ARTICLE IN PRESS
Alexandria Engineering Journal (2021) xxx, xxx–xxx

HOSTED BY
ELSEVIER

Alexandria University
Alexandria Engineering Journal
www.elsevier.com/locate/aej
www.sciencedirect.com

Performance enhancement of photovoltaic cells using phase change material (PCM) in winter

Mohamed Sharaf, A.S. Huzayyin, Mohamed S. Yousef *

Mechanical Engineering Department, Benha Faculty of Engineering, Benha University, Egypt

Received 25 March 2021; revised 15 July 2021; accepted 16 September 2021

KEYWORD

PV cooling;
Metal foam;
PCM;
Efficiency enhancement;
Winter

Abstract The performance of photovoltaic (PV) modules worsens due to increasing their operating temperature. In the current study, a passive cooling technique comprising an aluminum metal foam (AMF) with PCM for thermal regulation of a PV system is performed. Outdoors experiments are conducted comprising two modules: PV without any modifications and PV with AMF embedded in PCM denoted as PV/PCM/AMF. The temperature distribution on the surface of the PV panels, PCM temperature, open-circuit voltage, and output power produced were recorded during the winter period. The results revealed that the PV surface temperature of the PV-PCM/AFM system was 4 %, 7.4 %, and 13.2 % lower than that of conventional PV, and the power produced from PV-PCM/AFM system was 1.85 %, 3.38 %, and 4.14 % higher than that of conventional PV in December, January, and February, respectively.

1. Introduction

Energy has become one of the most critical necessities due to the constantly growing population and the introduction of recent technologies. Being clean, reachable, easy to utilize, and sustainable, solar energy has been one of the best widespread and broadly popular accepted renewable energy sources with unlimited potential [1]. Photovoltaic PV is one of the most established solar energy conversion technologies which converts solar energy directly into electricity with unrestricted potential and noiseless operation [2]. However, part of the radiation falling on the surface of the PV cell turns into electricity, while the remainder of incident radiation are absorbed inside the PV cell [3]. This in turn elevates its surface temperature, which results in a drop in its electrical efficiency [4]. Hasan et al. [3] reported that the electrical efficiency of the PV module decreased by 0.41 ~ 0.66 % for each degree increase in the PV module working temperature. Skoplaki and Palyvos [5] explained that with an increase in PV working temperature, the power output decreases because the voltage fall with temperature while current increases by a small amount; the net result is minimizing the electrical efficiency. Rahman et al.[6] explained that the power produced and the efficiency of the PV module reduced by 0.37, 0.33, 0.24, 0.17, and 0.06 % under solar intensities of 1000, 800, 600, 400 W/m^2 respectively due to a one-degree increase in the PV working temperature. Therefore, the heat absorbed inside the PV cell must be removed to raise its electrical efficiency by cooling

* Corresponding author.
E-mail addresses: Mohamed.mohamed@ejust.edu.eg, Mohamed.youssif@bhit.bu.edu.eg (M.S. Yousef).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2021.09.044
1110-0168

PV cells. Amelia et al. [7] explained through experimental measurements that there is an increase in the power produced by 12 % when the PV cell cooled using a DC fan, and by raising the number of fans to 2, 3, and 4, the power augmented by 37 %, 41 %, and 44 % respectively. Krauter [8] conducted experiments to cool the PV cell by pumping water on its surface, and the results proved that an increase in the electrical efficiency by 9 %.

In PV/T devices, the PV modules and the thermal units are mounted together and the systems convert the solar radiation into electricity and heat (simultaneously). A significant amount of work has been carried out on these systems. Ozgoren et al. [9] discovered that the electrical efficiency enhanced from 11.5 % to 13.6 % when using the PV/T system and that the overall efficiency reached 51%. Teo et al. [10] reported through experiments that using an air-based PV/T system successfully brought down the highest PV temperature by 30 °C, resulting in an increment of 45% in electrical efficiency. In another study, Wilson [11] made an experiment to cool the PV solar cell using the water at an appropriate head and he investigated that the PV solar cell temperature dropped by 30 °C along with an increase in the electrical performance of PV solar cell up to 12 %. Mehrotra et al. [12] conducted experiments to cool the PV cell by dipping it in a depth of water tank. The results showed that the greater the depth of the water, the lower the temperature of the surface of the PV cell, and thus cell efficiency increased by 4.76 % at a depth of 1 cm. Bayrak et al. [13] found that the maximum temperature difference between PV cells reached 3.39 °C under radiation 772 W/m^2 due to cooling the PV cell with fins, and the electrical efficiency reached 11.55 %.

Recently, phase change materials have been employed extensively for thermal regulation of PV solar cells, as it is characterized by high energy storage capacity and capabilities of operation under constant temperature [14,15]. The incorporation of PCM with PV systems was experimentally and numerically investigated by many researchers. Paraffin is suitable for use as a phase change material (PCM) because it is available in a large temperature range, it has a high heat of fusion and freeze without supercooling [16]. Stropnik and Stritih [17] explained through experimental measurements the influence of using (RT28HC) on the performance of PV panels. As compared to the traditional PV module, the findings indicated that there was an improvement in the power output and electrical efficiency by (4.3–8.7 %) and (0.5–1 %), respectively. Hachem et al. [18] did experiments to cool the PV solar cell using PCM and a combined PCM, the results showed an improvement in the electrical efficiency of the PV + PCM and PV + combined PCM systems by 3 % and 5.6 %, respectively. Waqas and Ji [19] experimentally examined the effectiveness of using PCM inside rotatable shutters to enhance the performance of PV solar cells. During sunshine hours PCM filled shutters are closed and absorb excess heat generated by the PV panel. The absorbed heat is discharged by rotating the PCM filled shutters to ambient during non-sunshine hours. The results showed that the best season for using PCM is the summer, and the rate of the enhancement in the electrical efficiency was 9 %. Fayaz et al. [20] analyzed through experimental and theoretical investigations the performance of PV solar cell by using thermal system PV/T and thermal system with PCM PVT + PCM and they investigated that from the theoretical results, the electrical efficiency of the three PV cells reached 11.35 %, 12.4 %, and 12.75 % for PV, PV/T, and PV/T-PCM, respectively. From the practical results, it was reported the electrical efficiency of the three cells reach 11.24 %, 12.37, and 12.6 for PV, PV/T, and PVT/PCM, respectively. It was also reported that the overall efficiency of PV/T and PV/T-PCM reached 89.6 % and 83.95 % respectively. Gaur et al. [21] theoretically investigated the influence of the addition of organic PCM (OM37) on the energetic and exergetic performance of the PV/T system under varying seasonal meteorological conditions. It was observed that the inclusion of PCM in the PV/T system enhanced the thermal, electrical, exergy, and overall performance by 64.3%, 5.8%, 18.6%, and 42.3% respectively in summer conditions, compared to the PV/T system without PCM. Whereas the corresponding enhancement in winter conditions was 41.7%, 0.53%, 0.95%, and 19.9% respectively. Hassan et al. [22] conducted experiments to cool the PV solar cell by using PCM, and a thermal system with PCM and nanofluid inside the water PVTn + PCM. The results indicated that the highest electrical efficiency was 15.4 % for PVTn + PCM PV solar cell, and the lowest electrical efficiency was 10.4 % for the conventional PV solar cell. They also showed that the thermal efficiency was enhanced by 20.8 %, as a result of using the nanofluid with water. In another study, the exergetic performance of using lauric acid as storage material in PV/T-PCM system having double side serpentine flow was examined by Hossain et al.[23]. The system was examined over a wide range of flow rates (0.5–4 L/min) to attain optimal performance. It was reported that, at a flow rate of 0.5 L/m, the highest exergy efficiency of PV/T-PCM and PV-only systems was 12.19% and 7.09% respectively. The effectiveness of using PCM (RT42) for thermal regulating of PV panels under hot climate conditions of UAE was experimentally examined by Hasan et al. [24]. It was reported that maximum reduction of 12 °C in PV temperature was observed due to using the proposed system while the annual electricity yield was augmented by 5.9 % compared to uncooled PV panel. Thermal regulation of an air based PV/T collector using palm wax as storage material was experimentally examined by Wongwuttanasatian et al. [25]. Comparative performance evaluation of three diverse configurations of PCM containers, i.e. tubed, finned, and grooved was conducted. The finned container exhibited superior cooling performance in contrast to the other container's configurations, reducing the solar cells temperature by roughly 6.1 °C and thereby, achieving a 5.3% increment in electrical efficiency compared to uncooled PV module.

