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Comparative analyses on dynamic performances of photovoltaic–thermal solar collectors integrated with phase change materials

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ABSTRACT

The operating conditions (especially temperature) of photovoltaic–thermal solar collectors have significant influence on dynamic performance of the hybrid photovoltaic–thermal solar collectors. Only a small percentage of incoming solar radiation can be converted into electricity, and the rest is converted into heat. This heat leads to a decrease in efficiency of the photovoltaic module. In order to improve the performance of the hybrid photovoltaic–thermal solar collector, we performed comparative analyses on a hybrid photovoltaic–thermal solar collector integrated with phase change material. Electrical and thermal parameters like solar cell temperature, outlet temperature of air, electrical power, thermal power, electrical efficiency, thermal efficiency and overall efficiency are simulated and analyzed to evaluate the dynamic performance of the hybrid photovoltaic–thermal collector. It is found that the position of phase change material layer in the photovoltaic–thermal collector has a significant effect on the performance of the photovoltaic–thermal collector. The results indicate that upper phase change material mode in the photovoltaic–thermal collector can significantly improve the thermal and electrical performance of photovoltaic–thermal collector. It is found that overall efficiency of photovoltaic–thermal collector in 'upper phase change material' mode is 10.7% higher than that in 'no phase change material' mode. Further, for a photovoltaic–thermal collector with upper phase change material, it is verified that 3 cm-thick phase change material layer is excellent both in electrical and thermal performance.

1. Introduction

With population explosion and technological progress, the world demand for energy is increasing. According to the Renewable 2015 Global Status Report, renewable energy represented approximately 59% of net addition to global power capacity in 2014 [1]. As an important renewable energy source, solar energy has been more attractive recently due to its easy availability, cost effectiveness, accessibility [2].

A photovoltaic (PV) cell is able to convert solar energy directly into electricity, because semiconducting materials absorb photons from sunlight and release electrons. However, the typical crystalline silicon cells only absorb incident light in 300–1100 nm range due to the band gap of the thin–film silicon [3]. Meanwhile, the operating temperature affects the electrical performance of silicon–based PV cells. Skoplaki and Palyvos [4] discussed most of the explicit and implicit correlations between module operating temperature and the electrical performance of PV cells. Radziemaka and Klugmann [5] investigated PV cells performance that showed a power drop of 0.65% per 1 K temperature increase. PV cells have limited efficiency and the remaining absorbed solar energy has to be transformed into heat. This leads to higher operating temperature and lower cell efficiency. An appealing solution to this problem is to utilize a part of this heat in solar thermal collector [6]. Typical thermal energy absorbers are composed of a black absorber and a heat transfer fluid to remove heat. Usually, there are three types of working fluids: air, water and refrigerant. In other words, a so–called hybrid photovoltaic/thermal (PV/T) collector, which can improve the efficiency of PV cells and reutilize exhaust heat at the same time, has been proposed.

Up to now, researchers have done both theoretical explorations and experimental studies on the hybrid PV/T collector, which can be classified as air–based PV/T collector and water–based PV/T collector. New forms of configuration designs of PV/T collector were put forward to satisfy the needs of various applications. Shahsavar and Ameri designed an air–based PV/T system with a thin aluminum sheet, which suspended at the middle of air channel to increase the heat exchange surface. The results showed that there was optimum number of fans, depending on the air mass flow rate, for achieving to maximum electrical efficiency [7]. The influence of air mass flow rate on both electrical and thermal performance of

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Nomenclature

c	specific heat capacity, kJ/kg K
D	equivalent diameter, m
F	packing factor
H	height, m
h	convective heat transfer coefficient, W/m^2 K
I	solar radiation intensity, W/m^2
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

a	airflow
b	backplane
c	solar cell
e	environment
g	glass cover
i	insulation layer
p	PCM layer
ref	reference value at reference conditions

