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Enhancing the Power Conversion of Photovoltaic Systems with Metallic Porous Media and Phase Change Material

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ABSTRACT

Photovoltaic system is one of the promising electricity generation devices due to its direct solar energy conversion, safe power transmission and practicability. However, its performance is very sensitive to high temperatures. Photovoltaic/Thermal systems were presented for enhancing the electrical efficiency and making use of the lost thermal energy. In this research, a combined usage of Paraffin as a phase change material, and a stainless-steel porous media was used to decrease its temperature and use its thermal energy. Two different systems were used for comparison. One contains Stainless steel wool with paraffin, and the other contains Paraffin without porous media. Three flow rates of 0.0033, 0.005, and 0.0067 L/s were used of water as a heat transfer fluid. It was found that, for all the tested flow rates, the system with a porous metallic media achieved lower surface temperature, higher electrical efficiency, and higher overall efficiency. The temperature of the PV cell decreased by 5 to 25^{o} C. The enhancement achieved was from 10% to 28% in the overall efficiency, and 1% to 4% in the electrical efficiency. This emphasizes the importance of the porous metallic media in enhancing properties of Paraffin as a phase change material when using with the Photovoltaic modules cooling.

1. Introduction

The photovoltaic (PV) panels are one of the most important clean sources of electricity in the world nowadays. Cooling the PV is very important for improving the system's efficiency. So, Abdelrazik et al. [1] compared the performance of two systems, the first one was a hybrid PV - Phase change material (PCM), and the second was PV thermal (PVT) system. He used nanoparticles in the two systems. The first system consists of a Nano PCM layer under the PV, which was covered by a box with cooling fluid channel under the Nano PCM layer. This comparison was performed in summer and winter with a traditional PV system. The PVT with Nano particles system achieved 22% and 6.9% higher efficiency compared to the PV system in summer and winter, respectively. Zhang et al. [2] investigated experimentally the performance of low concentrating photovoltaic thermal system (LCPVT) and a PVT system. They found that the electrical power of the LCPV/T system is higher than that of the PVT system by 3.1 times, and the thermal power for the two systems are 2247.95W and 1198.71W respectively. An investigation to show the benefit of

