EXPERIMENTAL PERFORMANCE OF PHOTOVOLTAIC/SOLAR THERMAL PANELS WITH WATER AND PCM COOLING SYSTEM

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ABSTRACT: This article evaluated the thermal and electrical efficiencies of different photovoltaic (PV) panels cooled by water-based systems and phase change material (PCM) under functional conditions to attain the appropriate operating state of the PV panel. Conventional PV panels, PCM-based PV systems, and water-based PCM PV systems were experimentally investigated. The copper tube arrangement was inserted within the aluminum container attached to the PV panel's bottom. The fully refined paraffin wax of 20 kg was filled inside the container. The experiment was presented at five volumetric flow rates: 1, 2, 3, 4, and 5 L/min. The electrical and thermal efficiencies are set as an indicator. For the experimental results, thermal efficiency rose gradually as the volumetric flow rate increased in the PV panel case cooled by the water-based system with PCM. Electrical efficiency progressively rose later, although it somewhat dropped. The PV panel's average electrical efficiency with a volumetric flow rate of 3 L/min was 27.5% that higher than the other cooling systems. Besides, it also offered an average thermal efficiency of 44%. Therefore, the water-based system with PCM at a volumetric flow rate of 3 L/min had a more appropriate application for the actual operation than the other cooling systems.

KEYWORDS: *Performance; Photovoltaic; Solar; Water Cooling and PCM Cooling.*

1.0 INTRODUCTION

Thailand's Alternative Energy Development Plan (AEDP) 2015 established a new renewable energy goal of 30% of total final energy consumption by 2036 [1]. This research investigated the three sub-sectors of electricity production, thermal consumption, and bioenergy, with focus on assessing the main difficulties in meeting the AEDP 2015 criteria. Therefore, solar energy is attractive because it can provide photovoltaic (PV) energy for generating electricity and thermal energy for producing heat. Producing power with PV panels has two significant advantages over fossil fuels: it is both renewable and cost-effective. Therefore, solar PV modules, which can convert solar radiation into useful electricity through conventional semi-conductor solar cells, have seen widespread application as a standard solar energy consumption technology due to their ability to provide clean and green energy reliably. Rooftops and exterior walls can be utilized to maximize solar radiation using PV modules [2].

However, it is generally known that a PV panel's efficiency decreases as temperature rises [2-4]. PV panels must thus be cooled when exposed to intense sunlight. The temperature management of PV panels may be accomplished using a variety of techniques, including air cooling [5, water cooling [6, 7], PCM cooling [8–11], and hybrid cooling [12–13]. For the air-cooling system, induced convection from the moving automobile may correct the uneven and uncontrolled character of a natural ventilation cooling approach [5]. This method was suitable for the cooling system with the external flow. The water-based cooling system was effective for the internal flow because liquid cooling can transfer heat much more efficiently than air cooling. At 1150 W/m^2 solar irradiation, Maha et al. [6] proposed that a water-film cooling system placed on a retrofitted rooftop PV system might boost power production by 32 W per 260-W-rated-PV-module (15% enhancement) and with a net energy gain of 0.0178 kWh/h/panel. Then, Abo-Zahhad et al. [7] studied the effect of longitudinal rectangular internal fins and varying mass flow rates of water input on the performance of a high-concentrator PV system. It was found that increasing the coolant flow rate could decrease the solar cell temperature by around 60%.

