Electrical and thermal performance assessment of photovoltaic thermal system integrated with organic phase change material

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Abstract. The integration of photovoltaic (PV) system in power system proved to be potential technology in terms of renewable energy sources. However, photovoltaic system has major drawback of rise in cell temperature, which results in low power production and reduced service life. To overcome the temperature rise in photovoltaic system, the addition of water cooling and phase change materials installed at rear side PV system termed as photovoltaic thermal (PVT) system has been adopted in this study. The organic phase change material (RT-42) having melting temperature of 42 °C and water cooling running at 0.45 litre per minute (LPM) under 440 W/m^2 irradiation has been taken as input parameters. The photovoltaic system and water cooled photovoltaic system performance has been analysed by using real time solar simulator. Additionally, the PVT-PCM system is assessed by use of TRNSYS simulation. Finally, this study compares the thermal and electrical efficiency of PV, PVT, and PVT-PCM systems. The findings indicated that maximum temperature for PV cells in a PV system was 59 °C. Water cooling alone reduces the temperature down to 49 °C, whereas water cooling combined with phase change material (PVT-PCM) lowers it down to 36°C. Further, the heat gain of 189 watt and 191 watt was achieved for PVT and PVT-PCM system. Additionally, the PV, PVT, and PVT-PCM systems achieved electrical efficiencies of 6.1%, 7%, and 9.5%, correspondingly.

1 Introduction

The issue of energy crises has emerged as a significant concern, mostly attributed to extensive consumption of energy resources and excessive use of fossil fuels. Hence, the need for the present moment is in the pursuit of novel and sustainable energy advancements [1]. The CO_2 emission-free, highly encouraging possibilities are provided by renewable energy sources [2]. Solar energy is often regarded as a very effective kind of renewable energy that has

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significant potential for large-scale applications. Further, in photovoltaic system, despite the fact that photovoltaic panels do absorb a substantial volume of solar radiation and they transform a fraction of it into electrical yield. A number of different kinds of solar cells are used in the process of directly converting the sun's energy into electrical energy. The efficiency with which solar energy is converted into electric energy is significantly influenced by the sort of solar cell that is used as well as the conditions under which it is operated. To put it into perspective, only 15–20 percent of the solar energy that is received is actually converted into electrical energy. The residual portion of solar energy is transformed into thermal energy, resulting in heating of PV panels' solar cells. The surface temperature of the PV panel may rise to high temperature in comparison to ambient temperature. At present, photovoltaic thermal systems have been the focus of intensive research and development efforts. Numerous creative ideas and products have been submitted for rigorous quality assessment by both scholars and experts in the field. The growing use of solar energy necessitates an increased focus on enhancing total efficiency of photovoltaic systems. However, solar energy's sporadic nature severely limits its usefulness in real-world scenarios. Moreover, an increase in cell temperature has an impact on PV system performance. Therefore, PV panel cooling techniques are of great importance to advance the electrical yield of PV panel along with thermal energy storage.

