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Research Article

Energy performance evaluation of a photovoltaic thermal phase change material (PVT-PCM) using a spiral flow configuration

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Abstract. A relatively new technology, a hybrid photovoltaic thermal (PVT) solar collector, allows for producing electrical and thermal energy. However, the module heats up more when exposed to sunlight thanks to the PVT collector's incorporation, reducing its efficiency. Consequently, lowering the operating temperature is crucial for maximizing the system's effectiveness. This research aims to create a photovoltaic thermal phase change material (PVT-PCM) solar collector and evaluate its energy performance through a controlled laboratory environment. Two different PVT collector designs, one using water and the other using a phase change material (PCM), were evaluated using a spiral flow configuration. Under a sun simulator, the PVT solar collector was subjected to 400 W/m^2, 600 W/m^2, and 800 W/m^2 of solar irradiation at three different mass flow rates. The results showed that under 800 W/m^2 of solar irradiation and 0.033 kg/s mass flow rate, the collector using water could only reach an overall maximum efficiency of 64.34 %, whereas the PVT-PCM configuration with spiral flow had the maximum performance, with an overall efficiency of 67.63%.

Keywords: Photovoltaic thermal (PVT), Phase change material (PCM), Solar collector, Spiral flow, Heat transfer

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1. Introduction

Energy plays an important role in facilitating various human endeavours, including but not limited to agriculture, illumination, healthcare communication, and industrial operations (Rahmat *et al.*, 2022). The global energy consumption in 2016 amounted a 474 exajoules, with a significant majority of 80-90% derived from the combustion of fossil fuels (Jain, 2019; Bilardo *et al.*, 2020; Abd Rahman *et al.*, 2021). The increased energy demand can be attributed to a country's concurrent rise in population and economic development (Han *et al.*, 2020; Goel *et al.*, 2020; Assadeg *et al.*, 2023). Solar energy technology offers a distinct ecological advantage compared to conventional energy sources (Ishak *et al.*, 2023). Furthermore, its utilization also fosters the advancement of sustainable energy practices (Ishak *et al.*, 2023a,b) The primary benefit of this technology is its direct correlation with the mitigation of CO_2 emissions and its operational efficiency that eliminates the generation of waste (Faizal *et al.*, 2013). Malaysia experiences an average daily sunlight duration ranging from 4 to 8 hours per day, accompanied by the monthly global solar irradiance of approximately 4 to 5 kWh/m^2 (Moshery *et al.*, 2021; Matheswaran *et al.*, 2018; Kuczynski *et al.*, 2023).

Solar energy systems can be categorized into photovoltaic and thermal systems. The combination of these two systems is known as photovoltaic thermal, which enables the collector to harness electrical and thermal energy simultaneously (Ewe *et al.*, 2022; Chen *et al.*, 2022; Bisengimana *et al.*, 2023). The integration of photovoltaic thermal (PVT) systems with additional elements, such as water, wind, and, more recently, phase change material (PCM), has been explored as means to enhance the overall efficiency of the photovoltaic systems (Hamzat *et al.*, 2021; Diwania *et al.*, 2020; Chandrasekar *et al.*, 2021). The systems are commonly referred to as thermal photovoltaic solar collectors with phase change materials (PVT-PCM) and can be implemented for both individual and large-scale applications (Tao *et al.*, 2019; Sharol *et al.*, 2022; Maithani *et al.*, 2021; Goel *et al.*, 2020; Das *et al.*, 2021). It is widely recognized that there was a notable rise in the utilization of solar energy, amounting to an additional 179 Terawatt-hours in the year 2021 (Tripanagnostopoulos *et al.*, 2002; Alktranee *et al.*, 2023). This figure signifies a growth rate of 22% compared to the previous year, as reported by the International Energy Agency (IEA) in 2020 (Ewe *et al.*, 2021).