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the PCM system in cooling the PV was introduced [3]. They found that using a Nano fluid in the cooling fluid was a very promising technique for cooling the system. An investigation for the effect of the high temperature of the PV on its performance and coupling the PV with the PCM was one of the effective solution for this problem [4]. Moreover, they tested improving the electrical and thermal output of the system considering the PCM melting point, the wind speed and the inclination angle of the PV. An investigation for the effect of the nanoparticle in PCM for PV cooling was introduced [5]. The working temperature of the PV was damped using the PCM. The poor heat transfer rate could be enhanced using a nanoparticle. They used four nanoparticles types. Aluminum oxide ($Al2O3$), Copper (Cu), Copper oxide (CuO), and Titanium dioxide ($TiO2$). The PCM was of n-Octadacane type with 28.2°C melting point. The Cu nanoparticle found to achieve the best result by keeping the temperature below 40 °C for 60 min with a fixed irradiance of 500 W/m^2. They found that the melting rate depends on the thermal conductivity and the density of the Nano particles. Nouira, and Sammouda [6] investigated the role of the PCM in cooling the PV system numerically. They used different PCMs with different melting point of (26.2 °C, 35 °C and 44 °C) with different layer’s thickness of (1cm, 1.5cm, 2cm, 2.5cm and 3cm) under different conditions of wind speed, wind direction, and dust accumulation. They found that the maximum operating temperature achieved were 87 °C, 72.5 °C, 69 °C, 66 °C, 64 °C and 63 °C for wind angles of 90°, 75°, 60°, 45°, 30° and 15°, respectively. The efficiency of the PV-PCM system was 13.1%, 13.4% and 13.5% under dust densities of 3 g/m^2, 6 g/m^2, and 9 g/m^2 with solar radiation of 72 W/m^2, 217 W/m^2 and 227 W/m^2, respectively. The output power of the system was 3 W, 2.8W and 1.2W for 9 g/m^2, 6 g/m^2 and 3 g/m^2 of dust density, respectively. Experimental and numerical test data were analyzed to show the performance of a PV-PCM system at two different cities with different climate continental and coastal climate conditions [7]. They found that the PV temperature could be reduced by 0.31°C to 10.26°C with improving the efficiency from 0.48% to 3.73%; and improving the annual efficiency by 1.59%. An experimental study was presented to analysis the performance of a PVT system combined with PCM [8]. They used fatty acid with melting point of 37°C as a PCM. They implemented rectangle metal fins inside the PCM, to improve the heat transfer. The experimental study was carried out in outdoor conditions for four days. Moreover, they used times regulation control to reduce the temperature and to heat the water tank. They found that the PV temperature dropped by 16.9°C and 12.6°C during the regulation with efficiency improving of 6.4% and 5.9% compared with Case 2. An investigation for the effect of Nano fluid in cooling the PVT-PCM system was performed numerically and thermodynamically [9]. PVT-PCM system consist of a PV panel, absorber, fluid pipe and PCM unit layer. The used Nano particle were MWCNT (multiwall carbon Nano Tube) and Nano-MgO (Nano-magnesium oxide) with water, using a PCM with 40 °C melting point. Moreover, the MWCNT-water has mass fraction of 3% and 6% which was higher in total energy efficiency. The phase change material was stable for almost 2 hours without melting. The outflow and surface temperature were reduced by increasing the PCM thickness from 0.5cm to 1.5cm, which enhanced the heat capacity of the system. An investigation was conducted for the performance of the PVT-PCM system using refrigerator to cool the PV [10]. The heat output of the PVT system was improved to 28,816 kW and the output power to 6687 kW. The refrigerator cycle used a part of the total power of the system and consumed 5395 kW at a temperature of 9°C all over the day. Moreover, increasing the radiation by 70% led to the electrical energy decrease by 4.128% although the thermal energy increased by 8.656%. Increasing the area of the solar collector by 14.45% increased the input heat to the generator of the refrigerator cycle by 14.45%, decreasing the thermal efficiency by 5.861%. The cooling by the refrigerator cycle increased to 13.81%. Finally, increasing of the area of the collector increased the mass flow rate by 14.89% and the thermal energy storage by 14.92%. An experimental investigation for the performance of PV, PVT and PVT-PCM systems were presented [11]. They compared the performance of three different systems of conventional PV system, PVT water system with double absorber plate and PVT-PCM water system. The absorber plate attached to the back of the PV panel, copper pipes are attached between the two absorber sheets. They used three different flow rates of 0.013 kg/sec, 0.023 kg/ sec, and 0.031 kg/sec. The PVT-PCM system consisted of a PV panel with aluminum container and the absorber is attached to its back with copper pipes. Nine Fins were installed inside the PCM container having 65 kg of paraffin wax with 28°C melting point. The maximum temperature achieved in the conventional PV was 85ºC. The PVT-PCM water system decreased the PV temperature by 53% and the PVT water system decreases the PV temperature by 47% at flow rate of 0.031 kg/sec. An experimental investigation was carried out to show the role of PVT-PCM system using two side serpentine of copper for cool the PV by water flow [12]. They used five different PCM materials with different melting points (paraffin range 52-54 ºC, 1-tetradecanol range 36-40 ºC, Lauric acid range 44-46 ºC, Decanoic acid synthesis range 27-32 ºC and Decanoic acid natural range 29-33 ºC). The maximum electrical efficiency obtained at 4 LPM flow rate was 14.42% with 160.29W maximum output power. With increasing the radiation by a 100 W/m^2 step, the electrical power decreased by 0.55% and the output power increased by 13.12 W. Every 1 ºC drop of the PVT-PCM system caused a total power increase of 8.76 W. The maximum thermal efficiency found to be 87.72% at 2 LPM flow rate.

In the present study, the PCM as a thermal storage material and temperature decrease element for the PV panels will be used in conjunction with a porous metallic foam material, which in this study is a stainless-steel wool (SSW). The effect of the SSW will be tested under different flow rates to study its effect on the PVT system performance. So, the main contribution of the present research lies in:

- Using paraffin wax as the PCM with low melting temperature 30ºC
- Using SSW in conjunction with the PCM material and HTF serpentine.
- Applying the test under three different flow rates.
- Analyzing the electrical, thermal and overall efficiency of the proposed PVT system

