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Research Article

Theoretical and Experimental Study on the Performance of Photovoltaic using Porous Media Cooling under Indoor Condition

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Abstract. This paper presents the theoretical and experimental investigation on performance of a photovoltaic (PV) panel cooled by porous media under indoor condition. Porous media offer a large exterior surface area and a high fluid permeability, making them ideal for PV cells cooling. The photovoltaic panel was cooled using 5 cm thick cooling channel filled with porous media (gravel). Several sizes of porosity (0.35, 0.4, 0.48, and 0.5) at different volume flow rates (1, 1.5, 2, 3, and 4 L/min) were tested to obtain the best cooling process. The theoretical analysis was performed at the optimum case found experimentally, which has a porosity of 0.35 and a volume flow rate of 2 L/min, to test various experimental results of the PV hot surface temperature, related power output, efficiency and I-V characteristic curve. The enhancement obtained in PV power output and efficiency is compared against the case without cooling and the case using water alone without porous media. Results showed that cooling using small size porous media and moderate flow rate is more efficient which reduces the average PV hot surface temperature of about 55.87% and increases the efficiency by 2.13% than uncooled PV. The optimum case reduced the PV hot surface temperature to 38.7°C, and increased the power output to 19 W, efficiency to 6.26%, and the open voltage to 22.77 V. The results showed that the presence of small porous media of 0.35 in the PV cooling process displayed the maximum effectiveness compared to the other two scenarios, because the heat loss from PV surface through porous media layer have developed a homogenous heat diffusion removed much quicker at high flow rate (2 L/min). A good agreement was obtained between experimental and theoretical results for different cases with a standard deviation from 3.2% to 5.6%.

Keywords: Cooling of PV panel; Solar cell efficiency; Porous media; Operating temperature; Indoor test.

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1. Introduction

Fossil fuels including oil, gas, and coal are the primary energy sources in the majority of countries. As a result, the globe confronts a major dilemma today because of the tremendous consumption that will occur in the next several years. For this reason, Jordan's economy is in freefall. Jordan imports most of its fossil fuels, and this drives up the cost of generating power (Badran *et al.* 2010; Elayyan *et al.*2020). With the country's current circumstances, thinking toward renewable energy applications have been considered as a main solution, and as a result, Jordan has some of the world's best renewable energy resources (Masalha *et al.* 2017) particularly in the area of solar energy, where daily solar radiation averages 5-8 hours (Hammad, *et al.* 2015). Solar energy is a clean, renewable, safe, and cost-effective way to generate electricity. Solar cells generate electricity, but one of the challenges is that when cell temperature rises, it affects the efficiency and this is a major issue. Solar cells can be more efficient by adding a cooling system in order to keep them at the proper operating temperature while still producing maximum power.

The performance and efficiency of PV systems have been examined by many researchers, and a variety of cooling strategies have been discovered. Among these studies, the work which was carried out by Ahmed, *et al.* (2019) attempted to improve the performance of a hybrid Photovoltaic/Trombe wall (PV/TW) system through employing a porous medium, DC fan and glass cover. The porous medium with DC fan increased the values of thermal efficiency by 13% and electrical efficiency by 4%, while the combination of porous medium with DC fan and glass cover increased the thermal efficiency by 20% and electrical efficiency by 0.5%. Özakina *et al.* (2019) studied fins inside a channel experimentally and numerically. They observed an increase in power; electrical efficiency and thermal efficiency. Soliman *et al.* (2019) investigated the performance of concentrated photovoltaic cells cooled by spreader-microchannels system. Three configurations for water cooling flowing inside the microchannel were tested. Their results showed an increase in the PV net power by about 9.2%.

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Kabeel *et al.* (2019) conducted a comparative study to improve three PV unit cooling technologies under Egyptian conditions. These technologies use air and water with the presence of reflectors. The results showed that the best way to cool the PV unit was to use water with the presence of reflectors. Elminshawy *et al.* (2019) investigated an integrated PV panel cooling system with buried heat exchanger (BHE) experimentally. Forced atmospheric air with temperatures of 35°C, 40°C and 45°C and flow rates of 0.0228 m^3/s, 0.0248 m^3/s, and 0.0268 m^3/s were used. It was found that the output power and electrical efficiency were improved. Elminshawy *et al.* (2019) performed experimental and numerical investigations using a buried water heat exchanger. They noticed an increase in the output power, electrical efficiency, and thermal efficiency.

Issa *et al.* (2018) investigated the effects of pure water, SiO2/water Nano fluid, and phase-change material (PCM) coolants on the performance of a photovoltaic thermal (PVT) system numerically. Their simulations were performed on PVT/PCM module and a PCM module without PVT. Also, they compared nanofluid with pure water as a working fluid. Using the water-based PVT/PCM, the average PV cell temperature was decreased by 16°C compared with the PVT system, while the electrical efficiency increased by 8%, and thermal efficiency by 25%. On the other hand, using nanofluid (SiO2 with 1 and 3% mass fraction) as a coolant caused an increase in the thermal efficiency by 3.51% and 10.40%, respectively, compared to the PVT/PCM with coolant. Alizadeh *et al.* (2018) used plastic heat pipes as well as copper fins, in order to reduce the PV panels' temperature; they noticed an increase in electrical efficiency.

Golzari *et al.* (2018) conducted an experimental work to enhance the temperature reduction by electro hydrodynamics (EHD) process. Heat transfer coefficient was increased by halo wind due to a secondary flow and vortex. Therefore, an increase in voltage leads to an increase in electrical energy and efficiency. Idoko *et al.* (2018) used the multi-concept cooling technique, involving three types of passive cooling: conductive cooling, air passive cooling, and water passive cooling. Two solar panels of 250 W were mounted at a height of 37 cm to create room for air-cooling. One was attached to an aluminum heat sink and iced water-cooled lead to surface temperature reduction of 20°C. An increase of 20.96 W in output power was also noticed for the iced water-cooling, and an increase in efficiency by 3% were recorded. Jamali *et al.* (2018) proposed a novel system to cool semi-transparent photovoltaic (STPV) system by employing it as a roof for a solar chimney. They found that the system could reduce the average temperature of the STPV to 15°C and power generation enhanced by 29%.

Al-Jamea *et al.* (2022) studied PV using water-cooling channel numerically. They investigated the temperature of the PV cell, inlet and outlet water, radiation, increase in efficiency, and electrical power. Mojumder *et al.* (2016) studied and designed a prototype of PV collector with cooling fins and induced air as a working fluid. Their results showed an increase in thermal efficiency by 56.19% and they validated their experimental results using theoretical and statistical analysis techniques. Aldossary *et al.* (2016) used a method based on two heat sinks cooling system with water passing between these two sinks. They realized that the temperature was reduced by 14°C, while the electrical efficiency increased to 39.5%. Bahaidarah *et al.* (2016) used contrasting techniques of cooling (non-uniform and uniform) using immersion cooling; the temperature of the concentrated PV system (CPV) cell has been decreased to 20–45°C while maintaining uniform cooling. When using heat sinks to passively cool cells, they were able to lower the temperature by as much as 37°C at the price of increasing the heat sink's surface area.

Stropnik *et al.* (2016) showed the cooling process was accomplished by the use of PCM (phase change material). The temperature of the PV panel was reduced to 35.6°C, while output power rose to 8.7% and efficiency improved by 1% in comparison to standard PV panels, according to their testing data. Bai *et al.* (2016) focused on the impact of sprinkling and refrigerant on cooling methods under Hungary climate conditions. Their PV panel's temperature was decreased down to around 29 °C while the efficiency increased by 25%. Amelia *et al.* (2016) installed cooling mechanisms of 4 DC (direct current) Fans at PV panel. The average temperature was decreased by 22.22%, and the power output increased from first fan to the fourth fan by 12.93, 37.17, 41.28, and 44.34% respectively. Radwan *et al.* (2016) employed a new method represented by a microchannel heat sink with nanofluids, nanofluids such as Aluminum Oxide (Al2O3)–water and Silicon Carbide (SiC), and water were used as a coolant. The electrical efficiency was a direct proportionality to nanoparticles volumes.

