

Evaluating the Impact of Cooling Technologies on Photovoltaic module Efficiency: An Experimental approach

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Abstract: The high operating temperature of photovoltaic (PV) modules significantly reduces their electrical efficiency and hinders the advancement of PV applications. Although various cooling techniques have been proposed, many exhibit limited effectiveness due to inadequate heat transfer rate between the cooling medium and the PV module surface. In this study, a PV/T system incorporating a serpentine cooling channel was designed to enhance the thermal and electrical performance of PV/T systems. Water was used as the cooling fluid due to its favorable thermal properties and availability. The system's performance was evaluated experimentally at Misan University, located in southern Iraq, during the months of August and September, when solar radiation is typically high. The results demonstrated that the average electrical efficiency of the PV module improved by 3%, increasing from 7.5% to 10.5% when Reynolds number (Re) rose from 750 to 1250. Moreover, the average cell temperature in the proposed serpentine channel design was reduced by 6°C compared to conventional PV modules. The findings also indicated that the new cooling configuration performed more effectively under high solar radiation conditions, highlighting its potential for improving PV module efficiency.

Keywords: Serpentine-channel, PV/T system, Thermal efficiency, Electrical efficiency

1. Introduction

The rising urbanization in emerging and developed nations is increasing energy needs, reaching new yearly records. Currently, the combustion of fossil fuel resources provides 81% of the world's energy demand. The combustion of fossil fuels emits various greenhouse gases that contaminate the Earth's ecosystem [1][2]. The pollution of the environment resulting from the consumption of fossil fuels highlights the urgent necessity to reduce the use of traditional fossil fuel-based energy production with renewable energy technologies [3]. Solar energy is considered an exceptional form of renewable energy because it is pollution-free, inexhaustible, and abundant in quantity. Photovoltaic modules (PV) are widely used to harness solar energy and convert sunlight into electrical energy [4]. Nevertheless, a significant obstacle in using PV modules is the reduced efficiency of solar cells due to raised cell temperatures. A rise in cell temperature by 1 °C led to a decrease in the PV electrical efficiency of 0.3–0.5% [5][6]. Consequently, several techniques have been suggested to control the heat buildup on the top layer of PV modules. PV/T are a new hybrid technology that generates heat and energy [7], [8], [9], [10], [11]. Numerous researchers attempted to improve the effectiveness of PV/T systems by optimizing the structural designs of cooling channels by various shapes, channel sizes, multi-channel, and arrangements to improve the thermal and electrical efficiencies of the modules. Ooshaksaraei et al. [12] reported that the PV/T systems with a double-path parallel cooling water flow exhibited the highest overall energy efficiency, ranging between 51% and 67%. This was followed by the double-path flow configuration, which achieved efficiencies of 47% to 62%. The single-path returning flow design demonstrated an efficiency range of 42% to 56%, while the standard single-path arrangement showed the lowest performance, with values between 28% and 49%.

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In another contribution by Fudholi et al. [13], they compared the implementation of PV/T systems used with three flow absorbers, direct flow absorbers, and spiral flow absorbers. They reported that highest total efficiency of 68.4% was attained with a spiral flow absorber at solar irradiance of 800 W/m² and cooling water flow of 0.041 kg/s, electrical efficiency being 13.8%, and thermal efficiency at 54.6%. Also, Baloch et al. [14] proposed a cooling system, 'converging channel heat exchanger,' to cool PV modules; there were sharp reductions in cell temperature, leading to 45.1 and 36.4 degrees Celsius for the month of June and December, respectively. On the other hand, the maximum recorded increment in power output was 35.5%, whereas the maximum increase in conversion efficiency was 36.1% as compared to an uncooled PV module. Nahar et al. [15] conducted a simulation to evaluate the performance of PV modules incorporating a pancake-shaped cooling channel. Their findings indicated that this configuration effectively reduced the average cell temperature to 42°C. Additionally, the electrical efficiency improved by 2% as the velocity of the cooling water varied from 0.0008 to 0.05 m/s. Sopian et al. [16] conducted a comparative analysis of steady-state models for PV/T systems utilizing air cooling, specifically examining single-channel and double-channel configurations. Their study revealed that the total efficiency of the double-channel design was 10–15% more than single-channel counterpart. Fudholi et al. [17] conducted an energy analysis featuring a V-groove design and determined that the mean electrical efficiency reached 12.66%. Sing et al. [18] conducted a parametric study on a PV/T system utilizing a spiral flow coolant, assessing the impact of different controlling parameters on overall performance. Their findings confirmed that the spiral flow configuration was the most effective absorber design. Additionally, they observed that while thermal efficiency increased with rising solar intensity and temperature, electrical efficiency showed a decline.

