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## Efficiency gains of photovoltaic system using latent heat thermal energy storage

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### Abstract

This paper presents experimental assessments of the thermal and electrical performance of photovoltaic (PV) system by comparing the latent heat-cooled PV panel with the naturally-cooled equivalent. It is commonly known that the energy conversion efficiency of the PV cells declines with the increment of the PV cell temperature, at a typical value of 0.5 %/K. Instead of exploring new semi-conducting materials to reduce the temperature-dependent effect, passive cell cooling is an alternative way to improve the PV power outputs. In the experiment, latent heat thermal energy storage was coupled to the rear side of the PV panel to achieve cell cooling passively. The phase change material (PCM) filled in the thermal storage containment (PCMTS) was organic based paraffin wax which has low melting point of 27 °C and high latent heat capacity of 184 kJ/kg. To overcome the poor thermal conductivity of the PCM, metallic fins were incorporated in the LHTES to increase the melting rate of the PCM. In addition, studies of the heat transfer performance using different numbers of metallic fins in heat enhanced PCMTS are compared and analysed. The experimental results show that the finned latent heat-cooled PV panel was able to reduce the panel temperature by 15 °C compared to the naturally-cooled PV panel. The maximum electrical conversion efficiency improvement of 5.39 % was achieved by the proposed passive cooling approach.

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## 1. Introduction

Photovoltaic (PV) cells convert incoming solar radiation into useful electrical energy which is essential source of alternative energy for our daily use. For a typically polycrystalline PV panel, it has a solar-to-electrical conversion efficiency about 13-18 % [1] and the remaining solar energy will be converted into waste heat. The waste heat will then increase the temperature of the PV cells and lead to decline of cell efficiency ( $-0.5\%$  per  $^{\circ}\text{C}$ ) [2]. Many studies on PV cells and panels cooling have been conducted to reduce the panel temperature and increase its conversion efficiency. Several kinds of cooling systems utilising different cooling methods such as air-cooled method (natural and forced convection) to remove the heat from the cells [3-5], water-cooled method [6-8] where heat is removed by water-circulating blocks, the use of heat pipes for cooling concentrated solar PV cells [9-12], using phase change materials (PCM) to cool the PV panel by storing the dissipated heat of the cells as latent heat during phase change [13-15] and other cooling methods [16-17]. This work will focus on the utilisation of latent heat thermal storage (LHTES) for cooling the PV panels passively.

There are two main kinds of energy storage which are the sensible heat storage and latent heat storage. This work will be centered on latent heat storage, which uses a phase change material (PCM) for storing thermal energy, with the great advantage of having a much higher heat capacity than the sensible heat methods, particularly due to latent heat of fusion during melting. This fact allows a more compact cooling system in terms of thermal mass and volumetric storage. This objective of this study is to assess the PV power output improvement by using the thermally enhanced PCMTS for cooling the PV panel passively and increase the energy conversion efficiency. Heat enhancement was implemented on the PCMTS through the utilisation of metallic fins to increase the heat spreading and melting rate of the PCM. In this paper, the thermal and electrical performance are compared between the PCM cooled PV panel and the naturally cooled equivalent and their experimental data are analysed.

## 2. Method and materials

In order to conduct a comparative assessment, two similar multi-crystalline PV panels (BP solar, SX 320 model) were used in this experimental study. One of the panels was naturally cooled by the surrounding air while the other was passively cooled by using PCMTS. In this experimental prototype, a simple thermal coupling of a PCMTS at the rear of the panel was implemented. This PCMTS- coupled panel is referred as a “PV-PCM” system” and the schematic diagram is shown in Fig.1 below.

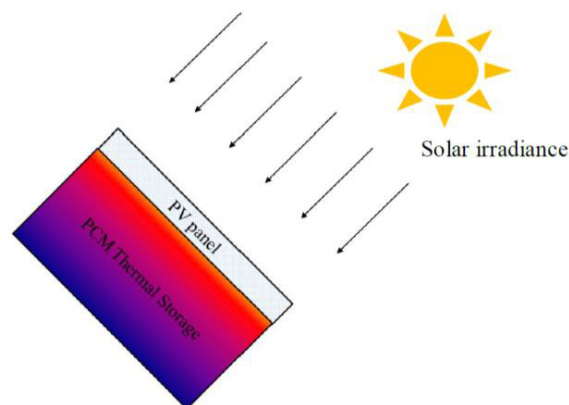


Fig. 1. Schematic PV coupled with PCMTS (PV-PCM System).