Ebrahimi *et al.* (2015) created a novel approach to cool PV cell by using natural vapor as coolant depending on the daylight on backward of the PV cells. It was found that their method decreased the temperature to about 16°C and increased the electrical efficiency to about 22.9%. Nižetić *et al.* (2015) studied one of most common ways of cooling PV panels' surfaces by using spray water, which gave good results through increasing the electrical efficiency and output power. Micheli *et al.* (2015) studied PV cooling system accomplished by using a micro fin. It caused a decrease in the PV surface temperature and enhanced the performance by increasing the output power up to 50%. Elnozahy *et al.* (2015) investigated cooling PV panels by employing an automatic cooling that controls the backside PV surface temperature to be close to the ambient temperature. They realized that the results showed a decrease in temperature by about 45.5% and an increase in efficiency to 11.7%.

Irwan *et al.* (2015) studied ways to enhance the work of PV panels based on the enhancing the electrical efficiency. To increase the electrical efficiency a halogen lamps as an extra daylight were used. The results revealed a decrease in temperature and an increase in the output power. Rahimi *et al.* (2015) suggested the best way to cool PV panels by using a multi-header microchannel design. Their result showed that 28% enhancement in electrical energy was obtained, while the temperature decreased by 19%. Hussien *et al.* (2016) used the water as a coolant for the PV cells using it in a heat exchanger. Water circulating in pipes located at the rear of panels where the heat loss by convection occurred between the water and panels. They noticed that the electrical and thermal efficiency were increased by 9.8% and 12.3%, respectively. Chandrasekar *et al.* (2013) studied new way to cool PV systems under Indian climate conditions by applying moist cotton wicks to PV panels for cooling. Results showed a reduction in temperature by 12% and an increase of 14% in electrical efficiency.

Tao Ma *et al.* (2015) used a PCM with solar thermal system to cool a PV cell. They realized that the electrical efficiency had increased by 9% and the thermal efficiency by 12%. Sahay *et al.* (2015) studied a low-cost way of PV cooling system in India called Ground Central Panel Cooling system (GCPCS). Smoking flow visualization technique was used and analyzed with ANOVA to show the cooling effect on PV performance but no specific efficiency enhancement of PV was obtained. Buker *et al.* (2015) used liquid desiccant-based dew point cooling to provide air to use it in heat exchanger as a heat source. Their tests showed that power performance was increased by 10.7%.

From the previous studies it can be seen that different methods were used for cooling the PV back surface to increase its power and efficiency but each method has its advantages and drawbacks. One of the drawbacks of some cooling techniques like spraying, they require lots of water and some techniques require huge and expensive facilities so they gain cooling effectiveness at high cost. Moreover, one of the good cooling techniques uses nanofluid, but it is expensive. Therefore, the reduction of the PV back surface temperature is the main target for many cooling processes, such that cooling using porous materials can be effectively better than cooling with air.

It can be seen from the literature review that porous media was considered as one of better cooling strategies that can accelerate the cooling process to enhance the PV performance. Also, previous studies used porous materials for cooling solar cells showed that there are needs for more practical and enumerative work that should be done in a comprehensive way. The objective of the present study is to find out an effective heat transfer condition using porous media to reduce the PV/T system's temperature and to increase the PV power output. Different porosities were considered to find out the best cooling condition. Also, different scenarios were compared with water alone cooling and how the cooling behaves at different volume flow rates (i.e. 1, 1.5, 2, 3, and 4 L/min) to improve the performance of the PV cell. These studies used gravels as porous media of different sizes that is globally available and have good conductivity.

2. Methodology

Solar energy is one of the cheapest technologies for generating power in developing and developed nations. However, as previously mentioned, one of the primary shortcomings of photovoltaic cells is the influence of heated surface temperature, which leads to poorer power generation, particularly in hot climates such as in Jordan during the summer. By absorbing the produced heat, the efficiency of the PV cells would be enhanced. In general, porous media was recognized as one of the most essential technologies employed for homogeneous cooling. The influence of porosity on the performance of a PV/T system will be explored experimentally and theoretically in this study. The PV cooling system shown in Fig. 1 was used to produce electrical power as well as absorbing the ejected heat from PV back surface to flowing water. Where Lg is glass thickness, Lc is solar cell thickness, LT is back surface of Tedlar thickness and Lin is insulation thickness.

To determine the best possible performance from photovoltaic panel, various experiments were conducted with several cooling processes. A 5 cm thick cooling channel was attached on the back of the PV hot surface exposed to fixed indoor radiation intensity of 1600 W/m^2 for all experiments (Fig.1). In the channel, porous material with different porosities of 0.35, 0.4, 0.48 and 0.5 was used along with different volume flow rates of 1 L/min, 1.5 L/min, 2 L/min, 3 L/min, and 4 L/min. Later the analytical study was used to validate the experimental results.

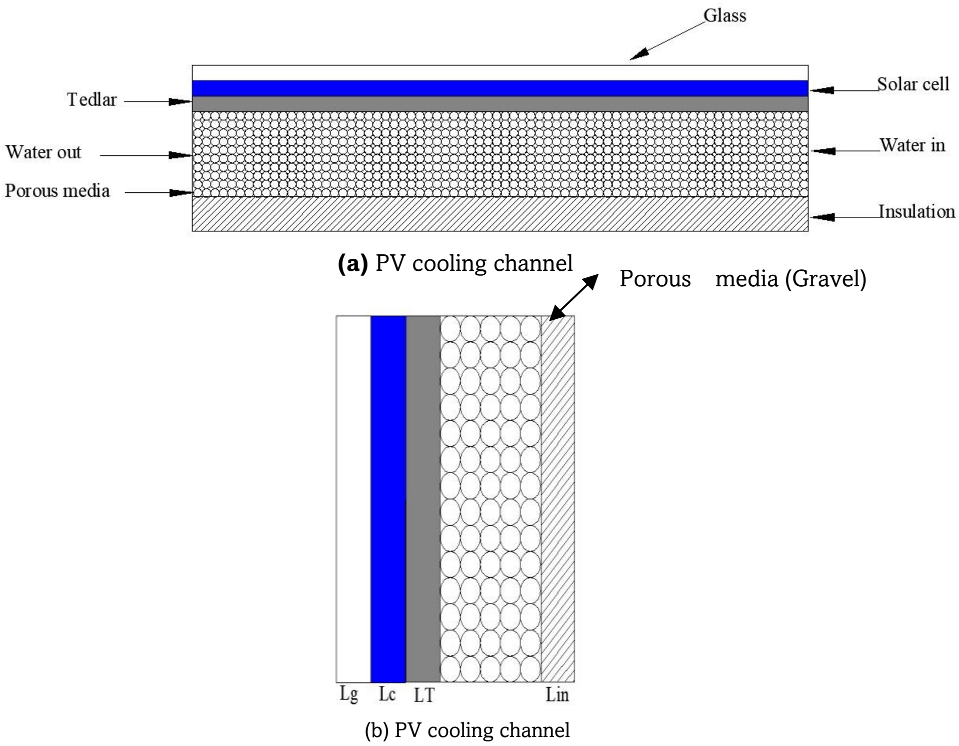

Fig 1. PV cooling channel with porous media

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3. Mathematical model formulation

In order to investigate the effect of different elements on the performance of a PV/T hybrid system cooled by porous media, the electrical and thermal models can be modelled and analysed.

