cost due to carbon credit earned. Gotmare et al. (2015) experimented the performance enhancement of PV panels utilizing passive fin cooling under natural convection. Different cross sectional fins with perforation was attached at the backside of the panel. The results showed that due to fin cooling temperature of the PV panel dropped significantly and the power output was improved by 5.5% under natural convection. Marc-Alain Mutombo et al. (2016) numerically simulated the behaviour of a thermosyphon hybrid PVT when exposed to variations of environmental parameters and to demonstrate the advantage of cooling photovoltaic modules with water using a rectangular channel profile for the thermal collector. Results revealed that the cooled PV electrical efficiency is more than that of the uncooled one by 24.1%.

The present work focuses on a hybrid PVT performance in Cairo, which is considered one of the most energy-consuming areas in Egypt where a promising solar intensity is found. The present test rig aims to discover the usefulness of the use aluminium cooling plate with straight and helical channels in cooling the PV solar panels and collecting thermal energy. Three systems each of 0.37 m^2 commercial poly-crystalline PV panels have been installed at the faculty of engineering at *Shoubra, Benha university, Cairo, Egypt* (30.1°N Latitude). Two of the systems are cooled using straight

and helical channels with dimensions of 10×10 mm^2 and compared with the uncooled panel during July 2016.

2. Experimental setup

In the experimental work, three identical 50 W PV panels were installed on the roof top of at the faculty of engineering at *Shoubra, Benha University, Cairo, Egypt* (30.1°N Latitude). The solar modules are being south oriented and adjusted at the same inclination 30° with the horizontal plane as shown in Fig. 1. The schematic of the experimental work and specifications of PV panels are presented in Fig. 2 and Table 1, respectively. Two of the systems are cooled using aluminium plate with straight and helical channels and to be compared with the uncooled panel as shown in Fig. 3. The dimensions of the aluminium plates installed to the back of PV panels are $641 \times 520 \times 18$ mm^3. The depth and width of channels used in both configurations are 10×10 mm^2. The spacing between grooves is 10 mm.

An AC pump of 1/2 hp is installed to feed the PVT solar systems with the required flow rate of water. The flow rates are adjusted through the flow metres and the installed valves, which are regulated to obtain the required flow rates in the primary lines and the remainder is bypassed to the water tank. Rectangular vertical of 49 L tank with internal dimension ($350 * 350 * 400$ mm) is fabricated and insulated using 1-inch wool glass to store water. Vapour compression refrigeration cycle is used to obtain constant inlet water temperature to the PV panels. In the experiments, current and voltage of PV, solar panel, ambient air, inlet and outlet water temperatures, wind speed and solar irradiation are measured. Two identical flow metres are used to record the flow rate directed to cooling PV panels. In order to measure the temperature at different points on the system, calibrated copper constantan thermocouples are used and connected to digital thermometer with ±0.1 °C resolution. Eight thermocouples are attached to each PV module to record the temperature of the solar cell. Also, two thermocouples are installed on inlet and exit of PV with straight and helical cooling plates. Two identical digital differential pressure transducers were employed for measuring the pressure drop of water between the water inlet and outlet from each PV. Table 2 reveals the specifications of main instruments in the experimental setup. An electric circuit shown in Fig. 4 is used to measure characteristics voltage and current (V, A) of each panel.

3. Experimental procedures and data reduction

The following procedures were conducted from 8 AM to 5 PM for the three systems;

Fig. 1. General view of the experimental system.