PV/T system is considerable. Bambrook and Sproul [8] found that thermal and electrical efficiencies improved with the increased air mass flow rates (0.03–0.05 kg/s), and the results indicated that thermal efficiency was in the range of 28–55% and electrical efficiency was between 10.6% and 12.2% at midday. However, Teo et al. [9] discovered that when further increasing air mass (beyond 0.055 kg/s) flow rate to a certain value, the heat extracted had reached a saturated level, and both electrical and thermal efficiencies cannot be increased further by increasing the flow rate. Shan et al. [10] developed mathematical models for air–based PV/T collector with five different configurations. The calculation results indicated that PV/T system with a single channel below PV cells got optimal electrical performance, and thermal performance was best in the system with dual channels. Gaur and Tiwari [11] proposed a thermal modeling to research the effect of water–cooling on the performance of commercially available PV cells. The results showed that electrical efficiencies of a–Si PV module with and without water–cooling were 7.36% and 6.85% respectively. Fudholi et al. [12] presented three fabricated design configurations of water–cooling absorbers: web flow absorber, direct flow absorber and spiral flow absorber. The third absorber produced an electrical efficiency of 13.8% and a thermal efficiency of 54.6%, which was the highest among all absorber designs. Su et al. [13] presented four configurations of the hybrid PV/T collectors with dual channels for different fluids, which were able to recover more heat and reach higher efficiency. This work helped to select a more desirable structure based on different needs. Aiming to cool PV/T collector at high solar concentration ratios, Radwan et al. [14] developed a new cooling technique for PV/T systems using a microchannel heat sink with nanofluids. The results indicated that the use of nanofluids achieved about 5 °C lower cell temperature and higher electrical efficiency than pure water cooling.

Both water and air have been utilized as heat removal medium for different applications. As solar energy is intermittent, a great disadvantage of this kind of energy is the large discrepancy between the supply and the demand. The heat demand is maximum in the evening while the solar radiation intensity is minimal or even zero [15]. In some applications, the exhaust heat needs to be stored, and water and air aren't the optimal medium. Thermal energy storage using phase change materials (PCMs) has great potential and vast application prospects, as suitable PCMs have high latent heat with small volume and relatively constant phase transition temperature [16]. However, some drawbacks limit the application of the PCM, such as the leakage of melted PCM and the required phase change temperatures. A theoretical analysis was presented to estimate the stored energy dependence on time in a tank containing PCM, and the results showed that parameters, like the PCM, cylinder radius, the mass flow rate, and the inlet temperature of the heat transfer fluid, impacted on the performance of the tank [17]. Then Esen et al. [18] undertook a series of numerical tests and put forward the optimal geometric design of the tank depending on these parameters and PCMs. An appealing solution to this problem is to integrate thermal energy storage into the PV/T collector which stores the heat during the day and releases it at night [19]. The PV/T collector with PCM consists of different layers including a glass cover, PV cells, backplane, PCM, heat transfer pipes and an insulation layer, as shown in Fig. 1.

Many studies concerning the thermal performance of water-based PV/T cells integrated with PCMs have been undertaken. Malvi et al. [20] presented an energy balance model to evaluate a PV/T system with PCM and found the optimum applicable PCM melting point. It was shown that 0.03 m-thick PCM layer was optimum, which increased the electrical efficiency by 9%. Ho et al. [21] introduced a water–surface floating PV/T system integrated with water–saturated microencapsulated phase change material layer. They found that 5 cm-thick PCM layer with a melting temperature of 30 °C had the best performance. Browne et al. [22] designed a novel photovoltaic/thermal collector with PCM and investigated the thermal performance of this system. It was shown that the introduction of PCM was an effective method to enhance heat removal in a PV/T system, and the maximum temperature difference of water in the system with and without PCM was 5.5 °C. Qiu et al. [23] presented the hybrid PV/T system using the microencapsulated phase change material as the working fluid. The results indicated that the MPCM slurry based PV/T system was superior to typical air–based and water–based PV/T systems. Yin et al. [24] put forward a PV/T system with a PCM storage unit to provide domestic hot water. Water was directly heated by solar thermal collector and carried away the exhaust heat during the day. The warm water can be used immediately, or the heat can be extracted into the PCM storage for use at nighttime.

However, few studies have been devoted to evaluate the dynamic performance of the air-based PV/T collector integrated with PCMs. Air-based systems are practically preferred for lesser use of materials and lower operating cost than water-based, despite of poor thermophysical properties of air. In this work, PCM layer is integrated into the heat transfer pipes of air-based PV/T collector, and both electrical and thermal performance under the operating conditions of Nanjing in China is simulated and analyzed. Table 1 shows design parameters of the PV/T collector. The