Furthermore, PCM, substances that collect and release energy as latent heat during the phase change process, is used to cool the PV panels because stable temperature and passive cooling are vital benefits. Investigation on PCM cooling systems has been carried out to enhance PCM heat transfer, such as higher thermal conductivity [8], lower melting temperature [9], and heat transfer using finned heat sinks [10, 11]. Nevertheless, this method still had drawbacks when solar radiation was low. Additionally, supercooling may occur with the extra weight of a PCM. Therefore, hybrid cooling systems have been experimentally investigated. In a hybrid PV/thermal system, the heat produced by the PV panels was used as a byproduct for the different heating applications rather than being released into the environment. Preet et al. [12] showed that the PV/thermal system was to increase the power output of PV module i.e., the electrical yield. Furthermore, the system could increase electrical and thermal efficiencies by increasing the mass flow rate. Nasef et al. [13] enhanced the electrical performance of PV panels by using nanofluid as heat transfer fluid. The suggested technology reduced the average temperature by sixty percent compared to typical direct PCM-PV and water-cooling standalone devices. When it comes to hot water, heating and cooling applications, Atanasova et al. [14] looked at the best designs of compact latent heat storage (LHS) systems on the market. It indicated the effective thermal energy storage design required to use the solid/liquid PCM with high conductivity encapsulation and/or additives. Among organic PCMs, paraffin stood out for its accessibility, low cost, and several application-friendly features.

The majority of previous studies using a PCM and nanofluid cooling system were somewhat complex, according to reviews of the previous literature reviews. The disadvantages might be high pumping power due to greater pressure drop, erosion inside flow loop parts, and high cost. The optimal condition has not been reported yet for the water-based cooling system with PCM in the previous study [12]. To emphasize the interesting issue, this study analyzes the electrical and thermal efficiencies of PV and thermal panels with water and PCM cooling system at different volumetric flow rates under environmental conditions. In order to identify the optimal operating state, the influence of fluid flow on both efficiencies is experimentally investigated.

2.0 METHODOLOGY

2.1 Experimental Setup and Procedure

The experiment was conducted at Rajamangala University of Technology Srivijaya in Songkhla, Thailand (latitude: 7.078°, longitude: 100.597°). The experimental setup consisted of PV panel cooling systems divided into PCM-based and Water-based systems with PCM. In the case of the cooling system without water circulating, it was defined as a PCM-based system. Both cooling systems were compared with the conventional (air-based) system. The experimental setup was displayed in Figure 1(a). The PV panels were monocrystalline silicon PV cells with a capacity of 120 W. In the water-based system, the absorber plate with dimensions of 1800 mm × 800 mm × 80 mm (length × width × height) was embedded behind the PV panel. Copper pipes were arranged in sheet, and parallel tube type, including headers with a diameter of 25.4 mm and the risers with a diameter of 12.7 mm and the seven risers were arranged in parallel flow arrangement in between the top header and the bottom header as shown in Figure 1(b). As PCM, a fully refined paraffin wax was used. This wax had a melting point of 55 to 60 °C, a specific heat capacity of 2.14 kJ/kg K, and a heat conductivity of 0.2 W/mK. The 20 kg PCM was fulfilled in the absorber plate between the risers. To decrease heat loss, glass wool was utilized as insulation at the back of the water solar thermal setup. Moreover, 20 L of the water tank was connected to a 12V DC water pump. The water tank was covered by Armaflex insulation to prevent heat loss.

For the experimental procedure, the effect of fluid flow on the electrical and thermal performances was also examined with five different volumetric flow rates, i.e., 1 L/min, 2 L/min, 3 L/min, 4 L/min, and 5 L/min. The volumetric flow rates were set by ANSI/ASHRAE STANDARD 93-2003 [16]. All tests started from 9.00 a.m. to 7.00 p.m. (i.e., the operating time of 10 h). In the experiment, the data acquisition module was a temperature recorder (Yokogawa FX1000 datalogger). K-type thermocouples were also used to measure five temperature points, as depicted in Figure 2. The temperature points consisted of the ambient temperature (T_a), the cooling system's inlet temperature (T_i), the cooling system's outlet temperature (T_o), the hot water temperature (T_w), and the surface of the PV panel (T_{sc}). Furthermore, a rotameter (Nitto VA10S-15) and a pyranometer (Modbus protocol SR20-D1) were employed to measure volumetric flow rates and solar radiation, respectively. The open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) were recorded hourly by voltmeter and ampere meter for electrical performance.