1- Straight

2- Helical

3- Reference
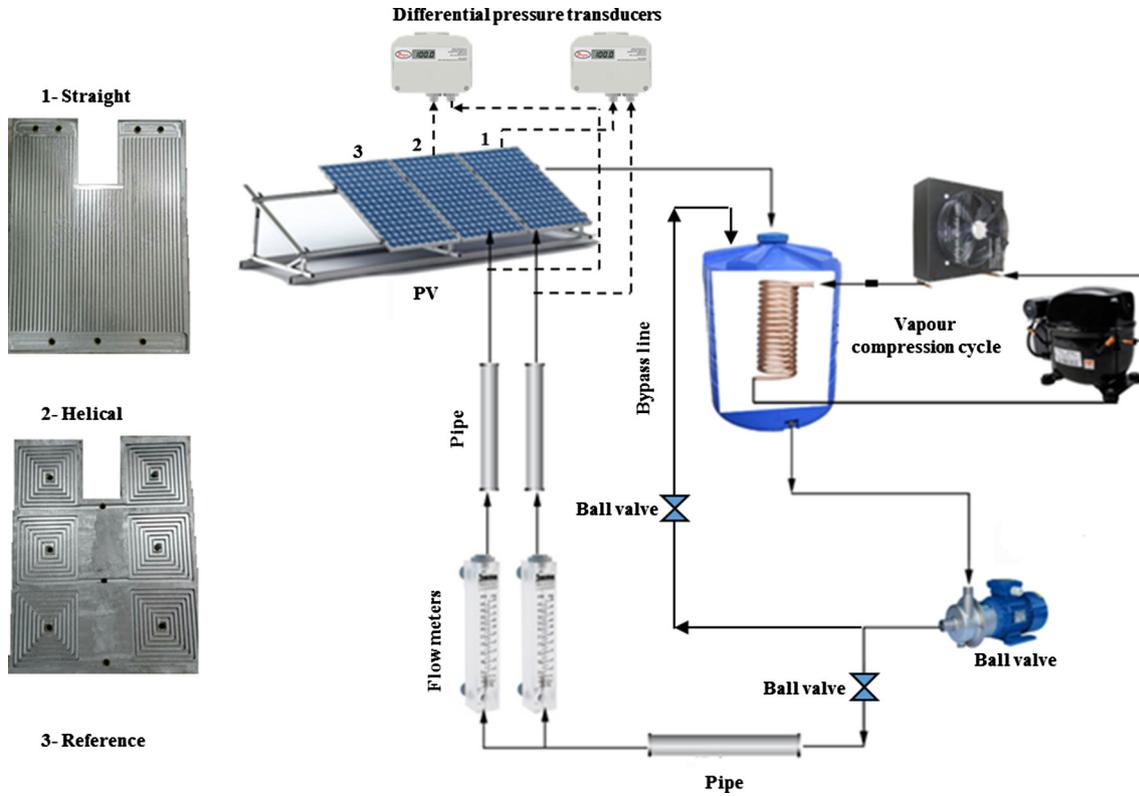
Fig. 2. Schematic of the experimental setup.

Table 1
Solar module specifications.

Cell type	Poly-crystalline
Peak power (Pmax)	50 W
Dimension	670 * 550 * 35 (±2 mm)
Maximum power voltage (V_{mp})	18 V
Maximum power current (I_{mp})	2.78 A
Open circuit voltage (V_{oc})	21 V
Short circuit current (I_{sc})	3.06 A
Maximum system voltage	1000 V
Normal operating cell temperature	25 °C

1- Checking the water level in the tank and ensure that the evaporator is completely submerged in water.
2- Adjust the two control valve at the inlet of the two cooled cells to get the same required flow rate of cooling water.
3- Start up the compressor of the refrigeration system to control the inlet temperature to cooled PV panels.
4- Record the incident solar radiation, temperatures, water pressure drop and wind speed.

Helical channels   Straight channels

Fig. 3. Cooling plate with straight and helical channels.

Table 2
Specifications of main instruments in the experimental setup.

Measured variable	Instrument	Specifications
Solar intensity	Solar power metre	• Model: TM-206 • Up to 2000 W/m² • Accuracy: ±10 W/m²
Weather conditions	Digital environmental multimeter	• Temperature: −10 to 60 °C, accuracy ±1.5% and resolution 0.1 °C • Relative humidity: 0–100%, accuracy ±3% and 0.1% resolution • Air velocity: 0.5–20 m/s with accuracy ±3% and 0.1 m/s resolution
Flow rates	Flow metres	Measuring range of 0.002–6.5 L/min
Pressure drop	Digital differential pressure transducer	Working range of 0–103.4 kPa and accuracy of ±1% of full scale
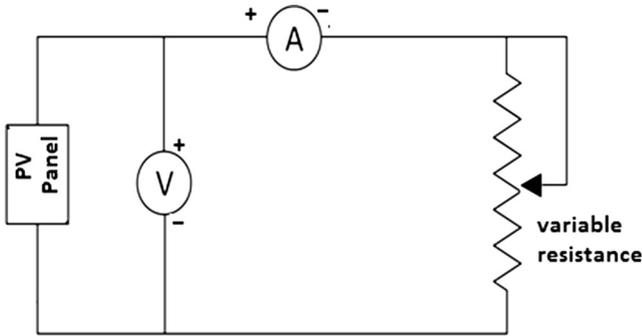
Fig. 4. Measurement circuit for the panel characteristic curve.

