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Research Paper

Thermal and electrical performances of a water-surface floating PV integrated with double water-saturated MEPCM layers

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HIGHLIGHTS

- We made water-surface floating PVs integrated with double water-saturated MEPCMs.
- Solar cell temperature control capabilities and PV generation efficiencies were investigated.
- A 5 cm/5 cm–30 °C/26 °C MEPCM-PV increases the electricity generation by 2.03%.

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ABSTRACT

In the present study, two water-saturated microencapsulated phase change material (MEPCM) layers are attached to the back of a photovoltaic (PV) to form a MEPCM-PV module, which then floats on the water surface. Numerical simulation is used to analyze the effects of the MEPCM layers on the temperature control of the solar cell and the power generation efficiency of the PV module during the day under local climate conditions. The results show that compared to the PV module without any MEPCM layers, the thermal and electrical performance of the MEPCM-PV module increased significantly. Compared to the untreated PV module, the power generation output of the MEPCM-PV module with a 3-cm-thick top MEPCM layer with a melting point of 30 °C and a 3-cm-thick bottom MEPCM layer with a melting point of 26 °C (3 cm/3 cm–30 °C/26 °C MEPCM-PV module) increased by 1.48%, and the power generation output of the 5 cm/5 cm–30 °C/26 °C MEPCM-PV module increased by 2.03% during the summer.

1. Introduction

The temperature of a solar cell is associated with the efficiency of solar irradiation energy that is converted into electricity. The efficiency of a photovoltaic (PV) module decreases as the solar cell temperature increases. A study conducted by Skoplak and Palyvos [1] shows that the generation efficiency of a typical crystalline-silicon solar cell decreases by 0.45% for every 1 °C increase in the temperature of the solar cell. Therefore, whenever possible, it is beneficial to enhance the heat dissipation of a PV module [2].

There are two common methods used to control the solar cell temperature: an active or a passive temperature control system. An active system removes heat from a solar cell by directly pumping water or air through the solar cell; however, it requires external energy. A passive system removes heat from a solar cell by using physical principles that do not require external energy, such as the natural convection of air or water.

Many studies have attempted to improve the generation efficiency of a PV module by using an active cooling system. Ueda et al. [3] placed one PV module on a lake surface and another PV module on the ground; lake water was pumped and sprayed onto the surface of the PV module on the lake surface during the day, and the temperature of the PV module on the lake surface was 20 °C lower than that of the PV module that was on the ground during the day. The daily generation outputs of the PV module on the lake surface and that on the ground were 61.4 kW-hr/day and 54.6 kW-hr/day, respectively, and the power required by the pump was 27 kW-hr/month. Teo et al. [4] designed a PV system in which copper cooling fins were attached to the back of the PV panel and air was pushed by a pump through the fins to remove heat; the power required by the pump was partially supplied by an external power source and partially supplied by the power generated by the PV panel. Simulation results showed that the surface temperature of the PV panel decreased by approximately 30 °C when the airflow rate was 0.055 kg/s. Airflow rates exceeding 0.055 kg/s had no significant impact on the generation efficiency and temperature control of the PV panel. Valeh-e-Sheyda et al. [5] attached copper cooling fins to

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the back of a PV panel and then used air and water to actively control the temperature of the PV panel. The results showed that when the water flow rate was fixed (92 mL/min), the PV panel achieved its highest generation efficiency and the power output increased by 38% when the airflow rate was 2.69 m/s; a higher airflow rate could result in an increase in the amount of heat removed by the airflow but could also decrease the cooling effect of the water.

During the melting or solidification processes, a Phase Change Material (PCM) can effectively store or release a large amount of latent heat. The temperature of the PCM can be maintained during the latent heat transfer process. Therefore, PCM is a very promising material for energy storage and for controlling the thermal environment.

Waqas and Kumar [6] integrated a solar collector with a multi-layered sheet-shaped PCM unit. The PCM unit was used to store the solar heat collected during the day and release the heat at night through the PCM solidification to address problems such as sudden temperature drops and dry and cold conditions during winter nights. It concluded that the closer the phase change temperature was to the temperature that was to be maintained, the better the performance of the storage unit, the lower the flow rate of the working fluid in the system, and the better the performance of the storage unit. Relatively high working fluid flow rates resulted in the acceleration of the phase change process. Jin et al. [7] placed a PCM inside the walls to improve the thermal inertia of the building envelope and analyzed the effect of the location of the PCM relative to the heat source on the temperature control capabilities of the system. It discovered that the closer the PCM was to the controlled end, the better its performance. Based on data of summer weather from the UK, Huang [8] used PCMs to control the temperature of a PV panel. The used prototype in Huang's study was a PV panel with an aluminum rectangular container containing two types of PCMs with different melting points attached to the back. Thin aluminum plates were used to separate and shape the two types of PCM: one type of PCM was formed into a triangular shape, while the other type of PCM was formed into a semi-circular shape. The entire system was placed vertically such that solar radiation was incident on the PV surface and there was natural convection between the back of the PV system and the ambient air; the top and bottom surfaces of the PV system were assumed to be insulated, and natural convection was assumed to be occurring inside the PCM system when the PCMs were melting. The results showed that optimum performance was achieved when using a combination of one PCM with a melting point of 27 °C and one PCM with a melting point of 21 °C, and an extra power output of 0.45 kW-hr/m^2 could be generated every day using such a combination of PCMs (the reference daily power output of a PV cell is 1.4 kW-hr/m^2).