The PCMs have a high latent heat of fusion [26], however, the low thermal conductivity of the PCMs is considered a negative aspect in case of using it in cooling the PV solar cells [25,26]. Therefore, many types of research have dealt with adding external materials to the PCM to improve the thermal conductivity [26,27], and thus improve the performance of PCM in the process of cooling PV solar cells. Huang et al. [28] cooled the PV solar by placing fins inside PCM. Rajvikram et al. [29] used an aluminum plate with PCM to work as a thermal conductivity enhancer. The results showed an improvement in the average electrical efficiency of the PV solar cell by 2 %. Mousavi et al. [30] studied through numerical simulations using an absorbent material with PCM to improve the performance of the PCM in cooling the PV/T, and the results showed an improvement in the electrical efficiency by 2 %. Abdulmunem et al. [31] investigated the performance enhancement of the PV solar cell by using PCM with copper foam matrix. The findings revealed that the electrical efficiency of the PV + PCM with copper foam matrix increased by 5.68 % as opposed to the traditional PV system, while the efficiency of the PV + PCM increased by 1.97 %.

Nada et al. [32] examined through experimental measurement the effectiveness of using Al_2O_3 nanoparticles dispersed with PCM as a heat dissipating system for cooling PV module. It was reported that using the proposed system with and without dispersing Al_2O_3 nanoparticles inside the PCM enhanced the electrical performance by 6.8 % and 12.1 %, respectively. Al-Waeli et al. [33] conducted experiments to augment the performance of the PV/T by adding nanofluid to water along with adding nano-SiC particles to PCM. An enhancement of 92% in the electrical efficiency was reported, and the thermal efficiency was 69 %. Siahkamari et al. [34] studied the addition of CuO nanoparticles to PCM to augment its thermal performance. About 6.5% increment in power output was reported due to using the proposed cooling scheme.

The aforementioned literature survey revealed that few investigations have been made on incorporating PCM with metal foams for thermal management of PV cells and most of these studied were based on simulations. Furthermore, there is still a lack in the literature of research that investigated experimentally the performance of PV-PCM systems under cold climate conditions. Therefore, the main objective of the current work is to study experimentally the performance enhancement of PV using an aluminum metal foam (AMF) embedded in PCM during the winter climate conditions of Benha city, Egypt. Experiments were conducted with and without PCM/AMF, and the temperature distribution on the surface of the PV solar cell, open-circuit voltage, and output power produced were presented during the winter period in December, January, and February.

2. Experimental setup

To investigate the feasibility of the proposed thermal dissipating system on the PV performance, an experimental setup was designed and constructed at the rooftop level of Benha Faculty of Engineering building, Benha University, Benha, Egypt, located at (latitude 30.466° North and longitude 31.185° East) during December, January, and February 2021. Explanation of the design of experimental setup components, as well as experimental measurements, are illustrated in the subsequent sub-sections.

2.1. Design of test rig

In this work, outdoor experiments were conducted to examine the impact of PCM addition to PV modules on its performance. In this setup, two different configurations of PV modules each of 20 W were designed and constructed i.e. convectional PV system and PV integrated with enhanced PCM using aluminum foam matrix PV-PCM/AFM. A photograph of the experimental setup is depicted in Fig. 1. Thermal and electrical performances of the two configurations were simultaneously compared with each other under the same weather conditions. Table 1 highlights the specifications of PV modules. In this setup, RT 42 paraffin is selected as PCM due to its favorable thermo-physical properties such as availability, low cost, durability, non-corrosive, along with its relatively high enthalpy of fusion, compared to other various types of PCMs. Further details about the properties of the designated PCM are depicted in Table 2.

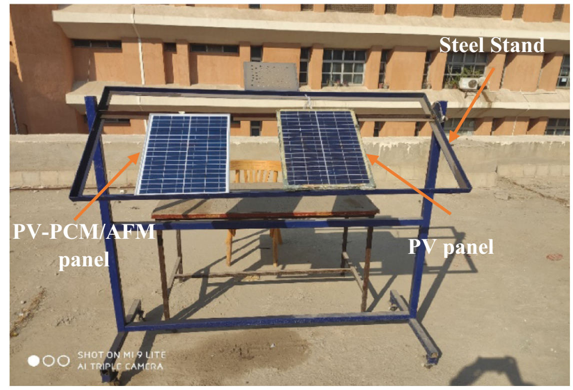


Fig. 1 A photograph of the experimental setup.

Table 1 Specifications of the PV module.

Silicon solar PV module	
model	SM-20P
P_m	20 W
V_{mp}	18 V
I_{mp}	1.11 A
V_{oc}	21.2 V
I_{sc}	1.18 A
Dimensions	485x345x18x mm
Max system Voltage	1000 V
Test conditions	AM 1.5 1000 w/m^2 25C^0

In PV-PCM/AFM system, an aluminum container having dimensions of 48 cm × 34 cm × 4 cm was incorporated underside the PV module in which paraffin wax RT-42 as PCM was stored for passive cooling purposes. Initially, paraffin wax was placed in an 85 °C water bath so that it started melting progressively; then, the melted wax was poured into the enclosure through two holes drilled at the top of the enclosure which also served as a breather to avoid the pressure building up. About 4.56 kg of paraffin wax was required to fill the enclosure after considering the potential volume expansion during phase

Table 2 Properties of PCM (RT-44) (RUBITHERM) [35].