2. Experimental Description

2.1 System Layout

In this study, a comparative study is performed on two PVT systems using PCM. The used PCM is Paraffin with melting point of 37 ºC. There were two types of PVT systems for comparison. Each of the two systems consist of a 50W photovoltaic panel. A brass box was installed at the back of the panels with copper serpentine having inner diameter of 6mm installed on the backside of the PV panels. The brass box dimensions were (680x630x30) mm, the serpentines tube used for the water flow. Both the brass boxes of the two systems are filled with paraffin wax, although the second system contains a porous metallic media inside the paraffin, to improve the heat transmission to and from the paraffin. The porous media was a stainless-steel wool (SSW). The internal composition of the PVT system, under study, is shown in Fig. 1. A solar simulator was used as the source of solar energy. It consists of 4x7 lamps array of 100W each. The solar simulator was installed on a 50cm height from the PV surface, with average irradiance power 900 W/m^2 as shown in Fig. 2.

The PVT system consist of two polycrystalline silicon PV with installed brass boxes under them with 1cm of thick wool glass thermal insulator to insulate the brass box.

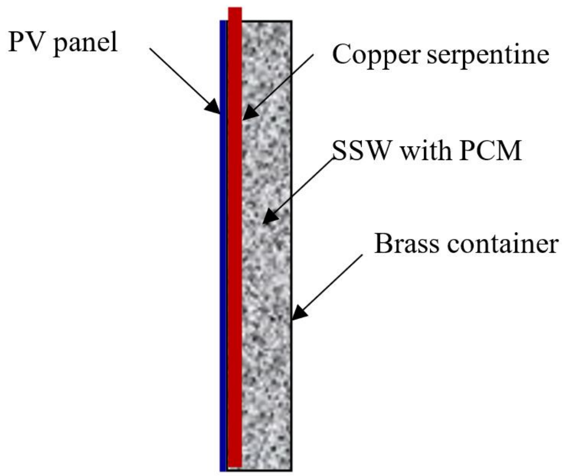


Fig. 1. The internal components of the PVT system understudy [13]

The PVT systems are set with inclination angle of 30º respect to the horizontal. A 0.6 HP pump was connected to a 200-liter tank of water with two rotameters for every system to measure the flow rate. The two flow systems are connected to the PVT and circulates the water back to the tank.

Fig 2. The PV system with the solar simulator

2.2 Instruments

The water temperature in the PVT system (inlet the system, outlet the system, and the water tank) are measured and collected during the test. The PV panels surface temperature are measured by three sensors. The PCM temperature is measured by DS18B20 waterproof temperature sensor for each system. These temperatures are recorded by using Arduino mega microcontroller. The electrical output of the panels is measured by voltmeters using 1 kΩ resistor as a gain. The specifications of the used sensors in the experimental tests are illustrated in table 1.

Table 1. Sensors properties

Sensor	Range	Error
LM35	-5 : 125 [ºC]	±0.5 [ºC]
DS18B20	-55 : 125 [ºC]	±0.5 [ºC]
T-thermocouple	-200 :200 [ºC]	±1 [ºC]
Rotameters	0 : 1.5 [LPM]	± 0.025 [LPM]
Pyranometer (PYR-1307)	200 : 2000 [W/m^2]	Less than 10 [W/m^2]
Voltmeter	0.02 : 200 [V]	± 1% [V]
Ammeter	0 : 20 [Amp]	± 1% [Amp]

2.3 Experimental Procedure

The experimental tests used a solar simulator inside the lab. The procedure of the test starts with water pump circulation in the two PVT systems with a flow controlled by a water flow meter to ensure the homogeny of the water temperature all over the system. Then, turn on the data logging of all the sensors after that turning on the solar simulator with average irradiance of 904 W/m^2 on both the PV panels. The irradiance is measured in several points in the panels to calculate the average value and to uniform the distribution. The temperature of the PV, PCM and the HTF start to increase gradually until reach the steady state mode. The data of the steady state mode take place for 60 minutes, then turning off the data logging and the simulator processes. The experimental tests were performed with different flow rates (0.0033, 0.005, 0.0067) L/s as in table (2).

Table 2. The test conditions

Test number	Flow rate [L/s]	Repeatability
1	0.0033	2
2	0.005	2
3	0.0067	2

3. Theoretical Analysis

Different energy forms appear in solar energy conversion to electrical and thermal energy in the PVT systems as shown in Fig .3. The reason behind the high PV cell temperatures is the elevated solar radiation without sufficient cooling.

