Phase Change Materials for Thermal Control of Building Integrated Photovoltaics: Characterisation and experimental evaluation

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Abstract

For silicon solar cells, the associated elevation of operating temperature reduces electrical power output, yielding a temperature coefficient of -0.4 to -0.5%/K beyond their characterisation temperature. Since silicon solar cells are characterized at 1000 W/m$^2$ and 25 °C, maintaining the cell temperature at 25 °C can retain the rated efficiency of the cell. In the most common passive approach to heat dissipation, a duct arranged behind the PV module or its mounting system allows natural convection and wind induced air-flow from the back of the PV panel. This method of cooling is inherently limited due to the poor heat transfer properties of air in natural ventilation therefore the heat dissipation effect is not satisfied. The accrual of airborne dust in inlet grilles and on duct surfaces further reduce the rate of heat transfer from the PV thus yields high operating temperatures for PV in real conditions. As a novel method to regulate the rise in PV temperature, phase change materials (PCM), which absorb energy as latent heat at a constant phase transition temperature, are employed. The phase change materials undergoing solid-liquid phase transition at or close to 25 °C can absorb the excess thermal energy during phase change, which otherwise would raise PV operating temperature, and can maintain the PV operating temperature at or close to 25 °C.

The most suitable PCM for this application with respect to melting point, latent heat of fusion and thermal conductivity were selected and characterized using Differential Scanning Calorimetry and Temperature History Method. The characterisation results are reported for paraffin wax RT 20, salt hydrate SP22 and CaCl$_2$, eutectics of capric-lauric acid and capric-palmitic acid. The temperature evolution on a polycrystalline silicon PV cell was recorded for insulations of 500 W/m$^2$, 750 W/m$^2$, 1000 W/m$^2$. Experimental integrated PV/PCM systems were fabricated and the temperature evolution on the system was recorded where the system was filled with different types of PCM and different insolation. The temperature evolution on PV cell and PV/PCM system and the temperature regulation effect are presented in this paper.
Introduction

Crystalline silicon photovoltaics (PV) show a decrease in power output by 0.4-0.5 \%/K when operating at temperature above 25 °C (Krauter, 1994). Radziemska and Klugman, 2002 and Radziemska, 2003 found that although the increased temperature of the PV cell increases marginally short circuit current yet decreases substantially the open circuit voltage yielding a net decrease in the power output of the PV cell. Based on the I-V curves the power output as a function of temperature at different irradiation was determined and -0.65 \%/K decrease in power output of the PV module was calculated (Radziemska 2003 ).

Phase change materials (PCM) have been used as heat sink for thermal management of electronics (Shankar et al., 2005) and compact heat sink when PCM are filled in aluminium foam (Sung and Herling, 2006). PCM integrated with PV were modelled with experimentally validated finite volume heat transfer model (Huang et al., 2004). The temperature evolution on the front surface of integrated PV/PCM system and temperature distribution inside the system was predicted. The PV/PCM system was experimentally evaluated with different configurations of metallic fins inserted in the PV/PCM rectangular container to enhance heat transfer by Huang et al., 2006a. A small scale 3D model was developed and validated with experimentally validated 2D model for temperature regulation of PV using PCM (Huang et al., 2006b). Hasan et al., 2007 integrated the PCM into real PV and experimentally evaluated eutectics of fatty acids (capric-lauric acid) as PCM for thermal regulation of PV.

Selection of the PCM

<table>
<thead>
<tr>
<th></th>
<th>RT20</th>
<th>CL</th>
<th>CP</th>
<th>CaCl2.6H2O</th>
<th>SP22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting onset, °C</td>
<td>21.23</td>
<td>20.78</td>
<td>22.33</td>
<td>29.17</td>
<td>22.97</td>
</tr>
<tr>
<td>Melting peak, °C</td>
<td>25.73</td>
<td>24.66</td>
<td>26.4</td>
<td>29.66</td>
<td>24.6</td>
</tr>
<tr>
<td>Heat of fusion, kJ/kg</td>
<td>240.3</td>
<td>171.98</td>
<td>196.07</td>
<td>213.12</td>
<td>182</td>
</tr>
<tr>
<td>Thermal conductivity, W/m-K</td>
<td>0.2</td>
<td>0.139-0.143</td>
<td>0.139-0.143</td>
<td>1.09</td>
<td>0.6</td>
</tr>
<tr>
<td>Density solid, kg/l</td>
<td>0.87</td>
<td>0.88</td>
<td>0.883</td>
<td>1.71</td>
<td>1.38</td>
</tr>
<tr>
<td>Density liquid, kg/l</td>
<td>0.75</td>
<td>0.863</td>
<td>0.84</td>
<td>-</td>
<td>1.378</td>
</tr>
<tr>
<td>Volumetric expansion, l/kg %</td>
<td>10</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Sub-cooling, °C</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Specific heat capacity, kJ/kg-K</td>
<td>1.8-2.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table1: The Thermophysical Properties of the PCM

Based on thermophysical properties of the PCM, five PCM were selected and thermophysical properties of melting onset, melting peak, heat of fusion and super cooling/subcooing of the PCM were confirmed by differential scanning calorimetry
(DSC) and temperature history method (THM) given in the table 1 (Hasan et al., 2008).