Tanuwijava et al. [9] investigated the heat transfer characteristics and thermal management performance of dry-packed microencapsulated phase change material (MEPCM) modules for photovoltaic applications under temporal variations of daily solar irradiation via computational fluid dynamics simulations. The results show that incorporating the appropriate MEPCM layer can improve the thermal and electrical performances of the photovoltaic module. The melting temperature and aspect ratio significantly affect the thermal and electrical performances of the PV module. Ho et al. [10] used a numerical simulation to investigate the thermal and electric performances of a PV module with a water saturated MEPCM layer. When the MEPCM layer was at an adequate thickness, it provided optimum control over the temperature of the PV module under different climatic conditions. Comprehensive reviews on PCMs, including their thermophysical properties, long-term stability, impregnation methods, current building applications, and their thermal performance analyses, as well as on numerical simulations of buildings with PCMs, can be found in the literature [11–13].

There have been few studies on the thermal control of PV modules through the incorporation of MEPCMs and bodies of water. Every PCM undergoes the phase change process within a specific range of temperatures. The phase change process of a single PCM can only occur within a very small temperature range; therefore, the use of a single PCM will be limited when there is a relatively large change in the ambient temperature. In the present study, two types of MEPCMs with different melting points were stacked to increase the period of time during which the phase change process can occur. Metal frames were used to separate the two types of MEPCMs. The heat transfer rate inside the MEPCM-PV module increased due to the heat bridge effect of the metal frames. Then the double MEPCM layers were attached to the back of a PV panel to form a MEPCM-PV module, which was then floated on the surface of a body of water. Numerical simulation was used to analyze the temperature control efficiency of the MEPCM-PV module and the generation efficiency of the PV panel based on the summer and winter climate conditions in Taiwan.

2. Problem formulation

Two MEPCM layers were attached to the back of a PV panel to form a MEPCM-PV module, which was then floated on the surface of a body of water. As shown in Fig. 1, the blue portion on the topmost surface represents solar cells; the brown portion represents the metal container that is filled with MEPCMs; and the gray portion represents the two MEPCM layers. (For interpretation of the references to color in this text, the reader is referred to the web version of this article.) $G_s(t)$ represents the solar irradiance that changes over time; $T_{amb}(t)$ represents the ambient temperature that changes over time; $T_{sky}(t)$ represents the sky temperature that changes over time; $T_{water}(t)$ represents the water temperature that changes over time; $h_{amb}(t)$ represents the heat convection coefficient of air that changes over time; and h_{water} represents the heat convection coefficient of water. The solar cell has a length of H, a width of H and a thickness of δ_{PV}. Each of the two MEPCM layers has a length of H, a width of H and a thickness of W. The top, middle and bottom frames inside the module all have a thickness of W_{pt}. The left and right frames both have a thickness of $H_{pt}/2$.

2.1. Mathematical model

2.1.1. Basic assumptions for the mathematical model

(1) In practice, we connected several solar cells in series and parallel to form an array. Therefore, the area around a single solar cell was assumed symmetrical.
(2) The heat transfer along the thickness of the solar cell was neglected.
(3) The glass at the boundary of the solar cell was an isotropic medium, and its thermal and physical properties were constants.
(4) The solar irradiation on the solar cell, $G_s(t)$, was evenly distributed.
(5) The heat radiation absorptivity of the solar cell surface, $\alpha_{r,pv}$, was constant.
(6) The thermal and physical properties of the material inside the pores of the MEPCM layer (water) were constant.
(7) The MEPCM layer was treated as evenly distributed and as an isotropic porous material that was filled with water with a porosity of ϕ_f.
(8) The MEPCM was treated as a sphere with an even particle diameter of d_p^+. However, for the phase change process, the MEPCM maintained a thermal balance with the material inside the pores (water).
(9) The enthalpy approximation model [14] was used for the solid–liquid phase change process of the MEPCM.