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Experimental study of the effect of using phase change materials on the performance of an air-cooled photovoltaic system

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ABSTRACT

Nowadays, solar energy is harvested in two different ways including the extraction of thermal energy in solar collectors and electrical energy generation in photovoltaic panels. The Photovoltaic panels convert a small fraction of absorbed solar radiation into electrical energy and waste the rest in the form of thermal energy that results in increasing the panel temperature and decreasing the electrical efficiency. Photovoltaic thermal systems (PVT) equipped with phase-change materials (PCM) are capable of benefiting from the storage when phase change happens. In this manuscript, the effect of PCMs deployment on the performance of an air-cooled photovoltaic system is investigated, experimentally. As such, the effect of PCM is deliberated in a setup provided in which the PVT is equipped with a sheet of PCM. Herein, the first case considers a natural convection and the other three cases regard three different forced air convection. The experimental results indicate that using PCM sheets of six millimeters thick leads to reducing the panel temperature to 4.3, 3.4, 3.6 and 3.7 °C in average in a natural flow mode, forced high-velocity, medium and low velocity, respectively. Moreover, decreasing the temperature results in increasing the outlet power and electrical efficiency. Accordingly, it is concluded that using PCMs leads to a significant increase in natural and forced convection situations.

1. Introduction

The building precinct consumes more than 39% of the total consumed energies in the world and due to using conventional energy resources, it is responsible for a major part of environmental threats including pollution propagation and global warming [1]. To solve the problem, considerable attention has been given to the renewable energy resources. Solar energy harvesting by photovoltaic (PV) technology which can convert solar radiation into electric energy by photovoltaic effect is the most popular one [2].

One of the challenges in the utilization of PV technology is that all of the incident solar radiation to the PV cell surface do not convert to electricity. The maximum efficiency is in the range of 5–20%, and the rest is dissipated as heat raises the PV temperature [3]. Increasing PV cell temperature leads to further decrease in the PV efficiency which worsens the situation. Therefore, cooling technologies are essential to control the rise in temperature and to enhance the performance of the solar cells [4]. It is demonstrated that each 1 °C increase in temperature of a typical silicon-based PV panel leads to decrease in efficiency of around 0.5% [5]. Another study revealed that at 1000 Wm^{-2} solar radiation power, the produced electricity would be decreased from 240 W to 195 W when the surface temperature rises from 0 °C to 75 °C [6]. Moreover, it is reported that in the crystalline silicon panel the power of module will decrease approximately 0.4–0.65% per each 1 K increase of temperature, if the temperature rises 25 °C [7,8].

To address the issue, many types of research have been accomplished on the cooling of PV panels using PVTs [9]. Specifically, a simple way is to cool the panel by heat transfer fluids such as water or air [10,11]. In PVT systems, the objective is to extract the extra heat from the PV surface by using an operating fluid. The hot fluid can be used for endothermic processes in industrial or residential applications. The fluid can flow through the system in natural or forced circulation ways [12]. In Ref. [13], it is shown that the forced ventilation provides higher heat transfer than the natural flow circulation. However, it is necessary to use pumps (for water) or fans (for air) to generate forced convection. Natural or forced air circulation is a simple and low-cost way to remove heat from PV panels while water heat extraction is more expensive and causes pressure stresses and electrical problems for the PV cells due to its exposure to the water flow [12].

Some studies have been performed regarding the air-cooled PVT

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systems [14]. Authors in [15] reviewed the PVT research focusing on the environmental issues of PVT technologies. Air-cooled PVT systems are easy to construct and can be implemented at low cost. In Ref. [16], an air cooling system was prepared which consists of a duct attached under the PV panel. Results showed that the thermal efficiency of the system with a 5 cm channel depth for an air mass flow rate of 0.018 kg/s, and 0.06 kg/s are 15% and 30%, respectively. Moreover, the electrical efficiency of the system was reported to be in the range of 12–12.4%. The performances of four types of air heating flat plate solar collectors were analyzed in Ref. [17] including a finned collector with an angle of 75°, a finned collector with an angle of 70°, a collector with tubes, and the base collector. The highest collector efficiency and air temperature rise were achieved by the finned collector with the angle of 75°, whereas the lowest values were obtained for the base collector. Authors in [18] experimentally and analytically investigated four air-based bifacial photovoltaic thermal collectors including single-path, double-path with the parallel flow, double-path with the counter flow and double-path with returning flow. The double-path parallel flow design indicated the highest total energy efficiency of 51–67%, and the single-path design indicated the lowest total energy efficiency of 28–49%.

Another technique to hold down the temperature of PV panel and to increase the solar energy harvesting is using phase change materials (PCMs). A PCM is a material with a high fusion latent heat which is capable of storing and releasing large amounts of energy at a certain temperature during the phase change of the material. Herein, the temperature could be fixed. The latent heat thermal energy storage has higher energy density than the sensible heat thermal energy storage [19]. Researchers showed that thermal management by utilizing PCMs is an effective way to confine the temperature rise of photovoltaic modules due to its higher energy density per unit volume [4]. The melting temperature of the PCM should be as low as possible for maximum electrical performance improvement [20]. However, the heat stored in phase change material layer is more difficult to utilize for lower melting points [21].

Authors in Ref. [22] investigated the effect of PCMs on the thermal regulation and enhancement of electrical efficiency of photovoltaic modules. The PCM module was a 10 cm × 10 cm × 3 cm aluminum box. In the study, a transient one-dimensional energy balance model was developed to deliberate the thermal performance of a photovoltaic module integrated with the PCM storage system. The numerical result was validated with experimental studies from the literature. The obtained results indicated that PCM is effective to limit the temperature rise in the PV devices and this could enhance the efficiency of the PV modules up to 5%.

