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Investigation on designed fins-enhanced phase change materials system for thermal management of a novel building integrated concentrating PV

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HIGHLIGHTS

- Design and develop a PCM system for a building integrated CPV thermal management.
- Experimental and numerical investigations of a building integrated CPV/PCM.
- Evaluation of the effects of vertical and horizontal fins on enhancing the heat transfer for PCM.
- The developed PCM system can improve the PV efficiency by over 12%.

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ABSTRACT

The solar to electrical conversion efficiency of the silicon based photovoltaics (PV) system decreases with its temperature increase, therefore, the thermal management of PV becomes important to improve PV power generation. In this paper, a designed Phase Change Material (PCM) system is integrated into the rear part of a novel building integrated concentrating PV system to moderate its temperature rise. The heat transfer of the developed concentrating PV/PCM system has been studied experimentally and numerically. A numerical 3D model was developed to predict the temperature distribution of the PCM during the phase change process and the predicted results agreed well with the experimental measurement. It was found that the addition of the PCM system to the concentrating PV system can reduce during the phase change process the solar induced temperature rise by over 20 °C. This can lead to approximate 10% increase in solar to electrical conversion efficiency. Furthermore, numerical simulations have been carried out to optimize the heat transfer within the PCM through installing horizontal and vertical aluminium fins with different thicknesses. It was found out that, both, the horizontal and vertical fins can improve the thermal performance of the PCM system. In addition, the system with vertical fins shows better performance on maintaining the temperature of the PV cells. At a solar irradiation exposure of 670 W/m^2 the PCM system, enhanced by vertical fins, can reduce the temperature of the concentrating PV system during the phase change process by 25 °C, when compared to the PV system without PCM.

1. Introduction

For commercially available photovoltaics (PV), approximately 5–25% of incidental solar energy can be converted into electricity, excluding reflection on the front surface, while the remaining solar energy is transformed into heat [1]. This increases the PV temperature, which leads to permanent degradation over time [2] and may shorten the lifespan of the PV modules [3]. The reduction of electrical conversion efficiency with increasing working temperature depends on the type of solar cells' material. For a crystalline silicon based PV, the solar to electrical conversion efficiency reduces by 0.5% with 1 K temperature increase, those are 0.21%, 0.25% and 0.32–0.36% for a-Si, CdTe or CIGS based PV respectively [4]. Therefore, it is important to moderate the PV temperature to enhance PV performance. It is common to use air or water to cool PV devices to maintain good electrical conversion efficiency. Tiwari et al. [5] mentioned that in the current market the use of hybrid photovoltaic thermal (HPVT) systems, to improve electrical efficiency, is more competitive than a stand-alone PV. For instance, Armstrong et al. [6] studied the thermal model of the photovoltaic panels under different wind speeds. The results showed that the wind speed has an effect on the surface heat transfer coefficient of the PV panels and changes their thermal performance. The performance of the PV module can be improved by 4–6% when installing a parallel array of air ducts with inlet/outlet manifold designed at the rear of the module

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Nomenclature

A_{mush}	mushy zone constant
C_p	specific heat capacity (J/ kg K)
g	gravitational constant (m/s^2)
H	enthalpy (J)
$H_{conv,amb}$	convection heat transfer coefficient from back aluminium plate to atmosphere (W/m^2 K)
k	thermal conductivity (W/m K)
L	latent heat of paraffin
P	pressure (Pa)
$\vec{S}$	momentum source term
$\overline{T_c}$	average temperature (K)
T_o	reference solar cell temperature (K)
T	temperature (K)
T_c	thermocouple
t	time (s)
V_W	wind velocity (m/s)

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
α	liquid fraction
β	expansion coefficient
Δ	difference

Subscripts

l	liquid phase
s	solid phase
amb	ambient
ref	reference
conv	convection

[7]. Gaur et al. [8] found out that a 7% efficiency increase can be achieved with the integration of a water thermal collector, when compared with a counterpart PV system. Castanheira et al. [9] investigated the use of water spray for PV cooling and found out that it can increase the annual energy production up to +12%. To enhance the heat transfer performance, the micro-encapsulated phase change material (MPCM) slurry based PV/T system has also been studied to determine the most suitable MPCM concentration [10]. Su et al. [11] explored a tracking-integrated concentrating photovoltaic-thermal (CPV-T) system with immersed encapsulated PCM spheres and water for system cooling. The results showed that the average increases of the electrical, thermal, and overall efficiencies for the CPV-T system with PCM are 10%, 5%, and 15% higher, respectively, than those for CPV-T system with water. Sharma et al. [12] used phase change materials to enhance the performance of low-concentration Building-Integrated Concentrated Photovoltaic system. The average PV temperature is 3.8 °C lower than a naturally ventilated PV system without PCM. Tian et al. [13] analyzed different PV-T collectors. It was found that the PV-T system can produce 10–40% more power than PV alone. However, the use of active systems to cool PV modules does not only increase the complexity of the devices, but also increases the maintenance and operation costs.