**Experimental Setup and Procedure**

Polycrystalline silicon PV cells with surface area dimensions of 10 cm x10 cm were encapsulated between two sheets of 3mm thick transparent perspex to simulate a cell size section of the PV module. Four types of rectangular containers were fabricated and were integrated into the back of PV to obtain PV/PCM systems illustrated in the figure 2 below (all dimensions in mm):

![Figure 1: Fabricated low conductivity perspex 3cm³/cm² (A), low conductivity perspex 5cm³/cm² (B), high conductivity aluminium 3cm³/cm² (C) and high conductivity aluminium 5cm³/cm² PV/PCM systems.](image_url)

The objective is to evaluate the performance of PCM contained in thermally insulating perspex boundary surfaces compared to thermally conductive aluminium boundary surfaces. The aluminium plates were welded together while the perspex sheets were glued with epoxy resin araldite to make PCM containers. The welded aluminium surface has an advantage of being leak free during PCM melt-freeze cycles while the glued perspex surfaces shows leakage after few melt-freeze cycles due to degradation of glue by the reactive PCM inside the container.

The temperature on the PV front surface was measured with five copper-constantan T-type thermocouples attached on the front surface of the PV section shown in the figure 2. The insolation level was measured with the Kipp and Zonnen CM6B pyranometer with a maximum spatial intensity distribution of ±2 %.
A reference test was undertaken by irradiating the PV section with Griven GR262 solar simulator at insolation levels of 500W/m$^2$. The average temperature evolution on the front surface of the PV section was recorded using delta-T data logger until the average temperature reached steady state. The paraffin RT20 PCM was melted, filled into the PV/PCM system, cooled until the PCM was fully solid, irradiated at 500W/m$^2$ and average temperature evolution on the front surface of the PV/PCM system was recorded. After the PCM was fully melted, the test was completed when the average temperature reached the steady state temperature of the reference test. The experiment was repeated at insolation levels of 750 W/m$^2$ and 1000W/m$^2$ with the same PCM. The experiments were undertaken for all PCM samples with all four PV/PCM containers at three insolation levels (500W/m$^2$, 750W/m$^2$ and 1000W/m$^2$).

**Temperature Control Potential of PCM**

In order to observe the deviation of temperature evolution using PCM from the temperature evolution without PCM, giving the temperature control potential of each PCM, the difference of the two curves is plotted for each PCM for different PV/PCM systems.

The representative curves given in figures 4a - d show the nature of deviation at 1000W/m$^2$ insolation level for all PCM indicating that for both 3cm$^3$/cm$^2$ and 5cm$^3$/cm$^2$ an increase in area of the curve is observed when moving from low conductivity containers to high conductivity, indicating an increased temperature control potential. Generally, capric-lauric acid and capric-palmitic acid perform better in high conductivity containers (4b and 4d) than low conductivity containers (4a and 4c). The second observation is that at this higher insolation level for both the low and high conductivity 3cm$^3$/cm$^2$ containers CaCl$_2$.6H$_2$O and SP22 reach the steady state temperature in shorter time (6-7) hours while for 5cm$^3$/cm$^2$ container they reach steady state temperature in longer time (9-11) hours.
Figure 4: Deviation of temperature evolution curve for each PCM from the reference curve at 1000W/m² for 3cm³/cm² low conductivity PV/PCM system (a), 3cm³/cm² high conductivity PV/PCM system (b), 5cm³/cm² low conductivity PV/PCM system (c) and 5cm³/cm² high conductivity PV/PCM system (d)

**Effect of insolation on melting time**

The time taken to reach steady state is an important indicator of the temperature control performance of certain PCM at particular insolation levels with different PV/PCM containers. The average day length is taken as 8 hours with ±2hrs considering varying day length depending on time of the year and the PCM is required to reach steady state temperature within this range to complete heat absorption. The PCM completing heat absorption within 8 ± 2hrs are considered to be performing optimally while those outside this range are not optimum.
Figure 5: Time to reach steady state for $3\text{cm}^3/\text{cm}^2$ volume to surface area low conductivity PV/PCM (A), $3\text{cm}^3/\text{cm}^2$ volume to surface area high conductivity PV/PCM (B), $5\text{cm}^3/\text{cm}^2$ low conductivity PV/PCM (C) and $5\text{cm}^3/\text{cm}^2$ high conductivity PV/PCM (D) systems.

**Conclusion**

The experimental results show that the PCM has a potential for temperature control of building integrated photovoltaics (BIPV). Different materials were evaluated at different insulations representing different geographical locations and it was found that a PCM performing optimally at one insolation level may not be optimum at another insolation level. Four different PV/PCM systems were fabricated and the effect of size and design of the container on PCM performance was evaluated. It was found that the thermal conductivity of the PCM and that of the PV/PCM system has a significant effect on the temperature control potential and melting characteristics of PCM which shows that by improving thermal conductivity of the PV/PCM system further temperature regulation can be achieved.
Acknowledgements

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References