Numerical and experimental investigation was performed to study the thickness effect of PCM, installed on a vertical-building-added photovoltaics. Experimental results showed that the thicker PCM absorbed more heat; however, the heat absorbed in the PCM was not released efficiently during the night [23]. Moreover, the thicker PCM led to increase in the weight and cost. It was figured out that using PCM in an optimized temperature and thickness condition led to the increase of electrical output power around 1–1.5% rather than conventional panels.

In [24], the addition of RT25 as PCM was conducted, which could maintain the panel temperature at 40 °C for 80 min at 1000 W/m^2 solar radiation. The same temperature by the panel without the PCM was achieved only for 5 min. Furthermore, the effectiveness of using PCM, for restricting the temperature rise in photovoltaic modules, was investigated in Ref. [25]. Numerical and experimental results revealed that equipping a PV/PCM panel by metal fins, significantly improved the thermal performance. Authors in Ref. [26] evaluated five PCMs with melting temperature of ~25 ± 4 °C and heat of fusion between 140 and 213 kJ/kg. The PCMs included Paraffin wax (RT20), Eutectic mixture of capric–lauric acid (C–L), Eutectic mixture of capric–palmitic acid (C–P), pure salt hydrate ($CaCl_{2.}6H_2O$), and a commercial blend (SP22). In the study, they investigated the effect of the mass of PCM and thermal conductivities on the temperature of the photovoltaic module. Moreover, results revealed that the maximum temperature reduction was 18 °C and 10 °C after 30 min and 5 h, respectively, when the solar irradiation was 1000 W/m^2. In Ref. [27], a 36 cm thick RT28HC was utilized on the back side of the panels. The maximum reduction in temperature of the panel was equal to 35.6 °C.

Authors in [28] experimentally studied the impact of the addition of RT42 PCM layer on the back side of the PV panel on the electrical and thermal energy efficiency. They revealed that, using integrated PCM and photovoltaics in building results at temperature drop of 12.3 °C and 22.6 °C at the front and back surfaces of PV, correspondingly compared to the case of PV without PCM. Moreover, the inclusion of PCM led to 7.2% and 5.5% growth of PV power production at peak and daily average values, respectively. Experimental study was performed on a PVT solar collector with compound parabolic concentrator and PCM. Results illustrated that even in a semi-cloudy day in winter thermal efficiency of solar collector reaches around 40% when PCM is used [29]. In [30], the effect of using PCMs with different melting temperatures was numerically evaluated. They used binary combinations of four different PCMs including RT21, RT27, RT31, and RT60. It was concluded that the PV/PCM system with multiple PCMs was more effective to maintain the temperature of photovoltaic module near 25 °C. The wide-ranging overview demonstrated that a PVT-PCM system technology has an immense potential to become a convenient alternative to conventional power plants [31]. The PVT-PCM systems are found to offer as high as 50% more heat storage potential than the conventional PVT-water systems. Besides, the power output has been enhanced 9%, and module temperature reduced 6 °C more, concerning PVT-water systems. In the work, carried out by Al-Waeli et al. [32], the heat was transferred from the PCM to the thermal energy consumer by using a heat transfer nanofluid, inside a heat exchanger. The heat exchanger between the heat transfer fluid and the consumer increased the cost of the system. Moreover, the indirect heat transfer rate was lower, with respect to the direct heat transfer mode.

As mentioned in the previous paragraphs, in recent years, several solutions have been proposed to reduce the temperature of a solar panel including the incorporation of convective air flow and PCMs. Each of these methods has been studied separately. However, simultaneous usage of both methods has not been considered in the literature. In this work, for the first time, the thermal behavior of a system equipped with the combination of these two methods is investigated. In the current work, the heat exchanger and heat transfer fluid are removed. The harvested heat in the current work is appropriate for the thermal consumers in which warm air is flowing, which could be located near the panel (like the fruit dryers). By removing the heat transfer fluid and heat exchanger, the heat transfer rate could be increased, significantly. The study is performed for different conditions of natural and forced air cooling.

2. Experimental procedure

2.1. Setup description

A schematic diagram of the test system and its components is shown in Fig. 1. The electrical section consists of two monocrystalline PV modules in a dimension of 1053 × 554 mm, made by Aria Solar Co. in Iran. The electrical properties of PV panels given by the manufacturer are shown in Table 1. Herein, a steel plate is attached to the back side of the PV panel in order to extract extra heat from it which is so called the "absorber plate". A PCM sheet is located under the absorber plate, and an air channel is situated next to it. The contact resistance due to air gaps between the plates is removed by increasing the joint pressure. This technique is effective, because all plates are smooth and the PCM sheet is formable to some extent.

Moreover, a kind of salt hydrate (PCM32/280 made in PGSCRCO

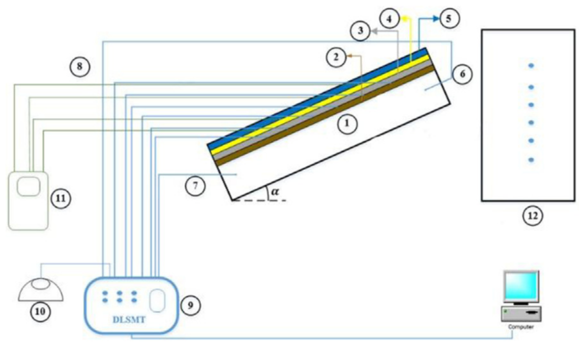


Fig. 1. Schematic of the PVT and its components: 1. Air channel, 2. PCM, 3. Absorber plate, 4. The aluminum oxide layer, 5. The photovoltaic panel, 6. Outlet air temperature sensors, 7. Inlet air temperature sensors, 8. Temperature sensors on the absorber plate, 9. Data logger, 10. Pyranometer, 11. Thermometer, 12. Positions of sensors on the absorber plate.