The PCMTS consisted of a simple rectangular containment filled with PCM. This containment was fully sealed with silicone sealant to avoid leakage of melted PCM. The containment was made of aluminium and had a high thermal conductivity ( $\sim 200$  W/m K). The waste heat accumulated at the rear side of the PV panel was transmitted to the PCMTS for heat absorption. The PCM used in the experiment was paraffin wax (RT 27). The paraffin wax RT27 has a melting temperature of  $27^\circ\text{C}$ , is non-corrosive and has high latent heat storage capacity ( $184$  kJ/kg) which makes it attractive for use in the PCMTS. Due to the fact that the thermal expansion of the PCM was approximately 16 % at  $40^\circ\text{C}$  (liquid state), the paraffin wax was charged to 80 % of the containment volume to allow thermal expansion during heat absorption. The remaining 4 % of the containment volume allowed for thermal expansion if the PCM temperature exceeded  $40^\circ\text{C}$ . Figs. 2 show the inner configurations of the PCMTS filled and pre-filled containment respectively.

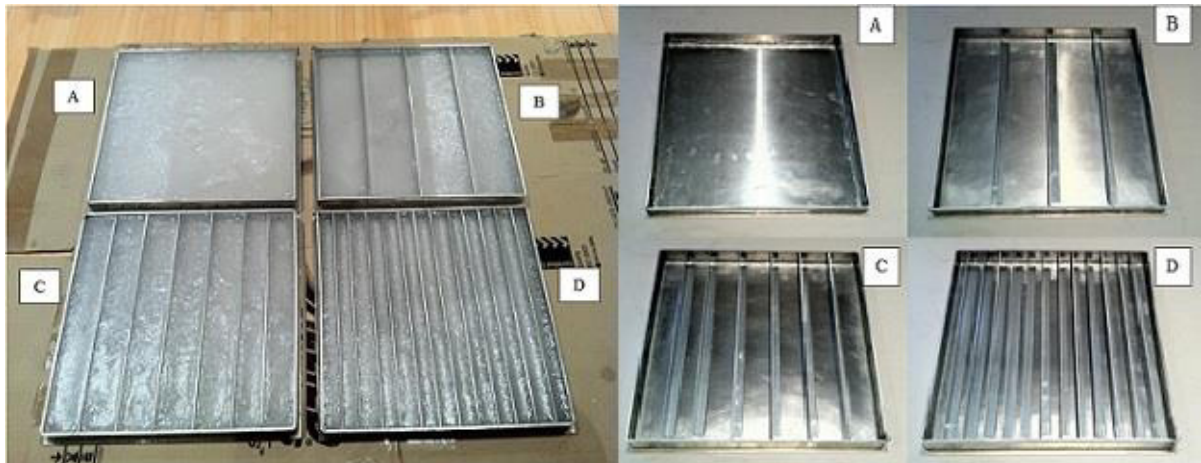


Fig. 2. PCMTS containments with different inner configurations filled with paraffin wax (left) and without paraffin wax (right); Finless (A), 3-fin (B), 6-fin (C) and 12-fin (D)

### 3. Experiment setup and procedure

The experiment was set up in an outdoor location in order to evaluate the passive cooling performance and the electrical power output improvement. The outdoor test arrangement is shown in Fig. 3. The main components of the experimental setup were two identical PV panels (BP Solar, model: SX320M) and four different heat enhanced PCMTS which were thermally coupled at the rear of the PV panel during testing. T-type thermocouples were used on the test rig for capturing all monitored temperatures at 30 seconds intervals.

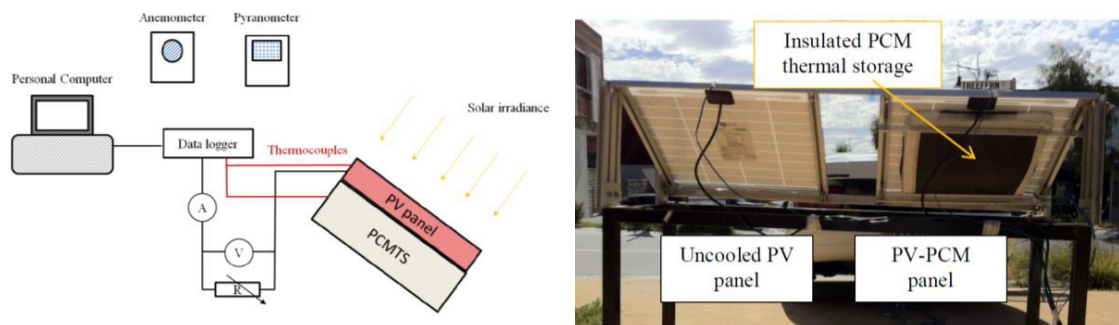


Fig. 3. Schematic diagram of experimental setup (left) and outdoor test rig for PV-PCM cooling (right).