PV/T systems generally extract heat from the top surface of the PV module, with the remaining surfaces thermally insulated. Enhancing the effective heat transfer area is therefore considered a practical and efficient method for improving the system's overall thermal performance. This study introduces an innovative collector design integrated with a PV panel to improve efficiency. The proposed solar collector incorporates baffles attached to the absorber's top surface, extending downward to enhance heat transfer from the PV cells to the working fluid, thereby increasing both electrical and thermal efficiency. Additionally, a serpentine-channel configuration is implemented to optimize flow circulation within the collector, ensuring more effective energy absorption across the entire system. Pure water is used as the working fluid for the rectangular baffle-based channel. This shows that the proposed system provides better results than the conventional configurations of thermal systems. So the main contribution of this research was to reveal how variation in solar radiation levels along with flow rates affects the temperature of the solar cells and that of the outlet fluid with the overall system efficiency. should be aware of. References on all topics are provided for more detail.

2. Experimental work

2.1. System setup and equipment

The experiment was conducted on the rooftop of the College of Engineering at Misan University, Iraq (47.14°N, 31.84°E). The PV/T systems were installed at a 30° tilt facing south and operated daily from 8:00 AM to 5:00 PM, as illustrated in Fig. 1. The setup included two polycrystalline PV modules, each with a power rating of 50 watts and dimensions of 66 mm × 56 mm × 3 mm. One module functioned as a reference, while the second was modified by a serpentine channel to induce turbulence and improve heat transfer. The collector was securely mounted on the back of the PV module using thermal glue and clamps. Additionally, a helical copper spiral was placed inside a cold water tank, which was supplied with mains water at a temperature of 32°C. The spiral consisted of seven coils, with a diameter of 25 cm and a tube diameter of 12.5 mm. This configuration was specifically designed to increase the surface area for heat exchange and to enhance heat dissipation by promoting turbulence within the water, thereby improving the overall thermal performance of the system. One port of the tank was connected to the PV/T system's outlet to receive the heat extracted from the PV module, while the other port was

connected to a secondary reservoir, which served as the main source of working fluid. This facilitated efficient heat dissipation and temperature control (see Fig. 2). The entire collector was insulated with thermal wool and aluminum to reduce energy losses. Further details regarding the design specifications and characteristics of the PV/T system are presented in Table 1.

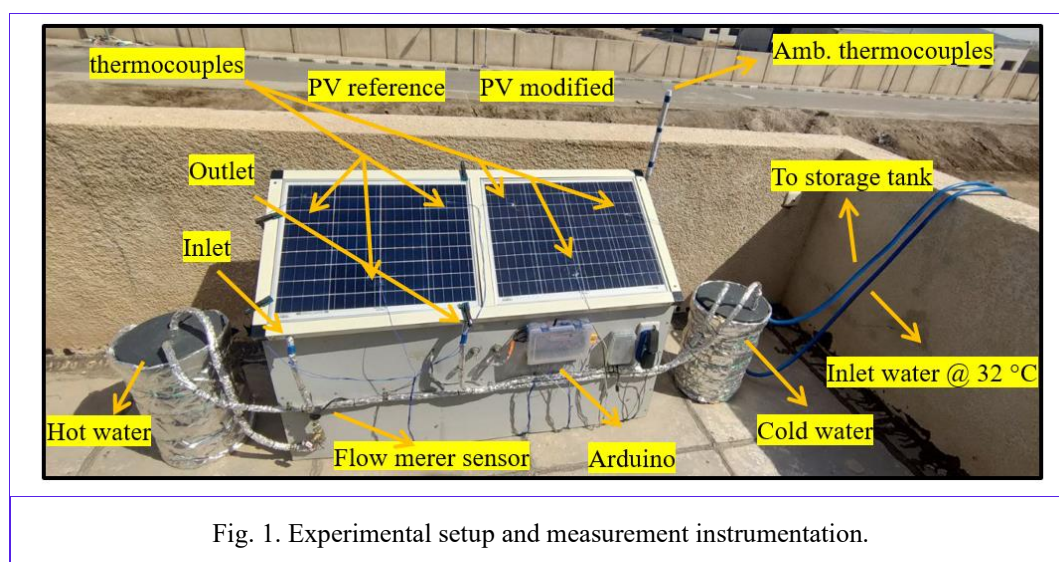
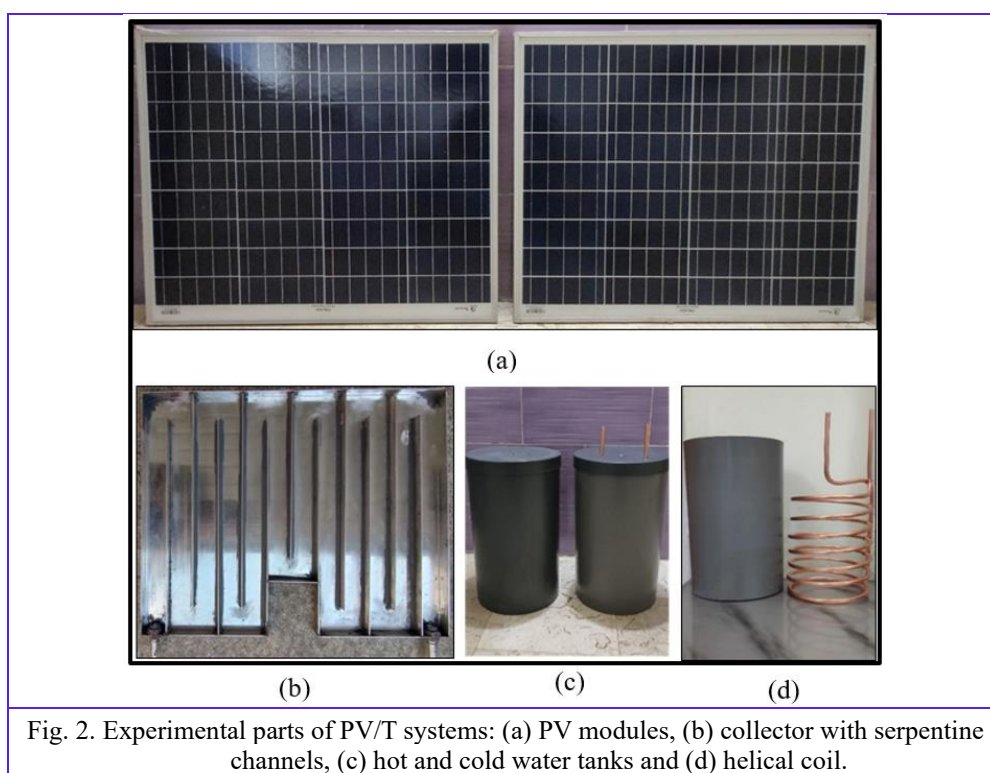