Table 1
Properties of the PV panels.

Parameter	unit	Specification
Peak power (Pmax)	[Wp]	90
Max. power current (Imp)	[A]	5.47
Max. power voltage (Vmp)	[V]	16.45
Short circuit current (Isc)	[A]	5.55
Open circuit voltage (Voc)	[V]	20.2
Temperature coefficient for Pmax	[%/°C]	− 0.46
Temperature coefficient for Voc	[%/°C]	− 0.356
Temperature coefficient for Isc	[%/°C]	+ 0.024
Max system voltage	[V]	1000

Table 2
Thermo-physical properties of PCM32/280.

Parameter	unit	Specification
Melting point	[°C]	32
Latent heat	[J/cm^3]	280
Thermal conductivity	[W/m °C]	0.4
Density (solid)	[g/cm^3]	1.5

Company) presented in Table 2. was used as PCM. The melting temperature and heat of fusion for this PCM are 32 °C and 280 J/cm^3, respectively. The PCM should be melted and solidified during the day and night, respectively. Therefore, the selection of PCM was according to the variation of ambient temperature in Tehran. The melting temperature of the selected PCM is less than the maximum day temperature, and more than minimum night temperature in Tehran. During the tests, the PVT system is tilted in the latitude of Tehran towards the south. In the forced convection mode, the mass flow rate of air in the duct could be adjusted with four DATECH 1238-12HBIA- fans whose rated voltage and current are 12 V and 1.5 A, respectively. The velocity of the air passing through the channel can be set in the range of 0.5–2.5 m/s by changing the voltage of the fans.

Several sensors and thermocouples are attached to the system in order to measure the temperature of different components at different locations including air inlet and outlet, ambient air and surfaces of absorber plate and PCM pack. The temperature of the panel and PCM were measured by K-type thermocouples and read by TM-946 type thermometer. The thickness of the panel was 35 mm, and the thermocouples were placed on the back side surface of the panel. The SMT160 sensors were used to measure the temperatures of the absorber plate, the inlet, outlet and the ambient air. Temperatures at different locations of the absorber plate were measured by seven SMT160 sensors and their average value reported as the temperature of the absorber. The

Fig. 2. The experimental setup of hybrid PVT air collector.

experimental set up was installed on the roof of a building in the University of Tehran Campus. The setup is shown in Fig. 2.

2.2. Preparing and installing the PCM pack

As it is demonstrated in Fig. 3.a, polycarbonate sheet was utilized in order to pack the PCM. The PCM was completely melted to make an easier condition for floating inside the polycarbonate splits. As such, PCM was heated inside a hot water bath for six hours. Then, the melted PCM was injected into the splits of the sheet. For measuring the PCM temperature, a sensor was placed inside a split at the middle of the PCM sheet. Ends of splits were sealed thoroughly at both sides. Fig. 3.b shows that PCM sheet was installed under the panel. Therefore, it could simply be uninstalled.

2.3. Data gathering process

The data was collected on the sunny days of September and October 2016. Data recording duration was from 10:00 to 16:00 for the case of not using the PCM pack and from 10:00 to sunset when PCM pack was added. It is possible to compare the performance of different cases when the environmental conditions are similar during the tests. Therefore, tests were repeated and days which had more similar conditions were compared. The mass flow in the channel could be changed by regulating the velocity of the fan. Moreover, the air flow in both natural convection and forced convection were laminar.

2.4. Calculating power and efficiency of photovoltaic panel

The Electrical efficiency can be calculated according to the following equation:

$$\eta_e = \frac{P_{mp}}{G{\cdot}A_{PV}} \times 100 \quad (1)$$

$$P_{mp} = V_{mp}{\cdot}I_{mp} \quad (2)$$

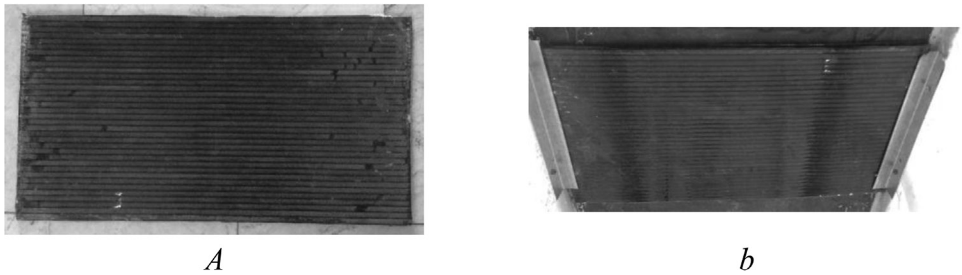


Fig. 3. a) Packed PCM, b) PCM pack installed at the back side of the panel.

where P_{mp} is the maximum output power (W), G is solar radiation (W/ m^2 K), A_{PV} is the active area of panels (m^2), I_{mp} and V_{mp} are the current and voltage of the maximum output power, respectively.