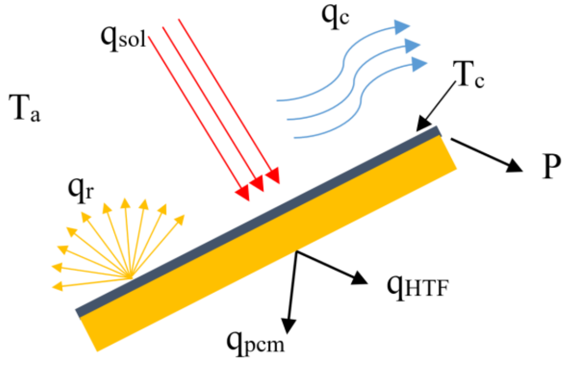


Fig. 3. Energy forms in the PVT system [13]

The solar radiation received on the PV panel surface is defined as:

$$q_{sol} = a(I * \Lambda) \quad (1)$$

In this equation a is the PV panel absorption coefficient, I is the solar irradiance in W/m^2, and Λ is the PV panel's area. The radiation received on the PV panel surface split up to two types of energy, first is the electrical energy converted (P) that defined as:

$$\eta_E = \frac{P}{I * \Lambda} \quad (2)$$

Second energy converted is the thermal energy that split up into several parts. First is discharged to ambient by convection as:

$$q_C = h\ \Lambda(T_c - T_a) \quad (3)$$

where h is convection coefficient, T_c is the temperature of the PV panel, T_a is the ambient temperature.

The q_r is the rate of heat removal by radiation, which is defined as:

$$q_r = \varepsilon\sigma\Lambda * (T_c^4 - T_c^4) \quad (4)$$

where ε is the emissivity and the σ is the Stefan-Boltzmann constant. The thermal energy that stored in the phase change material is calculated as follow:

$$q_{PCM} = m_{PCM}\, Cp\, (\Delta T_{PCM} / \Delta\tau) \tag{5}$$

where m_{PCM} is the phase change material mixture mass, Cp is the heat average of the SSW phase change material mixture, and ΔT_{PCM} is the change in the SSW phase change material mixture temperature average during a time step $\Delta\tau$. The heat absorbed by cooling water q_{HTF} is defined as follow:

$$q_{HTF} = \dot{m}_{HTF}\, C_{p_{HTF}}\, (\Delta T_{HTF}) \tag{6}$$

where $\dot{m}_{HTF}$ is the flow rate mass of HTF, the $C_{p_{HTF}}$ is the heat average of the HTF, and the ΔT_{HTF} is the inlet-outlet temperature difference of the HTF. The thermal efficiency η_{th} of the system can calculated as follow:

$$\eta_{th} = \frac{q_{HTF}}{I * \Lambda} \tag{7}$$

The overall efficiency of the system can be calculated as follow:

$$\eta_{tot} = \frac{(q_{HTF} + P)}{I * \Lambda} \tag{8}$$

4. Results and discussion

The main objective of this experiment is to study the cooling of the PV panel and how to keep cooling for keeping high efficiency. Moreover, making use of the thermal energy output of this system. Different performance parameters of the system are explored in the following subtitles.

4.1 Surface temperature

In this study the temperature of the PV cells for the PVT-PCM and PVT-PCM-SSW is represented in Fig. 4. This shows that the cell temperature is less for PVT-PCM system in (0.0033 and 0.005) LPM flow rates and the cells temperature is less for PVT-PCM-SSW system in 0.0067 L/s flow rate which helps in cooling the temperature of the PV panel. The average cell temperature reaches 65,73,60 ^{0} C for 0.0033, 0.005 and 0.0067 L/s, respectively.

This shows better cooling in case of higher flow rates. As the test is performed from stable conditions of temperature, the systems shows a transient performance, then reaches the steady state, in which the conditions is approximately fixed with time. The results shown is the steady state conditions of the test.

