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Experimental investigation on using ferrofluid and rotating magnetic field (RMF) for cooling enhancement in a photovoltaic cell

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ABSTRACT

A new cooling technique for a photovoltaic cell (PVC) system was developed by simultaneous using of rotating magnetic field (RMF) and ferro-nanofluid. In this study, pure deionized water and Fe_3O_4-water nanofluid with different volume fractions were used as cooling mediums. Results obtained from RMF and ferrofluid were compared with pure water in terms of the average temperature and electrical output of the PV cell versus time till the system reaches a steady-state condition. The influence of the concentration of magnetic nanoparticles (MNPs) (ϕ = 0.01, 0.02, 0.03, 0.04 and 0.05 (w/v)), the rotational speed of magnet (ω) and the magnetic field induction (B = 350, 450, 570, 720 and 880 mT) were investigated. Generally, using RMF and ferrofluid showed higher effect for the cooling enhancement of PV cell compared with using pure water and ferrofluid without magnetic field. Actuation of ferrofluid by RMF enhances the thermal efficiency (η) in the range of 17.8–30%. The electrical power generated in the range of 2.62–3.5 W related to ferrofluid concentration, magnetic field induction and rotational speed of magnets. The effect of ω in RMF on the cooling performance was evaluated and measurable enhancements of η and %P (max) increase were seen. Maximum values of the generated power (3.5 W), percentage of maximum power increase (47.5%) and thermal efficiency (30%) were attained for B = 880 mT, ω = 30 rad/s and ferrofluid concentration of 0.05 (w/v).

1. Introduction

Solar energy is one of the renewable and environmentally friendly energy sources that is always available and is free of charge [1–3]. Solar cell is a device which directly converts the solar radiation to electrical energy based on the photovoltaic effect [4,5]. One of the first developed and mostly used solar cells was mono-crystalline silicon (mc-Si) photovoltaic module owing to its advantages of low maintenance cost, high reliability, noiseless and eco-friendly [6]. The electrical and thermal efficiency of mc-Si photovoltaic (PV) systems strongly depends on light intensity or irradiance, tracking angle and cell temperature [6,7]. One of the significant current issues in the industry of PV cells is the enhancement of solar cell efficiency. Decreasing the operating temperature of the surface of a PV cell can be considered as an efficient and simple method to increase its efficiency [8,9]. Cooling the PV module during operation leads to higher heat dissipation rates from PV cells which this results in relatively good temperature uniformity and high electrical efficiency [10]. A review of the literature shows that one remedy to avoid the temperature increase of the PV cells is use of nanofluids as working fluids for cooling [11–16]. Studies about this issue have emerged owing to the possible mechanisms that lead to such effective heat transfer enhancement. Fluids have lower thermal conductivity in comparison with metal suspensions. Therefore, the presence of small amounts of metallic and other nanoparticles were dispersed in the carrier fluid (known as nanofluids) lead to large enhancements in their thermal conductivity and common heat transfer [17]. Different types of nanofluids such as Boehmite/water [8], Al_2O_3/water, MgO/water, Silica/water and carbon nanotube/water were used by many authors to investigate their effects on the performance of the solar cells. Magnetic nanofluids are ultra-stable colloidal suspensions of magnetic nanoparticles in a liquid carrier, commonly known as ferrofluids [18–20]. Ferrofluids behavior as smart or functional fluids and their rheological characteristics can be accurately controlled [21]; also ferrofluids exhibit fascinating properties such as viscosity and conductivity under the effect of an external magnetic field [17]. Ferrofluids have remarkable potential for heat transfer applications because of chaotic motion and stimulation of suspended magnetic nanoparticles (MNPs) due to their magnetic properties and capability of heat transfer enhancement [22]. The nature and characteristics of magnetic field that applied on ferrofluid has considerable influences on the behavior of

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MNPs in the liquid carrier [19]. Three types of magnetic field, i.e., static magnetic field (SMF), oscillating magnetic field (OMF) and rotating magnetic field (RMF) can be used for actuation of MNPs. RMF applies an angular torque on the MNPs and causes to gyration of nanoparticles in the adjacent liquid [27, 34]. This can augment the heat transfer process and lead to enhancement of the liquid transport properties beyond the conventional paradigm of thermal diffusion. Despite numerous works done in the field of using ferrofluid to enhance the rate of the convective heat transfer [22–25], there are limited available research studies about the simultaneous effects of using ferrofluid and magnetic field on PV cooling performance. In this context, Ghadiri et al. [17] investigated experimentally application of Fe_3O_4/water ferrofluid as coolant under constant and alternating magnetic fields in the cooling section to enhance the overall efficiency of a PV thermal system. Their experimental results show that using 3 wt% ferrofluid, the overall efficiency of the system enhanced by 45% compared to that of the distilled water as coolant.