In order to evaluate the errors, related to the experimental data which were inevitable, an analysis of experimental uncertainty was implemented. With this regard, the relative uncertainty of the electrical efficiency could be determined as followings:

$$u_\eta = \left[\left(\frac{P}{\eta}\frac{\partial \eta}{\partial P}u_P\right)^2 + \left(\frac{-G}{\eta}\frac{\partial \eta}{\partial G}u_G\right)^2 + \left(\frac{-A}{\eta}\frac{\partial \eta}{\partial A}u_A\right)^2\right]^{1/2} \tag{3}$$

where u_η, u_P, u_G, and u_A are the relative uncertainty of η, P, G and A, respectively. The relative uncertainty of the electrical power is:

$$u_P = \left[\left(\frac{V}{P}\frac{\partial P}{\partial V}u_V\right)^2 + \left(\frac{I}{P}\frac{\partial P}{\partial I}u_I\right)^2\right]^{1/2} \tag{4}$$

According to Eq. (3) and Eq. (4), the average relative uncertainty of the electrical efficiency and electrical power are obtained as 0.18 and 0.183, respectively.

For each condition, tests were repeated for several days and, after ensuring about the repeatability and accuracy of the results, the specific measurements of one day were represented in the figures.

3. Results and discussion

Experimental tests have been performed to study the effect of using PCM in the following cases:

- PV panel exposed to natural convection.
- PV panel exposed to forced convection.

Fig. 4 illustrates the solar radiation during the day on 12th September 2016. As it is shown in the figure, the solar radiation increases between 10:00 and 13:00 and then declines.

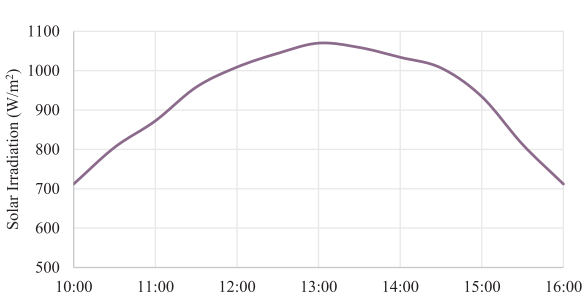


Fig. 4. Hourly variation of solar radiation on 12th September 2016.

3.1. The thermal effect of using PCM in PV panel exposed to natural convection

3.1.1. PV panel without PCM exposed to natural convection

Fig. 5. illustrates the temperature variations of inlet and outlet air versus time for the natural convection condition when the setup is not equipped with PCM. Moreover, the average temperatures of the absorber plate and back side surface of PV panel are indicated. A minor part of absorbed solar radiation in the panel is converted into electricity, and the rest is converted to heat and raises the temperature of the PV panel and the absorber plate. Therefore, the heat transfers to the air inside the duct which is in the vicinity of the absorber plate. This issue leads to air flowing inside the duct and the occurrence of free convection. Overall variation trends of temperatures in Fig. 5. are similar to the daily variation of solar radiation in Fig. 4. Therefore, the temperature variations are mainly functions of daily solar radiation.

As shown in Fig. 5. in the early morning and evening, the temperature difference between absorber and PV panel is small due to the low amounts of the solar radiation. However, it increases around midnoon. The temperature of the back surface of PV panel is higher than other locations, and it increases to 65.6 °C. Temperature variation between the inlet, and outlet air was about 10 °C. As ambient temperature is located in the shade, its value is smaller than the value of inlet temperature.

3.1.2. PV panel with PCM exposed to natural convection

When the packs of PCM are added to the PV panel, they receive the overheating by melting and confine rising temperature. During the evening and at night, when the sun sets, PCMs give back the thermal energy and solidification will happen. Fig. 6 illustrates the temperature differences between inlet and outlet air for natural convection condition in two different situations: PV panel with and without PCM pack. It is revealed from the figure that there is an oscillatory behavior for variation of temperature differences in both cases. The reason is that heat transfer from absorber plate to the input air is a time-consuming process. Therefore, the air temperature and density would be changed slowly. In the beginning, the air temperature is low and therefore, the speed of air flow is small. This low velocity causes the air remaining inside the duct for a long time and consequently temperature difference between input and output air temperature increases. However, as time passes, flow becomes faster due to the air temperature increase. Therefore, air remains in the duct for a shorter time and receives less heat. Consequently, the temperature difference between input and output air falls and the cycle will repeat.

As it is shown in Fig. 6, the graph curve is smoother and more uniform when PCM exists as it regulates the temperature. Moreover, the temperature difference between inlet and outlet air is higher in the case of not using PCM. The average temperature difference is about 11 °C and 6 °C in the cases of not using and using PCM, respectively. In fact, when no PCM is used, the input heat from the absorber plate is directly transferred to the air, and no heat is stored which leads to the higher difference between input and output air.

Fig. 7 demonstrates the variations of average temperature at the

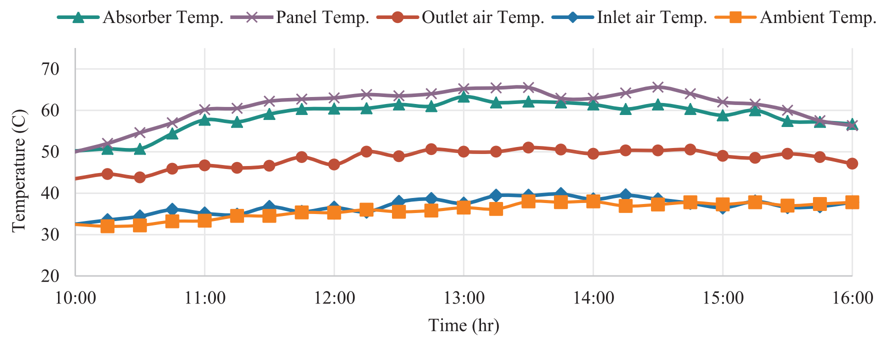


Fig. 5. Temperature variation on 12th September 2016 for the natural convection condition without PCM.