In order to enhance operational efficiency, it is advantageous to implement a cooling mechanism for the PV panel. Photovoltaic panels may be cooled using several methods, including active or passive cooling techniques. The process of actively cooling a solar panel is often accomplished by the usage of forced liquid or air. Active cooling systems consist of heat extraction mechanisms that use equipment like fans to facilitate the movement of air or convey fluid circulation to panels, so effectively removing extra quantity of heat. The practise of a hybrid technique in photovoltaic thermal (PVT) configuration serves to regulate temperature of solar cell while simultaneously enhancing the thermal collector's output efficiency. Additional advantages of this approach include the efficient use of space by integrating both systems inside the same area, as well as the potential reduction in installation expenses. As Abdullah et al. [3] constructed dual oscillating absorber copper tube pipe flow using the water-based PVT method. The work examines experimental data obtained via the use of the MATLAB programme in indoor setup based experimental tests of a water-based PVT system. The research outcomes of experimental work and simulation work has been compared in the study. The performance of the water-based PVT system was evaluated in terms of its electrical characteristics, thermal characteristics, and overall efficiency. The evaluation was conducted at solar radiation levels ranging from 500 to 1000 W/m^2, and with different mass circulation rates ranging from two to six LPM. The results demonstrate that the maximum electrical efficiency attained is 11.5% under conditions of 500 W/m^2 irradiance and a fluid flow rate of 6 litres per minute (LPM). Similarly, the greatest thermal efficiency is recorded as 58.64% when the irradiance was is 1000 W/m^2 and the flow rate was 5 LPM. Moreover, it is reasonable to propose that further improvements PVT systems may be achieved by the implementation of diverse design structures and the utilization of a variety of materials. Furthermore, due to the fact that phase change materials (PCMs) have the ability to absorb as well as discharge heat energy within a specific range of temperatures, integrating PCMs [4] into PV systems is one scheme that may lower temperature of PV module. The heat generated from elevated temperatures source accumulated in the liquid PCMs during a phase shift, and it is concurrently released to the side with lower ambient temperature and solidifies again [5]. Besides, controlling the surface temperature of PV panels has been identified as an effective approach in earlier research, attributed to the large latent heat capacity shown by phase change materials. In recent studies, a research was conducted to investigate the performance of a photovoltaic integrated with phase change material (PV-PCM) system using organic PCM with phase transition temperature of 28 °C. The study focused on specific geographical region of Ljubljana city. The study used testing and simulation methods. After the analysis, researchers reached the conclusion that the experimental findings demonstrated a 9.2% improvement in power output and a 2.8 percent boost in electrical efficiency via the use of PCM [6]. The investigators also concluded that results taken by simulation evaluation indicated substantial enhancement in PV-PCM output power of 4.3 to 8.7% coupled with electrical efficiency 0.5 to 1%. In additional research, the author investigated the effectiveness of the PV-PCM system in the environmental circumstances of United Arab Emirates, employing both theoretical and experimental methodologies. According to authors, the inclusion of paraffin PCM into PV panel resulted in decrement in peak panel temperature of around 10.5 °C and an annual gain in power output of 5.9% [7]. Further, study was conducted to analyse the PVT system performance by adopting micro fin tube with inner grooved and nano-enhanced PCM attached at back side of module. The phase transition temperature of PCM was 49 °C and nanoparticles were taken as silicon carbides for thermal conductivity improvement of PCM. As per the results, the PVT-NePCM system had electrical efficiency of 9.2% in comparison to simple PV of 5.8%. Besides, PVT-NePCM system had thermal efficiency of 74.8% in comparison to 56.3% if simple water circulating PVT system [8]. Similarly, hybrid PVT system was analysed in Malaysian weather condition by adopting PVT with PCM technique. The analysis demonstrated that the integration of PCM with PVT system has enhanced PVT system's performance. The outcome of study showed that the addition PCM with PVT system enhanced its electrical efficiency to 15.32% as compared to 14.57%. Further, the thermal efficiency for PVT-PCM system appeared to be 86.19% in comparison to 75.29% for simple water circulated PVT system [9]. The use PCMs in conjunction with a PVT system significantly improves the PV system's thermal and electrical efficiency, according to the literature. So, this research aims to find ways to make solar systems more efficient in terms of electricity and heat by including water circulation and phase change materials.

2 Materials and methodology adopted

The German company Rubitherm Ltd. supplied the organic PCM with a phase transition temperature of 42°C. Latent heat enthalpy and thermal degradation assessment were measured using the Differential Scanning Calorimeter (DSC) and the Thermogravimetric analyzer (TGA) equipment. An analysis of PCM (RT42) revealed a latent enthalpy of melting of 190 J/g. Further, PCM (RT42) was tested for thermal degradation. The PCM exhibited no weight loss stability until reaching a temperature of 140 °C, and its ultimate degradation temperature was shown to be 290 °C. The TGA analysis verified that the PCM (RT42) exhibits thermal stability, even at elevated temperatures. The latent heat enthalpy and thermal degradation evaluation are represented in Figure 1 (a) and (b).