3.1. Modeling of thermal system

A mathematical model was created based on Fig. 2 to calculate the hot surface temperature on the back of solar cells. The following assumptions were assumed for the model: (i) the system operates in a steady flow condition; (ii) there is no water leakage in the system because it was well sealed; (iii) the walls of the cooling channel insulated on all sides, except the upper surface on which the PV panel attached, so that there is no heat transfer to the surrounding and (iv) the change in the temperature is only along the length of the PV panel.

3.2. Energy balance analysis of the PV cell

Photovoltaic cells (PV) do not convert all entire solar intensity received on its surface to the electrical power, because some of energy received is converted into heat, then the rear temperature of the PV cell can be calculated by Eq. 1 (Abu Bakar *et al.* 2015)

$$G.\alpha_c = E + U_{front}(T_c - T_a) + U_{bottom}(T_c - T_T) \quad (1)$$

Where T_T is the PV cell's back surface temperature, the T_C cell's surface temperature, the T_a ambient temperature, G denotes solar radiation, E denotes electrical power, and α_c denotes absorptivity.

After rearranging Eq. (1), the temperature of the PV cells can be calculated using Eq. (2) as (Eq 2);

$$T_c = \frac{G.\alpha_c - E + U_{front}T_a + U_{bottom}\ T_T}{U_{front} + U_{bottom}} \quad (2)$$

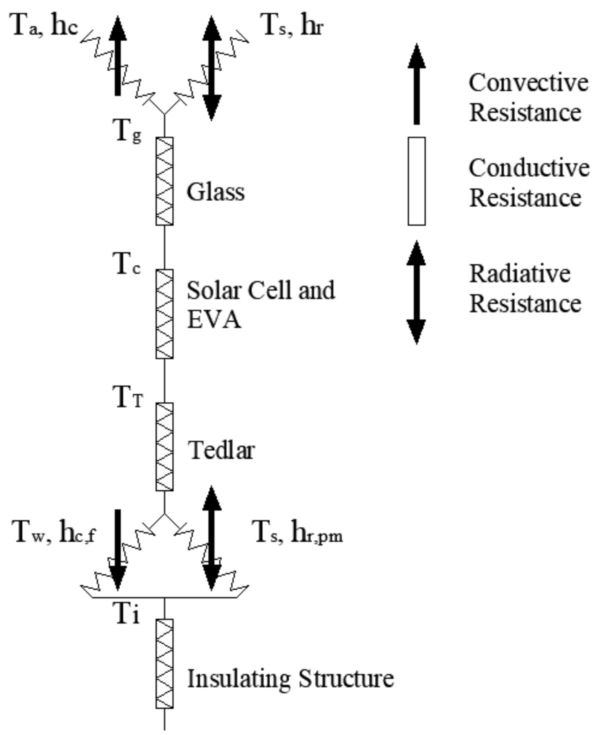


Fig 2. Thermal resistance circuit diagram

U_{front} is the coefficient of heat transfer between the PV cells and the surrounding environment, and can be calculated by Eq 3:

$$U_{front} = \left[\frac{1}{h_c + h_r} + \frac{L_g}{k_g}\right]^{-1} \quad (3)$$

Where k denotes thermal conductivity, h_c is convective heat transfer coefficient, h_r is radiant heat transfer coefficient, the values of the coefficients can be found from Eq. (4) and (5) respectively (Irshad *et al.* 2014)

$$h_c = 5.7 + 3.8V \quad (4)$$

Where V is the velocity of the surrounding air around the PV cells.

$$h_r = \varepsilon\, \sigma(T_c^{\,2} + T_a^{\,2})(T_c + T_a) \quad (5)$$

Emissivity (ε) and the Stefan-Boltzmann constant (σ).

$$U_{bottom} = \left[\frac{L_T}{k_T}\right]^{-1} \quad (6)$$

Where U_{bottom} is the overall heat transfer coefficient for Tedlar, L_T, and k_T are the thickness and thermal conductivity of Tedlar, respectively. The temperature of Tedlar can be evaluated by Eq 7 to Eq 9 (Ramadan *et al.* 2007)

$$G.\alpha_c = U_{front2}(T_T - T_a) + h_{c,f}(T_T - T_f) + h_{r,pm}(T_T - T_{pm}) \quad (7)$$

$$T_T = \frac{U_{front2}T_a + h_{c,f}T_f + h_{r,pm}T_{pm} + G.\alpha_c}{h_{c,f} + h_{r,pm} + U_{front2}} \quad (8)$$

$$U_{front2} = \left[\frac{1}{h_c + h_r} + \frac{L_g}{k_g} + \frac{L_T}{k_T}\right]^{-1} \quad (9)$$

Where U_{front2} is the overall heat transfer coefficient between Tedlar and ambient, $h_{c,f}$ is the convective heat transfer coefficient for water flowing through channel filled with porous medium and the Tedlar which can be calculated by Eq. 10 to Eq 12 (Ramadan *et al.* 2007)

$$h_{c,f} = \left[\frac{1}{\frac{Nu_{pm-f}\cdot k_f}{D_{hd}}} + \frac{D_{hd}}{\beta k_g}\right]^{-1} \quad (10)$$

$$D_{hd} = \frac{2\varphi d_{pm}}{3(1-\varphi)} \quad (11)$$

$$Nu_{pm-f} = \left(\frac{0.255}{\varphi}\right) Re_{pm}^{\frac{2}{3}} . Pr_f^{\,1/3} \quad (12)$$

Where D_{hd} is hydraulic diameter, $d_{pm}$is the particle diameter, φ is porosity of the porous medium, Nu_{pm-f} is Nusselt number, Pr_f is Prandtl number, Re_{pm} is Reynolds number,$\forall_f$is void volume and $\forall_t$ is total volume and can be computed as (Eq 13) (Masalha *et al* 2023);

$$\varphi = \frac{\forall_f}{\forall_t} \quad (13)$$

The $h_{r,pm}$ is the radiation heat transfer coefficient from Tedlar to the porous medium, which can be calculated based on the equation 14 (Ramadan *et al.* 2007).

$$h_{r,pm} = \mathcal{E}\sigma(T_T^{\,2} + T_{pm}^{\,2})(T_T2 + T_{pm}2) \quad (14)$$

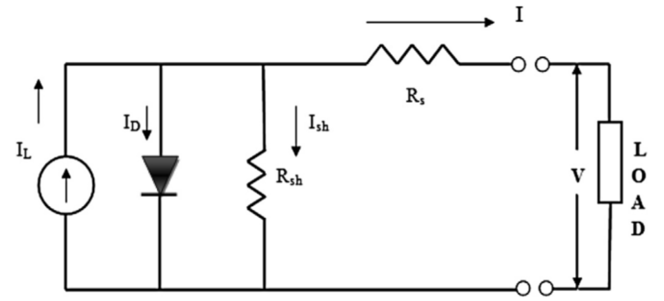


Fig 3. Demonstration of a PV cell circuit (Bahaidarah *et al.* 2013)

3.3. Modeling of the electrical system

The PV electrical system has been designed based on the following assumptions; the average temperature is calculated by taking the temperature in each stratum and averaging it out. In addition, the water flow in the channel and on the Tedlar was supposed to be consistent. Both sun light and the temperature have no effect on the resistances. Radiation is the only factor that affects shunt resistance, and temperature is irrelevant.