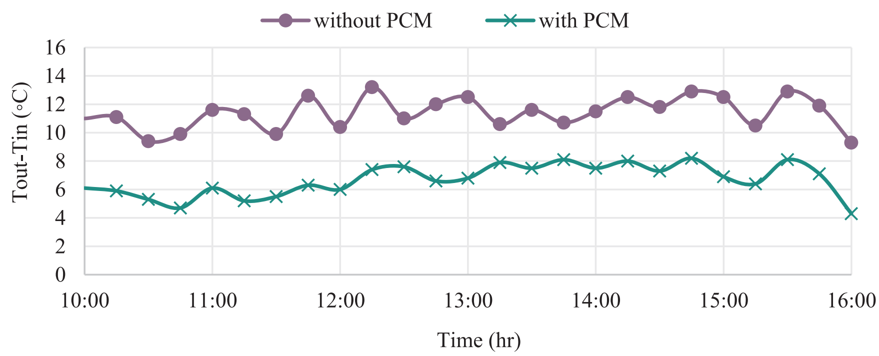


Fig. 6. Temperature difference between the inlet and outlet air for PV panel in the natural convection condition, equipped and not equipped with PCM pack.

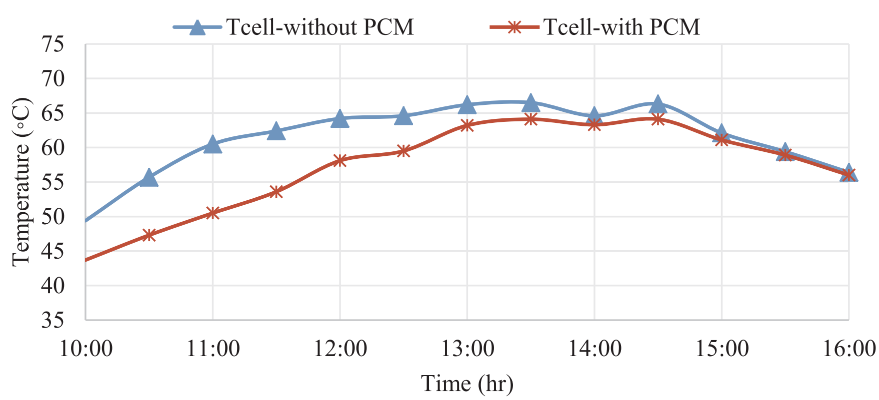


Fig. 7. Temperature of PV panel, equipped and not equipped with PCM, in natural circulation case.

Table 3
The Reynolds number at different forced convection cases.

Natural convection	Low speed	Mean speed	High speed
1750	9500	11,750	12,665

back side of the PV surface for two cases of PV panel equipped and not equipped with PCM pack in the natural convection condition. Using PCM results in 4.3 °C decrease in average temperature of the back side of the PV panel. In the early morning, the PCM is capable of absorbing a large amount of thermal energy, since it is completely solidified during the night before. However, the PCM is completely melted in the afternoon, and its latent heat storage capacity is removed. This phenomenon results in increasing the PCM temperature due to sensible heat storage. Therefore, the difference between the panel temperature, in case of using and not using PCM, is significant in the morning, while it is negligible in the afternoon. The maximum temperature difference of the back side of the PV is 10 °C between two cases of using and not using PCM.

As it is shown in Fig. 7, the differences between the value and the slope of cell temperature in the morning are higher than the afternoon. The reason is that, in summer, the sunset is between 19:00 and 20:00. In addition, in the beginning of spring in Iran, the official time of the country is shifted by one hour. So, the cooling effect of the air near the sunset is out of the time range, displayed in Fig. 7.

3.2. The thermal effect of using PCM in PV panel exposed to forced convection

To study the behavior of the PV panel in the forced convection condition, two fans installed at the output of channel and produced air flow by sucking the air. The experiments were performed for three different air flow rates by changing the speed of fans. Measured speeds inside the duct were 1.05, 0.95 and 0.75 m/s which are named high speed, mean speed, and low speed, respectively. The transition from laminar to turbulent flow takes place when the Reynolds number reaches the transition value which is around 2300 for flow through ducts. The average of Reynolds number for natural convection and forced convection are given in Table 3. The values in this table reveal