2.2 Performance Analysis

In this study, the electrical and thermal efficiencies of the PV panel with the cooling systems were computed using equations reported by Preet et al. [12].

(a) Electrical efficiency of the PV panel (η_e)

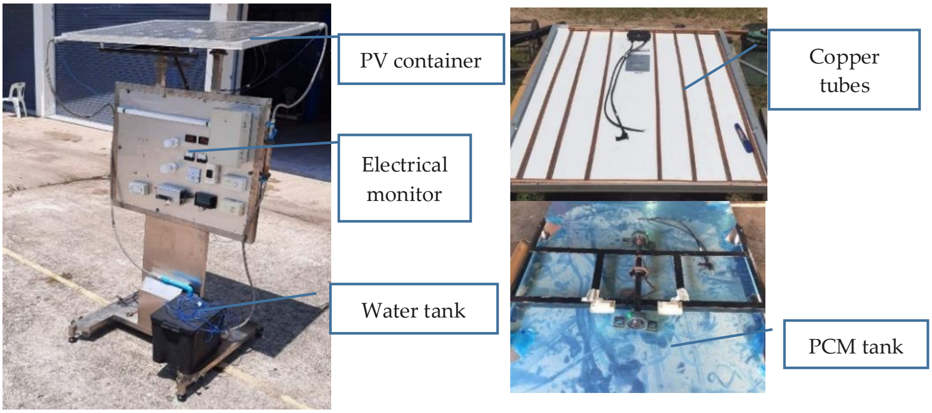
$$\eta_e = \frac{I_{oc} V_{sc} FF}{G A_c} \tag{1}$$

where FF is power factor, A_c is the absorbed thermal area and G is solar radiation.

(b) Thermal efficiency of the PV /thermal system $\left(\eta_{\text{th}}\right)$

$$\eta_{th} = \frac{\dot{m} c_p \left(T_o - T_i\right)}{G A_c} \tag{2}$$

where $\dot{m}$ is mass low rate and c_p is specific heating capacity



(a) (b)

Figure 1: Water-based system with PCM: (a) experimental setup; (b) copper tubes inserted within the container

Figure 2: Diagram of temperature positioning

All tests were repeated three times, and the uncertainties in the parameters for the PV panel and cooling systems were used as the final results, as shown in Table 1. To determine the overall uncertainty (W_R), also known as Equation 3, the uncertainties of the independent variables ($w_1, w_2, \ldots w_n$) were evaluated [16].

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right], \tag{3}$$

where $x_1, x_2, \ldots x_n$ were the independent variables

Table 1: Uncertainties of variables throughout PV panels

Variables	Uncertainty	Unit
Temperature	±0.5	°C
Water flow rate	±0.1	L/min
Solar radiation	±1.0	W/m²
Time measurement	±0.1	min

3.0 RESULT AND DISCUSSION

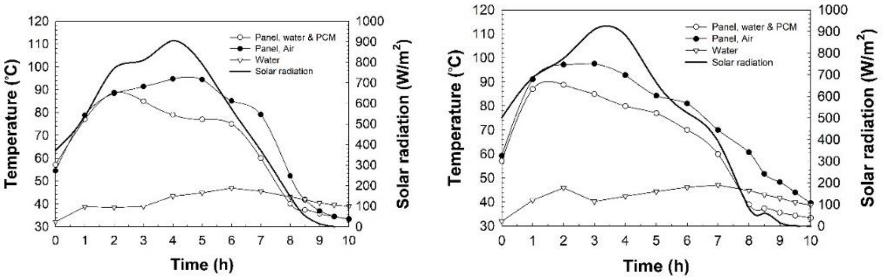
With various volumetric flow rates, PV panels' electrical and thermal efficiency with various cooling systems were examined. In April 2020, all studies were done on consecutive days with clear skies. For the clear sky condition, each experiment's solar radiation somewhat varied. Various sun conditions and the ambient temperature had a negligible effect on the electrical and thermal efficiency of the PV panels. The hourly variation of temperatures for PV panels with different cooling systems was discussed. Furthermore, this section evaluated the effect of fluid flow to determine the optimal condition of the PV panel with a cooling system.