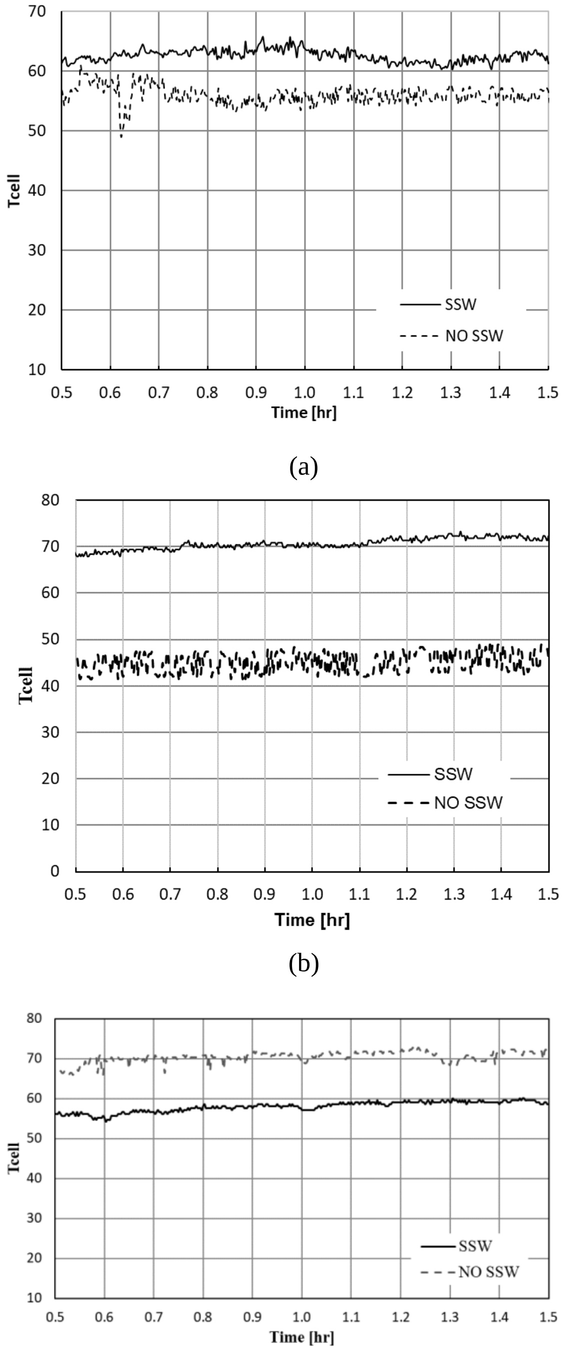
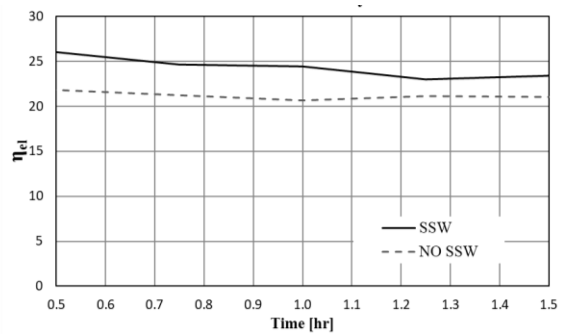


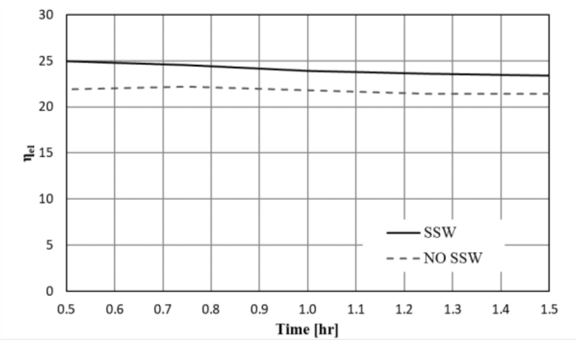
Fig.4. Cell temperature in the SSW and the No SSW PVT systems during the test for flow rates of (a) 0.003 L/s, (b) 0.005 L/s, (c) 0.0067 L/s.

4.2 Electrical efficiency

The electrical power from the panels is effected by the rise of the temperature. Fig .5. shows the variation of electrical efficiency of the SSW and the system without SSW for the three flow rates. It is noticed that the electrical efficiency of the SSW system in the three flow rates is higher than the system without SSW.