5- Connecting the output from each panel to the variable load circuit to draw V-I characteristic curve. All measured voltage and current values are entered to Excel program to draw the characteristic curve between current and voltage to obtain the optimum point from the curve as shown in Fig. 5.

6- Repeat these procedures every 30 min till sunset.

The incident solar radiation on the cell (W) is calculated from;

$$Q_{in} = G \times A \tag{1}$$

The average temperature can be obtained from for each module;

$$T_{PV,mean} = \frac{T_{PV,\text{average of front surface}} + T_{PV,\text{average of back surface}}}{2} \tag{2}$$
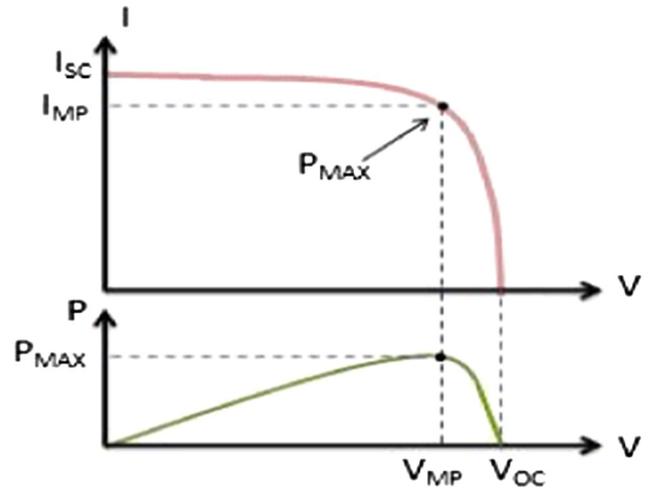
Fig. 5. Characteristic curve for PV cell.

The maximum module output power (W) is obtained from;

$$P_{max} = V_{MP} \times I_{MP} \tag{3}$$

The PV panel electric efficiency is calculated as follows;

$$\eta_{el} = \frac{P_{max}}{Q_{in}} \tag{4}$$
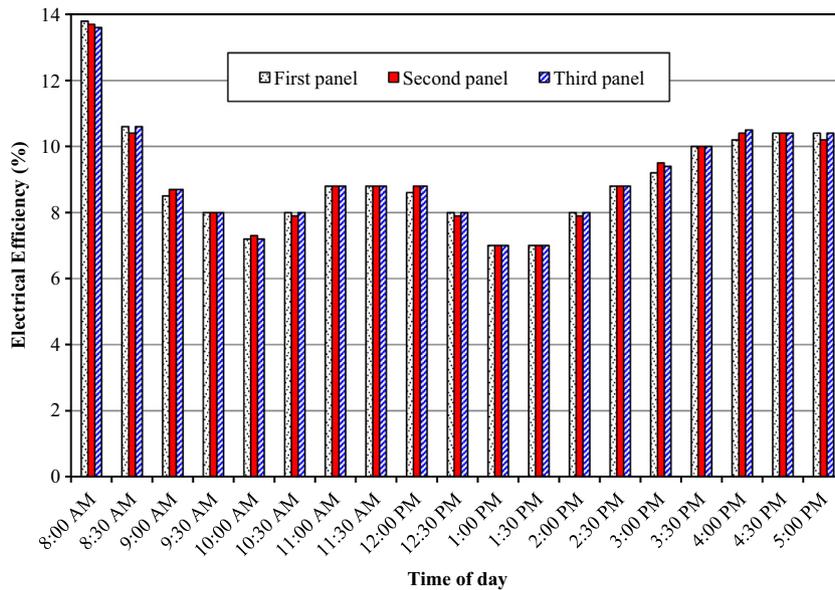
Fig. 6. Comparison between the three PV panels for non-cooling conditions.
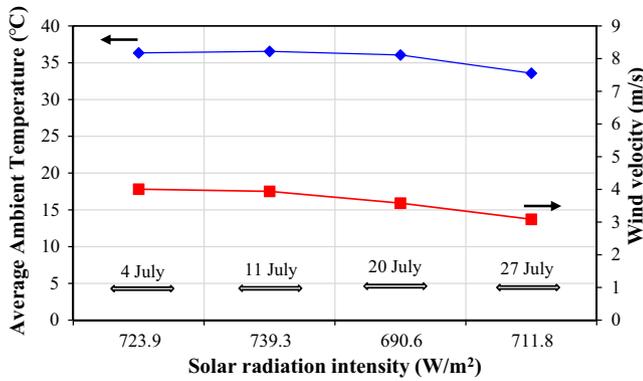
Fig. 7. Weather conditions during the experiments days.

