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An experimental investigation of a hybrid photovoltaic/thermoelectric system with nanofluid application

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ABSTRACT

Improving photovoltaic efficiency is fundamental to the large scale utilization of solar energy and reduction of carbon emission. In this field, reducing the temperature of the Photovoltaic (PV) panel will increase its efficiency and power production. Utilizing hybrid photovoltaic/thermoelectric (PV/TE) systems is an effective way to simultaneously release the excess heat of the PV panel and use this heat to produce power. The cooling method used for the thermoelectric module (TEM) plays an important role in the system efficiency as well as the produced power. A new nanofluid-based cooling method for a hybrid photovoltaic/thermoelectric system is proposed in this work and compared with the conventional cooling methods experimentally. To this end, five different cooling methods were investigated experimentally, namely natural cooling, forced air cooling, water cooling, SiO_2/water nanofluid cooling, and Fe_3O_4/water nanofluid cooling. The results showed the promise of SiO_2/water nanofluid cooling, which yielded the highest power and efficiency, showing 54.29% and 3.35% improvement, while Fe_3O_4/water nanofluid cooling showed 52.40% and 3.13% improvement in power production and efficiency respectively, comparing with the natural cooling method.

1. Introduction

As a result of increasing energy demand and environmental concern, developing renewable energy technologies has received strong and sustained interest for a few decades. Solar energy is the most promising energy source for our future and solar photovoltaic (PV) technology, i.e. converting solar energy to electricity, has been widely used. However for PV cells, around two thirds of the solar energy is absorbed as heat, which is not only wasted but decreases the performance of the PV cells. It has been reported that the PV efficiency decreases around 0.5% for every degree of temperature increase of the panel (Tonui and Tripanagnostopoulos, 2008). Currently, Low conversion efficiencies and high costs of PV cells are the major obstacles for their large scale deployment (Hajji et al., 2017). Many studies have been performed with the aim of removing the heat produced by PV cells, or using electricity and thermal energy together, i.e. PVT technology (Li et al., 2016; Zhang and Xuan, 2016). Thermoelectric devices, i.e. directly converting thermal energy into electricity under a temperature gradient, has shown great potential in cooling PV cells while providing extra electricity. Many experimental and numerical studies have been performed on photovoltaic–thermoelectric (PV/TE) hybrid systems in recent years (Bjørk and Nielsen, 2015; He et al., 2014; Rockendorf et al., 1999; Tayebi et al., 2014), some of which are briefly reviewed below.

Several novel hybrid systems are proposed and some of their aspects such as efficiency, performance, and manufacturing costs are investigated and compared in the literature. Wang et al. (2011) proposed a novel PV/TE system composed of a solar selective absorption (SSA), dye-sensitized solar cells (DSSC), and a thermoelectric module (TEM) and experimentally studied the energy conversion efficiency of the system. Water was used as the coolant to create a temperature gradient between the hot and cold sides of TEM, and the result showed that by using TEM, the overall efficiency of the system increased from 9.39% to 13.8%. Due to the low temperature gradient between the solar cell and the TEM, this model can be considered as a low grade heat source to produce electricity. Another type of PV/TE systems was investigated by Yang and Yin (2011), where water flows inside a copper pipe that is located in the matrix of a phase-change material (PCM). They

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compared the efficiency of a single solar cell as well as a Photovoltaic/thermal (PVT) system with the PV/TE system at the same conditions, which showed a higher efficiency for the latter case. Since manufacturing costs besides efficiency also play important role in the system's development justification, Chavez-Urbiola et al. (2012) experimentally investigated different configurations of solar cells and TEMs and compared their efficiencies as well as the manufacturing costs. In a novel attempt that used nanotubes for heat removal, a new model of PV/TE hybrid system was studied by Chang et al. (2011), in which water was used as coolant for cooling the system and nanotubes made of copper oxide covered the cold side of the TEM. The results showed that using this design caused the temperature difference across the TEM to increase by 2 K and the produced voltage to increase about 14.8%. Using a collector alongside the PV panel could improve the system performance. In this field, Deng et al. (2013) proposed a new type of PV/TE system that utilized a bowl shaped collector and found that using this design greatly increased the energy conversion efficiency of the PV cell. Also, different types of PV panels and TEMs could be considered in such attempts. In this field Kossyvakis et al. (2016) examined the performance of a tandem PV/TE system by employing poly-Si as well as dye-sensitized PV cells and indicated that the utilization of TEMs with shorter thermos-elements resulted in enhanced power output levels.