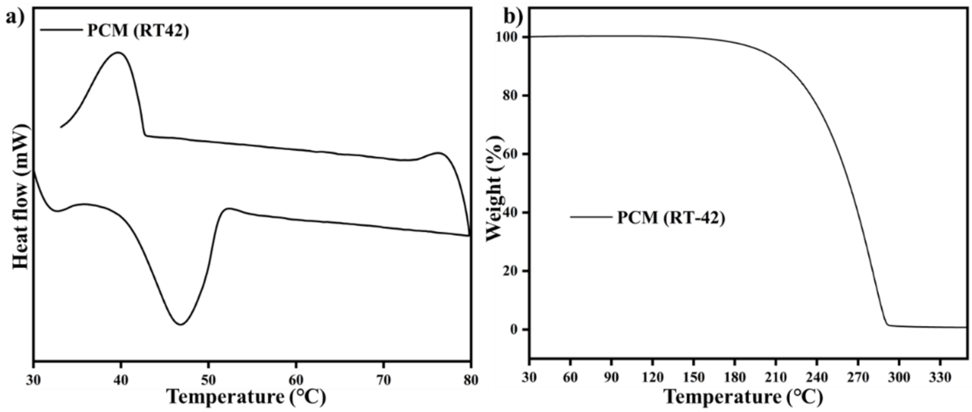

Fig. 1. (a) DSC curve for PCM (RT-42) (b) TGA curve for PCM (RT-42).

The commercially made solar simulator is utilized for the analyses of photovoltaic system and water circulated photovoltaic thermal system. The Figure 2 depicted the schematic arrangement of photovoltaic thermal system with water circulation The PV system was tested at 100 watt polycrystalline panel by taking 440 W/m^2 irradiation at 0.45 litre per minute (LPM) fluid flow rate for 1.5 hour. The water flow rate and the irradiation selected were set prior to power analysis. The PV module has graded open circuit voltage of 21.6 volts (Voc), a rated peak voltage of 18.0 V, and a maximum short circuit current of 6 amperes (A) for the photovoltaic (PV) module. In addition to serving as a heat absorber, copper tubes containing enhanced thermal conductivity are selected to promote the efficient movement of fluid over the back surface of panel. The copper tubes have been embedded into rear side of PV module. The copper tube encompasses diameter of 12.77 millimetres and thickness of 0.60 millimetres. Moreover, apparatus used for data acquisition from PVT system is tabulated in Table 1.

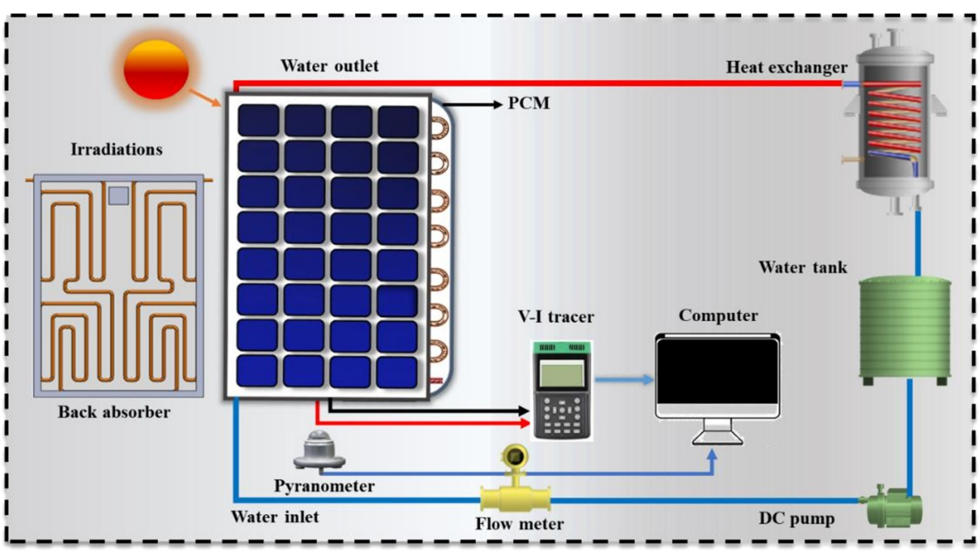

Fig. 2. Schematic scheme of photovoltaic thermal system.

Table 1. Apparatus with their accuracy and operating range used in experiment.