3.1 Temperature Distribution of PV Panels with Different Cooling Systems

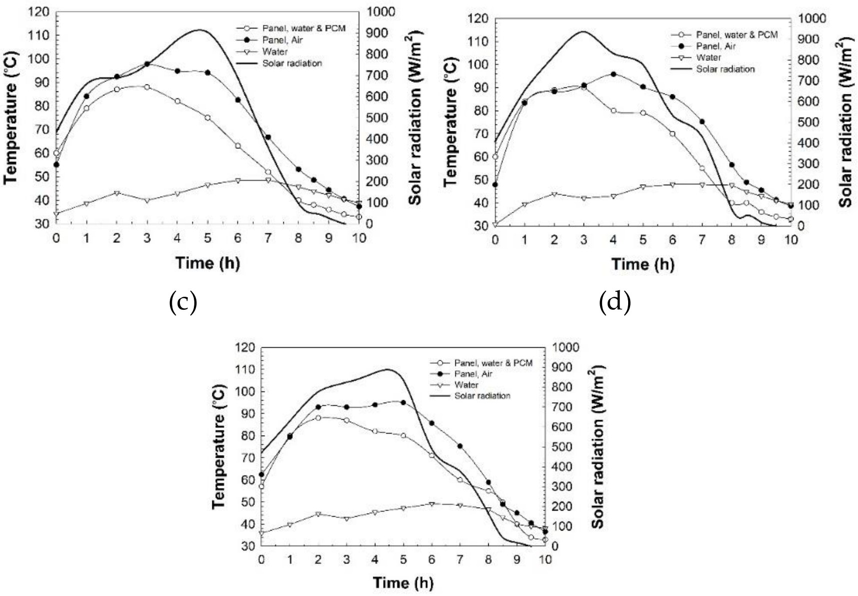
By comparing the PV panels' surface temperatures with different cooling systems, the experimental results recorded in April 2020 were selected because of smooth solar intensity and the average solar radiation of 700 W/m². Experiments were carried out from 9:00 a.m. to 7:00 p.m. (operating time of 10 h), as shown in Figure 3. It was indicated that the surface temperature of each operating condition was proportional to solar radiation. As depicted in the figures, the panel without PCM temperature profiles increased sharply at the beginning of the experiment and reached a quasi-steady state of approximately 90 °C when the heat input to the PV cell was caused by the convection heat transfer from the ambient due to the wind speed. The temperature profiles of the panel containing the water/PCM system exhibited a distinct response. In contrast to the panel without PCM, temperature profiles rose with a lower slope in the few hours after the experiment and reached a lower quasi-steady temperature of approximately 75 °C.

The finding might be explained by the PCM's heat absorption capability and the water's increased heat convection. As a result, the surface temperatures of PV panels cooled by water/PCM systems were lower than those of PV panels cooled by air-based systems. These findings were consistent with prior research [9]. Because of the increased heat convection, the PCM cooling system offered lower surface temperatures than the air-cooling system.

Surface temperature differences between the PV panel with the air-cooling system and the PV panel with the water/PCM cooling system were employed to indicate the water/PCM cooling system's significance. It was found that the surface temperature differences including 1 L/min, 2 L/min, 3 L/min, 4 L/min, and 5 L/min varied in the range of 2.5–16.6 ˚C, 2.8–16.3 ˚C, 2.7–15.3 ˚C, 2.4–15.9 ˚C, and 2.9–16.1 ˚C, with average values of 8.5 ˚C, 7.9 ˚C, 7.5 ˚C, 7.8 ˚C and 8.2 ˚C, respectively. For the water tank temperature, at nighttime (9th hour to 10th hour), the PV panel cooled by the volumetric flow rate of 3 L/min could keep the water temperature at approximately 40 ˚C which was higher than the other volumetric flow rates, as shown in Figure 3(c). It was implied that this condition provided the best energy balance between the latent heat of PCM and the sensible heat of fluid flow. Furthermore, the water/PCM cooling system could implement the thermal energy storage unit, which was one of the challenges in a small household heating or cooling utilizing low-temperature thermal energy as a source. This information, however, was only applicable to solar thermal applications. The electrical energy of each operating condition will be explained in section 3.2.