A 105HP handheld pyranometer and an AR856 handheld anemometer were used for measuring the solar irradiance and wind speed respectively. An electronic load device (BK Precision 8540) was used for tracking the maximum power point of the tested PV panels. An Agilent 349070A data logger unit was used to log all temperature and electrical data for transfer to a personal computer. The experiment was conducted for one hour under the average ambient temperature of 28 °C, average wind speed of 6m/s and average solar irradiance of 1000 W/m<sup>2</sup>.

#### 4. Results and discussion

The experiment was carried out on a clear sunny day (1000 W/m<sup>2</sup>,  $\pm 10$  W/m<sup>2</sup>), with wind speed of 4 m/s  $\pm 2$  m/s and ambient temperature of 28 °C  $\pm 2$  °C. The PCM-cooled and natural-cooled PV panels were situated beside each other to ensure that they were exposed to similar ambient conditions. For comparative analysis, all electrical data were taken at the mid-points of the experimental periods (30mins) for all PV panel configurations to ensure consistency.

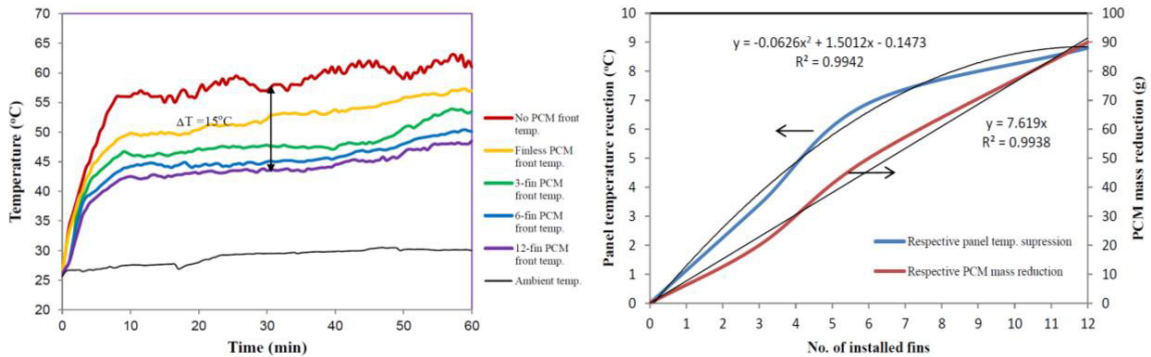


Fig. 4. PV frontal panel temperature of respective PCMTS configurations (left) and effect of installed fins on PV front panel temperature and PCM mass reductions (right).

Fig.4 (left) shows the temperature profiles of all tested front PV panels during a one hour experimental period. The experiment showed that the highest front panel temperature was the naturally-cooled PV panel and the lowest temperature was the 12-fin PV-PCM panel. It was observed that lower PV panel temperature can be achieved with a higher number of installed fins at similar testing conditions. This was due to greater heat transfer surface area of the fins enabling improved melting. There was also a clear indication that all PCM-cooled panels had achieved cooler panel temperatures as compared to the natural-cooled panel during the experiment. The thermal retardation of the PV panels was due to the increase in heat capacity of the rear PV panel by coupling the PCMTS. In addition, the latent heat of fusion of the PCM (184 kJ/kg) had significantly suppressed the temperature rise of the front panel in spite of constant solar insolation. The maximum temperature difference achieved by the 12-fin PV-PCM panel was 15 °C compared to that of the natural-cooled panel. The temperature gaps between the 6-fin, 3-fin and finless PV-PCM panels were 13 °C, 10 °C and 5 °C respectively. There was a consistent effect of lowering the panel temperature with an increasing numbers of metallic fins in the PCMTS containments. Fig.4 (right) shows the relationship of PV front panel temperature and PCM temperature reductions to increasing numbers of installed fins, relative to the finless PCMTS configuration. The graph shows that increasing the number of installed fins does not linearly lower the panel temperature. This is attributed to the effect of diminishing natural convection in the melted PCM within the close fin gaps in the PCMTS containments. The reduction of PCM mass due to the greater number of installed fins is not significant for a ~1000g of PCM filling mass in the PCMTS containment. The 2nd order approximated expression for the panel temperature reduction  $\Delta T_{pv}$  and the linear approximation of PCM mass reduction  $\Delta M_{pcm}$  are given as:

$$\Delta T_{pv} = -0.626(N_{fin})^2 + 1.5012(N_{fin}) - 0.1473 \quad (1)$$

$$\Delta M_{pcm} = 7.619(N_{fin}) \quad (2)$$

Occasional higher speed winds contributed to the significant temperature fluctuation on the natural-cooled panel. The PV-PCM panels showed a small fluctuation of the front panel temperature during the windy period but still can be considered “insensitive” despite the small temperature drop (within 1-2°C). This shows that a natural-cooled panel may have better cooling performance under windy conditions because of higher convective heat transfer. However, the wind speeds during the experimental period were between 4-6 m/s which had little impact on the PV cell cooling. The results have confirmed the capability for constant cooling as indicated by the small temperature fluctuations of the PV-PCM panels even when there was a change in ambient conditions.