Fig. 1. Experimental setup and measurement instrumentation.

Table 1. Design specifications and characteristics of the PV/T system.

Parameter	Specification
PV Module Type	Polycrystalline
PV Dimension (mm)	650 × 550
Rated Power	50 W
Number of cells	36
Cell efficiency (%)	16
Module Dimensions	66 mm × 56 mm × 3 mm
Number of channels	12
Area of baffles (mm)	430 × 25
Tilt Angle	30° (Facing South)
Cooling Mechanism	Plate with serpentine channel
Collector Insulation	Thermal wool and aluminum
Heat Transfer Enhancement	Turbulence-induced serpentine channel
Heat Dissipation System	Helical copper spiral in water tank
Working Fluid	pure water
Operating Hours	8:00 AM – 5:00 PM
Installation Location	Misan University, Iraq (47.14°N, 31.84°E)



In this study, pure water was employed as the cooling medium, and data collection was facilitated using a multichannel Arduino AT Mega 2560, provided by Ardunin Sinaa in Baghdad. This device was equipped with sensors to measure current and voltage output, along with K-type thermocouples to monitor temperature variations. Fluid circulation was controlled by a pump located within the tank, maintaining at various Re 750, 1000, and 1250 throughout all experiments. A flow sensor was placed between the pump and the inlet to continuously monitor and measure the flow rate. Additionally, a thermocouple was used to track ambient temperature. Solar radiation levels were recorded at 30-minute intervals with the help of a solar power meter. Data acquisition and retrieval were managed by Signal Express 2015 software, ensuring that data was systematically collected every 30 minutes. The specifications of the measurement instruments are listed in Table 2. The performance of the PV/T system can be very sensitive to abrupt changes in weather, e.g., sudden cloud cover and immediate changes in ambient temperature. Experiments were conducted in August and September for more dependable results such that the uncertainties contributed by weather conditions, ambient temperature, solar radiation, which remained more or less constant during this period, could be kept to a minimum.

Table 2. Details of sensor and measurement device specifications.

Item	Range	Model	Accuracy	Units
Pump	1000	LH-1600C	--	L/h
Flow rate sensor	1–30	YF-S201	±9%	L/min
Thermocouples	–200 to 1350	K (3 m length)	0.25	°C
Voltage sensor	up to 25	Module 25 V	0.02445	V
Solar power meter	1–3999	SM209	10	W/m ²
Current sensor	up to 30	ACS712	0.04	A

2.2. Data reduction

In this study of finned-serpentine channels and PV/T systems, the governing equations should be understood accurately in terms of fluid dynamics and heat transfer. The most important dimensionless parameter is the Re , which will give a clear picture of the flow regime within the channel and can be expressed as [19]:

$$Re = \frac{u_m \times D_h}{\nu} \quad (1)$$

where u_m is the average velocity, ν is the kinematic viscosity, and D_h is the hydraulic diameter. The hydraulic diameter is determined by the following equation [20]:

$$D_h = \frac{2(W \times H)}{W + H} \quad (2)$$

This equation factors in channel geometry dimensions, W and H being the width and height of the channel.

The electrical efficiency (η_{el}) of the PV/T system is determined by the following equation [21]:

$$\eta_{el} = \frac{V \times I \times FF}{G \times A} \quad (3)$$

where V is the voltage, I is the current, G is the solar intensity, and A is the area of the PV/T surface. The fill factor (FF) indicates the maximum PV efficiency and can be calculated by [19]:

$$FF = \frac{V_{pv} \times I_{pv}}{V_{oc} \times I_{sc}} \quad (4)$$

The electrical power output, P is calculated using the following expression [19]:

$$P = V \times I \quad (5)$$

The thermal efficiency (η_{th}) is determined by the equation [22]:

$$\eta_{th} = \frac{\dot{m}C_p \times (T_{out} - T_{in})}{G \times A} \quad (6)$$

where C_p is the specific heat capacity, $\dot{m}$ is the mass flow rate, and T_{out} and T_{in} are the outlet and inlet temperatures, respectively.