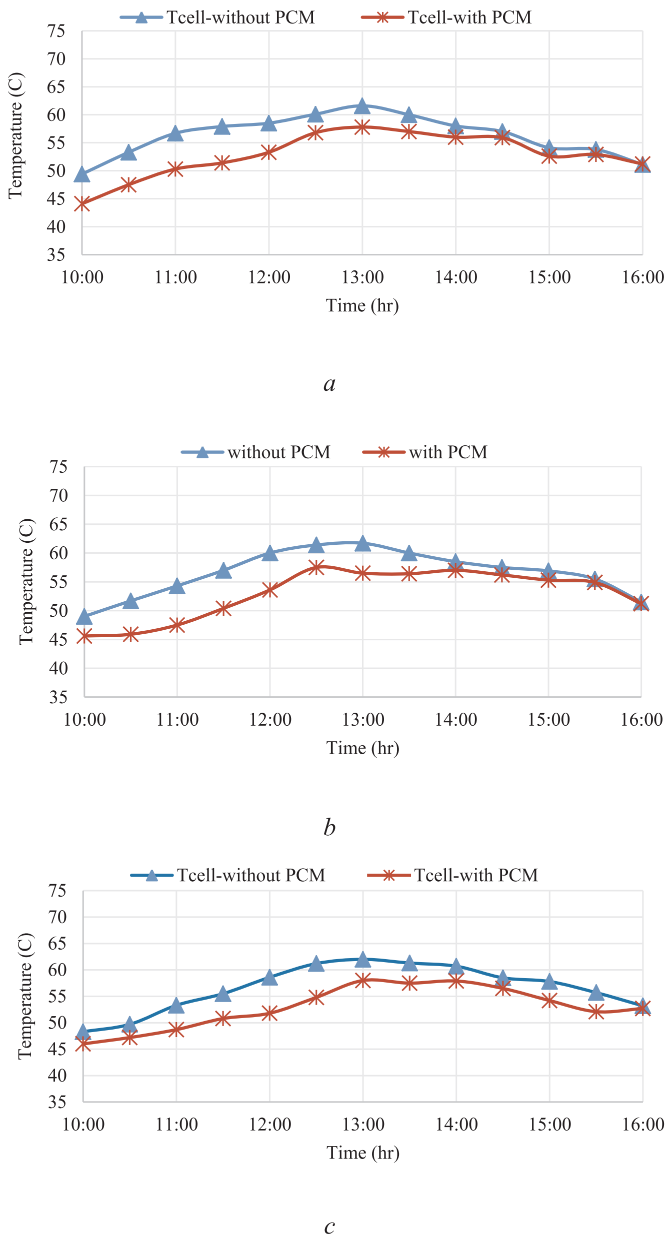


Fig. 8. Temperature of panel in forced convection: a) high speed fan (1.05 m/s), b) mean speed fan (0.95 m/s), c) low speed fan (0.75 m/s).

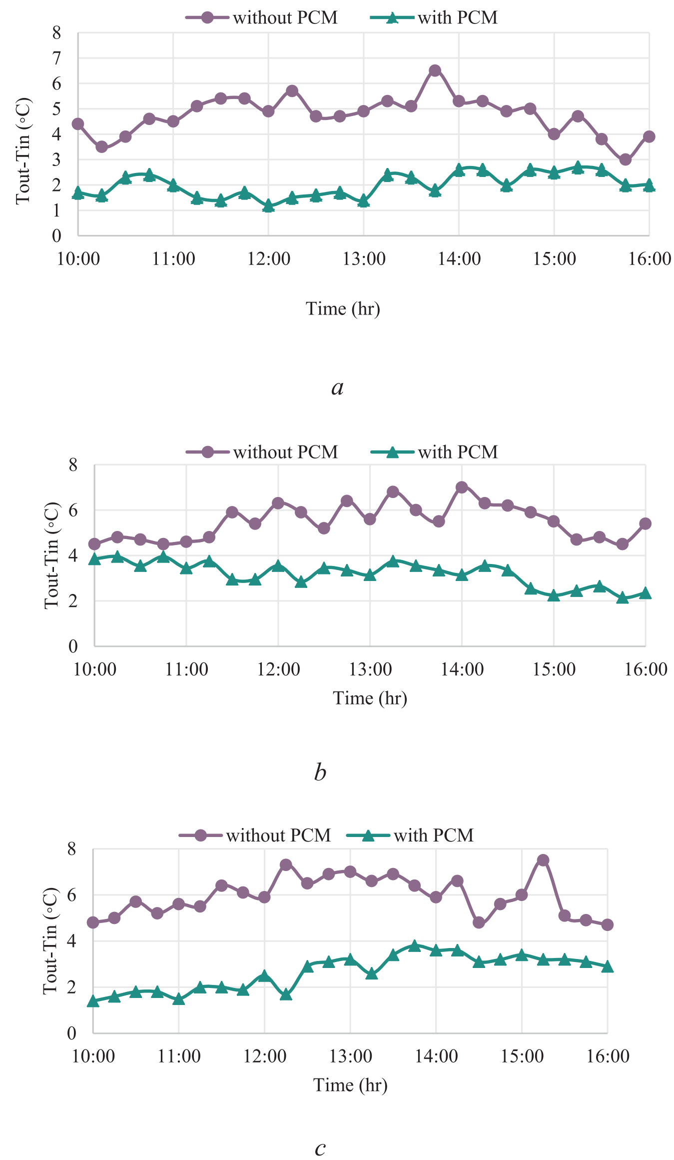


Fig. 9. Temperature differences between the outlet and inlet air in forced convection: a) high-speed fan (1.05 m/s), b) mean speed fan (0.95 m/s), c) low speed fan (0.75 m/s).

Table 4
Average and maximum temperature reduction of PV panel due to the utilization of PCM pack at different speeds of fans and in natural convection.

Fan speed (m/s)	Max. reduction in PV panel temperature (°C)	Average reduction in PV panel temperature (°C)
High (1.05)	6.4	3.4
Mean (0.95)	6.8	3.6
Low (0.75)	6.7	3.7
Natural convection (0)	10	4.3

that the flow is laminar in natural convection case and turbulent in forced convection conditions.

Fig. 8 demonstrates the variations of temperature of PV panel surface for both cases of using and not using PCM pack. Overall variation of panel temperature is similar to the natural convection case. For each air flow rate, the experiment was conducted twice, once without PCM pack and once with PCM pack. Then, the difference of PV panel