All parameters were estimated using an electrical model (V_{open}, I_{short}, power, and electrical efficiency). A PV cell's equivalent circuit is shown in Fig. 3. In order to describe a PV module, we must look at its current-voltage curve (I-V). The parameters of the electrical model were evaluated similar to the parameter model presented by (Bahaidarah *et al.* 2013)

An ideality factor (a), light generated current (I_L), series resistance (R_s), and shunt resistance (R_s) are the primary parameters of the PV electrical model. Table 1 shows the typical conditions specified at three I-V points on the PV curve.

According to the conditions mentioned in Table 1, the following characteristics are derived:

$$I = I_L - I_O\left[exp\left(\frac{V+IR_S}{a}\right) - 1\right] - \frac{V+IR_S}{R_{Sh}} \quad (15)$$

$$I_{SC,ref} = I_{L,ref} - I_{O,ref}\left[exp\left(\frac{I_{sc,ref}R_{s,ref}}{a_{ref}}\right) - 1\right] - \left(\frac{I_{sc,ref}R_{s,ref}}{R_{sh,ref}}\right) \quad (16)$$

Where $I_{SC,ref}$ is the reference short circuit, this means short circuit at standard test conditions (STC), diode reverse saturation current (Io), $I_{L,ref}$ is light generated current at STC (A). The reference maximum current can be calculated from Eq. 17;

$$I_{mp,ref} = I_{L,ref} - I_{O,ref}\left[exp\left(\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}\right) - 1\right] - \left(\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{R_{sh,ref}}\right) \quad (17)$$

$$I = I_L - I_O\left[exp\left(\frac{V+IR_S}{a}\right) - 1\right] - \frac{V+IR_S}{R_{Sh}} \quad (18)$$

Table 1
Typical conditions specified at three I-V points on the PV curve.

Point	Conditions
Short circuit current	$I = I_{sh}, V = 0$ $[dI/dV]_{sc} = \frac{-1}{R_{sh,ref}}$
Open circuit voltage	$I = I_{sh} = 0, V = V_{OC,ref}$
Maximum power	$I = I_{max,ref}, V = V_{max,ref}$ $[d(IV)/dV]_{max}$

Where series resistance at standard test conditions ($R_{s,ref}$), $I_{mp,ref}$is reference maximum current, $V_{mp,ref}$ is reference maximum voltage, $R_{sh,ref}$ is reference shunt resistance, as shown in Eq. 19 to 21;

$$\frac{I_{mp,ref}}{V_{mp,ref}} = \frac{\left(\frac{I_{O,ref}}{a_{ref}}\right)exp\left(\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}\right)+\frac{1}{R_{sh,ref}}}{1+\left(\frac{I_{O,ref}R_{s,ref}}{a_{ref}}\right)exp\left(\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}\right)+\frac{R_{s,ref}}{R_{sh,ref}}} \quad (19)$$

$$\frac{a}{a_{ref}} = \frac{T_C}{T_{c,ref}} \quad (20)$$

$$I_L = \frac{S}{S_{ref}}\left[I_{L,ref} + \mu I_{sc}\left(T_C - T_{C,ref}\right)\right] \quad (21)$$

Where the T_c is current cell temperature and $T_{c,ref}$ is reference cell temperature. The absorbed solar radiation can be estimated from Eq. 22;

$$\frac{S}{S_{ref}} = M\left(\frac{G_b}{G_{ref}}RK_{\tau\alpha,b} + \frac{G_d}{G_{ref}}K_{\tau\alpha,d}\left(\frac{1+cos(\beta)}{2}\right) + \frac{G}{G_{ref}}\rho_g K_{\tau\alpha,g}\left(\frac{1-cos(\beta)}{2}\right)\right) \quad (22)$$

Where S_{ref} is absorbed solar radiation at STC (W/m^2), s is absorbed solar radiation, G_{ref} is solar intensity (W/m^2).

$$I_O = I_{oref}\left(\frac{T_C}{T_{C,ref}}\right)^3 exp\left(\frac{\varepsilon}{KT_{C,ref}} - \frac{\varepsilon}{KT_C}\right) \quad (23)$$

$$\frac{R_{sh}}{R_{sh,ref}} = \frac{S_{ref}}{S} \quad (24)$$

Solving Eq. 20 to 24 we can get an optimum condition. Next, the operational values I_{mp} and V_{mp}can be found from the Eq 25 to 28 (Bahaidarah *et al.* 2013);

$$\frac{I_{mp}}{V_{mp}} = \left[\frac{\frac{I_O}{a}exp\left(\frac{V_{mp}+I_{mp}R_S}{a}\right)+\frac{1}{R_{sh}}}{1+\frac{R_S}{R_{sh}}+\frac{I_O R_S}{a}exp\left(\frac{V_{mp}+I_{mp}R_S}{a}\right)}\right] \quad (25)$$

$$I_{mp} = I_L - I_O\left[exp\left(\frac{V_{mp}+I_{mp}R_S}{a}\right) - 1\right] - \left[\frac{V_{mp}+I_{mp}R_S}{R_{sh}}\right] \quad (26)$$

Where the maximum power P_{max} and efficiency η_c can be found by Eq 27 and 28 as follows:

$$P_{max} = I_{mp}V_{mp} \quad (27)$$

Electrical efficiency is defined as the ratio of the power output produced by the PV cell to the solar intensity and the unit area of the PV cell (Bahaidarah *et al.* 2013)

$$\eta_c = \frac{I_{max}V_{max}}{A_c G} \quad (28)$$

3.4. Correlations

$$P = GA\emptyset e^{-a\left(1+\frac{\upsilon L}{Q}\right)} \quad (29)$$

Where G solar radiation, A area of PV, $\emptyset$ porosity, $\dot{Q}$ volume flow rate, L length of PV and υ kinetic viscosity.
In order to get the temperature correlation, Eq 34 and 35 were used as following;

$$T = \frac{G\alpha_{eff}\emptyset}{K\,a\left(1+ln\left(\frac{\dot{Q}}{\upsilon L}\right)\right)} + T_{in} \tag{30}$$

Where G solar radiation, K thermal conductivity, $\emptyset$ porosity, $\dot{Q}$ volume flow rate, L length of PV, υ kinetic viscosity, and T_{in} inlet water temperature.

$$\alpha_{eff} = \tau_G[\alpha_C + \beta_C + \alpha_T(1-\beta_C)] \tag{31}$$

3.5. Non-uniformity radiation and temperature

$$\text{Radiation non-uniformity}(\%) = \frac{E_{\max}-E_{\min}}{E_{\max}+E_{\min}} *100 \tag{32}$$

$$\text{Temperature non-uniformity}(\%) = \frac{T_{\max}-T_{\min}}{T_{\max}+T_{\min}} *100\% \tag{33}$$

Where E_{max} is the maximum radiation, T_{max} is the max temperature above the PV cell, respectively. E_{min} and T_{min} are minimum radiation and temperature above the PV cell respectively.
The rate of increase in temperature and energy output:

$$\%T_{max,increase} = \frac{T_{withoutcooling}-T_{cooling}}{T_{withoutcooling}} * 100\% \tag{34}$$

$$\%P_{max,increase} = \frac{P_{cooling}-P_{withoutcooling}}{P_{withoutcooling}} * 100\% \tag{35}$$

4. Experimental setup

4.1. Solar simulator

The solar simulator was designed and assembled at the workshops and installed in the innovation lab in the Faculty of Engineering Technology at Al-Balqa Applied University - Jordan. The solar simulator can provide the amount of radiation independent of time or weather conditions. Throughout all the experimental work, the irradiance value remained constant at 1600 W/m^2. Fig.4 shows a solar simulator with 50 halogen bulbs each one of 50 W and 220 V. The height of the lamp was about 51 cm from the surface of the PV panel to obtain radiation of about 1600 W/m^2. Furthermore, the solar simulator has been calibrated by placing a wooden board instead of the photovoltaic panel to obtain temperatures that are more consistent. Because of the poor heat conductivity of the wood, it reflects the uniform radiation possible. To produce uniform radiation, each bulb was individually adjusted to reach a maximum temperature non-uniformity of 1.7 %, which is class A. To provide the required radiation and to reduce the non-uniformity radiation, the solar simulator was built with an area larger than the area of the solar panel. However, radiation non-uniformity was determined to be 3.5 %, which corresponds to class B according to Eq 32 and 33 (Rajput *et al.* 2018 and Meng *et al.* 2011).