2.3. Uncertainty analysis

An uncertainty analysis was carried out for both the instruments employed in the experimental setup and the relevant physical quantities to assess the measurement errors. This analysis focused on quantifying the uncertainties associated with key parameters such as thermal efficiency, electrical efficiency, and power output. The uncertainties for these parameters are formulated in Equations (7), (7), and (9). To calculate these uncertainties, established methodologies were applied, as referenced in [23], [24]. A detailed summary of the uncertainty analysis and the results is provided in Table 3, offering a

comprehensive overview of the accuracy of the measurements and potential sources of error in the experimental procedure.

$$\frac{UP}{P} = \sqrt{\left(\frac{UV}{V}\right)^2 + \left(\frac{UI}{I}\right)^2} \quad (7)$$

$$\frac{U\eta_{el}}{\eta_{el}} = \sqrt{\left(\frac{UV}{V}\right)^2 + \left(\frac{UI}{I}\right)^2 + \left(\frac{UG}{G}\right)^2 + \left(\frac{UFF}{FF}\right)^2} \quad (8)$$

$$\frac{U\eta_{th}}{\eta_{th}} = \sqrt{\left(\frac{UG}{G}\right)^2 + \left(\frac{U\dot{m}}{\dot{m}}\right)^2 + \left(\frac{UT}{T}\right)^2} \quad (9)$$

Table 3. Measurement uncertainty.				
No.	Parameter	Symbols	Values	Range of uncertainty %
1	Power	P	15.71–41.38	0.76–0.8
2	Electrical efficiency	η_{el}	9.96–15.8	0.21–0.88
3	Thermal efficiency	η_{th}	34.81–50.51	4.7–6.78

2.4. Estimation of PV/T economic feasibility

A significant component of this study is the evaluation of the economic implications of the proposed cooling technique in comparison to traditional PV modules. This analysis is crucial for determining the payback period of the PV/T systems. The assessment takes into account several factors, such as low maintenance requirements, operational costs associated with components like the pump and flow sensor, as well as the overall energy consumption of the system. The hybrid PV/T system consists of various elements, including an aluminum serpentine channel, cover, pump, insulation, plastic tubing, and plastic containers. The net profit is calculated using equation (10), which incorporates the costs associated with each individual component.

When compared to conventional PV modules, the hybrid PV/T systems, which utilize serpentine channels, show a payback period of 780 days. In contrast, traditional PV modules have a longer payback period of 863 days. This difference underscores the economic advantage of integrating cooling method, which not only enhance the system's efficiency but also reduce the payback period, making the PV/T systems more economically viable. Additional details regarding the cost breakdown and calculations are presented in Table 4.

$$\text{Net profit} = \text{energy production costs (electrical and thermal)} - \text{operational costs} - \text{maintenance expenses} \quad (10)$$

Components/Aspects	PV module	PV/T system
Configurations	35 \$	172 \$
Maintenance	0.00397 \$/day	0.007 \$/ day
Operation cost	–	0.00157 \$/ day
Energy productivity	0.0445 \$/day	0.229 \$/day
Net profit	0.0405 \$/day	0.2204 \$/day
Payback period	863 days	780 days

3. Results and discussion

A comparative assessment of weather data in Al Amarah with regional and global climate trends offers a broader perspective on climate variability. Situated in a semi-arid zone, Al Amarah has experienced temperature increases aligned with warming patterns observed throughout the Middle East. Precipitation levels fluctuate in a manner similar to nearby regions, including western Iran, Kuwait, Saudi Arabia, and the UAE, where a hot desert climate prevails, characterized by intense heat, arid summers, cooler winters, and sporadic rainfall [25]. Due to these climatic parallels, the study's findings can be extended to areas with analogous environmental conditions. This analysis highlights the interconnected nature of climate systems, strengthening the reliability of the study's conclusions and supporting the development of adaptation strategies for Al Amarah and comparable regions. The collected data, recorded at the University of Misan, indicate that the highest ambient temperature reached 48°C , while peak solar radiation was measured at 1160 W/m^2 . Observations reveal fluctuations in temperature and solar radiation, with maximum values occurring at 12:30 PM, followed by a gradual decline as the day progresses as shown in Fig 3.

The effect of solar intensity and different flow regimes on the electrical power is illustrated in Fig. 4. The results indicate that as solar irradiation increases, electrical power also rises due to the greater energy absorption by the PV module at higher solar intensities. Additionally, electrical power improves with increasing flow velocity. At $\text{Re} = 1250$, the flow velocity is higher than in $\text{Re} = 750$ and $\text{Re} = 1000$, leading to enhanced convective heat transfer within the fluid. Consequently, at a given temperature, greater flow velocity facilitates more efficient heat dissipation.