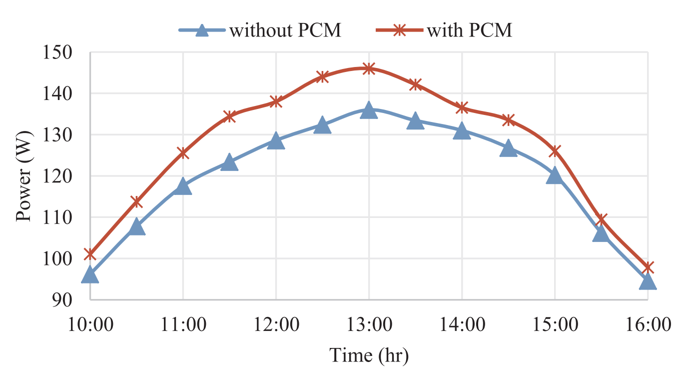
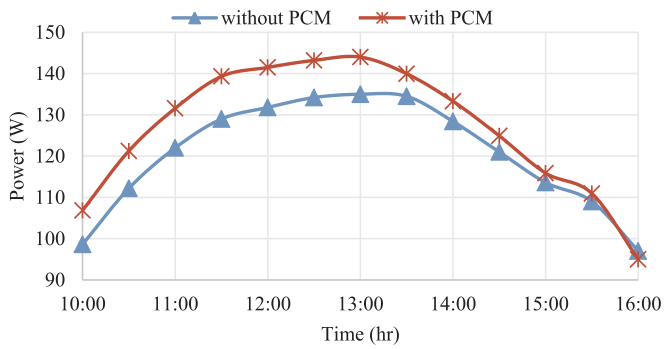


Fig. 10. The variation of output power for PV, with and without PCM pack, in natural convection.

temperature variations between the cases in the same air flow rate was calculated to evaluate the effectiveness of using PCM in mentioned air flow rate. Based on the calculation, an average and maximum temperature reduction of PV panel due to the utilization of PCM pack are



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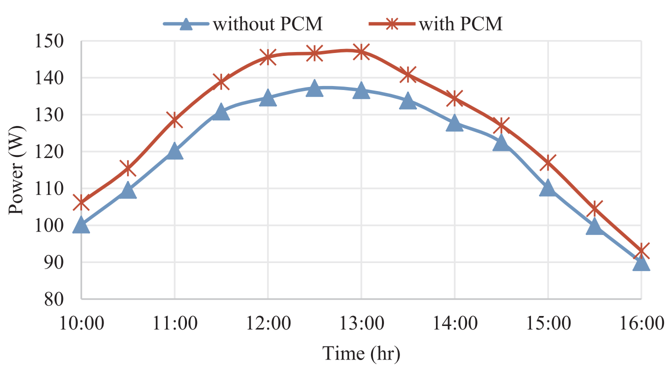

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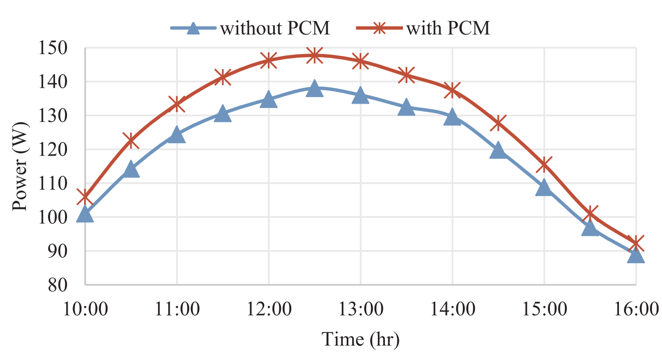

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Fig. 11. The variation of output power for PV panel, with and without PCM pack, in forced convection: a) high-speed fan (1.05 m/s), b) mean speed fan (0.95 m/s), c) low speed fan (0.75 m/s).

Table 5
Variation of output power due to using PCM at different forced and free convection cases.

Fan speed (m/s)	Max. increase in output power (W)	Average increase in output power (W)	Average increase in output power minus fan power (W)
High (1.05)	10.3	5.9	5.71
Mean (0.95)	9.2	6.1	5.97
Low (0.75)	6.7	6.7	6.63
Natural mode (0)	11.7	7.2	7.2

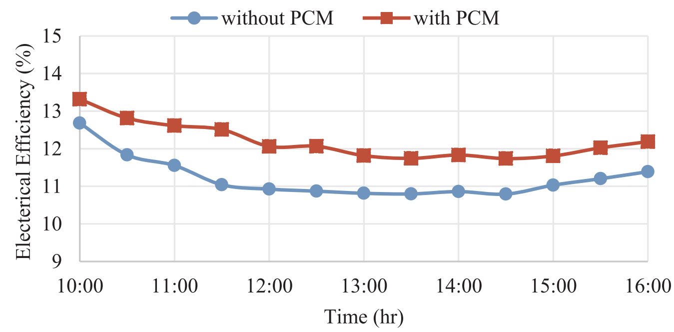
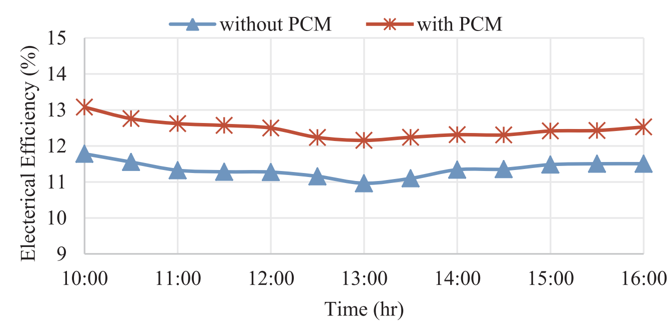


Fig. 12. The variation of electrical efficiency for PV panel equipped and not equipped with PCM pack in natural convection.