4.2. Cooling system setup

As illustrated in Fig. 5, the cooling experimental setup consisted of a PV panel (30W poly crystalline) and a thermal collector. Table 2 lists the specifications of the PV unit used in the solar simulator. The cooling channel (collector) filled with porous media and connected to the inlet/outlet water flow apertures, and was attached to the rear side of the PV panel. The channel's dimensions were the same as the PV panel. Five different flow rates of water were used through the cooling channel. The cooling water came from a tank that was linked to the PV/T system through plastic tubing. A water pump (0.37 kW) was utilized to circulate water through the cooling channel, and a flow meter was used to measure and control the volume flow rate of water via the cooling channel.

Fig 4. Schematic view of a complete setup of PV simulator.

Fig 5. Solar thermal cooling channel.

Table 2
Specifications of the Photovoltaic panel

Solar PV module parameter	Value at AM 1.5 spectra STC[1]	Value at halogen light[2]
Maximum power, P_{max}	30 W	18.72 W
Open -circuit voltage, V_{oc}	22 V	23 V
Short -circuit current, I_{sc}	1.84 A	1.25 A
Voltage at P_{max}	18 V	19.3 V
Current at P_{max}	1.67A	0.97 A
Operating temperature, °C	-40 to +85	-40 to +85
Dimensions	(545x345) cm	(545x345) cm
Radiation intensity, G	1000 W/m^2	1600 W/m^2

[1] Values refer to (standard test conditions) with T_{cell} = 25°C, 1000 W/m^2 and 1.5 AM spectra.
[2] Values refer to the present study conditions with Tcell = 27°C and zero m/s wind speed under halogen light.

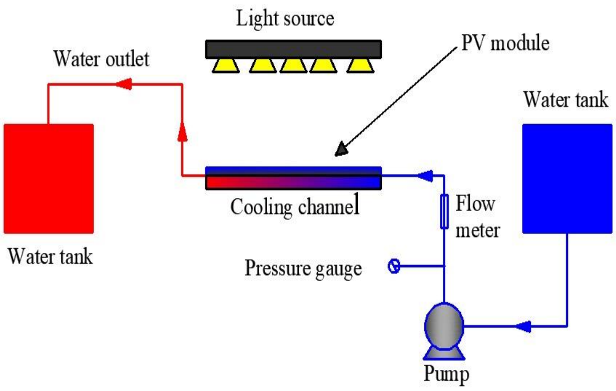


Fig 6. Schematic diagram of the PV simulator setup

Fig. 6 shows that when the water flows through the channel underneath the PV panel, the heat from the PV panel is dissipated to the porous media and the associated water flow. To prevent mixing hot and cold water, the heat rejected from the PV unit warms the water in the channel, and then the water flows out of the channel is stored in another tank. The water flows at a rate of one cubic meter per hour. Hence, the temperatures of the flowing water were monitored at the channel's inflow and outflow.

4.3. PV electrical model setup

The measurement instruments were used to measure the PV unit performance. It consists of a thermometer, voltmeter, ammeter and solar density meter. Front and back temperatures were measured at three different locations, and the mean temperatures were calculated. Variable resistance was used to obtain the highest output power of the photovoltaic panel by measuring the highest volts and the current. The accuracy/ sensitivity values of the measuring instruments used are given in Table 3.

Table 3
The accurateness/ sensitivity of the used measuring devices

Device	Accurateness/ sensitivity
Solar power meter	±10% W/m^2
Voltmeter and ammeter	± 1mV and ± 1μA
Thermocouple	±0.1°C

5. Results and discussions

5.1. PV Performance using Porous Media

Porous media offer a large exterior surface area and a high fluid permeability, making them ideal for PV cells cooling (Ahmed *et al,* 2019 and Masalha *et al* 2019). A porous media cooling system is typically composed of a coolant fluid (water) flowing through the porous medium's in the channels. The coolant fluid and the porous media transports heat away from PV back surface through by conduction and convection, thereby cooling the PV system. The fluid movement of the coolant through the porous medium determines the porous media's efficacy of transporting heat away from the PV hot surfaces.

Based on this approach, multiple indoor tests were carried out to measure the average PV hot surface temperatures with varied porosities (0.35, 0.4, 0.48, and 0.5) and at volume flow rates (1 L/min, 1.5 L/min, 2 L/min, 3 L/min, and 4 L/min). The results were collected and displayed in Fig. 7. It can be clearly seen that the minimum average PV back surface temperature occurred at porosity of 0.35 and flow rate of 2 L/min and it is considered the best case (optimum condition). This may be due to larger surface area of low porosity that makes high homogenous mixtures between porous media structure and flowing fluid, so that they provided higher heat transfer medium interactions at the moderate flow rate of 2 L/min, as can be seen in Fig. 7.

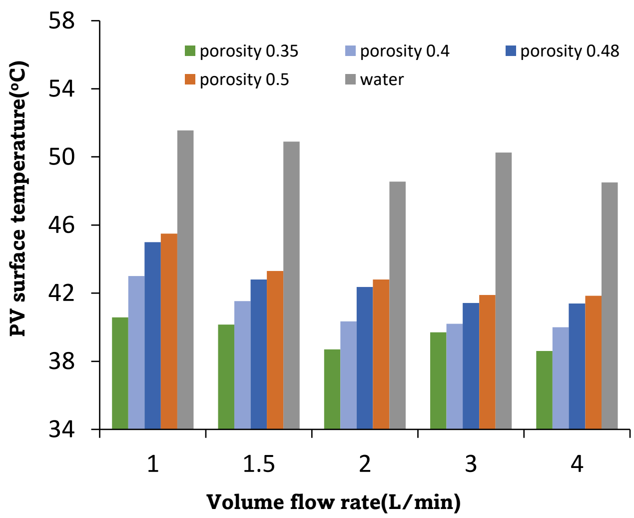
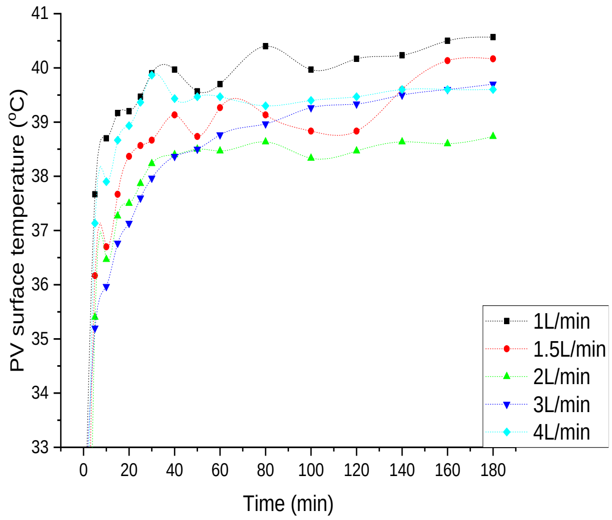
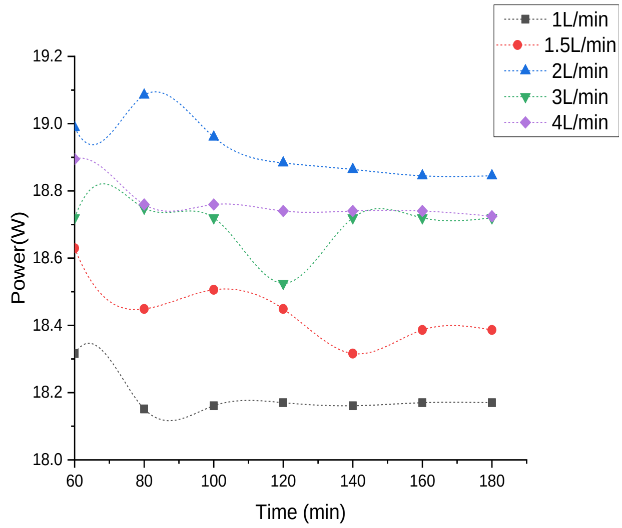