The most important data	Typical Values
Melting area	41–44 °C
Congealing area	44–40 °C
Heat storage capacity ± 7,5%	250 KJ/Kg
Density solid	0.8 Kg/litter
Specific heat capacity	2 Kj/Kg. °C
Heat conductivity	0.2 [W/(m °C)]
Density liquid	0.7 Kg/l
Flashpoint	> 180 °C
Volume expansion	12 [%]
Max. operation temperature	75 °C

change processes. To avoid leakage of liquid PCM, a rubber gasket with silicone sealant was provided between the PV rear and PCM enclosure followed by compressing with the help of screws. A rectangular aluminum foam having the same dimensions as that of a PCM container with 94% porosity and high thermal conductivity was embedded in paraffin wax to overcome the PCM shortcoming and to act as a heat transfer enhancer. Fig. 2 shows a photograph of the modified module PV-PCM/AFM before pouring PCM. To receive maximum solar radiation, both panels are fixed on a stand at a south-facing 30.5-degree inclination angle, according to the Benha city latitude as depicted in Fig. 1.

2.2. Experimental measurements

In this setup, T-type thermocouples were used during the experimentation. Three thermocouples are used to give the average PV front surface temperature. Besides, another two thermocouples were used to measure the temperature of the rear surface of PV modules. Also, to monitor the transient temperature variation inside the PCM enclosure, two thermocouples were used which are positioned at depths of 1.5 cm and 3 cm from the top surface of the container, and noted as PCM1 (upper point) and PCM2 (lower point), respectively. Even though two temperature sensors in each container could not be adequate to completely express the temperature distribution inside the PCM reservoir, it might assist in understanding the thermal behavior of PCM inside the container. The intensity of solar energy at the inclined surface, wind velocity, and ambient temperature was monitored with the help of Davis 6153EU Vantage Pro II weather station, as shown in Fig. 3. Output current and output voltage were measured using ampere and voltmeter meter at a systematic interval of time and recorded manually for subsequent use in calculations. All thermocouples and other sensors were directly connected to data logger type A NI 9321 for data storing at an interval of every five minutes. The experiments were conducted during December, January, and February winter months 13/12/2020, 12/1/2021, and 9/2/2021, from 7 am to 5 pm. These days were selected as the weather was stable and the sky was clear for better measurement.

2.3. Uncertainty analysis

The experimental errors and uncertainty are considered in this study. Uncertainty analysis is accomplished in agreement with

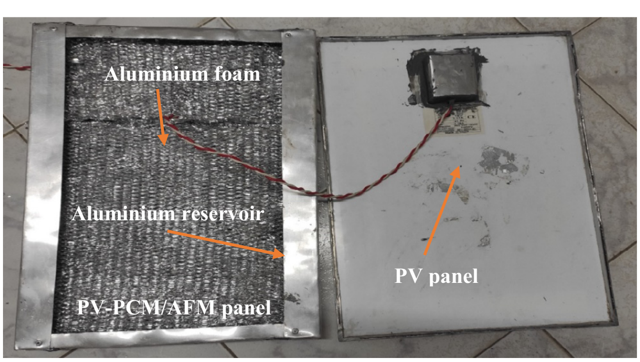


Fig. 2 A photograph of the modified module PV-PCM/AFM.

Fig. 3 A photograph of the weather station.

the instructions provided by Taylor [36]. Table 3 demonstrates the uncertainties of the measured parameters from the utilized devices, instruments, etc. All required precautions are performed to minimize measuring errors. The uncertainty (δ_q) of any calculated values (q) depending on measured values (x_1 x_2, x_3, … and x_n) as PV power and electrical efficiency etc., from uncertainties of the measuring instruments (δ_1 δ_2 , δ_3 , …, and δ_n) of measured values (x_1 x_2, x_3, … and x_n) is computed based on the following formula [37–40]:

$$\delta_q = \sqrt{\left(\frac{\partial u}{\partial x_1}\right)\delta_{x_1}^2 + \left(\frac{\partial u}{\partial x_2}\right)\delta_{x_2}^2 + ... + \left(\frac{\partial u}{\partial x_n}\right)\delta_{x_n}^2} \quad (1)$$

Then, the measured value of any value q is computed from$q \pm \delta q$: Based on the earlier formula, the uncertainty of the PV efficiency (as a function of the uncertainty of the measured input solar intensity, measured current, and measured voltage) is 1.9%.

3. Results and discussions

In this section, the experimental results due to the addition of an aluminum foam matrix embedded in the PCM to PV system during the winter season were reported. The experiments were conducted on three days during December, January, and February.

Table 3 Uncertainty of measuring instruments.

Instrument	Uncertainty
Solar intensity measurement	± 10 W/m^2
Voltmeter	± 0.123 V
Ammeter	± 0.042 A
Thermocouples (measuring temperature)	± 0.5 °C

3.1. Weather data

The evolution of solar intensity and ambient temperature during the days of the experiments were displayed in Figs. 4 and 5, respectively. As can be depicted from Fig. 4, the largest value of solar intensity was 492 W/m^2, 459 w/m^2, and 683 w/m^2 during December, January, and February respectively. Also, Fig. 5 showed that the highest ambient temperature reached 22.3 °C 20.6 °C, and 22.2 °C during December, January, and February respectively.

3.2. Thermal performance

3.2.1. PV temperatures

The evolutions of solar cell temperatures for PV and PV-PCM/AFM configurations during December, January, and February were depicted in Fig. 6. The maximum surface temperature of the conventional PV system was 46.7 °C, 48.6 °C, and 54.5 °C during December, January, and February respectively, while the highest surface temperature of the PV-PCM/AFM system was 44.8 °C, 45 °C, and 47.3 °C, respectively. Using PCM with aluminum mesh successfully brought down the temperature of the solar cell by a maximum of 4.3, 8, and 15% during December, January, and February respectively. The surface temperature of the PV-PCM/AFM system remained less than that of the conventional PV due to the effect of PCM as a thermal dissipating system and this trend continued until 14:00. However, after that time surface temperature of the PV-PCM/AFM system become higher. This could be attributed to that after 14:00 the PCM begins discharging the stored heat to the PV panel, leading to elevating its temperature.