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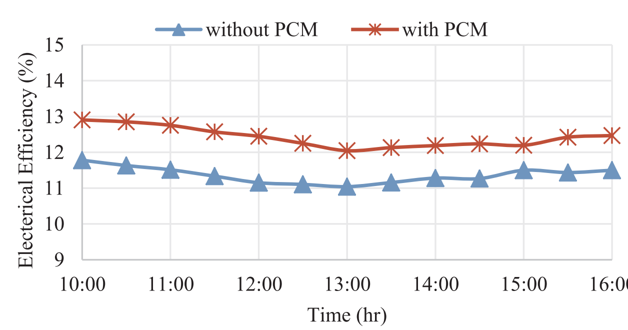

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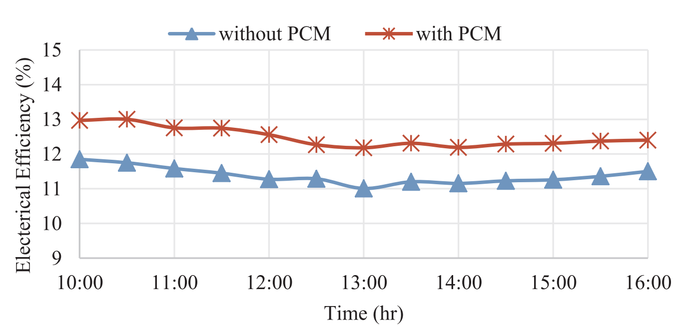

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Fig. 13. The variation of electrical efficiency for PV panel, equipped and not equipped with PCM pack: a) High-speed fan (1.05 m/s), b) Mean speed fan (0.95 m/s), c) Low speed fan (0.75 m/s).

Table 6
Variation of efficiency with different fan speeds.

Fan speed (m/s)	Max. efficiency increasing (%)	Average increasing in efficiency (%)
High (1.05)	1.29	1.11
Mean (0.95)	1.29	1.06
Low (0.75)	1.29	1.11
Natural mode (0)	1.47	0.98

presented in Table 4 for different speeds of the fan. For comparison, the results of the natural convection case are displayed in Table 4, as well.

The results in Table 4 reveal that in the forced convection case, the effectiveness of using PCM pack increases along with the fan speed decrease. Moreover, in the natural convection case, applying PCM pack is more impressive. The maximum difference between average temperatures of PV panel in different fan speeds is only 0.3 °C. The reason is that, although the PCM sheet absorbs heat from absorber layer by changing phase, it acts as a thermal resistance layer and decreases temperature difference and consequently convective heat transfer between the flowing air and adjacent surface. As heat transfer rate in natural convection case is much weaker compared to forced convection case, decreasing forced convection is more significant when PCM is used.

Fig. 9 illustrates the temperature differences between outlet and inlet air for different forced convection conditions in two situations: PV panel with and without PCM pack. As it is shown in Fig. 10, where PCM exists the temperature difference values are lower, and the curves are smoother. By raising the fan speed, the temperature differences will be reduced because the air in the channel does not have enough time to raise its temperature. Moreover, comparing the results in Figs. 7 and 10 reveals that the oscillatory behavior for variation of temperature differences is attenuated. The reason is that in forced flow condition, the flow rate is intrinsically independent of fluid temperature.

To more precisely understand the effectiveness of different cooling methods, electrical energy generation is compared in the next section.

3.3. The effect of cooling methods on the electrical energy generation

The variation of output power for two conditions of using and not using PCM pack are shown in Fig. 10 and Fig. 11 in free convection and forced convection conditions, respectively. In the forced convection case, similar to the natural convection case, using PCM leads to the increase of output power. As it is clear from the figures, using PCM is more effective in the middle of the day and does not have an important effect in the evening as it is melted. Comparing Figs. 10 and 11 with Fig. 7 and Fig. 8 reveals that reducing the temperature of the panel leads to the output power increase and then raises electrical efficiency.

The maximum and average variation of output power in each case are shown in Table 5. Using PCM in all conditions leads to around 5% increase in the averaged panel output power.

Increasing the output power leads to the augmentation of electrical efficiency. Figs. 12 and 13 demonstrate the calculation results for electrical efficiency for natural and forced convection conditions, respectively.

During the day, solar irradiation and PV temperature increases. Increasing solar irradiation results in raising the output power, however, PV temperature has a negative effect on the efficiency of PV panel. Therefore, as it is shown in Figs. 12 and 13, in the middle of the day the electrical efficiency decreases. The maximum and average of output power variation for different forced convection cases are shown in Table 6. The results in the table reveal that the average increase in efficiency is in the order of one percent. As it is shown in Fig. 12 and Fig. 13, when PCM is not used, the value of averaged electrical efficiency is around 11% for natural convection case and around 11.5% for forced convection case. Therefore, using PCM results in at least a 9% increase in the electrical efficiency of PV panel which is considerable.

4. Conclusion

A photovoltaic thermal system, integrated with phase change materials (PVT/PCM) was investigated in this study. Herein, the effect of PCM on PV panel and air temperature, output power, and electrical efficiency was investigated. It was revealed that there was an oscillatory behavior for variation of temperature differences in natural convection condition which attenuates when PCM was used. Moreover, the experimental results demonstrated that PCM incorporation led to average temperature drop at the back side of PV panel of around 4.3 °C and 3.6 °C in the natural and forced convection, respectively. In the early morning, the PCM is capable of absorbing a large amount of thermal energy, since it is completely solidified during the night before. However, the PCM is completely melted in the afternoon, and its latent heat storage capacity is removed. This case results in increasing the PCM temperature, due to the sensible heat storage. Therefore, the difference between the panel temperature, in case of using and not using PCM, is significant in the morning, while it is negligible in the afternoon. It was shown that, reducing temperature of the panel led to the output power increase and then electrical efficiency augmentation. Furthermore, it was observed that the averaged value of electrical efficiency was around 11% for natural convection case and around 11.5% for forced convection cases when PCM was not incorporated in PVT. Therefore, using PCM at least results in 9% increase in the electrical efficiency of PV panel which is considerable.

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