The integration and external installation of photovoltaic systems can lead to a rise in temperature on the modules when exposed to the sun, reducing the panels' efficiency (Prakash *et al.*, 2022; Chaibi *et al.*, 2021). According to Dwivedi *et al.*, (2020), empirical evidence suggests that the module's temperature increases to 70°C when directly exposed to sunlight, leading to a subsequent decline in efficiency. Due to that, significantly vital to decrease the operating temperature to achieve maximum efficiency in the system (Wai *et al.*, 2022; Siah *et al.*, 2020; Mohammadpour *et al.*, 2022). One primary challenge associated with traditional PVT collectors is contingent upon the arrangement of the PVT collector (Choudhury *et al.*, 1991). The present configuration exhibits non-uniform cooling as a consequence of its diminished efficiency under elevated ambient temperatures (Goel *et al.*, 2020). The appropriate arrangement of the PVT collector and its unique configuration

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is essential for facilitating the fluid flow and sustaining the energy within the collector (Xu *et al*., 2021). Consequently, it is imperative to configure and verify the PVT collector to ensure optimal performance (Sheikholeslami *et al*., 2021). The experimental investigation is carried out herein to learn more about a PVT-PCM with a spiral flow arrangement output. This study aims to develop and evaluate the performance of a Photovoltaic Thermal Phase Change Material (PVT-PCM) using a spiral flow configuration by conducting an indoor experiment.

2. Experiment Setup

2.1 Spiral Flow Hollow Tube Configuration

An indoor experiment was conducted to assess the energy performance using a spiral flow configuration collector integrated with a PCM material. A square hollow tube was installed in a spiral flow configuration under a flat plate photovoltaic module with a capacity of 100W, as shown in Figure 1. A metal bonding technique was employed as an adhesive to affix the spiral flow hollow tube, ensuring a complete absence of gaps between the tube and the module. This approach effectively prevents the occurrence of heat transfer, as demonstrated by Abdullah *et al*., (2018). The spiral flow tube was constructed from a durable stainless-steel material and assembled using the Tungsten Inert Gas (TIG) welding method. Additionally, a nipple was affixed to the posterior surface to facilitate the manifold's attachment.

The PVT collector comprises a singular unilateral channel that facilitates the fluid's movement within the system. The dimension of the flat plate photovoltaic module is 1 x 0.65 x 0.3 m (width x length x thickness). Insulation material is placed strategically underneath the PVT collector to mitigate heat loss, simultaneously promoting a homogeneous temperature distribution within the system. After being sealed and made waterproof, the PVT collector is affixed to the back of the photovoltaic module. It was then encapsulated within polyvinyl resin, forming a comprehensive PVT system with water and a PVT-PCM system. The dimension of this system is 1190 mm x 540 mm x 35 mm. There are two configurations of the PVT collector: the PVT collector, which only uses water, and the PVT-PCM collector, which uses PCM.

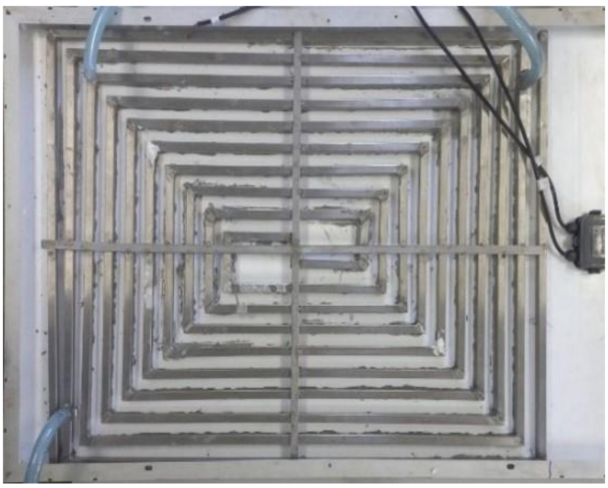

Fig. 2 Spiral flow hollow tube attached beneath a flat plate photovoltaic module.