Fig 7. Measured results of a PV cell average temperature at different volume flow rates and porosities



(a) Average PV surface temperature



(b) Power output

Fig 8. Measured average PV surface temperature and power output with respect to different volume flow rates at a porosity of 0.35

An average PV surface temperatures and power output for different volume flow rates vs time are shown in Fig. 8a and 8b respectively. The results of different volume flow rates and fixed porosity of 0.35 were carried out for three hours for each test. Therefore, it can be seen clearly from Fig. 8 that the lowest recorded temperature of 38.70°C and highest power of about 19 W occurred at volume flow rate of 2 L/min and porosity of 0.35, which has been considered as a best scenario (optimum condition) evolved from the best heat removal condition from PV surface to the cooling agents. The variations of the temperatures between various flow rates were around 7 to 8%. The results in this research are somewhat similar to the previous works (Msoud *et al* 2014; Nizetic *et al* 2016)

Such an experimental work can be applied in a bulky real PV stations, so that the channels can be made from plastic materials, while porous media is available globally and the circulated water can be used for irrigation after long use.

5.2. Numerical analysis validation

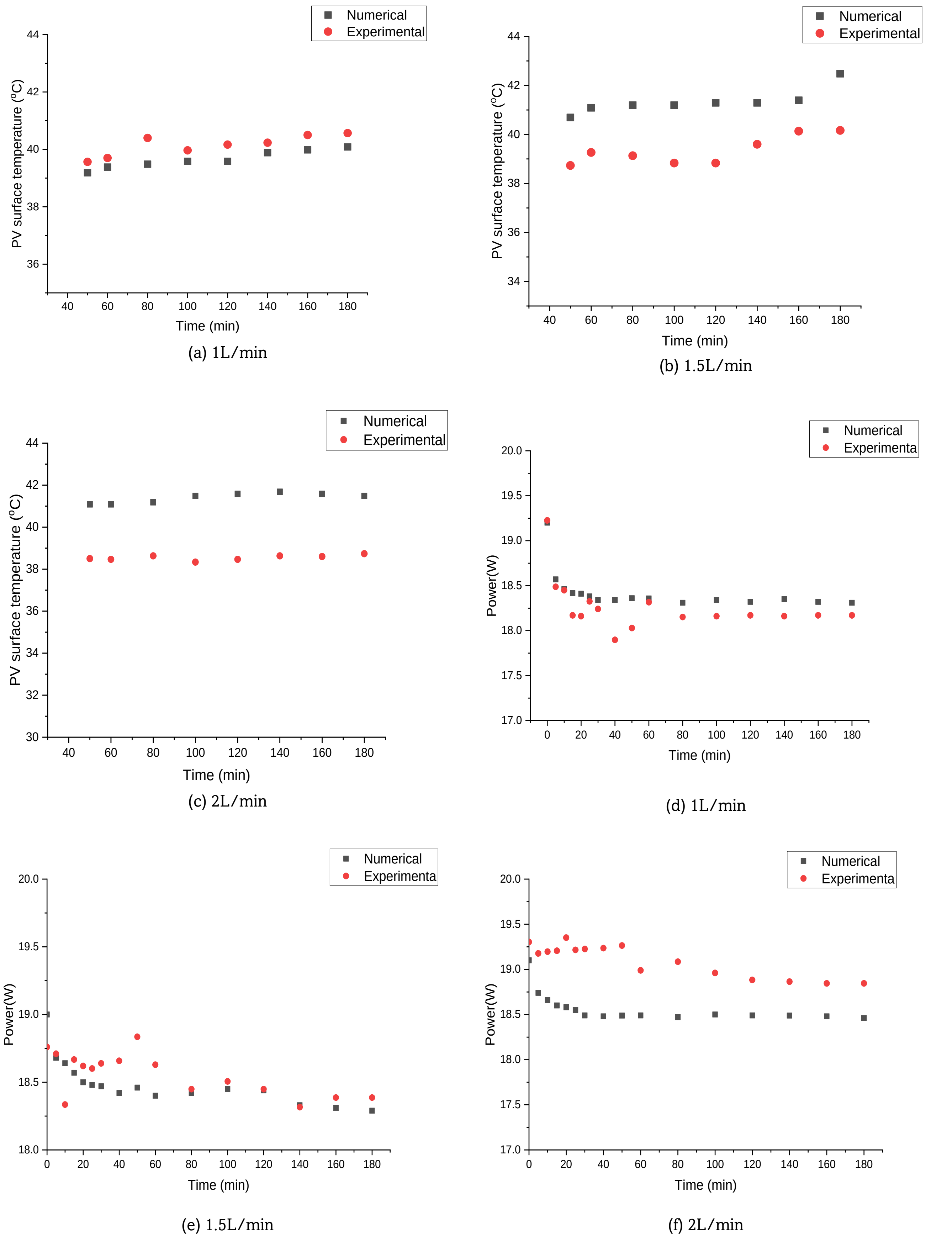
Different factors affected the performance of the cooled PV/T hybrid system by porous media can be examined using electrical and thermal models analyses that can be linked together. Equations 2 and 27 were used in the mathematical model to verify numerically the experimental results, through the determination of the average PV back surface temperature and power output at various porosity and volume flow rates, as shown in Fig. 9a and 9b. It was found out that the deviation between the experimental and numerical findings ranged between 3.2 % to 5.6% for average PV surface temperature and 1% to 2.8% for power output respectively, according to the discrepancy's analyses. Therefore, the numerical analysis results matched the experimental results trend with small deviation. The deviation between both methods can be attributed to steadiness and idealization of the flow and heat transfer assumptions considered in the numerical results. The numerical simulation showed that it can be used to estimate the behaviour of the PV cooling processes in prior of commencing any laborious experimental work.

Experimental tests of the cases of the PV water alone cooling and PV without cooling over a test period of three continuous hours have been compared with optimum case. The purpose of these tests is to get an overall view of the PV performance under these conditions. The main performance parameters such as surface temperature, power output, efficiency, and I-V characteristic curve were investigated, as shown in Fig. 10.

Fig.10a shows an average surface temperature, power, efficiency and current-voltage characteristic curve of the PV panel for three cases (without cooling, water alone cooling, and optimum case (porosity of 0.35 and volume flow rate of 2 L/min). It can be noticed that the PV surface temperature increased dramatically at the beginning of the PV operation without cooling and then stabilizes for the rest of time, while the cooling with porous media was stabilized from the beginning to the end of the test due to the homogeneity in thermal mass flow rate through porous media. Also, it is better than water alone cooling. Therefore, the 0.35 porosity had reduced PV panel surface temperature by 55.8% compared to uncooled process.