3.2.2. PCM temperature

To completely understand the behavior of the proposed cooling system, the variation of PCM temperature during the three months was depicted in Fig. 7. It is worthy to mention that the PCM temperature was measured at two depths inside the PCM enclosure: one point is at a distance of 1.5 cm from the upper surface of the enclosure (labeled as PCM1) and the second point is at a distance of 1.5 cm from the lower surface of the enclosure (Labelled as PCM2). It was observed that the maximum PCM temperature was 37.4 °C, 36.8 °C, and 37 °C during December, January, and February respectively. This finding means that the paraffin wax was not fully melted due to the low solar intensity and ambient temperature, and the heat absorbed inside the PCM stored as sensible heat. Also, Fig. 7 indicated that the temperature distribution inside the PCM enclosure during all months was nearly uniform as PCM temperature at both locations was close together.

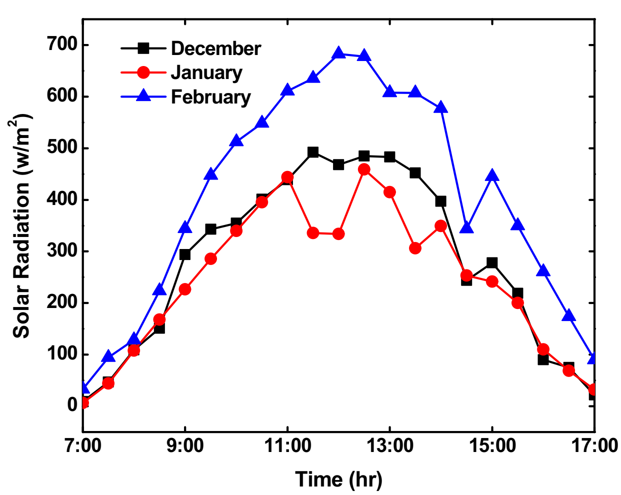


Fig. 4 The variation of solar radiation during the days of the experiments.

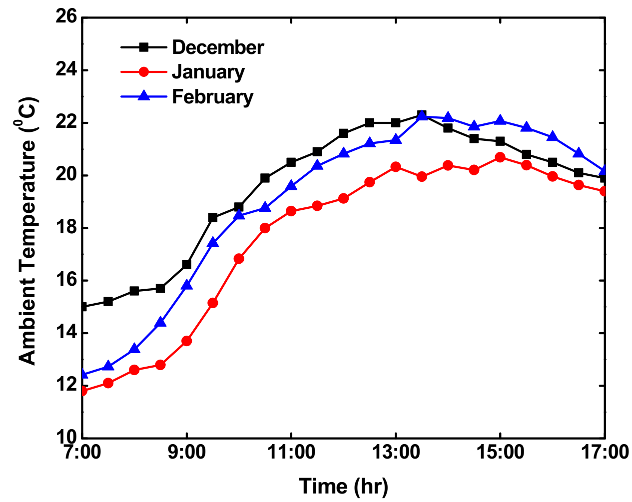


Fig. 5 The variation of ambient temperature during the days of the experiments.

3.3. Electrical performance

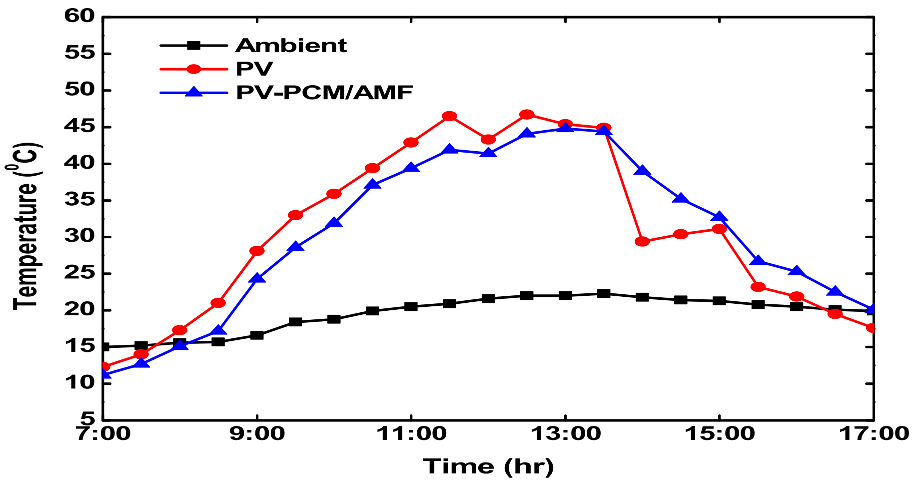
The electrical power of PV panels is governed by the short circuit current and open-circuit voltage outputs. However, since there were insignificant differences in the short circuit current values of both PV and PV-PCM/AFM systems, only the open circuit voltage for both system were presented in this section followed by a comparative assessment of power output.

3.3.1. Open-circuit voltage

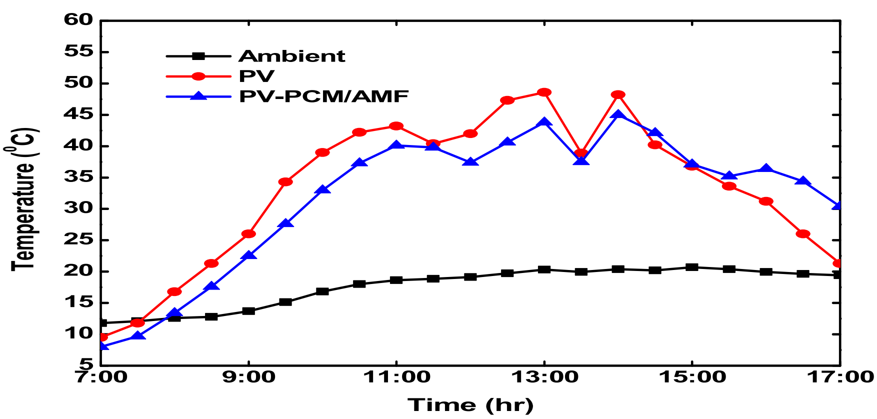
Fig. 8 showed the measured values of open-circuit voltage throughout the day for PV and PV-PCM/AFM systems during December, January, and February. It is obvious that as the day progresses, the open-circuit voltage declined with time due to the increase in the solar radiation falling on the PV and thus increasing the surface temperature of the PV panels. As can be seen from Fig. 8, until 14:00, the open-circuit voltage for the PV-PCM/AFM system was greater than that of traditional PV panel due to the temperature difference between the two PV solar cell surfaces as mentioned before. However, after that time the value of the open-circuit voltage of the conventional PV solar cell becomes greater than that of PV-PCM/AFM due to the negative impact of heat discharging from PCM to PV panel, causing an increase in its temperature during this period.