Apparatus	Operating limit	Accuracy in %
Thermocouple K-type	500 °C	±0.5%
Pyranometer	0 to 2000 W/m^2	±5%
Data logger	1 to 8-channels	±2%
I-V power meter	0 to 50 V and 0 to 16 A	±5%
Multimeter	400 mV to 1000 V	±0.4%
Flow meter for fluid	0.2 to 2.0 LPM	±0.5%

Further, for PVT-PCM TRNSYS simulation study has been utilized. In a similar manner, PVT experimental setup's input data for PVT-PCM system was simulated using TRNSYS software, and outcomes were subsequently equated for all PV systems. The simulation of results for the PVT-PCM system was carried out using "Type 213" parameter of the TRNSYS software, as depicted in Figure 3. The subsequent set of presumptions has been used to develop the intended structure of "Type 213" module in TRNSYS. The thermal model in consideration is a single-dimensional model that makes the assumption that surface has a steady temperature distribution.

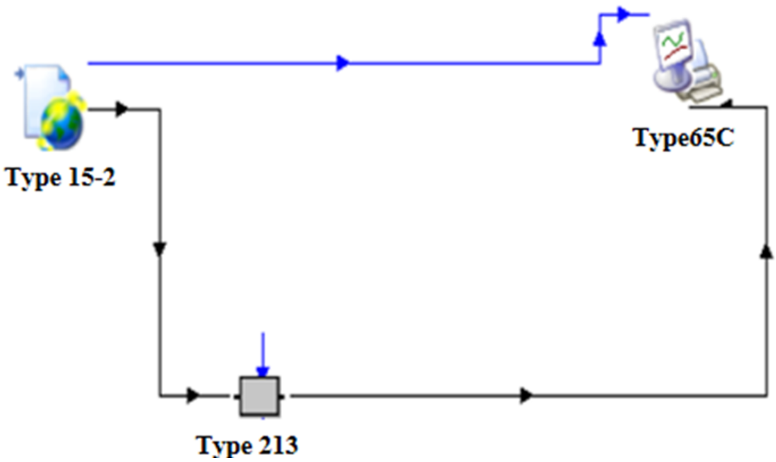

Fig. 3. Developed TRNSYS model for assessment of performance for PVT-PCM.

This research ignores effects of dust and shadow on photovoltaic systems, frictional losses in the tubes, and lateral losses in the tubes. Furthermore, it is presumable that the system's starting temperature was equal to the ambient temperature outside. Furthermore, it is presumed that the flow inside the tubes has reached a state of complete development. Additionally, the simulated outcomes were obtained for a test duration of 90 minutes. The data input specifications used TRNSYS program have been shown in Table 2. Besides, characteristic values of phase change material are obtained from supplier data and latent heat enthalpy value has been evaluated by DSC investigation data.

Table 2. Input data parameters.

Specification	Magnitude	Specification	Magnitude
PVT's total area	0.596 m^2	PCM's Density	880 Kg/m^3
PVT thickness	0.003 m	PCM's Specific heat	2000 J/kgk
Glass thickness	0.005 m	Coil area	0.4 m^2
Packing factor	0.8	Fluid specific heat	4190 J/kgk
Thermal conductivity of PCM	0.2 W/mk	Flow rate of fluid	0.45 LPM
Irradiance	440 W/m^2	Atmospheric temperature	25.0 °C
Phase transition temperature of PCM	42 °C	Inlet water temperature	25.0 °C
PCM's heat enthalpy	190 J/g		

3 Results and discussion

It is possible to undertake an assessment of the electrical parametric performance and thermal functionality of photovoltaic-thermal systems by making use of the formulae that are supplied below, in accordance with the first law of thermodynamics. The electrical efficiency can be found by utilizing equation; (1) [10]

$$H_{el} = \frac{P_{max}}{A \times G} \tag{1}$$

Where Pmax is the maximum power output of PV given by Pmax = VocIsc, A is area of panel and G is irradiance. Similarly, the value of thermal efficiency of PV system can be establish by equation; (2) [11], here, Q is the total heat gain of system.