Furthermore, at $\text{Re} = 1250$, the improved cooling effect enhances electrical performance compared to $\text{Re} = 750$ and $\text{Re} = 1000$ in the PV/T system. While solar radiation increases from approximately 300 W/m^2 to 1100 W/m^2 , electrical power increases by 7.2% to 9.6% for $\text{Re} = 750$ to $\text{Re} = 1250$, respectively. Simultaneously, the average electrical power rises from 26.6 to 29.3 as solar intensity increases comparing to the conventional PV modules .

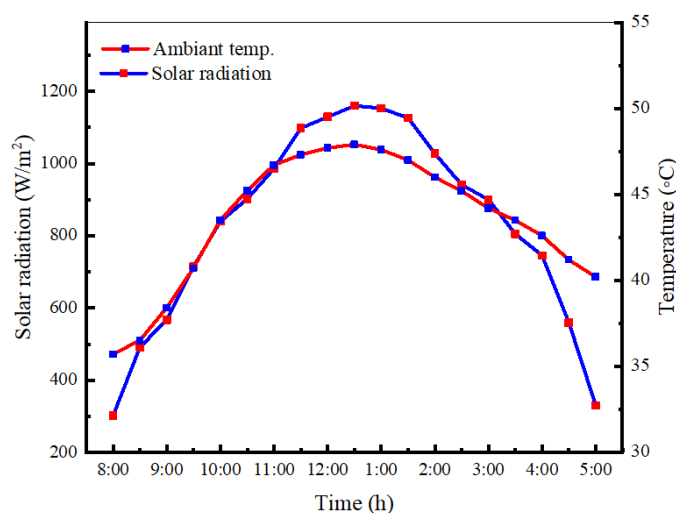


Fig. 3. Solar radiation intensity and ambient temperatures.