Thermal heat transfer gained to the cooling water in straight and helical configurations (W) is obtained from;

$$Q_{th} = \dot{m}_w Cp_w (T_{w,o} - T_{w,i}) \qquad (5)$$

The thermal efficiency for cooled PV panels can be get from;

$$\eta_{th} = \frac{Q_{th}}{Q_{in}} \qquad (6)$$

The expression for overall thermal gain can be defined as,

$$\eta_o = \eta_{th} + \frac{\eta_{el}}{\eta_{ctp}} \qquad (7)$$

where η_{ctp} is a conversion efficiency of thermal power plant, which depends upon quality of coal ($\eta_{ctp} = 0.38$ for good quality of coal). This electrical energy has been converted to equivalent thermal by using electric power generation efficiency conversion factor as 0.20–0.40 for a conventional power plant (Huang et al., 2001) and it depends on quality of coal. Usual value of this factor is taken as 0.38 for conversion (Agrawal, 2011).

The exergy analysis is based on the second law of thermodynamics, which includes accounting the total exergy inflow, exergy outflow and exergy destructed from the system (Agrawal, 2011; Agrawal and Tiwari, 2015). Exergy is defined as the available energy obtained by subtracting unavailable energy from total energy and is equivalent to the work transformable. The use of overall exergy efficiency (second law efficiency) thus enables qualitative evaluation of PVT overall performance by comparing electrical and thermal energy based on the same standard.

$$\eta_{EX,o} = \eta_e + \eta_{th}\left[1 - \frac{T_a}{T_{w,o}}\right] \qquad (8)$$

T_a is the reference ambient temperature in Kelvin.

4. Results and discussions

The present measurements were carried out through the four weeks of July 2016. The electric power of PV panels and the heat transfer gained are measured every 30 min from 8 AM to 5 PM. Firstly, the electrical efficiency of the three panels were compared for non-cooling case to test the similarity of three panels as shown in Fig. 6. Also, the recorded variation in weather conditions through the four weeks is limited as presented in Fig. 7. The weather conditions are as follow: wind velocity range is 3.1–4 m/s, ambient temperature range is 33.6 to 36.1 °C solar radiation intensity range is 690.6 to 739.3 W/m². Tiny differences between the three panels shown in Fig. 6 and limited variation in weather conditions (Fig. 7) assures that they are identical and can be compared for helical and straight channels at different cooling mass flow rates.