Figs 10b and c show the experimental findings for the time-dependent variation of the PV panel power production and the efficiency for all three scenarios. It was found that, as experiments progressed, the power output and efficiency of the PV panel without cooling dropped dramatically before stabilization after certain period of time, while for the optimum case it remained steady with high power and efficiency till the end of operation. Therefore, the porous media cooling enhanced the PV power and efficiency more than 51.69% during its operation compared to uncooling; and 2.13% more than water alone cooling. Fig. 10d shows the variation of I-V curve of PV panel versus the open voltage for all three cases at a volume rate of 2 L/min. It is clearly seen that the optimum case reached a higher voltage of 22.54 V than other cases.

Overall, the results showed that the presence of low porosity media of 0.35 in the PV cooling process was more effective than the other two scenarios, because the heat loss from PV surface through porous media layer have developed a homogenous heat diffusion removal and specially at moderate flow rate (2 L/min). The result was similar the result done by Msalha *et al* (2019)



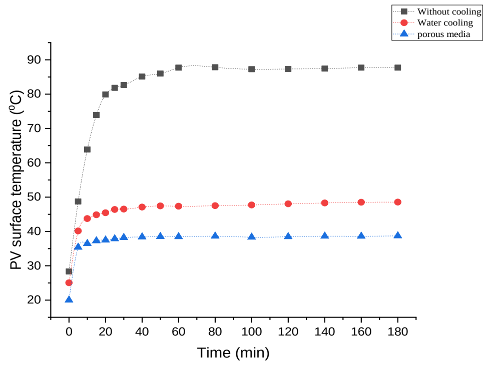
(a) 1L/min (b) 1.5L/min (c) 2L/min (d) 1L/min (e) 1.5L/min (f) 2L/min

Fig 9. Comparison between numerical and measured results of PV output power and its surface temperature at various volume flow rates (1, 1.5 and 2 L/min

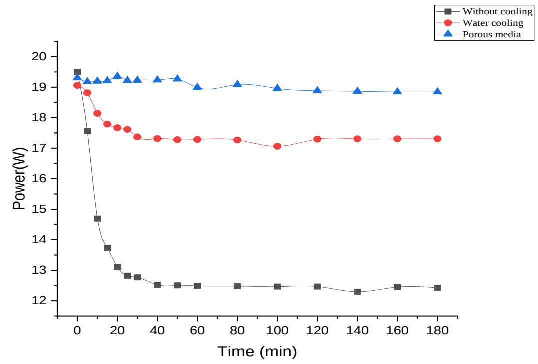
Table 4

Reduction percentage in PV surface temperature at various volume flow rates and porosities in comparison with water alone cooling process.

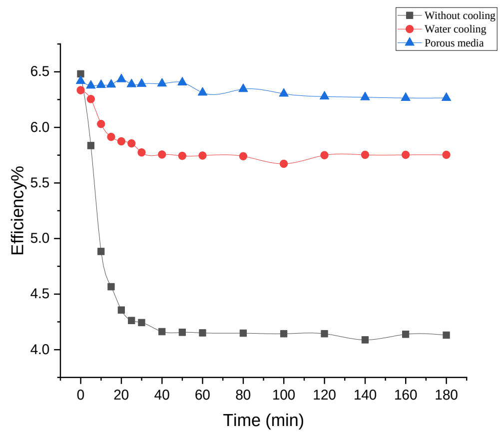
Volume flow rate (L/min)	PV cell surface temperature (°C) with different porosity					Reduction (%) in PV surface temperature with water alone cooling process			
	0.35	0.40	0.48	0.50	Water alone	0.35	0.40	0.48	0.50
1.0	40.57	43.00	45.00	45.50	51.55	21.30	16.59	12.71	11.74
1.5	40.16	41.53	42.80	43.30	50.90	21.10	18.41	15.91	14.93
2.0	38.70	40.35	42.36	42.80	48.55	20.29	16.89	12.75	11.84
3.0	39.70	40.20	41.43	41.90	50.25	21.00	20.00	17.55	16.62
4.0	39.60	40.00	41.40	41.85	48.50	18.35	17.53	14.64	13.71



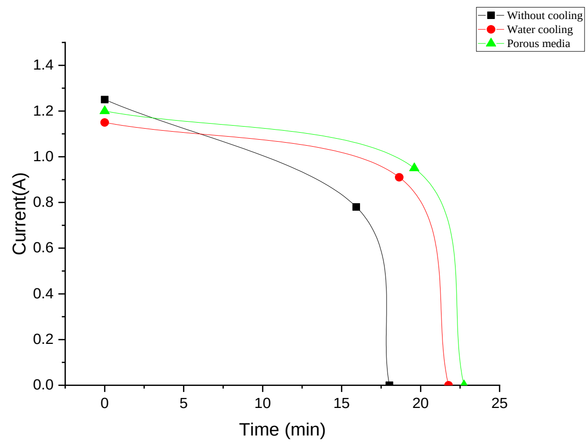
(a) PV surface temperature



(b) Power output



(c) Efficiency



(d) I-V curve

Fig 10. Comparison of PV Performance under three circumstances (without cooling, water cooling with a flow of 2 L/min, and cooling with a flow of 2 L/min through porous media)

5.3. Photovoltaic panel power enhancement and surface temperature reduction

To investigate the percentage increase in the output power and reduction in the surface temperature of the PV panel due to cooling and without cooling PV panel. Karami's *et al* (2014) formulae were used to calculate the percentage decrease in average PV surface temperature and increase in power. Tables 4 and 5 compare the reduction percentage in PV surface temperature calculated for different volume flow rates and porosities with the water alone cooling and uncooled process. It was noticed from the results in the Tables 6 and 7 that the moderate flow rates and low porosity media removed PV heat loss much quicker than other cases,

PV panel power output was measured, and the efficiency was estimated for various volume flow rates (1, 1.5, 2, 3, and 4 L/min) and porosities (0.35, 0.4, 0.48, and 0.5) as shown in Tables 6 and 7. Additionally, power production and PV efficiency improvement percentages are computed as well. It can be seen that optimum case proved to be the best scenario because it has the highest power production of 18.84 W and the highest efficiency 6.26 %. In addition, the data in the tables showed that porosity size has a greater impact on power production beside the flow rates. However, it is worth noting that the optimal case increased electricity production by 51.69 % and PV efficiency by 2.13 % compared to uncooled process. The PV power output and efficiency for the water alone case was found to be 39.29% and 0.39% respectively, compared with uncooled process. Therefore, the optimum case enhanced the PV power and efficiency by 9% more than water alone process.

6. Correlations

The correlation process is one of the good methods of analysis, because it allows better understanding of relationships between different parameters affecting the PV performance, before conducting an experimental work that needs time, cost and efforts. So that correlations were developed to enable quick prediction of PV surface temperature and power due to cooling.

6.1. Power correlation

Equation 29 was used to generate a power correlation as a function of several PV/T geometrical factors, such as solar radiation, PV area, porosity, volume flow rate, PV length, and kinetic viscosity. The comparison of experimental and correlation results for various PV panel power output with time was shown in Fig. 11 for optimum case (*i.e.* porosity of 0.35 and volume flow rates of 2 L/min).

The coupled power model was developed to examine several performance characteristics of the PV/T hybrid system cooled with porous media. Correlation findings were calculated using Eq. 29 to ensure the accuracy, and then these correlations have been checked against optimum case for optimization purposes. Fig. 11 shows the experimental and correlations outcome for optimum case. Both trends were nearly similar with a deviation of about 1.7% especially during the stable period of cooling process.

Table 5
Reduction percentage in PV surface temperature at various volume flow rates and porosities in comparison with uncooled process.