$$\eta_{th} = \frac{Q_u}{A \times G} \tag{2}$$

Further, equation (3) [11] represents the heat gain of the system

$$Q_u = [mCp(T_{out} - T_{in})] \tag{3}$$

Here, m indicates the water volume flow rate of the circulating water, Cp represents the liquid's heat capacity, and Tin represents the water's beginning and end temperatures. In a same way for PVT-PCM amount of heat gain the equation is specified in equation (4) [11].

$$Q_u = [mCp(T_{out} - T_{in})] + [m'Cp(T'_{out} - T'_{in})] \tag{4}$$

Here, m' stands for PCM mass, while T'out and T'in stand for PCM's initial and ultimate temperatures.

The evaluation of the PVT system's performance was carried out at an ambient temperature of 25 °C using a solar simulator. In addition, PVT-PCM configuration was further examined via the use of a TRNSYS simulation tool. The experimental evaluation were carried out under constant solar radiation of 440 W/m^2 and uniform flow rate of 0.45

LPM. As per result outcomes, maximum PV cell temperature of PV, PVT and PVT-PCM configuration is achieved to be 59 ℃, 49 ℃ and 36 ℃, respectively. The maximum surface temperature with response to solar radiation was found for PV system that may be attributed to conversion of a portion of incident solar energy into electrical energy by the PV panel, with the remaining energy contributing to heating of panel surface. The diminished efficacy of the PV panel can be attributed to this additional heat that it generates while producing power. However, by adopting PVT and PVT-PCM scheme can reduce maximum surface temperature of PV. The Figure 4 illustrates the highest recorded temperature of the cells and the fluid while implementing the PVT and PVT-PCM method.

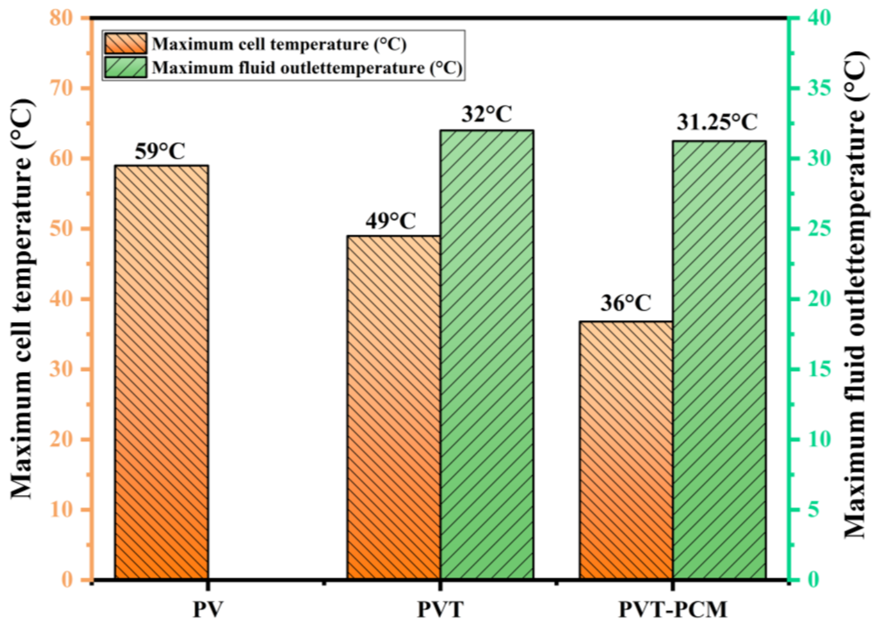

Fig. 4. Maximum cell temperature and maximum outlet fluid temperature.