(a) (b)



(c) (d)

(e)

Figure 3: Hourly distribution of temperatures at different flow rates (a) 1 L/min; (b) 2 L/min; (c) 3 L/min; (d) 4 L/min; (e) 5 L/min;

3.2 Electrical Efficiency of PV Panels with Different Cooling Systems

Based on the solar water heater's experimental results, the volumetric flow rate of 3 L/min of the water-based system with PCM offered a high-potential application. In the electrical efficiency case, the six cases, including the conventional system (air-based) and water/PCM cooling system (0 L/min, 1 L/min, 2 L/min, 3 L/min, 4 L/min and 5 L/min) were evaluated to determine the maximum efficiency. The electrical efficiencies at different volumetric flow rates were displayed in Figure 4. It was found that most electrical efficiencies gradually increased with the time of the day. The lowest electrical efficiency appearing in the conventional cooling system was approximately 11%. On the other hand, the highest electrical efficiency occurring at the water/PCM cooling system under the volumetric flow rate of 3 L/min was approximately 27.5%. For the PCM cooling system, the electrical efficiency steadily increased with time because the discharging mode of PCM could reduce the PV panel's surface temperature. The behavior was similar to the previous works [2, 13]. It was noted that the temperature of the PCM inside the panel was lower than the melting temperature. The PCM then absorbed the sensible heat from the PV panel until its melting point was achieved. The energy storage was accomplished by melting the PCM at a steady temperature and storing it as latent heat while the charging process progressed. The charging method was then repeated until the temperature of the PCM reached the liquid PCM storage temperature. The discharge process was carried out by using cold air or cold water at ambient temperature.

In the case of the water/PCM cooling system, it was indicated that the flow rate significantly affected electrical efficiency under the starting time (9.00 a.m. to 10.00 a.m.). The cooling system's electrical efficiency with a flow rate of 5 L/min was higher than that of the cooling system with a flow rate of 1 L/min, approximately 37.5%. The main reason was that the PV panel's temperature was directly reduced by the sensible heat in terms of the flow rate through the PCM-based absorber during the PCM charging mode. It can be verified that a PV panel's electrical efficiency is inversely proportional to the surface temperature [4, 10]. From 1.00 p.m. to 5.00 p.m., the PCM state was the discharging mode. The cooling system with a flow rate of 3 L/min had higher electrical efficiency than the others. These results were similar to the thermal analysis presented in section 3.1. However, the effect of fluid flow on the electrical and thermal efficiencies will be further described in the next section.

3.3 Effect of Fluid Flow on the Efficiencies

The effect of fluid flow rates on the electrical and thermal efficiencies was shown in Figure 5. The PCM was controlled at 20 kg, whereas the flow rates ranged from 1 L/min, 2 L/min, 3 L/min, 4 L/min, and 5 L/min, respectively. The average thermal and electrical efficiency were used to calculate the optimal operating conditions for PV panels with various cooling systems. In thermal efficiency, the flow rate rose from 1 L/min to 5 L/min, significantly improving average thermal efficiency. In addition, the average thermal efficiency rose from 31.3% to 42.2%. Despite this, increasing volumetric flow rates from 3 to 5 L/min resulted in a 0.5% to 1.0% increase in thermal efficiency due to achieving saturation during heat removal. It was concluded that the volumetric flow rate directly altered thermal efficiency. In addition, the volumetric flow rate of 5 L/min had the highest thermal efficiency, while the flow rate of 1 L/min possessed the lowest thermal efficiency. These findings seem to support earlier research [12].