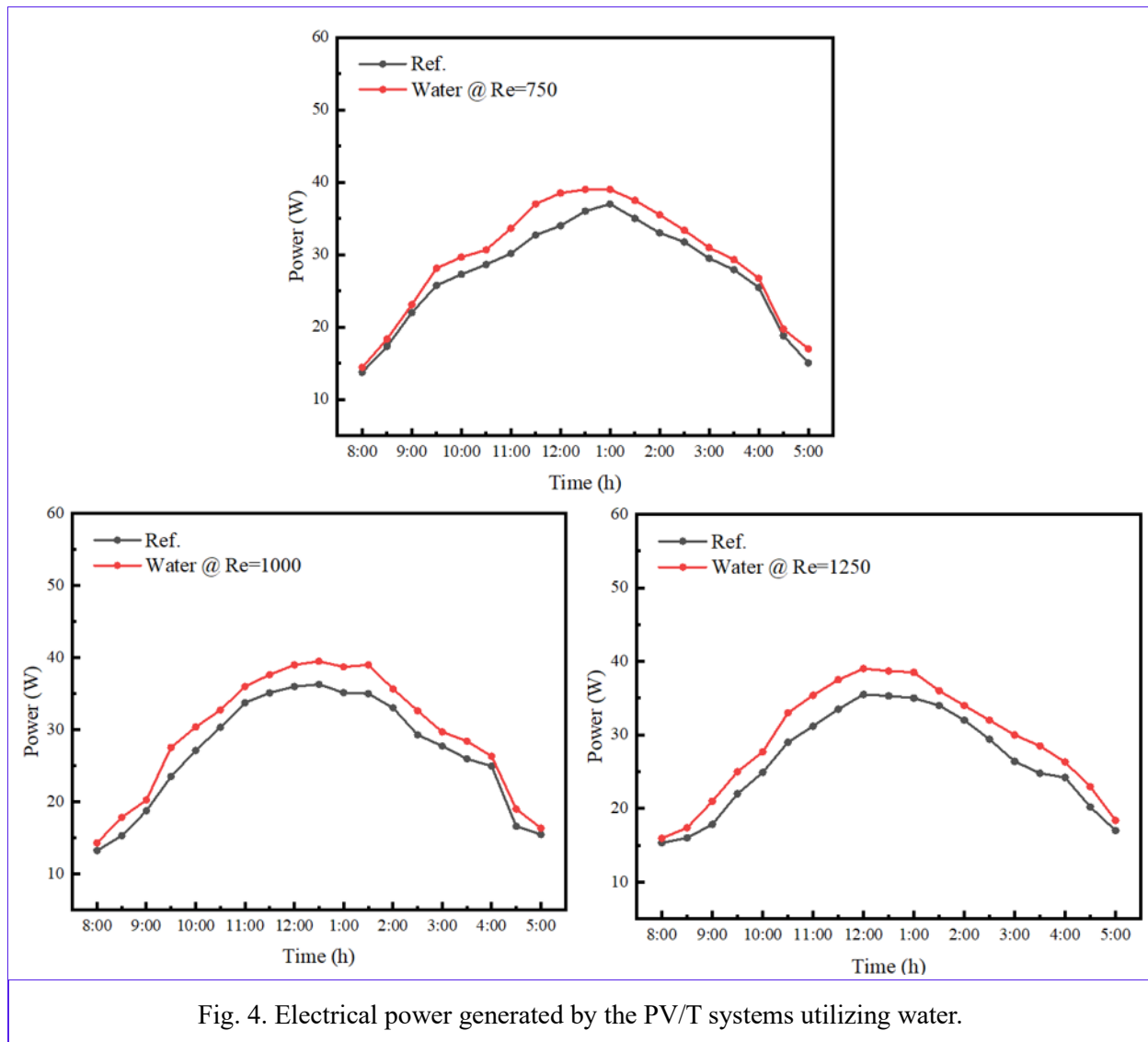
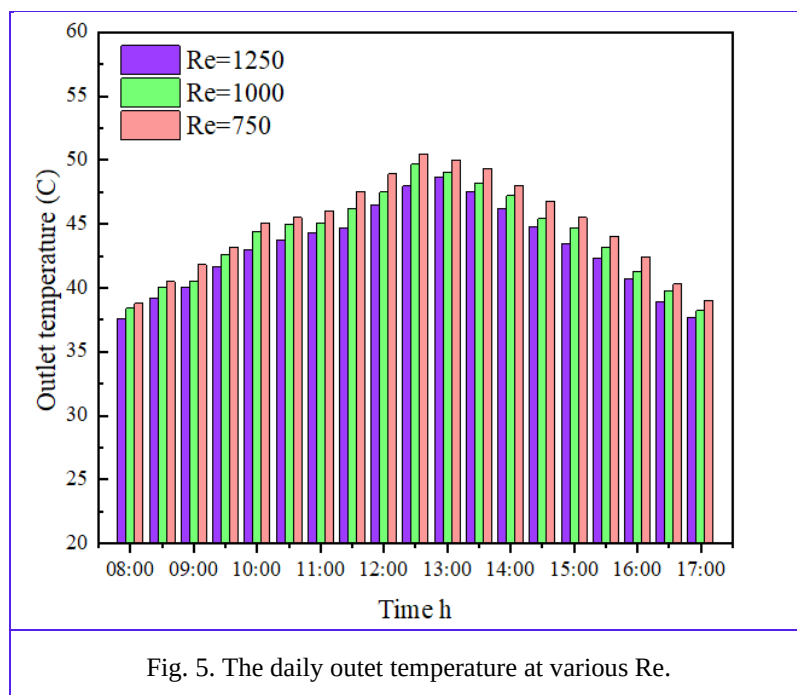
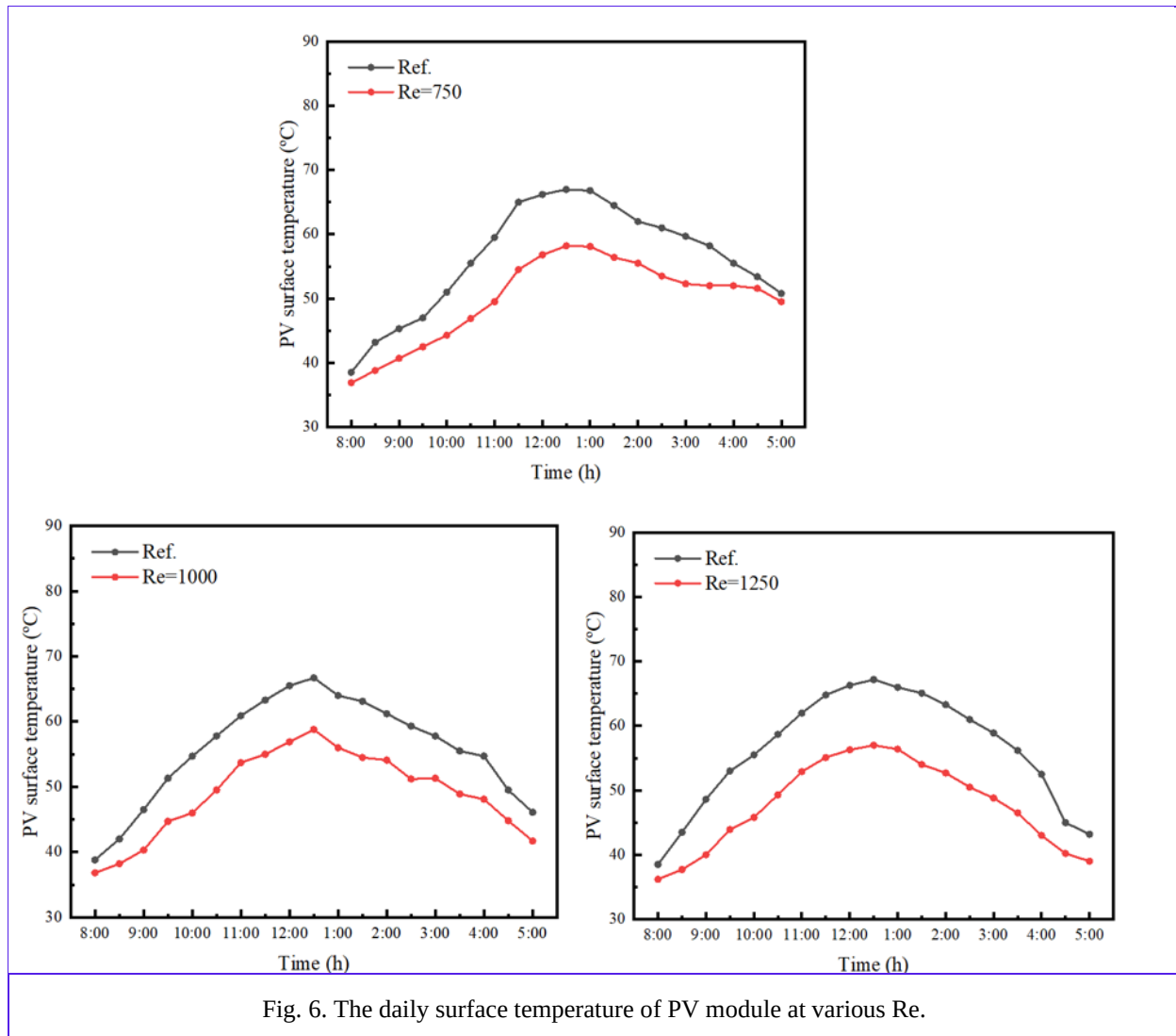