Fig. 8 is the curve between instantaneous solar cell module temperature and time during system running. It can be seen that the temperature of the solar cell module is directly affected by solar radiation intensity. The temperature of the solar panels and ambient exhibit the same trend with the average solar radiation intensity that increases at first and then decreases as the time
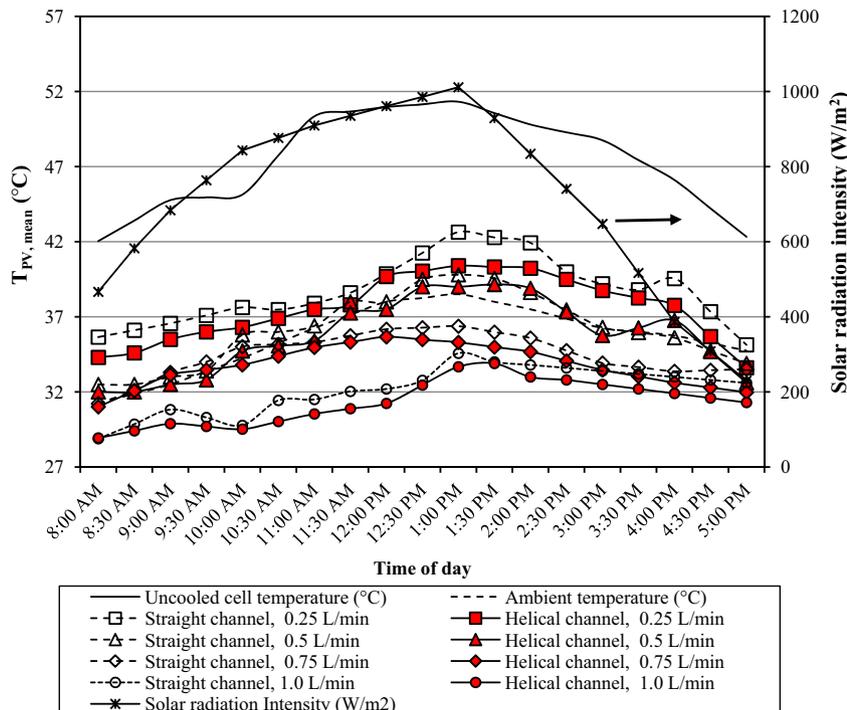
Fig. 8. Solar cells temperatures versus system running time.
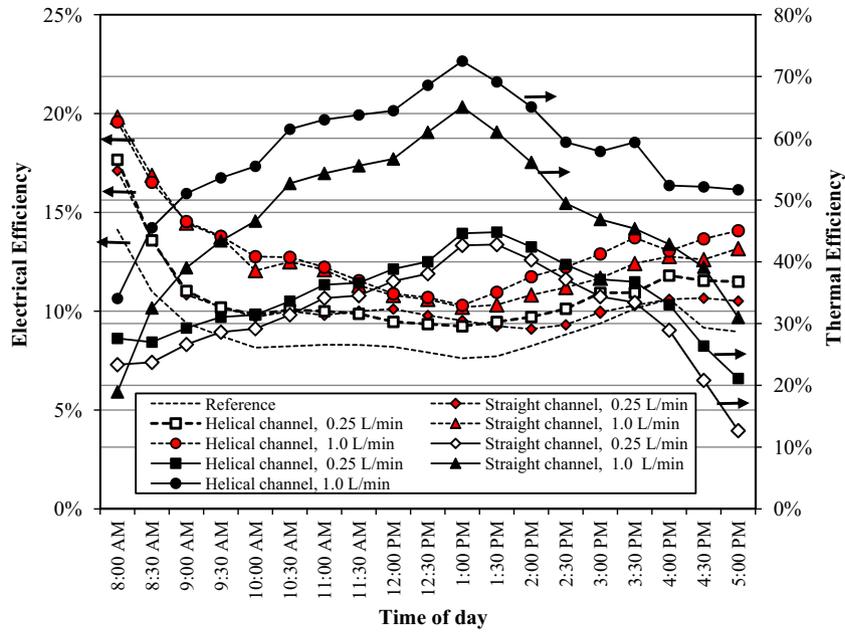
Fig. 9. Instantaneous electrical and thermal efficiencies.
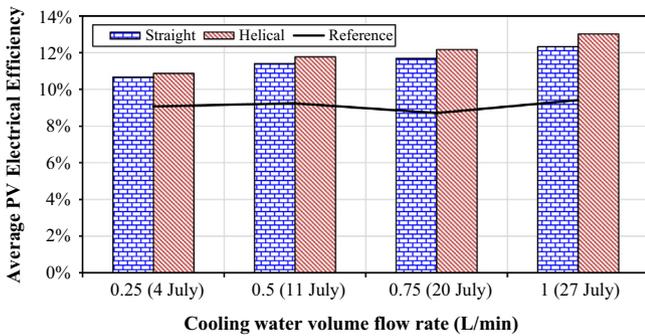
Fig. 10. Average electrical efficiency of solar panels versus cooling water flow rate.

moves towards the sunset. Applying cooling system with straight and helical channels provides a noticeable drop in cells temperature compared with non-cooled reference panel. At flow rate 0.75 L/min, the temperature of the cooled panels can be decreased to ambient temperature level. At flow rate of 1.0 L/min, a drop of 17 °C in panel temperature is obtained (at 1–2 PM) for the recorded weather conditions. In addition, helical channels provides a lower cell surface temperature than that of straight configuration by 1 °C in average as shown in Fig. 8.