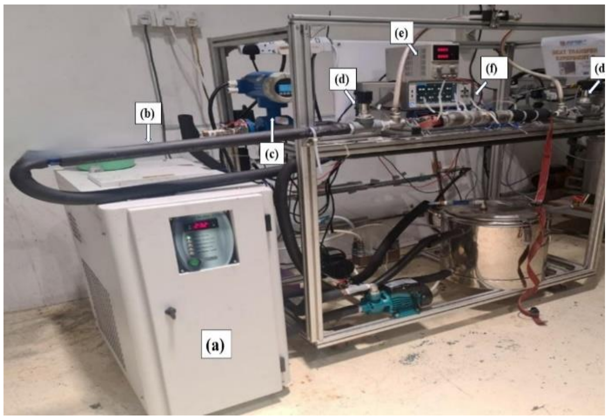

Fig. 1 Experiment Test Rig, which consists of (a) cooling unit, (b) coil pipes, (c) flow meter, (d) RTD thermocouples, (e) IV-checker, and (f) Data taker.

2.2 Indoor Experiment Setup

The efficiency of the PVT collector was tested in a lab with a simulated halogen light bulb at a temperature of 20 °C. The solar irradiance ranged from 400 W/m^2, 600 W/m^2, and 800 W/m^2 while subjected to a variable mass flow rate. The experiment was performed by adjusting the solar irradiance to the predetermined power configuration. Once the system is steady, the medium (water) flows through the PVT collector. The parameters measured include the current (I), voltage (V), short-circuit current (Isc), Open-circuit voltage (Voc), and the PV module temperature (Ts). These measurements were taken at regular intervals of 20 seconds. The experimental rig consists of the test section, cooling unit, flow meter, differential pressure gauge, IV checker, Data Taker, and heat exchanger, as shown in Figure 2 and Figure 3.

A water storage facility is close to the collector to uphold water pressure. A manifold pipe links the water reservoir to the flat plate module. The water was circulated through the system utilizing the pump. There are several assumptions made:

- The pipes connected to the test rig are adequately insulated to mitigate heat dissipation while the PVT collector assimilates energy.
- The only source of energy loss is the water storage tank.
- The water temperature in the storage tank is the same as the water temperature entering the collector.

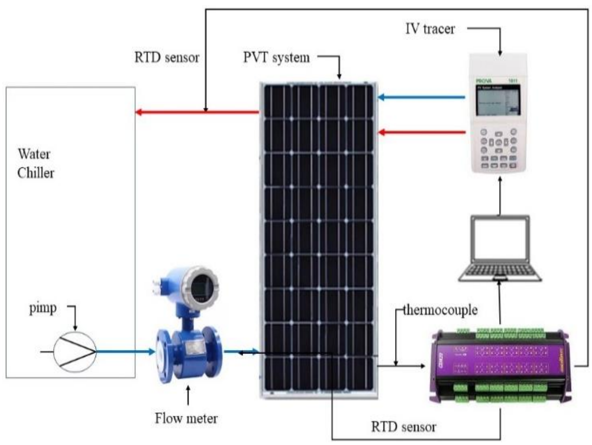

Fig. 3 Schematic diagram of the experimental setup.

Table 1
Measurement Uncertainty

Equipment	Parameters	Uncertainty (%)
I-V Checker	Solar irradiance	± 0.01 %
Data Taker	Temperature	± 0.1 °C
Thermocouples	Temperature	± 0.5 °C
Thermocouples	Temperature	± 0.01 °C
Pyranometer	Solar irradiance	± 0.05 %
Digital Flow Meter	velocity	± 0.5 %

- The temperature of the water entering the tank and the water leaving the collector are identical.

2.3 Uncertainty Analysis

A systematic process used to quantify estimating errors, known as uncertainty analysis, was performed. Typically, measurement inaccuracies raise doubts regarding the validity and credibility of the data. Table 1 displays the findings of each measuring device's uncertainty analysis. It was observed that less than 2% of the variation was found during the uncertainty analysis, which is a sign of highly accurate and reliable measurements. The standard deviation was calculated using the following:

$$s = \sqrt{\frac{\sum_i^n (x_i - \bar{x})^2}{n-1}} \tag{1}$$

In this context, the variables n, x_i and $\bar{x}$ are used to denote the number of measurements, the mean of the measurements, and the individual measurement results, respectively. The uncertainty, denoted as u, is mathematically represented as:

$$u = \frac{s}{\sqrt{n}} \tag{2}$$

3. Energy Balance

The performance of the PVT collector in a steady state can be characterized by an energy balance equation, which illustrates the allocation of incident solar energy into useful energy gain, heat loss, and optical loss. The thermal efficiency, (η_{th}) is determined through the utilization of the following equation (Bassam *et al.*, 2023):

$$\eta_{th} = \frac{Q_u}{G} \tag{3}$$

The variable *Qu* represents the quantification of useful heat gain (W/m^2), while G denotes the solar irradiance (W/m^2) that enters the collector surface. The exploration of the useful heat gain, *Qu,* can be determined by the following formula:

$$Q_u = \dot{m} C_p (T_{out} - T_{in}) \tag{4}$$

Where the mass flow rate is denoted by ṁ (kg/s), specific heat is denoted by Cp (J/kg.K), while the outlet and inlet temperature is measured in Kelvin. If *Qu* is the quantity of heat collected by the water, the energy balance equation is defined as the following (Bassam *et al.*, 2023):

$$Q_u = A_c F_R [S - U_L (T_{in} - T_a)] \tag{5}$$

The solar irradiance absorbed by the collector is denoted by S is expressed as:

$$S = (\tau\alpha)_{PV} G_T \tag{6}$$

Ac represents the area of the PVT collector (m^2). The heat removal efficiency factor, F_R, can be calculated using equation 7, and the efficiency factor, *F,* can be calculated using equation 8. U_L represents the total collector heat loss (m^2.K), T_a is the ambient temperature (K), ταPV is the PV thermal efficiency, and *GT* is the solar irradiance (W/m^2).

$$F_R = \frac{\dot{m} C_p}{A_c U_L}\left[1 - exp\left[-\frac{A_c U_L F'}{\dot{m} C_p}\right]\right] \tag{7}$$

$$F = \frac{tanh\left[m\left(\frac{W-Dh}{2}\right)\right]}{\sqrt{m\left(\frac{W-Dh}{2}\right)}} \tag{8}$$

$$\dot{m} = \sqrt{\frac{U_L}{K_{abs} \cdot L_{abs} + K_{PV} \cdot L_{PV}}} \tag{9}$$

Where the mass flow rate is denoted by, ṁ and the thermal conductivity is denoted by K_{abs} (W/m^2.K), L_{abs} is the PVT thickness (m), K_{pv} is the photovoltaic thermal conductivity, and LPV is the collector thickness. The corrected fin efficiency *F'* is calculated using the following (Bassam *et al.*, 2023):

$$F' = \left[\frac{\frac{1}{U_L}}{U_L (D_h + (W - D_h) F)}\right] + \frac{1}{C_{bPV}} + \frac{1}{2(a+b)_{hfi}} \tag{10}$$

Equation 11 is used to identify the photovoltaic efficiency, (η_{Pv}) (Khodadadi *et al.*, 2022):

$$\eta_{pv} = \eta_r [1 - \beta (T_c - T_r)] \tag{11}$$

Where n_r represents the photovoltaic module efficiency (n_r = 0.12), β is the temperature coefficient (0.0045 °C), T_c is the solar cell temperature (K), T_r is the reference temperature (K), and the PV efficiency performance based on current and voltage can be calculated using the following formula:

$$\eta_{pv} = \frac{I_m V_m}{A_p G_T} \times 100\% \tag{12}$$

Where I_m is the maximum current (A), and V_m is the maximum voltage (V).

4. Results and Discussion

The electrical and thermal properties exhibited by the collector will determine the performance and efficiency of the PVT and PVT-PCM collectors. These qualities are dependent on one another. The evaluation carried out on the collector was segmented into three parts: an assessment of the photovoltaic (PV) efficiency, an evaluation of the heat efficiency, and a combined evaluation of both efficiencies. Except for the dimensions of the collector (width x length), the previously listed influential parameters will be investigated in great detail. According to the typical configuration of a photovoltaic module, the widths and lengths of the module are both fixed by their respective dimensions.

4.1 The Influence of Module Temperature on The Photovoltaic Efficiency of PVT and PVT-PCM

The temperature of the PV module, represented as Ts, is directly influenced by the properties of the module cells. The increase in module temperature tends to influence the open-circuit voltage *(Voc)*, short-circuit current *(Isc)*, and maximum power output *(Pmax)*. The correlation between the module temperature and its electrical characteristic has been observed.