Figure 5 shows the outlet temperatures of the fluid domain at different flow rates. The fluid remains in contact with the PV panel for a longer period, which means it can absorb more heat. However, at the same time, the cells remain hot for a longer period, reducing their electrical efficiency because the higher temperature reduces the PV conversion efficiency. At a high flow rate (high Re): Heat is removed more quickly, preventing the solar cells from overheating. This maintains high PV conversion efficiency because the cells operate best at relatively low temperatures. The results reveal that the highest outlet temperature occurs at $Re = 750$ for all levels of solar irradiation. This is because, at low Re values (creeping flow), so the water flows slowly and absorbs more heat from the system. The second highest outlet temperature is observed at $Re = 1000$. As water velocity increases, it removes heat more efficiently, which results in slightly lower outlet temperatures. For example, compared to $Re = 750$, the average outlet temperatures at $Re = 1000$ and $Re = 1250$ drop by about 2% and 4%, respectively.

Moreover, increasing solar irradiation causes the outlet temperature of the fluid to rise. This is due to more solar energy being transferred through the PV/T system, which is then absorbed by the fluid. Higher radiation levels also enhance heat transfer within the PV layers through both conduction and convection, directing more heat toward the cooling channel. As a result, the fluid carries away more thermal energy, leading to higher outlet temperatures with stronger solar input.



The influence of solar irradiation on the average surface temperature of PV modules is depicted in Fig. 6. The results indicate that the highest average cell temperature occurs at $Re = 750$, while the lowest is observed at $Re = 1250$. since the flow pattern is limited by velocity of water, a higher velocity enhances heat dissipation, leading to more effective cooling. Consequently, the surface temperature at $Re = 750$ remains higher compared to $Re = 1000$ and $Re = 1250$. The average surface temperature of the PV module at $Re = 750$ is $50\text{ }^{\circ}\text{C}$ while at $Re = 1250$ is $46.6\text{ }^{\circ}\text{C}$. This difference decreases the surface temperature of the PV module by up to 15.3%. In comparison with the conventional PV module, the average surface temperature shows a decreases in temperature ranging from $7\text{ }^{\circ}\text{C}$ to $9\text{ }^{\circ}\text{C}$ at $Re = 1000$ and $Re = 1250$. The rise in fluid velocity enhances heat transfer through conduction and convection, contributing to better thermal regulation. Moreover, the average surface temperature exhibits an increase with rising solar irradiation. As irradiation levels grow, the PV module absorbs more heat flux, resulting in greater heat generation and an overall elevation in temperature.



The effect of solar radiation and flow system on electrical efficiency is illustrated in Fig. 7. The results indicate that electrical efficiency increment as velocity increases due to the rise in heat transfer between the PV module and the collector, which is decreasing the surface temperature of the PV module. Therefore, the electrical efficiency increases by up to 7.6%, 9.5%, and 11.4% for $Re = 750$, 1000, and 1250, respectively.

Conversely, electrical efficiency improves as the flow shifts from $Re = 750$ to $Re = 1250$. The most substantial efficiency reduction is observed at $Re = 750$, as this flow condition transports the fluid at a lower velocity compared to $Re = 1000$ and $Re = 1250$. Consequently, convective heat transfer in $Re = 750$ is less effective than in the higher Re cases, leading to greater thermal accumulation and a more pronounced decline in efficiency.