Fig.6 (left) shows the electrical current and voltage output (I-V) plots of all tested PV panel configurations. Generally, the results have clearly indicated that low panel temperature provides greater gain in voltage output compensated by a little drop in current output. Conversely, a hotter panel has a little gain in current output but a significant drop in voltage output. Because of the imbalance between the gains in voltage and current outputs, the cooler PV panels will generate more electricity than the hotter panels.

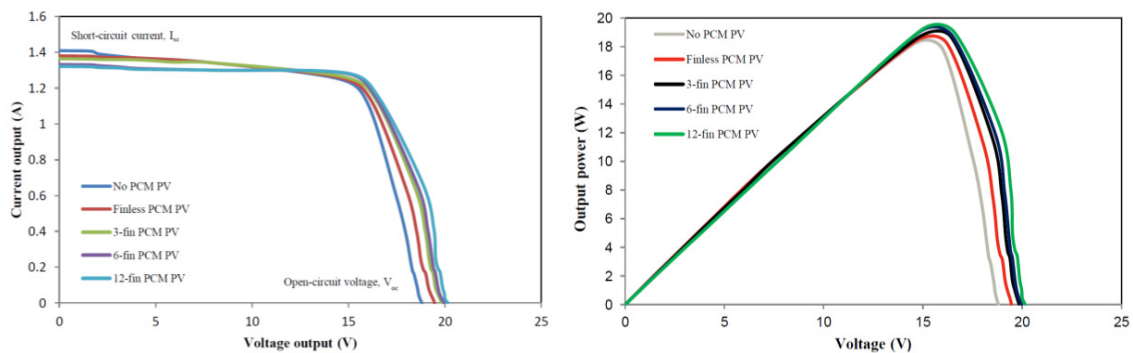


Fig. 6. I-V plots of respective PV with installed PCMTS configuration comparison (left) and Power curve of respective PV with installed PCMTS configuration comparison (right).

Fig.6 (right) shows the power curves of the respective panel configurations. The 12-fin PV-PCM panel was able to deliver higher output power (19.14 W) compared to the naturally-cooled panel (18.16 W). The electrical conversion efficiency was 5.39 % which was higher than for the natural-cooled PV panel. The rest of the PCM-cooled panels of 6-fin, 3-fin and finless PV-PCM panels had achieved 3.44 %, 2.92 % and 1 % power improvement respectively. This is because of the protection from voltage decrease by maintaining lower temperature by using the high heat capacity PCM. It is also interesting to observe that a finless type of PV-PCM panel was able to increase the electrical power output by 1 % relative to the naturally-cooled PV panel without any heat transfer area enhancement. Hence, the PCM plays a major role in passive cooling the heated PV panels by melting (heat absorption).

## 5. Conclusion

This work presents an experimental investigation into improving PV power generation using the PCMTS passive cooling approach. Two identical PV panels were used in the experimental assessment. The results show that the PV-PCM panel was able to reduce the panel temperature by 15 °C (12-fin configuration) compared to the naturally-cooled PV panel. In addition, the maximum electrical conversion efficiency improvement of 5.39 % was achieved by the proposed cooling approach. Hence, PCMTS has proven to be capable of limiting the PV cell temperature under constant solar insolation. In spite of having good passive cooling performance, the existing PCMTS orientation on the 45° upward facing PV panel has limited the heat transfer performance. This is because the heat source which was provided by the sun was situated at the top side of the PCMTS containment where the natural convection heat transfer effect was not optimal. Natural convection current is driven by buoyancy and gravity wherein the temperature of the

PCM plays an important role in density transition. Because the liquid PCM has lower density than the solid PCM, the present orientation of the PCMTS has greatly hindered the natural convection effect within the PCM. Hence, the best orientation for utilizing natural convection heat transfer is by placing the heat source at the bottom region of the PCMTS. The proposed orientation is not possible for a conventional PV system for power generation but it is possible for a low solar concentration parabolic reflector system.

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