Fig. 9 presents the variation in electrical and thermal efficiencies through the day time. This figure reveals that the electrical efficiency of the cooled panels is always higher than that of the un-cooled cell. They start high at 8 AM and then decrease to reach their minimum values at 1 PM. This is due to the increase in the panel temperature with increasing the incident solar radiation. As the radiation intensity is going down later, the electrical
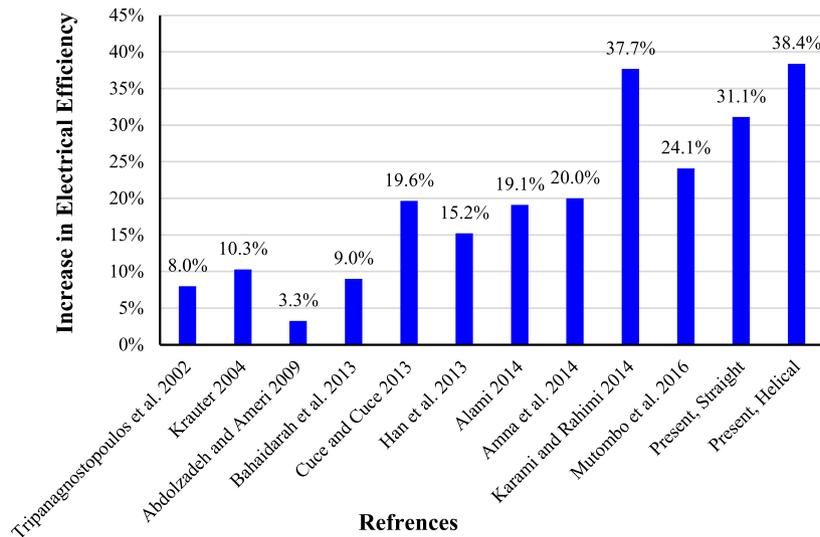
Fig. 11. Comparison of the increase in present PV electrical efficiency with other researchers. (See above-mentioned references for further information.)

efficiency is going up gradually due to the decrease in temperature of the solar cells. It can be noticed that cooled photovoltaic panels with helical channels has a slight increase in the electrical efficiency due to the higher cooling rate in this channel configuration. Also, increasing flow rate enhances the electrical efficiency which can be returned to the enhancement in heat transfer rate and consequentially decreasing temperature of PV cells. From Fig. 10, the increase in the electrical efficiency for PV with helical channel is 20% and 38.4% for cooling water flow rates of 0.25 and 1 L/min, respectively. While for PV with straight channels, the increase in the electrical efficiency is 17.7% and 31.1% for cooling water flow rates of 0.25 and 1 L/min, respectively.

Fig. 11 reveals a comparison for the percent increase in the PV electrical efficiency in the present study, for cooling water flow rate of 1 L/min, with that obtained using other enhancement techniques by other researchers. It is clearly shown that the present design for PVT cooling system gives remarkable enhancement in the electrical efficiency compared with other works. In addition, the channels of helical configuration can be considered one of the highest enhancement techniques.

The thermal efficiency of the PVT system follows the solar intensity changes. It is noticed that helical configuration channel provides higher thermal performance. This can be returned to the increase in cooling rate since the flow rate is divided in lower number of passes in helical configuration compared with straight channel design. Increasing the flow rate notably improves the thermal efficiency up to 72.1% at 1:30 PM for helical channel configuration at the flow rate of 1 L/min. The average thermal efficiency increases from 31.6% to 47.2% for straight channels and 34.3% to 57.9% for helical configuration when flow rate was varied from 0.25 to 1.0 L/min as shown in Fig. 12.