3.3.2. Power output

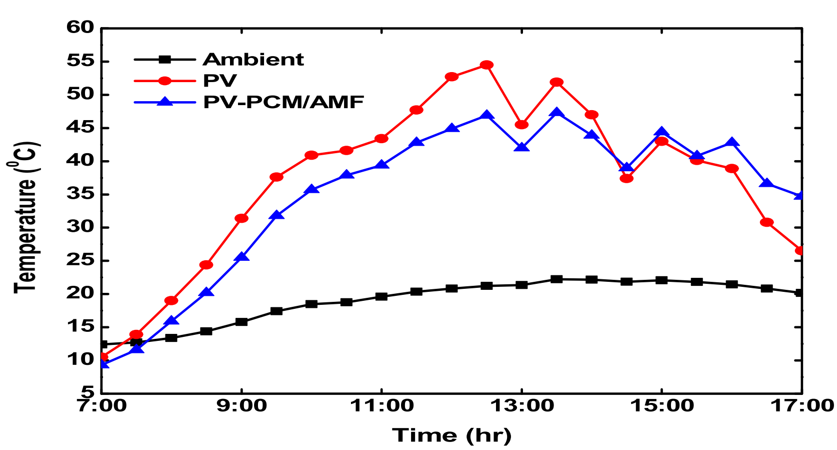
The evolution of power output throughout the day for PV and PV-PCM/AFM systems during December, January, and February were presented in Fig. 9. The results indicated that the power output values increased progressively from the



(a) December



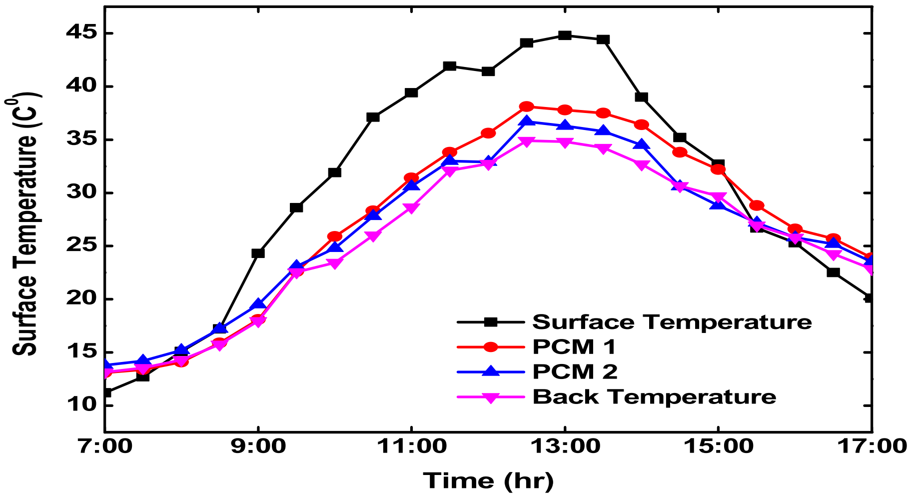
(b) January



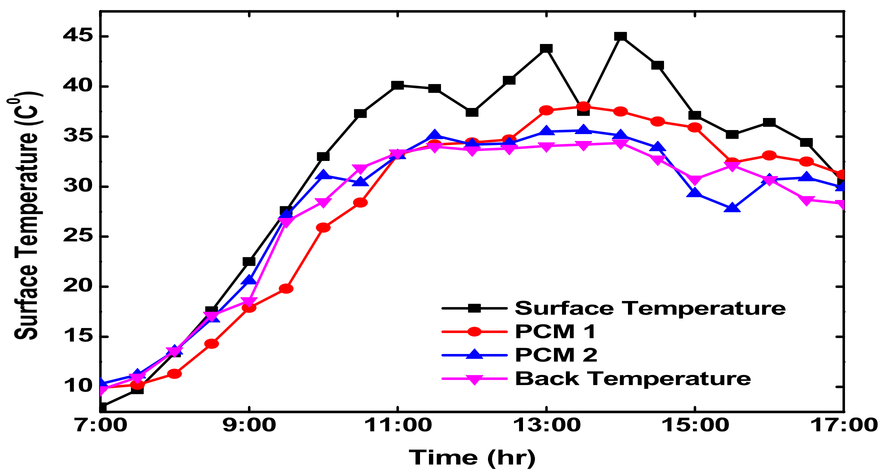
(c) February

Fig. 6 The variation of solar cell temperatures for PV and PV-PCM/AFM systems.

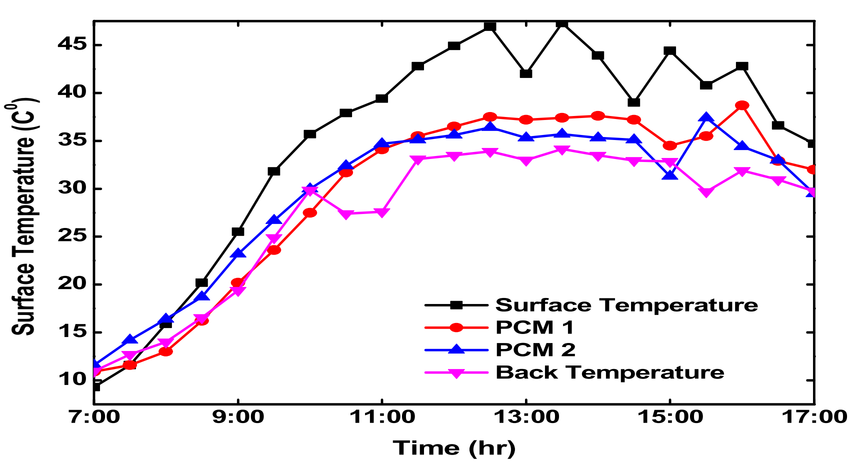
starting of the day until noontime and then it dropped again until sundown. It was observed that the highest power produced for conventional PV was 8.7 W, 8.2 W, and 11.4 W in December, January, and February, respectively, while the corresponding value for PV-PCM/AFM was 9.3 W, 8.7 W, and 12.6 W respectively, leading to an increase in electrical power by 6.9%, 6%, and 10.5%, respectively. The preceding results revealed that the highest percentage of improvement in electrical power was achieved in February as compared to December and January due to the higher solar radiation during February than in December and January. Also, it was found that the power produced from PV-PCM/AMF system was on average 1.85 %, 3.38 %, and 4.14 % higher than that of conventional PV in December, January, and February, respectively.