(a)



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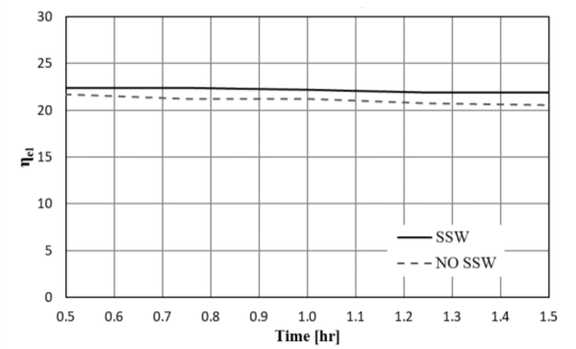
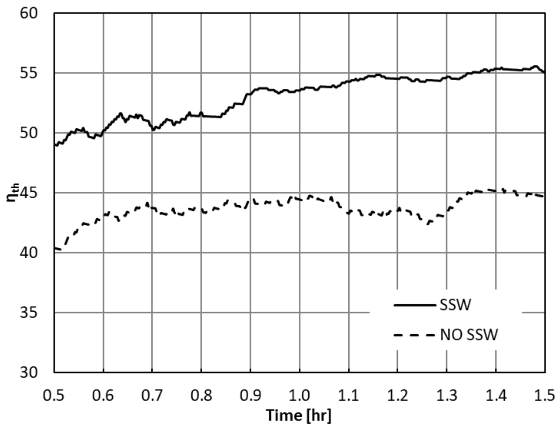


(c)

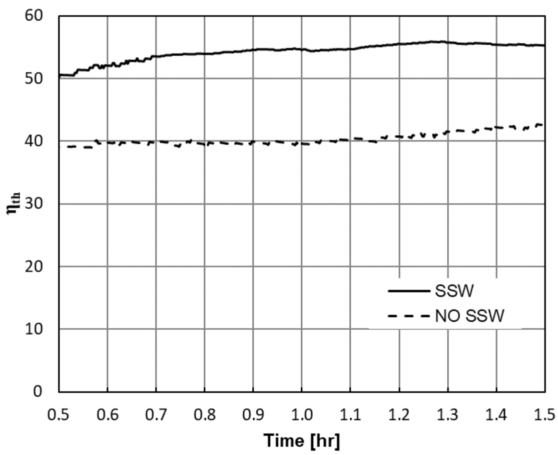
Fig. 5. The electrical efficiency in the SSW and No-SSW PVT systems during the test for flow rates of (a) 0.003 L/s, (b) 0.005 L/s, (c) 0.0067 L/s.

4.3 Thermal efficiency

The thermal efficiency of the PVT systems with SSW or without SSW in the steady state mode is shown in figure 6. The system with SSW achieved better performance during the tested flow rates in this study. This the importance of the SSW in the PVT system for cooling and making a good heat transfer between the PV panel. The maximum thermal efficiency has been achieved in the 0.0067 L/s flow rate that achieved the best cooling for the panel.



(a)



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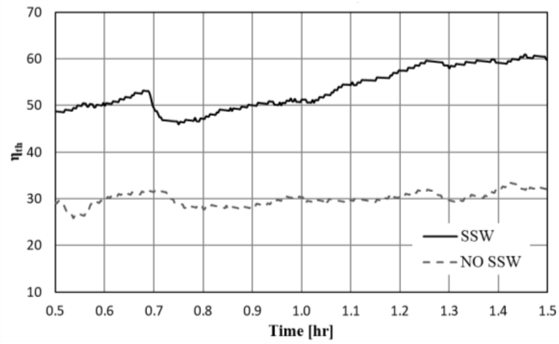
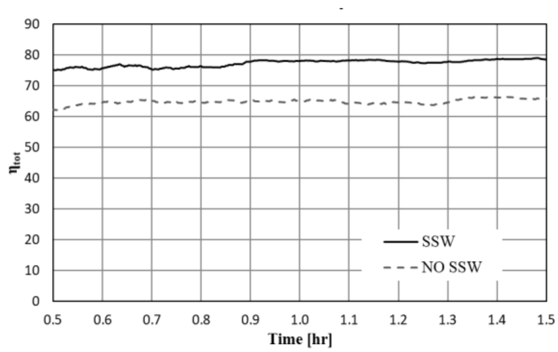


(c)

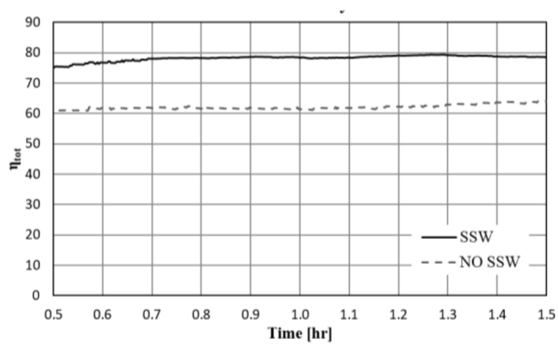
Fig. 6. Thermal efficiency in the SSW and No-SSW PVT systems during the test for flow rates of (a) 0.003 L/s, (b) 0.005 L/s, (c) 0.0067 L/s.