It was noticeable that there is a direct correlation between the temperature of the module and a decrease in the open-circuit voltage *(Voc)*, following a linear trend. Furthermore, a marginal rise in the short-circuit current *(Isc)* and a corresponding decline in the maximum power output *(Pmax)* are observed.

According to the scenario, it is anticipated that an increase in the module temperature will lead to a decline in the performance efficiency of the PVT system employing water and PCM. The graphs presented in Figure 4 to Figure 6 provide observable evidence of this scenario. The outcome of the experiment conducted with water collectors and PVT-PCM subjected to solar irradiance ranging from 400 W/m^2 to 800 W/m^2 with a mass flow rate varying from 0.017 to 0.033 kg/s is presented in Figure 4 to Figure 6.

The collector demonstrates a significant variation in photovoltaic efficiency when exposed to varying solar irradiance and mass flow rate. It was also noticeable that the overall efficiency had an improvement. The empirical findings suggest that the incorporation of water utilization within a PVT system can result in a significant improvement in overall efficiency. Additionally, the overall photovoltaic efficiency increased from 11.47% to 11.85% due to a temperature elevation from 46.94 °C to 50.84 °C. Following this, when the solar irradiance is adjusted to 600 W/m^2, there was a noticeable enhancement in the overall photovoltaic efficiency from 11.90% to 12.35% within the temperature range of 48.04 °C to 52.04 °C. Meanwhile, when exposed to solar irradiance of 800 W/m^2, it was observed that the photovoltaic efficiency experienced an enhancement from 12.22% to 12.8%. The efficiency improvement was associated with a rise in temperature from 49.63 °C to 53.84 °C.

On the other hand, the PVT-PCM underwent testing, which yielded comparable findings. The photovoltaic efficiency increases from 11.99% to 12.52% when subjected to a temperature range of 46.24 °C to 50.86 °C, with a solar irradiance of 400 W/m^2. Meanwhile, the temperature ranges from 46.84 °C to 51.95 °C, while the photovoltaic efficiency ranges from 12.49% to 13.07% under solar irradiance of 600 W/m^2. Results from this experiment reveal an improvement when solar radiation is raised to 800 W/m^2. This skew occurs because the collector's cooling impact lowers average efficiency. The numbers show that the mass flow rate and efficiency drop with increasing temperature. As a result, between 48.03 and 53.35 °C, collector efficiency rose from 13.01% to 13.81%.

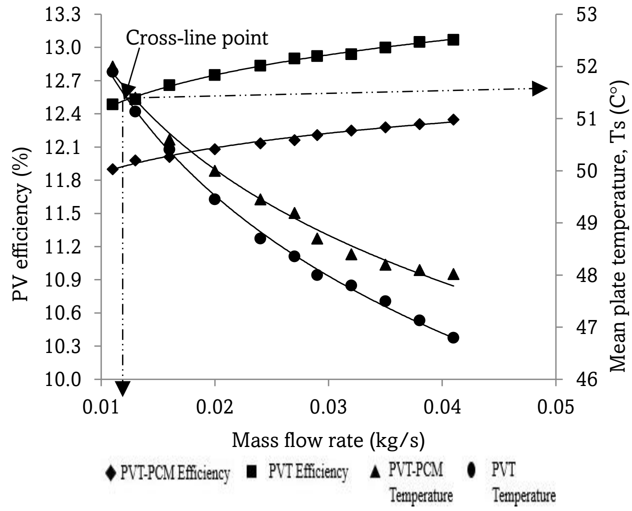

Fig. 4 PV efficiency over mean plate temperature, Ts at solar irradiance of 600 W/m^2.