(a) December

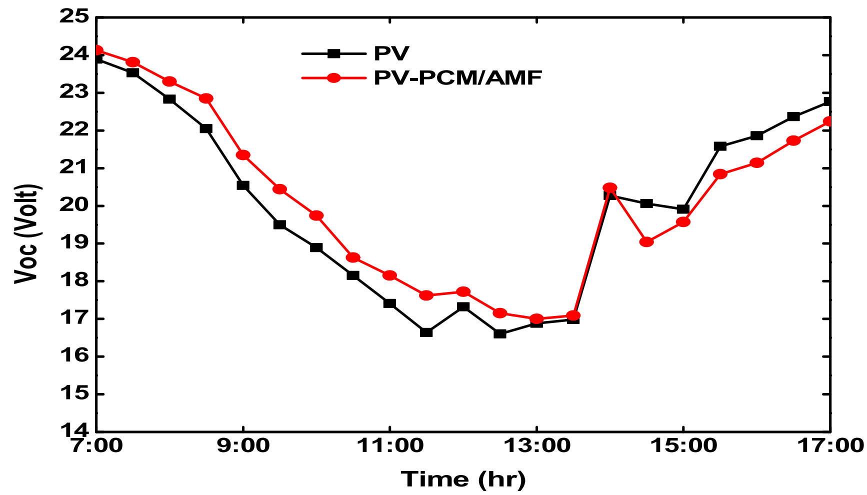


(b) January

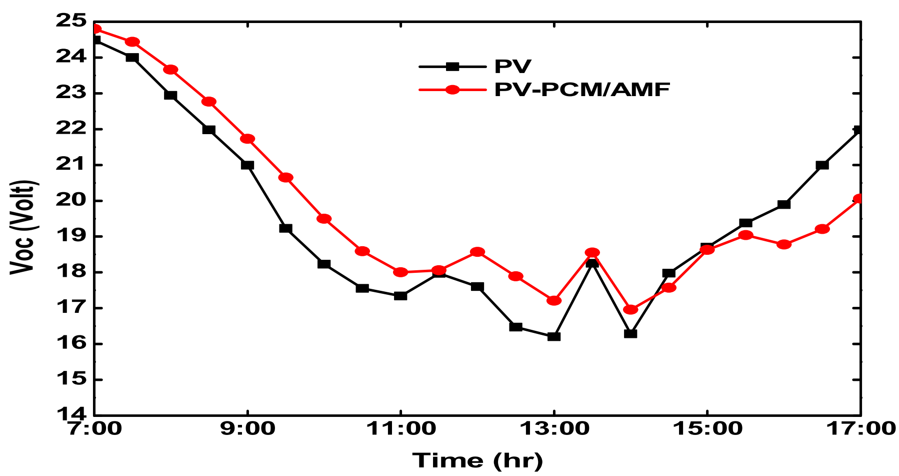


(c) February

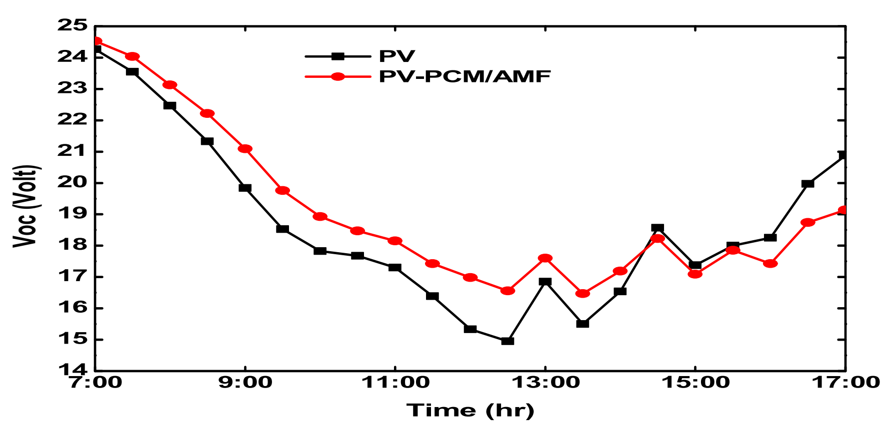
Fig. 7 PCM temperature distribution inside PV-PCM/AFM system in three winter months.