4.4 Overall efficiency

The total efficiency of the two system is affected by the electrical and thermal efficiency. That shows that the efficiency of the SSW system is higher than other system for all the tested flow rates. The 0.0067 L/s flowrate has achieved the optimum performance for the system. The overall efficiency of the PVT systems for the flow rates is presented in Fig. 7.



(a)



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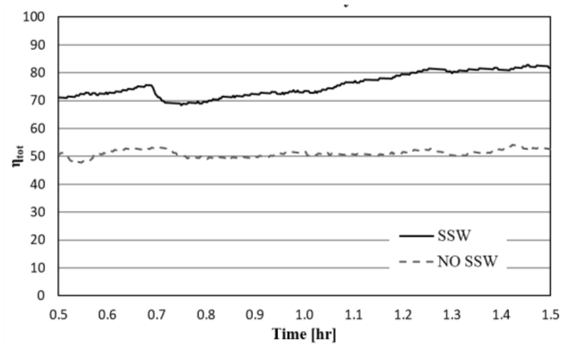

(c)

Fig. 7. Variation of the overall efficiency in the SSW and No-SSW PVT systems for flow rates of (a) 0.003 L/s, (b) 0.005 L/s, (c) 0.0067 L/s.

5. Comparison with other research results

Many enhancement methods were recently published for increasing the productivity of the PVT systems. a comparison of the efficiencies for different PVT systems with the present work is shown in figure 8.

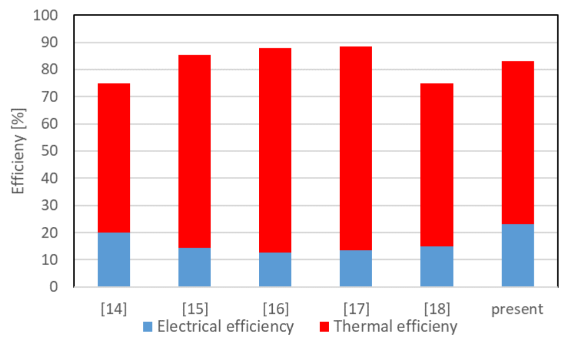

Figure 8. efficiency comparison with other research works [14][15][16][17][18]

It can be observed that the performance of the present system indicates the highest electrical efficiency among the other systems. this refers to the cooling effect caused by the PCM usage with the SSW and water circulation. Moreover, the thermal efficiency is comparable with the other proposed systems in the literature during recent years. The details of the compared systems is shown in table 3.

Table 3. compared systems details

	η_E	η_{th}	System type	Fluid
[14]	20	55	PVT-PCM	water
[15]	14.35	70.89	PVT-	Ethylene - Glycole water
[16]	12.75	75	PVT-PCM	water
[17]	13.4	75	PVT-PCM	water
[18]	15	60	PVT-micro-encapsulated PCM	water
present	23	60	PVT-PCM	water

6. Conclusion.

An experimental investigation for the performance of two PVT-PCM systems was performed. A HTF serpentine was used as the thermal energy extraction system. The first system contains SSW with the phase change material to improve the heat transfer. The other PVT-PCM system contains PCM without SSW. This experiment was conducted under three different flow rates of water as the HTF. The findings of this research were:

- With all the tested flow rates the PVT-PCM with SSW achieves better performance in electrical and thermal efficiencies than the other system.
- The electrical efficiency enhancement with the SSW ranged from 1% to 4% through different flow rates.
- The SSW caused an enhancement in the thermal performance in the range 10-28%. The optimum thermal efficiency of 60% has been achieved at the maximum flow rate of 0.0067 L/s.
- The overall efficiency enhancement of the system ranged from 13% to 30% due to the use of SSW under the tested flow rates. The enhancement found to be proportional to the flow rate due to increasing the convective heat transfer effects.

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