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Maximizing the energy output of a photovoltaic–thermal solar collector incorporating phase change materials

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ABSTRACT

Photovoltaic–thermal collector can simultaneously generate both electricity and heat, making full use of the solar energy. It is worth to increase the electrical output by reducing the operating temperature. An effective method of cooling the cell temperature is incorporating phase change materials into the collector. In order to maximize the energy output and improve the performance of the collector, we perform comparative analyses on a hybrid photovoltaic–thermal solar collector incorporating phase change materials with different melting point. Solar cell temperature, electrical power, electrical efficiency, outlet temperature of water, thermal power output of the collector by varying melting point and thickness of phase change material layer are evaluated using one dimensional energy balance method. The corresponding graphical representations are described to explain the way of maximizing the electrical and thermal energy output of this system. And the numerical results have provided guidance for further experiment. In this theoretical work, it is found that phase change material layer with lower melting point has better electrical properties of the collector, while the heat stored in phase change material layer is more difficult to utilize. The results show that the photovoltaic–thermal solar collector gets a maximum of overall energy output by incorporating 3.4cm-thick phase change material layer with 40 °C melting point. By contrast of the electrical power of 30 °C melting point case and no phase change material case, the biggest value of difference is 16.12 W at 12:00. It means that the electrical power of the collector has increased around 13.6% by incorporating phase change material layer with 30 °C melting point.

1. Introduction

As a clean renewable source, solar energy has good prospects for solving the energy and environment problems in the future. The photovoltaic (PV) technology is currently the most common way of converting the solar energy to electricity directly by using solar cells. For every 1 °C rise in solar cell temperature, the electrical efficiency drops by around 0.45% [1]. Typically, the solar cells using silicon technology convert about 15%–25% of the solar radiation into electricity, and the remaining incident solar energy is converted to heat [2]. In order to enhance the solar cell efficiency and the energy output, it requires a device to remove this waste heat [3].

A practical method to prevent overheating of PV modules is embedding a thermal absorber to remove the exhaust heat. This combined system is known as the photovoltaic thermal (PV/T) collector, which can simultaneously generate both electricity and heat [4]. According to the type of working fluids used in absorber, the PV/T collectors can be divided into three types: air–based PV/T collector, water–based collector and combination of water/air collector. Up to now, several experimental, analytical and numerical studies on the performance evaluation of PV/T collectors have been performed by many researchers. Herrando et al. [5] developed a model to estimate the performance of PV/T systems based on domestic water, and achieved a higher overall efficiency than air–based systems. Slimani et al. [6] presented a PV/T solar collector embedded in an indirect solar dryer system. The calculation results showed that the hybrid PV/T collector provided a more suitable air temperature for drying agricultural products. Shan et al. [7] assessed the performance of a PV/T collector for water heating in building through numerical simulation methods, and the results showed that more number of series–connected PV cells lead to higher outlet temperature and lower electrical efficiency. The configurations of the PV/T collector have profound effects on the system performances. A comparative study was carried out in four solar devices: PV module, conventional hybrid solar air collector,

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Nomenclature

c	Specific heat capacity (kJ/kg K)
D	Diameter of the pipe (m)
F	Packing factor
h	Convective heat transfer coefficient (W/m^2 K)
I	Solar radiation intensity (W/m^2)
K	Overall heat transfer coefficient (W/m^2 K)
L	Length (m)
$\dot{m}$	Mass flow rate (kg/s)
T	Temperature (K)
U	Overall heat transfer coefficient (W/m^2 K)
v	Flow velocity (m/s)
W	Width (m)
x	Distance in flowing direction (m)
α	Absorption coefficient
δ	Thickness (m)
μ	Dynamic viscosity
η	Photovoltaic efficiency
λ	Thermal conductivity (W/m K)
τ	Transmission coefficient
γ	Kinematic viscosity (m^2/s)

Subscripts

b	Backplane
c	Solar cell
e	Environment
g	Glass cover
i	Insulation layer
p	PCM layer
t	Tube
w	Water flow
ref	Reference value at reference conditions

glazed hybrid solar air collector and glazed double–pass hybrid solar air collector. The fourth configuration reached the highest daily average of overall energy efficiency at 74% [8]. Su et al. [9] compared four configurations of the PV/T collector with dual channels, in which water and air were used as working fluids. This work gives guidance to select a suitable working fluid depending on different needs. Water is a good working fluid for the PV/T systems, due to its high heat conductivity and high specific heat capacity. Furthermore, to increase the efficiency of the PV/T systems, it seems to be a useful way to improve the thermal properties of the working fluid [10].