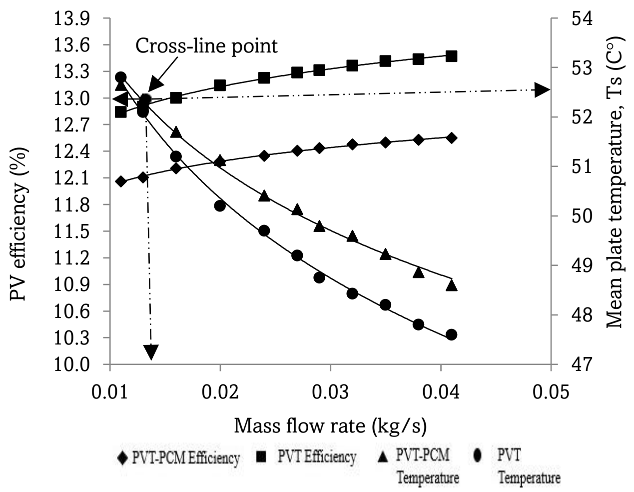

Fig. 5 PV efficiency over mean plate temperature, Ts at solar irradiance of 800 W/m^2.

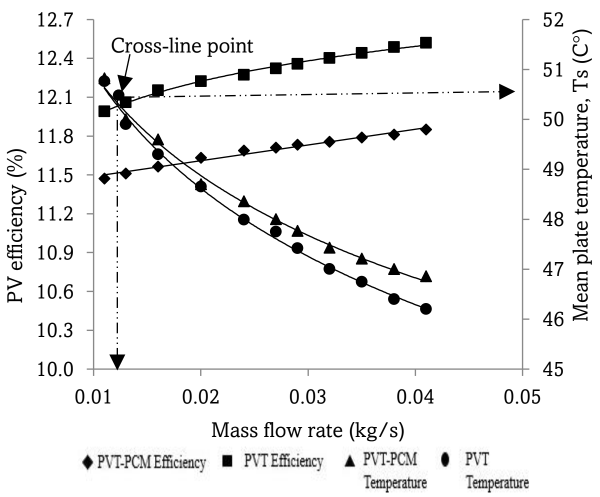

Fig. 6 PV efficiency over mean plate temperature, Ts at solar irradiance of 400 W/m^2.

4.2 Thermal Performance of the PVT Collector

As the mass flow rate increases, the PVT collector's performance generally improves at all solar irradiance levels. The inverse relationship between the operating temperature and efficiency of photovoltaic solar cells is widely acknowledged, as well as the positive impact of cooling on the performance of the PV modules. Figure 7 depicts the thermal efficiency of the collector at 800 W/m^2 solar irradiance, which recorded the highest thermal efficiency. The thermal efficiency increased from 44.16% to 52.63% at 0.017 kg/s to 0.033 kg/s. As temperature decreases, the PV module efficiency increases. In addition, the temperature decreases non-linearly with the mass flow rate. The decrease in temperature is observed to transpire across a wider spectrum when the mass flow rate is significantly reduced. The temperature decreases once it reaches a mass flow rate of 0.017 kg/s. Table 2 presents a concise overview of the values associated with the input temperature (Ti), output temperature (To), and thermal efficiency (n_{Th}) of the PVT collector.

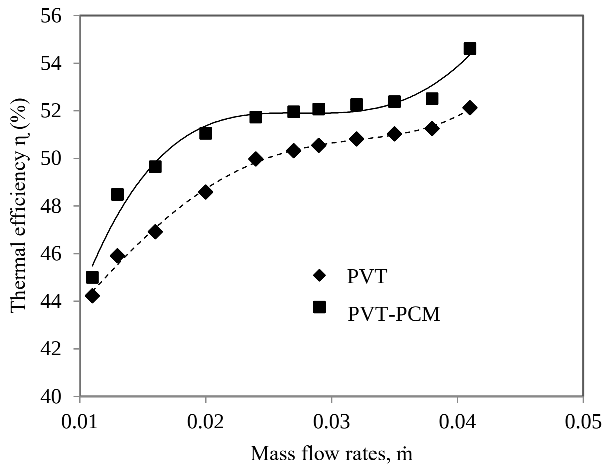

Fig. 7 Thermal efficiency over various mass flow rates at solar irradiance of 800 W/m^2.

Table 2
Values for input temperature Ti, output temperature To, and thermal efficiency over various mass flow rates ṁ at 800 W/m^2 solar irradiance for (a) PVT and (b) PVT-PCM collectors.