Considering the power generation from PV systems generally decreases with an elevation in PV cell temperature, the electrical properties of PV panels have improved as a consequence of the reduction in PV cell temperature. The electrical parameter and efficiencies of PV, PVT and PVT-PCM configurations attained as 6.1, 7 and 9.5%, correspondingly. Similarly, thermal efficiencies of PVT-PCM resulted as 73% in comparison to 72% of PVT, as shown in Figure 5. As per outcomes, the thermal efficiency achieved to be high. This is due to higher temperature difference between inlet and outlet water temperature and heat accumulated in the PCM. Further, the overall efficiency achieved to be 79% for PVT and 82.5% for PVT-PCM. Additionally, PV-PCM panel demonstrated a higher level of electrical efficiency as compared to the reference PV panel. This might be explained by the PV-PCM panel's decreased surface temperature, which is achieved by effective dissipation of heat from PV panel to phase change material and circulating water. Similarly, thermal efficiency of PVT and PVT-PCM was intended by using equation (2). It was observed that fluid outflow temperature of the PVT system was comparatively greater than that of the PVT-PCM system. However, improved thermal efficiency of PVT-PCM configuration may be attributed to heat energy accumulated through phase change material's ability [12].

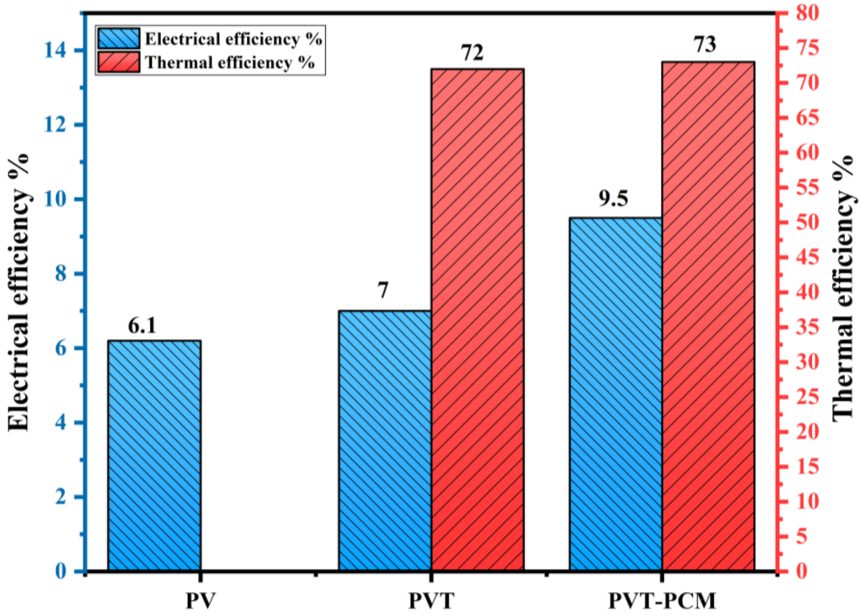

Fig. 5. Outcome of electrical and thermal efficiencies of PV systems.

4 Conclusion

Phase change material (RT42) having thermal conductivity of 0.2 W/mK was tested for latent heat and thermal stability. According to results the latent heat of PCM found to be 190 J/g and pcm remain stable till 140℃ with zero weight loss. Further, photovoltaic (PV) systems and photovoltaic thermal (PVT) system were evaluated experimentally by using solar simulator and PVT with PCM by using TRNSYS simulation at 440 W/m^2 solar radiations. Besides, the fluid flow rate of 0.45 litre per minute has been considered in evaluation. The outcomes of the study showed maximum cell temperature for photovoltaic system found to be 59 ℃. However, for PVT and PVT-PCM it is reduced to 49 ℃ and 36 ℃. Further, the electrical efficiencies appeared to be 6.1%, 7% and 9.5% for PV, PVT and PVT-PCM system, correspondingly. Besides, fluid outlet temperature for PVT system found as 32 ℃ in comparison to 31.25 ℃ of PVT-PCM. However, thermal efficiency of PVT-PCM system achieved to be 73% in comparison to 72% of PVT. Furthermore, the overall efficiency for PVT and PVT-PCM system achieved to be 79% and 82.5%, respectively. The enhancement in thermal efficiency of PVT-PCM was because of added heat storage inside the PCM. Based on the aforementioned findings, it can be inferred that the research yielded improved thermal management of PVT-PCM module in comparison to base PV module. This can be attributed to active dissipation of superfluous heat from PV panel to phase change material and circulating fluid, leading to a decrease in temperature on the top surface of the PVT-PCM panel. As a result, phase change material oriented photovoltaic system may be used to extend the solar panels' service life while also improving the system's electrical and thermal capabilities.

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