Another effective method of cooling the cell temperature is increasing thermal capacitance of the collector [11]. Phase change material (PCM) integrated into a PV module helps to limit the temperature of PV cells by absorbing heat when melting, because of its high latent heat capacity [12]. In fact, the PCM layer not only maintains appropriate temperature of the PV cells, but also acts as a heat sink storing the exhaust heat for a later use [13]. It is known that solar energy is intermittent, therefore thermal energy storage used in the PV/T collector can ameliorate this problem, by storing the heat during the day and releasing it at night. Over the years, the potential of the PV/T collector incorporating PCM has been demonstrated in theoretical simulations and experimental tests by researchers. A schematic diagram of the PV/T collectors with PCM is illustrated in Fig. 1. Stropnik et al. [14] designed a novel photovoltaic/thermal collector with PCM and investigated the thermal performance of this system. Results indicated that the addition of PCM was an effective means to enhance heat exchange between PV cells and absorber in a PV/T collector, and the maximum temperature difference on the surface of PV cells without PCM was 35.6 °C higher than on a system with PCM. Al Imam et al. [15] examined energy storage incorporating PCM in the PV/T collector system with compound parabolic concentrator. For system with PCM, up to around 3 m from entrance, the plate temperature rose and then it stayed almost steady. But in case of applying same system without PCM, the plate temperature was sharp. Japs et al. [16] conducted an experimental analysis of two different PCMs used in PV/T system considering actual electricity prices. At the tests, the PCM with a higher thermal conductivity had a corresponding higher yield. Su et al. [17] performed comparative analyses on an air–based PV/T collector with PCM, and it was demonstrated that 3cm–thick PCM layer glued to PV cells was optimum both in electrical and thermal performance. Navarro et al. [18] tried to integrate PCM into a PV/T collector. The prototype was tested in the outdoors, and it was demonstrated that the PCM layer could achieve about 20% of energy savings compared to the PV/T collector with no PCM layer. Serale et al. [19] developed a physical–mathematical model for a solar collector with slurry–PCM, which increased the latent heat of the heat carrier fluid. Simulation results showed the PCM slurry could improve the efficiency of system about 20%–40%. Photovoltaic systems integrated PCM are often used in building, providing benefits of generating electricity and thermal management [20]. Lin et al. [21] compared the three types of buildings using PV/T collector only, using PCM only, and without using PV/T collectors and PCMs. The results showed that these two methods could effectively improve the indoor thermal performance of the house.

However, few studies have been devoted to improve the energy output, especially the heat stored in PCM layers, of the PV/T collector integrated with PCMs. In this work, panels with water fluid are embedded to PCM layer to make full use of the heat. A theoretical model of PV/T collector with PCM layer is presented to maximize its energy output. In addition, the thermal and electrical energy output and heat stored in PCM are presented. The influence of melting point and thickness of PCM on the energy output of the systems are analyzed in detail. The goals of this article are: (1) to analyze the electrical and thermal performance of the PV/T collector with PCM, (2) to evaluate the influences of the melting point of the PCM layer, and (3) to determine the optimal melting point and thickness of PCM layer to maximize electrical and thermal energy outputs.

2. Mathematical models

The sectional view of the PV/T collectors with PCM is shown in Fig. 2, and the collector is mainly made up of: a protective tempered glass cover exposed to the ambient, an aluminum–alloy backplane, a PCM layer with embedded 2.54 cm diameter copper pipes through which the water flows, and an insulation layer. The thickness of tubes is 0.8 mm with center to center distance 6.66 cm. In order to simplify the calculation, the following assumptions have been made:

(1) Mean temperature is assumed across each layer.
(2) Horizontal temperature in each layer is uniform except for the water in pipes.
(3) The radiant heat transfer and reflection of sunlight are neglected.
(4) Heat capacities of the PV/T components are neglected. It is mainly because the equivalent heat capacity of the PCM in melting process is much larger than heat capacity of the PV/T components. The equivalent heat capacity of PCM using in this work is greater than 105 kJ/kg K when phase transition temperature variation range is less than 2 °C. For PV/T components, the specific heat capacities rang from 0.5–1.25 kJ/kg K [22].