ṁ (kg/s)	(a) PVT Configuration			
	T_i (°C)	T_o (°C)	T_o-T_i (°C)	η_{th} (%)
0.033	40.30	53.63	13.33	52.12
0.025	42.06	54.24	12.18	50.81
0.017	49.00	62.89	13.89	44.23

ṁ (kg/s)	(b) PVT-PCM Configuration			
	T_i (°C)	T_o (°C)	T_o-T_i (°C)	η_{th} (%)
0.033	38.00	50.00	12.00	54.61
0.025	42.42	54.54	12.12	52.25
0.017	54.00	70.00	16.00	45.00

The total efficiency of the PVT collector was calculated to assess its overall performance. The results of the studies on collector analysis indicate a favourable correlation between efficiency and mass flow rate. Therefore, as the mass flow rate rises, so does the overall efficiency. Figure 8 and Table 3 display the total efficiency figures for the PVT and PVT-PCM collection at various mass flow rates. The highest total photovoltaic thermal (PVT) efficiency was observed at 0.017 kg/s for both PVT and PVT-PCM collectors. However, PVT-PCM achieved the highest PVT efficiency of 58.81% compared to the PVT collector, which achieved 57.03%.

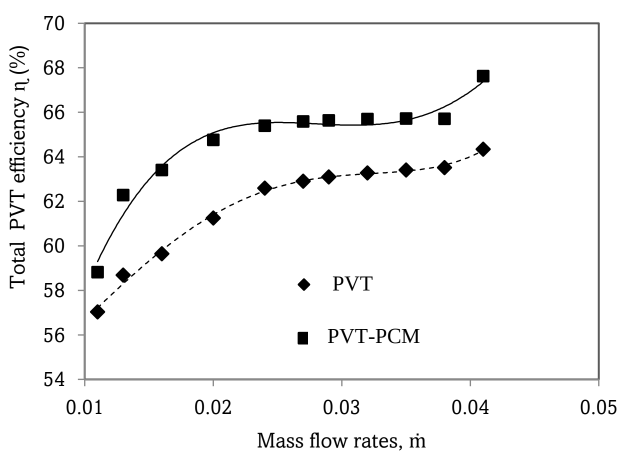

Fig. 8 Total Efficiency of PVT and PVT-PCM.

Table 3
Total Efficiency of PVT and PVT-PCM under varying mass flow rates.

ṁ (kg/s)	PVT Configuration			PVT-PCM Configuration		
	η_{th} (%)	η_{PV} (%)	$\eta_{overall}$ (%)	η_{th} (%)	η_{PV} (%)	$\eta_{overall}$ (%)
0.033	52.12	12.22	64.34	54.61	13.01	67.63
0.025	50.81	12.47	63.27	52.25	13.44	65.69
0.017	44.23	12.80	57.03	45.00	13.81	58.81

5. Conclusion

The rise in mass flow rates at varying levels of solar irradiation has a negative impact on the overall performance of photovoltaic thermal phase change material (PVT-PCM) collectors. This occurs when the mass flow rate and the PV module cell's cooling factor increase simultaneously. PVT-PCM collector temperature rise is mediated by mass flow rate. Collecting structures for more complex patterns like PVT and PVT-PCM are frequently implemented as long, continuous coils or tubes. Each of the spiral coils includes at least one inlet and one outlet to allow for the medium's entry and exit, consisting of water and phase change material. The configuration involves the utilization of a medium consisting of water and phase change material. This medium, characterized by a lower temperature, is introduced into the coil, which proceeds to flow toward the midpoint. Subsequently, it exits the coil, having undergone a transformation into heat energy. Subsequently, thermal energy has the capability to be stored for both residential and industrial applications. This configuration allows for the optimal utilization of solar radiation energy, resulting in the highest overall efficiency compared to other PVT collectors' configurations. It was determined that at a mass flow rate of 0.033 kg/s, the PVT-PCM configuration had the highest overall efficiency (67.63%), while the PVT configuration had the lowest (64.34%) overall efficiency.

Acknowledgment

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