Apart from designing and investigating experimental setups from different aspects, some studies have theoretically investigated different PV/TE hybrid models and reported performance characteristics under various conditions. They also evaluated and compared the effects of different setup configurations on the overall performance of the system. Ju et al. (2012) studied theoretically the effects of spectrum splitting of solar irradiance on the efficiency of PV/TE systems and showed that using this system is beneficial for high solar irradiance concentrations. The heat transfer mechanism could play an important role in the efficiency of such systems and in this field, Woodbury (2015) studied a theoretical model about heat transfer in a PV/TE system, where heat transfer mechanism was investigated at various layers of the hybrid system. A theoretical investigation on a PV/TE system was performed by Zhang and Chau (2011a,b) to investigate the effects of solar concentration on solar cell as well as the overall system efficiency. Finned structure was used to intensify the cooling of PV cells and the results showed that the overall efficiency can be increased by 1–8%. Dallan et al. (2015) showed that under the same radiation conditions, the efficiency of the PV/TE system increased to about 39% compared to a bare PV cell.

The electricity produced by TEM (depending on materials that are used in its structure) is too low comparing with a PV cell. However, TEM's role in the production of electricity will be increased by using the materials that have a higher figure of merit. Verma et al. (2016) investigated the capability of a PV/TE system for power generation from waste heat of the PV panel in addition to the PV system's main generation As well as the effects of load disturbance and solar insolation variations on the performance of this system. In the case of theoretically assessing the effects of environmental conditions on the performance of such a system, Rezania et al. (2016) described a theoretical model of PV/TE system and showed that radiation losses from the outer surface of the PV cell as well as convective losses due to the wind blow on this surface caused critical effect on the efficiency of the PV/TE system.

In the field of nanofluids, the performed attempts are mostly theoretical (Jin et al., 2016a, 2016b). In one of such attempts, Wu et al. (2015) established a theoretical model for estimating the performance of glazed/unglazed PV/TE systems and use nanofluid as a coolant in order to increase heat removal. The results showed that nanofluid improved the system efficiency comparing to water while the enhancement was more significant for glazed systems. Khanjari et al. (2017) evaluated the environmental parameters affecting the performance of a photovoltaic thermal system using nanofluid and numerically investigated the use of nanofluid in a water-cooled PVT system (Khanjari et al., 2016). In the latter attempt, they showed that both thermodynamic first and second law efficiencies increased by increasing the nanoparticle volume fraction.

As briefly reviewed above, most of the studies are focused on theoretical and numerical attempts to evaluate different methods of PV/TE system cooling. But, no specific and comprehensive study was found in the literature to experimentally investigate these methods, especially efficient nanofluids cooling methods and their effects on PV/TE system performance characteristics. The present study is a novel experimental attempt, which aims to do so. In this study, five different cooling methods of the PV/TE system, namely natural air cooling, forced air cooling, pure water cooling, water-based SiO_2 nanofluid cooling, and water-based Fe_3O_4 nanofluid cooling are experimentally studied. The produced power and acquired efficiency are compared for each case and the corresponding efficiencies are compared.

2. Methodology

Fig. 1(a) and (b) shows schematic diagrams of the experimental setup, which shows air cooling and liquid cooling systems, respectively. In both systems, the PV cell absorbs solar irradiance and converts it into electricity. On the back side of the cell, a TEM is installed that uses the dissipated heat of the cell as the heat source, and liquid or air as the heat sink. Two air-based methods and three liquid-based methods are assessed in this work.

2.1. Materials

For this experiment, the crystalline silicon PV cell with dimensions of $30 \times 15\ cm^2$ is utilized. It is manufactured by EVERSUN SOLAR TECHNOLOGY. The cell's characteristics are given in Table 1.

For driving the flow of coolant liquid within the liquid cooling methods, a miniature pump was used, which consumed negligible power comparing with the produced power by the hybrid system. Also, one piece of TEM, TEC-1206, manufactured by Hebei I.T. (Shanghai) Co., Ltd is employed in the experiment. Bismuth Telluride was considered as the best thermoelectric material for the study considering its maximum operating temperature of about 90 °C. The characteristics of the TEM are reported in Table 2. In order to collect the heat from the back side of the PV cell and efficiently transferring it to the hot side of TEM, an aluminum sheet was sandwiched between the PV cell and TEM.

In this section, the utilized equations for estimating the system efficiency are also presented. The efficiency of the PV cell is computed as follows (Skoplaki and Palyvos, 2009):

$$\eta_{cell} = \eta_{cell.ref}\left[1 - \beta_{ref}(T - T_{ref})\right] \tag{1}$$

in which $\beta_{ref} = 0.0041\ ^{\circ}C^{-1}$, $\eta_{cell.ref} = 0.15$, and $T_{ref} = 25\ ^{\circ}C$ respectively represent the efficiency temperature coefficient, PV cell's efficiency, and the reference conditions' temperature. The TEM's efficiency is calculated as follows (Tse and Klug, 2006):

$$\eta_{max.TEM} = \frac{(T_H - T_C)}{T_H}\frac{(1 + ZT_M)^{0.5} - 1}{(1 + ZT_M)^{0.5} + \frac{T_H}{T_C}} \tag{2}$$

in which T_H, T_C, T_M, and Z represent hot side temperature, cold side temperature, average temperature, and figure of merit parameter, respectively. The latter is calculated as follows (Xi et al., 2007):

$$Z = \frac{S^2}{\rho K} \tag{3}$$