Volume flow rate (L/min)	PV cell surface temperature (°C) with different porosity				Reduction (%) in PV surface temperature compared with uncooled process			
	0.35	0.40	0.48	0.50	0.35	0.40	0.48	0.50
1.0	40.57	43.00	45.00	45.50	53.74	50.97	48.69	48.12
1.5	40.16	41.53	42.80	43.30	54.21	52.65	51.20	50.63
2.0	38.70	40.35	42.36	42.80	55.87	53.99	51.70	51.20
3.0	39.70	40.20	41.43	41.90	54.73	54.16	52.76	52.22
4.0	39.60	40.00	41.40	41.85	54.84	54.39	52.79	52.28

Table 6
Percentage increase in power output at various volume flow rates and porosities in comparison with uncooled process.

Volume flow rate	Output power (W) with different porosities					Uncooled power = 12.42W Increase power (%)			
(L/min)	0.35	0.4	0.48	0.5	Water alone	0.35	0.4	0.48	0.5
1.0	18.01	17.63	16.9	16.9	16.67	45.01	41.95	36.07	34.62
1.5	18.43	18	17.67	17.5	17.15	48.39	44.93	42.27	39.25
2.0	18.84	18.4	17.8	17.67	17.3	51.69	48.15	43.32	40.57
3.0	18.7	18.4	18.16	18	16.97	50.56	48.15	46.22	43.12
4.0	18.73	18.4	18.16	18.1	17.3	50.81	48.15	46.22	43.89

Table 7
Percentage increase in efficiency at various volume flow rates and porosities in comparison with uncooled process.

Volume flow rate	Efficiency (%) with different porosities					Uncooled efficiency = 4.13% Enhancement (%) in efficiency			
(L/min)	0.35	0.4	0.48	0.5	Water alone	0.35	0.4	0.48	0.5
1.0	5.99	5.86	5.62	5.62	5.54	1.86	1.73	1.49	1.49
1.5	6.13	5.98	5.87	5.82	5.70	2.00	1.85	1.74	1.69
2.0	6.26	6.12	5.92	5.87	5.75	2.13	1.99	1.79	1.74
3.0	6.22	6.12	6.04	5.98	5.64	2.09	1.99	1.91	1.85
4.0	6.23	6.12	6.04	6.02	5.75	2.1	1.99	1.91	1.89

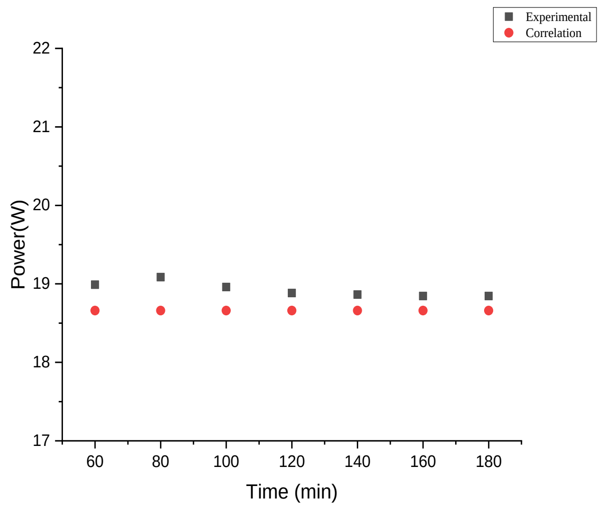


Fig 11. Comparing experimental data and correlation data of power output at a volume flow rate of 2 L/min with porosity of $\varphi = 0.35$

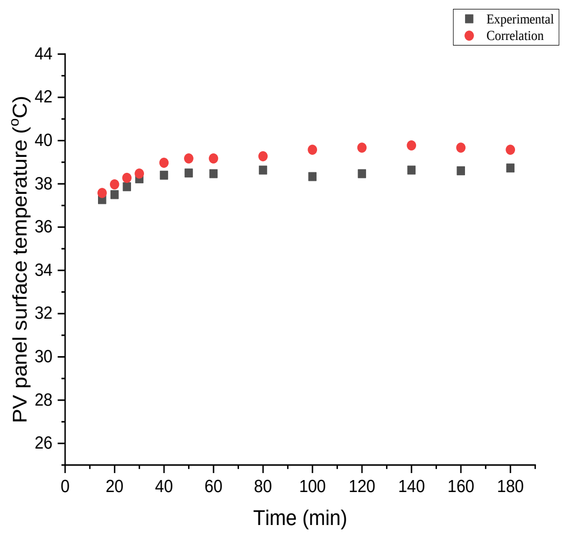


Fig 12. Comparing experimental data and correlation data of PV surface temperature for a volume flow rate of (2 L/min) with porosity of $\varphi = 0.35$

6.2. Correlation for temperature

As a coupled model, the PV cell surface temperature model was developed to examine various performance characteristics of a PV/T hybrid system with optimum case. Fig. 12 shows the experimental and correlation for optimum case. It can be seen that the maximum deviations between experimental and correlation results were found to be 5.2%. This means that the experimental data can be validated with the correlation data for validity.

The experimental and correlations results showed that they are in good agreement and had same trend of the behaviour for the optimum case. Therefore, the correlation model and experimental data gave clear indication that 0.35 porosity and 2 L/min flow rate is the best possible option for the PV panels cooling.

Table 8 presents many researchers found different findings on the reduction of PV temperatures and increase of power, this is due to different solar radiation measurements and different ambient conditions as well. It can also be noticed from Table 8, that some researchers got nearly the reduction of temperature similar to current results such as Msoud *et al* (2014), Nizetic *et al* (2016), and Hernandez *et al* (2013) but with lower power output than current study. Therefore, current study showed that the cooling process used enhanced the power output and efficiency more efficiently than other cooling processes used by previous researchers.

7. Conclusions

The experimental and theoretical study on cooling the PV panel using porous media with various porosities and volume flow rates have been investigated. Cooling PV panel using a porosity of 0.35 and flow rate of 2 L/min showed the highest increase in the power output, efficiency and I-V curve characteristics, correspondent to a higher reduction in the PV hot surface temperature of 55.87% more than uncooled process. The highest PV hot surface temperature of 87.7°C occurred for uncooled PV panel. Using water-alone cooling, the temperature reduced to 48.55°C, while, using water cooling with porous media of porosity 0.35 and volume flow rate of 2 L/min (optimum case), the temperature reduced to 38.7°C. Also, it is noticed that the optimum case registered a higher voltage of 22.54 V than other cases.

Table 8
A comparison between the current work and the previous work. The decrease in temperature and the increase in the output power percentage

References	Reduction of temperature(°C)	Increase of power %
Current work	32	34-51
Ahmad *et al*, 2016	10	6.6
Bahaidarah *et al,* 2013	17	15.5
Hernández *et al,* 2013	26	15
Masalha *et al,* 2019	31	7.48
Masalha *et al,* 2020	22	7.5
Masalha *et al,* 2021	26	9.6
Masoud *et al,* 2014	26	15
Meysam *et al,* 2014	13	7.7
Nižetić *et al,* 2016	26	14
Shenyi *et al,* 2014	12.5	15
Stefan et al, 2004	22	10.5
Xiao *et al,* 2010	8	5.4

It can be concluded that optimum case proved to be the best scenario because it has the highest power production of 19 W and the highest efficiency 6.26 %. Also, the optimum case enhanced the PV power and efficiency by 9% more than water alone process. The PV power output can be increased by changes in porosity and volume flow rate cooling.

There is a clear correlation between the average PV hot surface temperature and porosity. When the porosity decreases the reduction in PV panel surface temperature increases, that is due to the homogeneous diffusivity of convective heat lose attained at lower porosities and higher flow rate. Also, porous media offer a large exterior surface area and a high fluid permeability, making them ideal for PV cells cooling. The experimental and correlation results showed that they are in good agreement and had same trend of the behaviour for the optimum case. Further studies shall be conducted in near future on the nano porous media to find out their effect on PV cooling process.

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