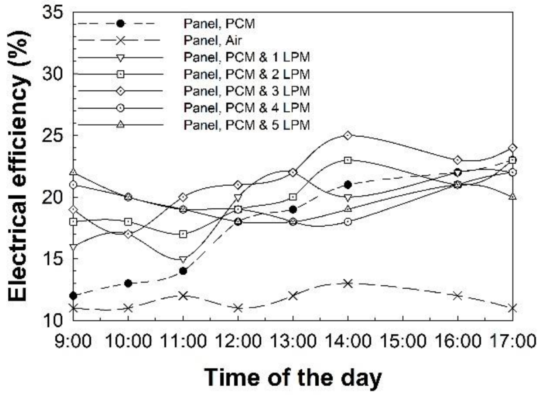


Figure 4: Electrical efficiencies at different flow rates

For the electrical efficiency, when the volumetric flow rate increased from 0 L/min to 3 L/min, the electrical efficiency steadily increased. Nevertheless, as the flow rate increased from 3 L/min to 5 L/min, the electrical efficiency slightly dropped. It was implied that the change in flow rate from 3 L/min to 5 L/min barely affected the surface temperature reduction of the PV panel. The improvement in electrical efficiency was only 9.0%. Notably, a comparison between each efficiency trend was able to explain each other. As the flow rate increased from 3 L/min to 5 L/min, the electrical efficiency decreased slightly because the thermal efficiency was almost constant.

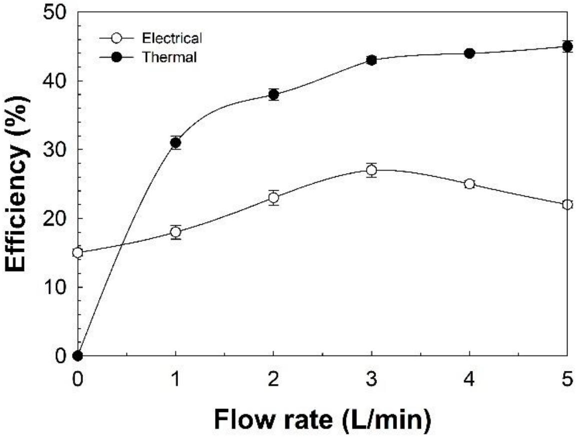


Figure 5: Effect of fluid flowrates on the efficiencies

It is possible to conclude that the optimal working state of the PV panel cooled by the water-based system with PCM comprised a PCM equal to 20 kg and a fluid flow rate equal to 3 L/min. This research offered a maximum electrical efficiency of 27.5%, which was somewhat higher than others compared to prior studies [10, 12], which proved that this study gave maximum efficiency. On the other hand, the PV panel's thermal efficiency was found to be 44% in this study, which was slightly lower than the thermal efficiency found in earlier research [12] due to the larger-scale solar heating output. Therefore, PV panels with water/PCM cooling systems will be investigated further in future work in case of the optimal PCM thickness to design the water-based system with PCM on a larger scale for commercialization.

4.0 CONCLUSION

The PV panels cooled by the water-base system with PCM (paraffin wax) were designed to generate electricity and produce hot water applications directly and indirectly. Experiments were carried out to identify the proper working conditions for PV panels equipped with a variety of cooling systems, and one of those experiments focused on the influence of fluid flow. From the experimental results, the electrical stability of PV panels depended on the surface temperature. The PV panel cooled by the water-based system with PCM had higher thermal and electrical efficiencies than that of the PV panel cooled by the PCM-based system and the conventional cooling system. Increasing the flow rate for the water-based system with PCM could increase the electrical and thermal efficiencies to the optimal values. Hereafter, both efficiencies slightly changed because of lower heat transfer in the PCM absorber. Furthermore, the water-based system with PCM under the volumetric flow rate of 3 L/min was recommended to remove the PV panel's accumulated heat. This system provided 27.5% and 44% electrical and thermal efficiencies, respectively, which led to a beneficial solution for commercial PV panels.