As indicated in Fig. 13, also the PVT overall thermal efficiency nearly follows the solar intensity changes, and its values for PVT with helical channels are more than that for straight configuration at same water flow rate. Additionally, the overall thermal efficiency increases with increasing the cooling water flow rate for both channels arrangements. The average overall thermal efficiency increases from 59.3% to 80.4% for straight channels and 63.2% to 92% for helical configuration when flow rate was varied from 0.25 to 1.0 L/min.

Fig. 14 presents the variation in overall exergy efficiency through the day time. This figure reveals that the exergy efficiency of the cooled panels is always higher than that of the un-cooled cell. It can be observed also that cooled photovoltaic panels with helical channels has a noticeable increase in the exergy efficiency due to the higher electrical and thermal efficiencies for PVT with this channel configuration. Also, increasing flow rate enhances the exergy efficiency. The average exergy efficiency increases from 11.1% to 12.9% for straight channels and 11.5% to 13.5% for helical arrangement for flow rate range of 0.25–1 L/min.

To be a successful heat transfer augmentation technique, the rise in the electrical and thermal energy of the active cooled PV panel should be limited in consuming pumping power. Therefore the pressure drop across cooling channels was measured to calculate the consuming pumping power as illustrated in Table 3. The consumed water pumping power through channels does not exceed 3.3% of the converted electrical power of the cooled solar cells at flow rate 1.0 L/min. From this it is clear that the consumed pumping power is not comparable with the increasing in converted electrical power in PV panels using cooling plate with helical channels that reaches 33.3% of uncooled solar cells. Average electrical power of the reference uncooled cell is 22.5 W.
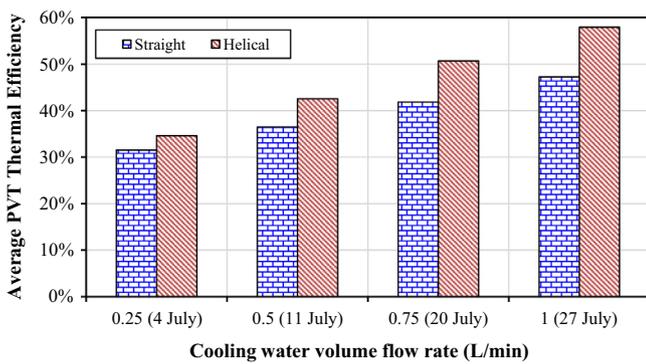
Fig. 12. Average thermal efficiency of the PVT at different flow rates.
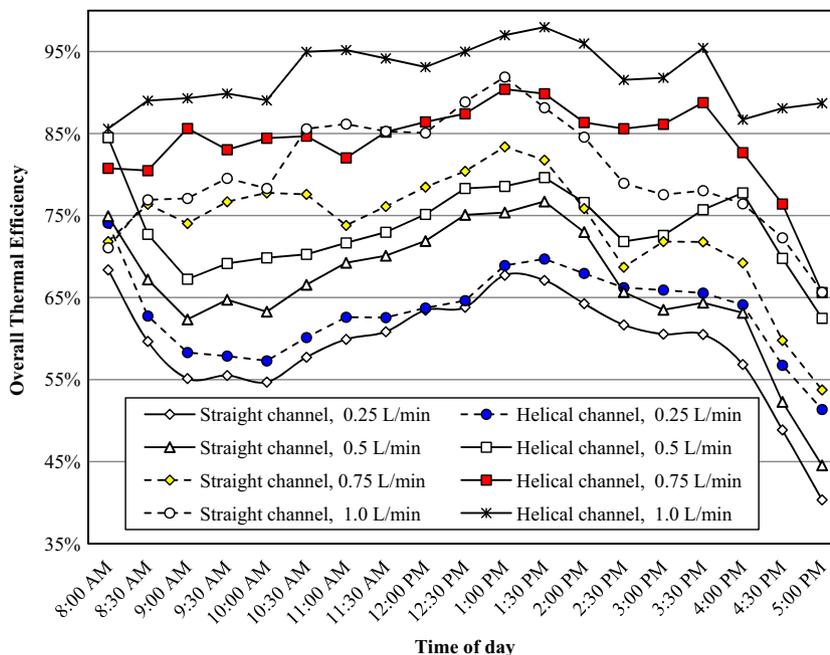
Fig. 13. Instantaneous PVT overall thermal efficiency.
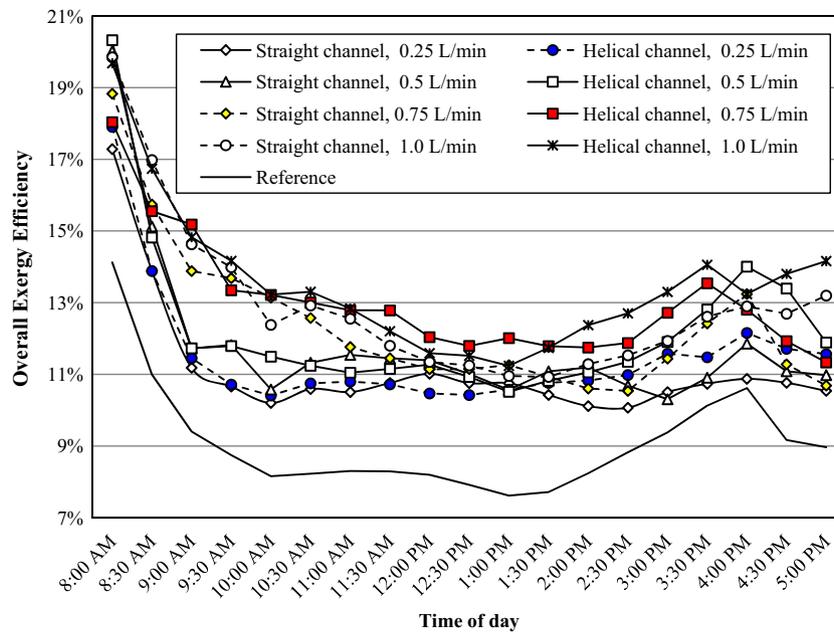
Fig. 14. Instantaneous PVT overall exergy efficiency.