(a) December

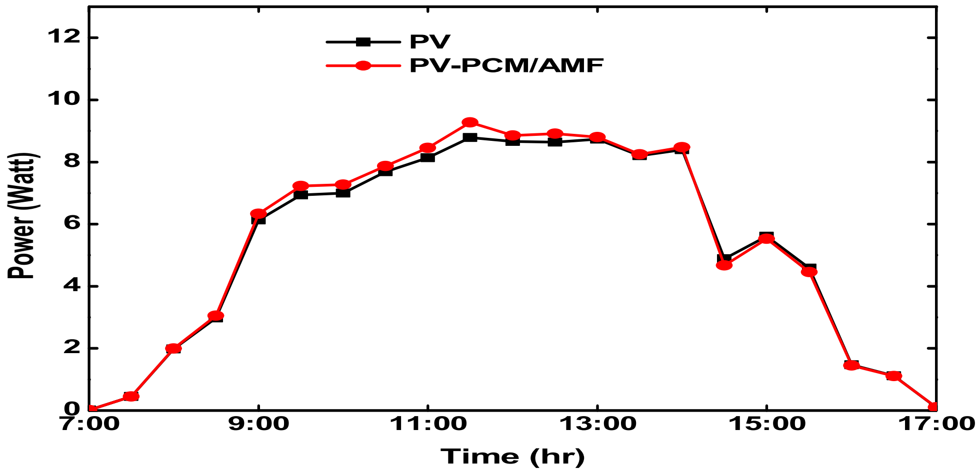


(b) January

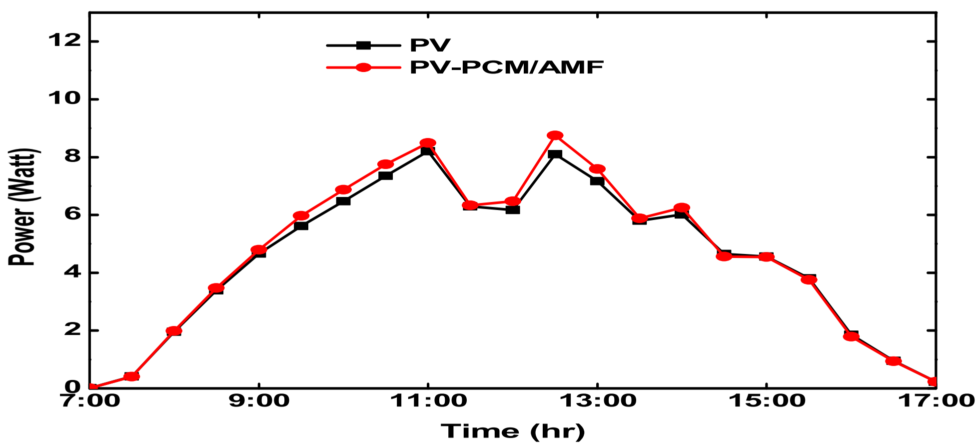


(c) February

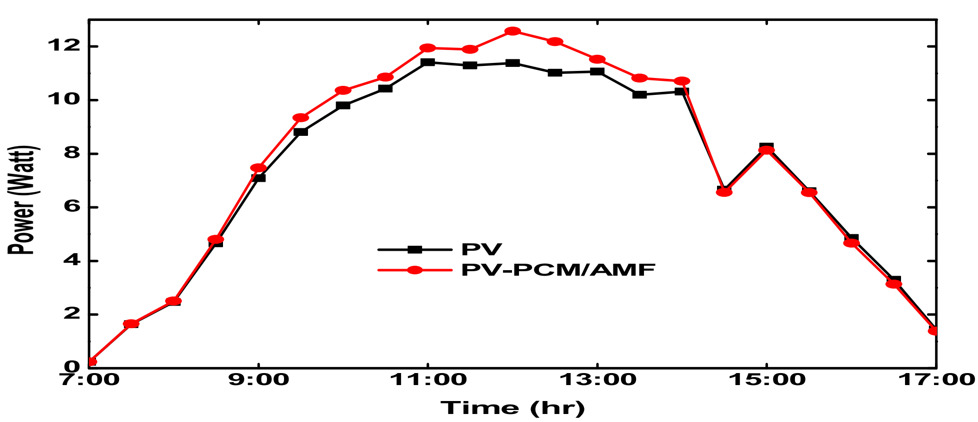
Fig. 8 Variation of open-circuit voltage for PV and PV-PCM/AFM systems.



(a) December.



(b) January



(c) February

Fig. 9 Variation of electrical power produced for PV and PV-PCM/AFM systems.

4. Conclusions

In the current work, the performance enhancement of PV using an aluminum metal foam (AMF) embedded in PCM during the winter climate conditions of Benha city, Egypt was conducted. Experiments were conducted with and without PCM/AMF, and the temperature distribution on the PV surface, open-circuit voltage, and output power produced were presented during the winter period in December, January, and February. Using PCM with aluminum foam successfully brought down the temperature of the solar cell by a maximum of 4.3, 8, and 15% during December, January, and February respectively. Also, it was found that the power produced from PV-PCM/AMF system was on average 1.85 %, 3.38 %, and 4.14 % higher than that of conventional PV in December, January, and February, respectively. It is evident from the current research that the use of PCM during the winter months gives a slight improvement in the performance of the PV solar cells as a result of the decrease in ambient temperature during the winter season and the failure of the PCM to reach the melting point and consequently the lack of benefit from PCM's latent heat. Thus, it is recommended to conduct that experiment during the summer to determine the ability of the PCM to improve the performance of PV solar cells during this period. Better energetic and economic scenarios could be obtained by integrating PCM/AFM in a hybrid electricity-and-heat cogeneration PV/T system, which could be considered in a future study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

None.

References

[1] H.M. Teamah, Comprehensive review of the application of phase change materials in residential heating applications, Alexandria Eng. J. 60 (4) (2021) 3829–3843, https://doi.org/10.1016/j.aej.2021.02.053.
[2] M.S. Yousef, A.K. Abdel Rahman, S. Ookawara, Performance investigation of low – Concentration photovoltaic systems under hot and arid conditions: Experimental and numerical results, Energy Convers. Manag. 128 (2016) 82–94, https://doi.org/10.1016/j.enconman.2016.09.061.
[3] A. Hasan, S.J. McCormack, M.J. Huang, B. Norton, Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics, Sol. Energy. 84 (9) (2010) 1601–1612, https://doi.org/10.1016/j.solener.2010.06.010.
[4] M. Sandberg, Cooling of Building Integrated Photovoltaics by Ventilation Air, First Int, One Day Forum Nat. Hybrid Vent. (1999) 1–10.
[5] E. Skoplaki, J.A. Palyvos, On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations, Sol. Energy. 83 (5) (2009) 614–624, https://doi.org/10.1016/j.solener.2008.10.008.
[6] M.M. Rahman, M. Hasanuzzaman, N.A. Rahim, Effects of various parameters on PV-module power and efficiency, Energy Convers. Manag. 103 (2015) 348–358, https://doi.org/10.1016/j.enconman.2015.06.067.
[7] A.R. Amelia, Y.M. Irwan, M. Irwanto, W.Z. Leow, N. Gomesh, I. Safwati, M.A.M. Anuar, Cooling on photovoltaic panel using forced air convection induced by DC fan, Int. J. Electr. Comput. Eng. 6 (2016) 526–534, https://doi.org/10.11591/ijece.v6i1.9118.
[8] S. Krauter, Increased electrical yield via water flow over the front of photovoltaic panels, Sol. Energy Mater. Sol. Cells. 82 (1-2) (2004) 131–137, https://doi.org/10.1016/j.solmat.2004.01.011.
[9] M. Ozgoren, M.H. Aksoy, C. Bakir, S. Dogan, P. Dančová, P. Novontý, Experimental performance investigation of photovoltaic/thermal (PV-T) system, EPJ Web Conf. 45 (2013) 01106, https://doi.org/10.1051/epjconf/20134501106.
[10] H.G. Teo, P.S. Lee, M.N.A. Hawlader, An active cooling system for photovoltaic modules, Appl. Energy. 90 (2012) 309–315, https://doi.org/10.1016/j.apenergy.2011.01.017.
[11] E. Wilson, Theoretical and operational thermal performance of a "wet" crystalline silicon PV module under Jamaican conditions, Renew. Energy. 34 (6) (2009) 1655–1660, https://doi.org/10.1016/j.renene.2008.10.024.
[12] S. Mehrotra et al, Performance of a solar panel with water immersion cooling technique, Int. J. Sci., Environ. Technol. 3 (3) (2014) 1161–1172.
[13] F. Bayrak, H.F. Oztop, F. Selimefendigil, Effects of different fin parameters on temperature and efficiency for cooling of photovoltaic panels under natural convection, Sol. Energy. 188 (2019) 484–494, https://doi.org/10.1016/j.solener.2019.06.036.
[14] M.S. Yousef, H. Hassan, Energetic and exergetic performance assessment of the inclusion of phase change materials (PCM) in a solar distillation system, Energy Convers. Manag. 179 (2019) 349–361, https://doi.org/10.1016/j.enconman.2018.10.078.
[15] M.S. Yousef, H. Hassan, Energy payback time, exergoeconomic and enviroeconomic analyses of using thermal energy storage system with a solar desalination system: An experimental study, J. Clean. Prod. 270 (2020) 122082, https://doi.org/10.1016/j.jclepro.2020.122082.
[16] A. Abhat, Low temperature latent heat thermal energy storage: Heat storage materials, Sol. Energy. 30 (4) (1983) 313–332, https://doi.org/10.1016/0038-092X(83)90186-X.
[17] R. Stropnik, U. Stritih, Increasing the efficiency of PV panel with the use of PCM, Renew. Energy. 97 (2016) 671–679, https://doi.org/10.1016/j.renene.2016.06.011.
[18] F. Hachem, B. Abdulhay, M. Ramadan, H. El, M. Gad, E. Rab, M. Khaled, Improving the performance of photovoltaic cells using pure and combined phase change materials e Experiments and transient energy balance, Renew. Energy. 107 (2017) 567–575, https://doi.org/10.1016/j.renene.2017.02.032.
[19] A. Waqas, J. Ji, Thermal management of conventional PV panel using PCM with movable shutters – A numerical study, Sol. Energy. 158 (2017) 797–807, https://doi.org/10.1016/j.solener.2017.10.050.
[20] H. Fayaz, N.A. Rahim, M. Hasanuzzaman, R. Nasrin, A. Rivai, Numerical and experimental investigation of the effect of operating conditions on performance of PVT and PVT-PCM, Renew. Energy. 143 (2019) 827–841, https://doi.org/10.1016/j.renene.2019.05.041.
[21] A. Gaur, C. Ménézo, S. Giroux-Julien, Numerical studies on thermal and electrical performance of a fully wetted absorber PVT collector with PCM as a storage medium, Renew. Energy. 109 (2017) 168–187, https://doi.org/10.1016/j.renene.2017.01.062.
[22] A. Hassan, A. Wahab, M.A. Qasim, M.M. Janjua, M.A. Ali, H. M. Ali, T.R. Jadoon, E. Ali, A. Raza, N. Javaid, (2020), "Thermal management and uniform temperature regulation of photovoltaic modules using hybrid phase change materials-nanofluids system", Renew. Energy 145 (2020) 282–293, https://doi.org/10.1016/j.renene.2019.05.130.
[23] M.S. Hossain, A.K. Pandey, J. Selvaraj, N.A. Rahim, M.M. Islam, V.V. Tyagi, Two side serpentine flow based photovoltaic-thermal-phase change materials (PVT-PCM) system: Energy, exergy and economic analysis, Renew. Energy. 136 (2019) 1320–1336, https://doi.org/10.1016/j.renene.2018.10.097.
[24] A. Hasan, J. Sarwar, H. Alnoman, S. Abdelbaqi, Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate, Sol. Energy. 146 (2017) 417–429, https://doi.org/10.1016/j.solener.2017.01.070.

