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Potential of water natural circulation coupled with nano-enhanced PCM for PV module cooling

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A R T I C L E I N F O

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This paper introduces a new photovoltaic module passive cooling system that works with natural cooling water circulation. The heat was removed from cooling water by a PCM-based cooling system. A special zig zag geometry of PCM container was considered to increase the heat transfer surface. At the first stage of experiments, a composed oil consisting of 82 wt% coconut oil and 18 wt% sunflower oil was used as PCM. Then, in order to increase the performance of heat transfer between PCM and cooling water, the composed oil was mixed with Boehmite nanopowder (0.009 (w/w)). The cooling performance of the composed oil and nano - composed oil was assessed by monitoring the temperature and the generated electrical power of the panel at various radiation intensities. The results reveal the reliability of the proposed system for cooling of the PV module without need to any pumping system. Moreover, the results show that using nano - composed PCM is more efficient than the plain one. The highest increase in the maximum produced power relative to the reference case were obtained in the presence of nano - composed oil, which were 44.74, 46.63, 48.23% at the radiation intensities of 410,530,690 W/m^2, respectively.

1. Introduction

In the last decades, solar energy has attracted increasing attention as a renewable, clean and cheap energy source [1,2]. Photovoltaic (PV) technology is a cheap method for electricity production in which solar energy is transformed into electricity [3]. Around 80–85% of solar radiation attracted by PV panel is wasted as heat and the residue is transformed into electrical energy [4]. This leads to an increase in PV panel temperature and so decrease in its efficiency [5]. One of the important issues in the photovoltaic industry is solar panel efficiency enhancement, which is reached by decreasing its temperature [6,7]. Therefore, introducing efficient cooling techniques to extract heat from PV panels must be taken into consideration [8,9]. Heretofore, various studies have been carried out to reduce the PV panel temperature [10,11]. The suggested techniques for PV panel cooling are sorted into active and passive methods. In the active techniques, additional power is needed for the PV panel cooling. However, no external power is needed for passive cases [12]. No need to input power makes the passive cooling methods more popular [13]. Investigators have proposed various reliable and practical passive cooling techniques to control the PV panel temperature. For instance, the potential of a passive cooling method for heat extraction from solar panel was studied by Tina et al. [14] in an experimental investigation. In this study, the solar panel was directly immersed in water in real sunlight. In the water immersion method, the layer of water acts as a selective filter for different wavelengths of sunlight. The considered water depth above the PV panel changed from 1 cm to 15 cm. The highest growth in generating power was achieved at a depth of 5 cm. A passive cooling system based on natural air convection was introduced by Chen et al. [15] for increasing the electrical efficiency of the PV panel. In this cooling system, U-shape and L-shape aluminum fins were mounted behind the panel. It was found that by increasing the module slope, the efficiency was increased at the beginning and then decreased.

One of the most favorite PV cooling methods is using PCM, which was first proposed by Slultz and Wren [16]. The cooling capacity of a PCM is attributed to its high latent heat of fusion. In the melting process of a PCM, a large amount of energy is absorbed as latent heat of fusion. A PCM by absorbing large amounts of heat in a cooling system leads to enhancing its efficiency. Choubineh et al. [17] introduced a hybrid PV cooling system consists of phase change material (PCM) and natural air convection. A PCM plate was placed under the PV panel and an air duct was located next to it. The outputs revealed that the PCM presence in the system leads to

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decreasing the PV module temperature to 4.3 °C when air flows naturally through the duct in the morning. Thermal conductivity and so the cooling performance of a PCM can be increased by mixing it with metal or metal oxide nanoparticles. Siahkamari et al. [2] used sheep fat as a new PCM for PV panel cooling. The rear chamber of the panel was filled with the PCM and metal tubes in which water was flowing were posited into the PCM. CuO nanoparticles were added to the PCM to enhance the cooling performance of the sheep fat. It was found that the output power of the panel in the presence of the cooling system was increased 24.6%–26.2% in comparison with the plain one.

Another class of passive PV cooling methods is using a heat pipe in which no external power is needed for working fluid movement. Heat pipe contains three parts; evaporator, adiabatic part and condenser [18]. In this method, heat extraction from the PV panel is done by embedding the evaporator part of the heat pipe behind the panel. Chen and Yang [19] proposed a hybrid system made of a panel and a heat pipe. They studied the effects of the working fluid and the pattern of the condenser's fins on heat transfer. The outputs show that acetone is the best working fluid compared to water and ethanol. Also, it was seen that heat extraction from the PV panel increased by decreasing the fins interval.

In a PV cooling system suggested by Ebrahimi et al. [20], moist air above the rivers and water ducts were considered as a coolant. The moist air and sunlight were simulated in this experimental investigation. They studied the effects of flow rate and distribution of the moist air, which encountered the rear part of the panel vertically. Based on the obtained data, the highest increase in panel efficiency can be reached by optimizing the numbers of distributors and increasing the moist air flow rate.