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REFERENCES

[1] *Renewable Energy Outlook: Thailand*, International Renewable Energy Agency (IRENA), Abu Dhabi, 2017, pp. 1-118.

[2] B. Zhao, M. Hu, X. Ao, Q. Xuan and G. Pei, "Spectrally selective approaches for passive cooling of solar cells: A review", *Applied Energy*, vol. 262, pp. 1-18, 2020.

[3] S. Sargunanathan, A. Elango and S.T. Mohideen, "Performance enhancement of solar photovoltaic cells using effective cooling methods: A review", *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 382–393, 2016.

[4] U. Sajjad, M. Muhammad, A. Dahiya and N. Abbas, "Cost effective cooling of photovoltaic modules to improve efficiency", *Case Studies in Thermal Engineering*, vol. 14, pp. 1-7, 2019.

[5] W. Pang, H. Yu, Y. Zhang and H. Yan, "Solar photovoltaic based air-cooling system for vehicles", *Renewable Energy*, vol. 130, pp. 25-31, 2019.

[6] C. Maha, B.H. Lim, C. Wong, M.H. Tan, K.K. Chong and A.C. Lai, "Investigating the performance improvement of a photovoltaic system in a tropical climate using water cooling method", *Energy Procedia*, vol. 159, pp. 78-83, 2019.

[7] E.M. Abo-Zahhad, S. Ookawarac, M. F.C. Esmail, A.H. El-Shazlya, M.F. Elkadya and A. Radwan, "Thermal management of high concentrator solar cell using new designs of stepwise varying width microchannel cooling scheme", *Applied Thermal Engineering*, vol. 172, pp. 1-12, 2020.

[8] Z. Luo, Z. Huang, N. Xie, X. Gao, T. Xu, Y. Fang and Z. Zhang, "Numerical and experimental study on temperature control of PV panels with form-stable paraffin/expanded graphite composite PCM", *Energy Conversion and Management*, vol. 149, pp. 416-423, 2017.

[9] S.R. Mousavi Baygi and S.M. Sadrameli, "Thermal management of photovoltaic solar cells using polyethylene glycol 1000 (PEG1000) as a phase change material", *Thermal Science and Engineering Progress*, vol. 5, pp. 405-411, 2018.

[10] L. Siahkamari, M. Rahimi, N. Azimi and M. Banibayat, "Experimental investigation on using a novel phase change material (PCM) in microstructure photovoltaic cooling system", *International Communications in Heat and Mass Transfer*, vol. 100, pp. 60–66, 2019.

[11] S. Khanna, K.S. Reddy and T.K. Mallick, "Optimization of finned solar photovoltaic phase change material (finned pv pcm) system", *International Journal of Thermal Sciences*, vol. 130, pp. 313–322, 2018.

[12] S. Preet, B. Bhushan and T. Mahajan, "Experimental investigation of water based photovoltaic/thermal (PV/T) system with and without phase change material (PCM)", *Solar Energy*, vol. 155, pp. 1104–1120, 2017.

[13] H.A. Nasef, S.A. Nada and H. Hassan, "Integrative passive and active cooling system using PCM and nanofluid for thermal regulation of concentrated photovoltaic solar cells", *Energy Conversion and Management*, vol. 199, pp. 1-15, 2019.

[14] D. D. Atanasova, A. Georgiev, S. Nakov, S. Panyovska, T. Petrova and S. Maiti, "Compact Thermal Storage with Phase Change Material for Low-Temperature Waste Heat Recovery-Advances and Perspectives", *Energies*, vol. 15, pp. 1-21, 2022.

[15] *ASHRAE 93-2010 (RA 2014)*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, 2014, pp.11-12.

[16] S. Sevik, "Experimental investigation of a new design solar-heat pump dryer under the different climatic conditions and drying behaviour of selected products", *Solar Energy*, vol. 105, pp. 190–205, 2014.