[25] T. Wongwuttanasatian, T. Sarikarin, A. Suksri, Performance enhancement of a photovoltaic module by passive cooling using phase change material in a finned container heat sink, Sol. Energy. 195 (2020) 47–53, https://doi.org/10.1016/j.solener.2019.11.053.

[26] H.M. Teamah, M.F. Lightstone, Numerical study of the electrical load shift capability of a ground source heat pump system with phase change thermal storage, Energy Build. 199 (2019) 235–246, https://doi.org/10.1016/j.enbuild.2019.06.056.

[27] H.A.M. Teamah, M.F. Lightstone, J.S. Cotton, Numerical Investigation and Nondimensional Analysis of the Dynamic Performance of a Thermal Energy Storage System Containing Phase Change Materials and Liquid Water, J. Sol. Energy Eng. Trans. ASME. 139 (2017) 1–14, https://doi.org/10.1115/1.4034642.

[28] M.J. Huang, P.C. Eames, B. Norton, Phase change materials for limiting temperature rise in building integrated photovoltaics, Sol. Energy. 80 (9) (2006) 1121–1130, https://doi.org/10.1016/j.solener.2005.10.006.

[29] M. Rajvikram, S. Leoponraj, S. Ramkumar, H. Akshaya, A. Dheeraj, Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium, Sol. Energy. 188 (2019) (2019) 327–338, https://doi.org/10.1016/j.solener.2019.05.067.

[30] S. Mousavi, A. Kasaeian, M. Behshad, Numerical investigation of the effects of a copper foam fi lled with phase change materials in a water-cooled photovoltaic/thermal system, 163 (2018) 187–195. https://doi.org/10.1016/j.enconman.2018.02.039.

[31] A.R. Abdulmunem, P.M. Samin, H.A. Rahman, H.A. Hussien, I.I. Mazali, Enhancing PV Cell's electrical efficiency using phase change material with copper foam matrix and multi-walled carbon nanotubes as passive cooling method, Renew. Energy. 160 (2020) 663–675, https://doi.org/10.1016/j.renene.2020.07.037.

[32] S.A. Nada, D.H. El-Nagar, H.M.S. Hussein, Improving the thermal regulation and efficiency enhancement of PCM-Integrated PV modules using nano particles, Energy Convers. Manag. 166 (2018) 735–743, https://doi.org/10.1016/j.enconman.2018.04.035.

[33] A.H.A. Al-Waeli, K. Sopian, H.A. Kazem, J.H. Yousif, M.T. Chaichan, A. Ibrahim, S. Mat, M.H. Ruslan, Comparison of prediction methods of PV/T nanofluid and nano-PCM system using a measured dataset and artificial neural network, Sol. Energy. 162 (2018) 378–396, https://doi.org/10.1016/j.solener.2018.01.026.

[34] L. Siahkamari, M. Rahimi, N. Azimi, M. Banibayat, Experimental investigation on using a novel phase change material (PCM) in micro structure photovoltaic cooling system, Int. Commun. Heat Mass Transf. 100 (2019) 60–66, https://doi.org/10.1016/j.icheatmasstransfer.2018.12.020.

[35] RUBITHERM, RUBITHERM, (n.d.) https://www.rubitherm.eu/en/index.php/productcateg.

[36] J.R. Taylor, An introduction to error analysis, the study of uncertainties in physical measurements, University Science Books, California, USA, 1997.

[37] H. Hassan, M.S. Yousef, An assessment of energy, exergy and CO_2 emissions of a solar desalination system under hot climate conditions, Process Saf. Environ. Prot. 145 (2021) 157–171, https://doi.org/10.1016/j.psep.2020.07.043.

[38] H. Hassan, M.S. Yousef, Productivity, exergy, exergoeconomic, and enviroeconomic assessment of hybrid solar distiller using direct salty water heating, (2020).*Environ Sci Pollut Res* **28,**5482–5494 (2021). https://doi.org/10.1007/s11356-020-10803-2

[39] S. Abo-Elfadl, M.S. Yousef, H. Hassan, Energy, exergy, economic and environmental assessment of using Different passive condenser designs of solar distiller, Process Saf. Environ. Prot. 148 (2020) 302–312, https://doi.org/10.1016/j.psep.2020.10.022.

[40] S. Abo-Elfadl, M.S. Yousef, H. Hassan, Assessment of double-pass pin finned solar air heater at different air mass ratios via energy, exergy, economic, and environmental (4E) approaches, Environ. Sci. Pollut. Res. 28 (11) (2021) 13776–13789, https://doi.org/10.1007/s11356-020-11628-9.