Despite extensive studies on PV passive cooling, still more researches are needed to use PVs as practicable devices for producing electricity. Accordingly, the motive behind this study is to devise an effective passive cooling method for PVs based on combined of natural water circulation and PCM. In the proposed cooling system, natural water circulation was formed as a result of buoyant force, without using external power. Besides, a PCM-based cooling system was used to remove the heat of the cooling water in the circulation. To the best of our knowledge, this hybrid system is a novel idea in PV cooling systems. In order to enhance the cooling effect of PCM, the PCM was mixed with Boehmite nanopowder. The experiments were conducted in the presence of PCM and nano-PCM at different radiation intensities. To survey the performance of the introduced cooling system, the average panel temperature and generated power of the panel were measured. The effects of related factors on the performance of the PV module will be discussed.

2. Experimental work

In the present study, a passive cooling system based on natural water circulation was used to cool the PV module, without need to any external power. A new PCM was prepared from a mixture of two types of oils mixed with a proper nanoparticle. This PCM was employed to remove heat from the PV module.

2.1. Methodology description

The goal of a free energy system for cooling PV panels is achieved by using natural water circulation and a PCM-based cooling system. Upward natural water flow is formed as a result of buoyant force in the rear duct of the panel. The heat of cooling water flow is removed using a PCM-based cooling system. A mixture of Coconut and sunflower oils are used as a potential new PCM. Coconut and sunflower oils are organic materials and quite environmentally friendly. Also, due to their great latent heat of fusion, their mixtures are suitable to be used as PCM. By mixing different percentages of coconut oil and sunflower oil, various PCMs can be made. Moreover, Boehmite nanopowder was added to the PCM, with the aim of enhancing the cooling efficiency of the system.

2.2. Experimental setup

In order to study the combination of natural water circulation and phase change material, an experimental setup was formed to survey the effect of temperature on the efficiency of the PV panel. The schematic layout and the real picture of the designed system are presented in Fig. 1. The fundamental elements of the solar system are; PV panel, solar simulator, reservoir, PCM container and measuring instruments.

The PV panel is a poly-crystalline silicon PV panel with a maximum power of 10 Watt. The PV panel (ZT10-18-P) with dimensions of $215 \times 320\ mm^2$ consists of 36 cells linked in parallel and series. The Open-circuit voltage (V_{oc}) and Short-circuit current (I_{sc}) of the panel are 21.96 V and 0.59 A, respectively.

A passageway for water flow was created behind the module by attaching glass to the aluminum frame of the panel. Besides, to diminish the dead zones at the back of the module, three inlets and outlets were created for the duct. 9 K-type calibrated thermocouples with the precision of ±0.75% were fixed at the top face of the panel, as displayed in Fig. 2, to gauge the temperatures of different points of the PV module surface. The silicone rubber glue was used to fix the thermocouples on the panel surface as well as to eliminate the effect of the surrounding temperature on the PV surface temperature values.

Moreover, temperatures of the inlet and outlet of the duct as well as PCM in the container were measured with three other thermocouples. A thermometer (Lutron, BTM-4208SD) with the precision of ±0.4% was used to measure the temperatures. In order to measure the voltage of the panel at various requested electrical currents, an electrical load system with the precision of ±0.5% was joined to the DC electrical output of the PV module.

A solar simulator was substituted for natural solar radiation because of the fact that sunshine is not continually useable and is influenced by various parameters. This type of simulator was widely used in other studies [21]. The created solar simulator is equipped with six 400 W Metal Halide (MH) lamps to prepare a continuing spectrum of light. In order to measure the intensity of the entering radiance (I in W/m^2) to the panel, a digital solar power meter (Pyranometer) created by the Testo Company (Tes1333R) was used. It should be mentioned that the radiation intensity was adjusted by putting the cell at a suitable distance from the simulator. The PCM container made up of aluminum, 1 mm thick, was located in the water reservoir. The PCM container was manufactured in a zigzag shape, as illustrated in Fig. 3, to increase the contact surface between PCM and water in the reservoir.

In order to cool the water which flows through the present closed passive cooling system, a composed oil involves 82 wt% coconut oil and 18 wt% sunflower oil, was used as PCM. According to the reported advantages for coconut oil as a PCM in the literature [22], it was decided to use this oil as PCM in a new PV cooling system. A PCM with a melting temperature of about 25 °C was desired, but the purchased coconut oil has a melting point of about 29 °C. So, in order to reach the desired melting temperature, it was mixed with sunflower oil. Finally, a composed oil which contained 82 wt% coconut oil and 18 wt% sunflower oil was selected as proper PCM for this work. This was found by a series of DSC test done on various percentages of these two oils. The DSC (Differential Scanning calorimetry) result of the selected mixture, measured by the DSC200 F3Maia- Germany, is shown in Fig. 4. According to the figure, it was found that the melting temperature and latent heat of