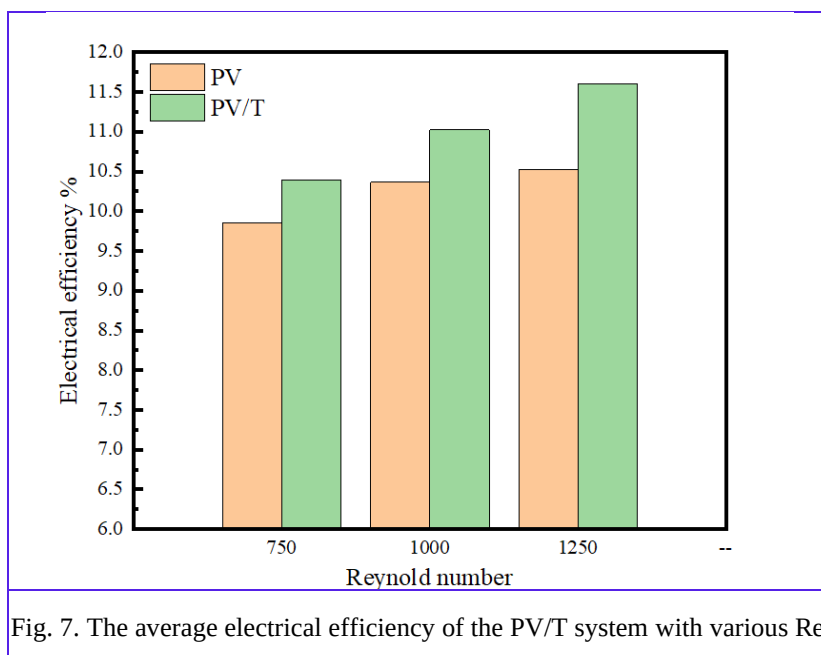


Fig. 7. The average electrical efficiency of the PV/T system with various Re.

The impacts of solar intensity on thermal efficiency under different flow are illustrated in Fig. 8. The results demonstrate that thermal efficiency decreases as solar intensity increases. This is attributed to the rise in conductive heat flux caused by higher solar intensity, leading to an increase in system temperature. As a result, although the total absorbed energy increases, thermal efficiency declines.

Although the thermal efficiency decreased as more heat was dissipated into the ambient air through convective and radiative heat transfer, the thermal efficiency of the PV/T systems improved by up to 3.21 % for $Re = 1000$ and 5.5% for $Re = 1250$ comparing to the $Re=750$. However, the thermal efficiency at $Re = 1000$ and $Re = 1250$ remains higher compared to $Re = 750$. This improvement is attributed to the greater temperature gradient generated by higher flow rates, which enhances heat transfer rate between the water and the collector.

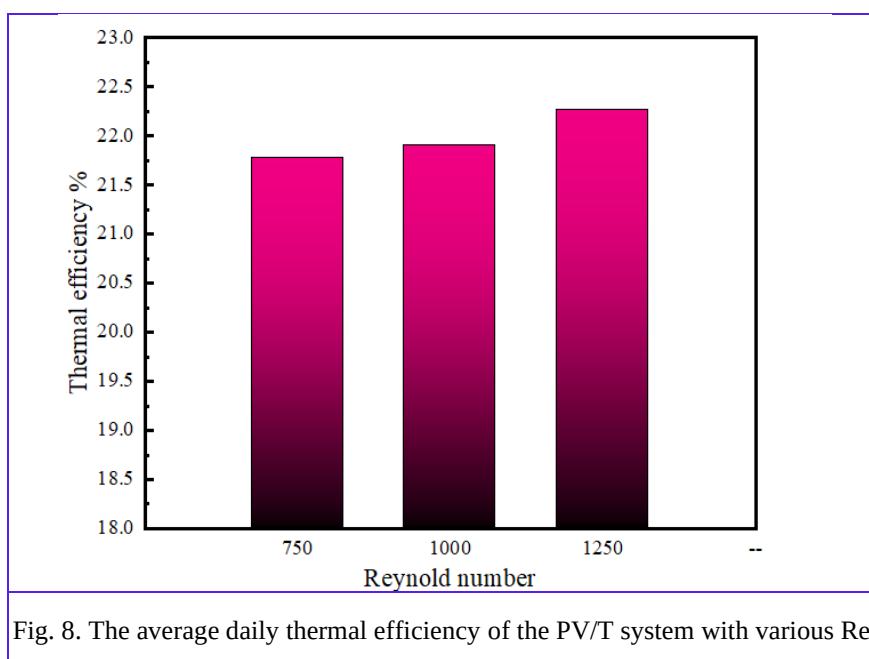


Fig. 8. The average daily thermal efficiency of the PV/T system with various Re.

4. Conclusion

This research seeks to enhance the performance of a photovoltaic/thermal (PV/T) system by developing an advanced cooling unit that employs serpentine channels and water for uniform heat dissipation. The study evaluates the thermal and electrical efficiencies of the system under varying solar irradiance levels and different flow regimes. The key findings of this study are summarized as follows:

- The temperature of the PV modules, the outlet temperature, and the electrical power all increase as solar radiation rises.
- When Reynold number increases, electrical efficiency increment by up to 7.6%, 9.5%, and 11.4% comparing to the conventional PV modules.
- When solar radiation increases from approximately 300 W/m² to 1100 W/m², electrical power increases by 7.2% to 9.6% for Re = 750 to Re = 1250, respectively.
- Hybrid PV/T systems with serpentine channels achieve a shorter payback period of 780 days, compared to 863 days for conventional PV modules.

This research provides a guide for establishing a PV/T systems in Al-Amarah or other regions with comparable climatic conditions, facilitating the identification of the most suitable flow regime for given operational parameters. Further research could explore various PV/T system designs using different nanofluids, incorporating cost analysis. Furthermore, a life cycle assessment utilizing a deep learning-based artificial neural network method could be considered to evaluate the performance of the different flow regimes in this system.

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