Table 3
Summary of the required pumping power.

Flow rate (L/min)	Straight channels			Helical channels		
	Pressure drop (Pa)	Pumping power (W)	Average electrical power (W)	Pressure drop (Pa)	Pumping power (W)	Average electrical power (W)
0.25	19000	0.12	27.8	22400	0.14	28
0.5	23000	0.28	30.2	26300	0.32	30.6
0.75	30500	0.56	28.7	33800	0.63	30.2
1	39000	0.96	31	43000	1.06	30.1

5. Conclusions

The results of cooled solar modules with straight and helical channels were presented and compared with uncooled reference panels. The panels were installed on faculty of engineering at Shoubra, Cairo (at 30.1°N Latitude) and tests during July 2016. The calculated average electrical efficiency of the reference uncooled PV panels was 9.2% with maximum PV cell temperature of 51.3 °C at peak time for the mentioned weather conditions. The following conclusions can be expressed;

1. The PV temperature decreases as cooling water flow rate increases in both channels configurations where the PV cell temperature decreases to the ambient temperate level at flow rate of 0.5 L/min.
2. Compared with uncooled panel, the increase in electrical efficiency is of 17.7% to 31.1% for straight channels and 20% to 38.4% for helical configuration when the flow rate increases from 0.25 to 1 L/min.
3. The instantaneous thermal efficiency of system could reach 72.5% for helical channel configuration at flow rate of 1 L/min. The average thermal efficiency increases from 31.6% to 47.2% for straight channels and 34.3% to 57.9 for helical configuration when flow rate was varied from 0.25 to 1.0 L/min.
4. PVT overall efficiency nearly follows the solar intensity changes. The average overall efficiency increases from 59.3% to 80.4% for straight channels and 63.2% to 92% for helical configuration when flow rate was varied from 0.25 to 1.0 L/min.

5. The exergy efficiency of the cooled panels is always higher than that of the un-cooled cell. The average exergy efficiency increases from 11.1% to 12.9% for straight channels and 11.5% to 13.5% for helical arrangement for flow rate range of 0.25 to 1 L/min.
6. The pumping power does not exceed 3.3% of the converted electrical power of the cooled solar cells while the increase in the converted electrical power is of 30% with relative to uncooled cell power.

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