The passive temperature-regulating technique for PV cells requires less maintenance and operation costs [14]. PCM with high energy storage density and capabilities of maintaining almost constant temperature is a good strategy for passive PV temperature moderation [15]. Browne et al. [16] designed a PV/T system where the heat is removed by a heat exchanger embedded in PCM through a thermosiphon flow. Huang et al. [17] studied the PV/PCM system and suggested that PCM can alleviate the temperature rise of PV cells and lead to the improvement of operation efficiency. Biwole et al. [18] numerically studied a PV/PCM system, it was found that the PV/PCM system can keep the operating temperature of the solar panel under 40 °C for 8 min under a constant solar radiation of 1000 W/m^2. Hasan et al. [19] used two types of phase change materials (a salt hydrate, $CaCl_2 \cdot 6H_2O$ and a eutectic mixture of fatty acids, capric acid–palmitic acid) for PV cooling under two different climates. Maiti et al. [20] used a paraffin wax with 56–58 °C melting range as phase change material at the back of a V-trough PV module, to absorb the excess heat. When irradiation was 2300 W/m^2, the module temperature can be maintained at 65–68 °C for 3 h, while the temperature of the solar module without PCM rose beyond 90 °C within 15 min. Klugmann-Radziemska et al. [21] used paraffin, with a phase change temperature of 42–44 °C, to cool PV modules. This allowed to maintain the operation temperature for more than 5 h 7 °C lower than PV modules without PCM. Park et al. [22] tested the vertical PV module with and without PCM and concluded, that the maximum electrical conversion rate of the system can be increased by almost 3% using PCM. Smith et al. [23] analyzed the annual energy output of a PV system with integrated PCM layers, which worked as a heat sink, to limit the temperature rise of PV cell, thereby, increasing efficiency of the PV system from 2% to 6%.

The low thermal conductivity of PCMs is a well know issue. Heat conducting fins have been used in previous work to improve the thermal performance of PCMs. Tan et al. [24] conducted a numerical study investigating the thermal and electrical performance of PV system which were cooled by using metallic fins enhanced paraffin wax, with a melting point of 27 °C. The results showed that PV/PCM system with a 12-fin configuration can reduce PV temperature by 15 °C and increase the power conversion efficiency by 5.39%, compared to naturally air cooled PV systems. Emam and Ahmed [25] investigated the thermal performance of a concentrating photovoltaic system with four types of PCM heat sink configurations. The study concluded that increasing the number of fins leads to a significant reduction in the solar cell temperature. The optimization of the patterning of PCMs also plays an important role in thermal regulation of Concentrating PV-PCM systems. A number of researchers [26,27] have reported on the use of expanded graphite (EG) enhanced paraffin as PCM for PV temperature moderation. With this modification the temperature of the PV-PCM panel can be kept below 50 °C for 200 min (extended by 146 min when compared with that of the PV-PCM without EG) with the average ambient temperature under 25 °C and the irradiation of 901 W/m^2. Meanwhile, the output power was increased by 7.28% during the heating process [26]. Although the expanded graphite can enhance the thermal conductivity by several times, their own structure blocks the formation of natural convection of the PCM. Therefore, the overall heat transfer performance of the EG applied PCM needs to be further improved. Sharma et al. [2] investigated the heat transfer of building-integrated concentrated photovoltaics incorporating micro-fins, phase change material and nanomaterial enhanced PCM (n-PCM). The study found, that in comparison to PV alone system, the average temperature reduction of PV was 9.6 °C for PCM and only 12.5 °C for micro-fins with n-PCM, respectively.

From the aforementioned research, it can be concluded that the pattern of natural convection plays an important role in the melting process of PCMs. Most researchers designed the PCM container and PV cells with the same height. However, a major problem with this kind of application is that when the PCM is under melting process, the hot melted PCM stays close to the PV cells, and the upper part of the container blocks the heat transfer between the PV and the unmelted PCM. This behavior of the system cancels out the advantage of the temperature control for the PCM during the phase transition. There is a need for higher temperature difference to transport heat from the PV cells through the hot melted PCM to the unmelted PCM. Therefore, in