The purpose of this study is to exhibit experimentally whether ferronanofluid, as working fluid, and RMF can enhance the PV cell performance better than pure water. The measured results for surface temperature, maximum power enhancement and electrical efficiency of the PV cell have been reported. The layout of using pure water has been selected as a reference for comparison with layout of using ferrofluid.

2. Experimental section

2.1. Apparatus and data acquisition system

The mono-crystalline silicon photovoltaic module used in this study was consists of 72 cells connected in parallel and series. In order to measure temperature, 12 K-type sensors have been attached on the surface of the PV cell, with an extremely thin layer of a thermal epoxy. Fig. 1 depicted a schematic illustration of PV module and the thermocouple position. The experimental setup was fabricated to investigate the effect of rotating magnetic field (RMF) on the efficiency of a PV system with ferrofluid as working fluid. A schematic view of the experimental setup is shown in Fig. 2. Since, the natural sunlight is not constantly available; five Metal Halide (MH) lamps were used to produce a continuous spectrum of light. A steel frame was built to handle the PV cell under the light of halide lumps at constant position toward the halide lumps. The solar simulator apparatus was consisting of a power driver unit for continuous lighting. Total of five MH lamps were located on an aluminum heat sink plate at a height of 50 cm from the PV cell. The flat sheet of aluminum was chosen owing to its stiffness, availability, low cost and satisfactory reflection. The total the incoming radiation (I (W/m^2)) was measured by a digital solar power meter ((Pyranometer), Testo Company (Tes1333R)) mounted parallel to the photovoltaic surface. Table 1 shows the major components and the characteristics of experiment apparatus in this study. By using a thermometer (Lutron, BTM-4208SD), temperature changes was tracked in

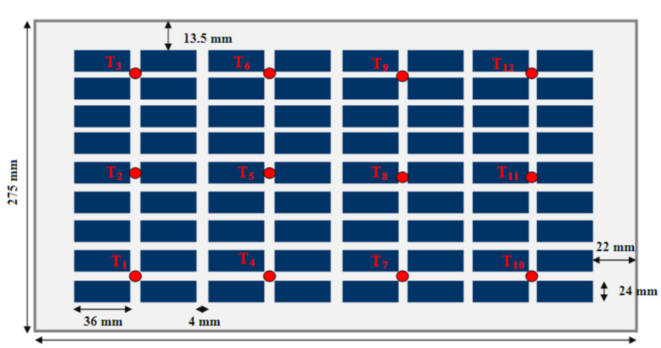

Fig. 1. The scheme of PV cell and the thermocouple positions.

short step times (under 10 s) during the experimental period. During the experiments, the electrical load was used to measure PV voltage at different demanded electrical current. In order to establish RME, two cubic permanent magnets (50 × 25 × 10 mm) with magnetic induction of 1300 mT were attached to a specially designed rotating blade that rotate at the backside of PV cell using a stepper motor. A schematic diagram of the rotating blade and its driver was also depicted in Fig. 2. As it can be seen in this figure, designed rotating blade was fabricated from two attached triangle plates of Plexiglas that attached to a shaft and it is rotate by the stepper motor. In this study, for deep investigation on the effect of RMF, different rotational speeds of the rotating blade, i.e., 8, 14, 18, 23 and 30 rad/s were evaluated. It is important to notice here that the magnetic field and magnetization direction (z-direction) were perpendicular to the surface of PV cell (x-direction). The magnetic field induction (B) was adjusted by change in the distance of the magnet from the surface of PV cell and it was measured with a digital TESLA meter (accuracy better than 0.1%). That distance (d) was fixed to 3, 6, 9, 12, and 15 mm, which they are corresponded to B = 880, 720, 570, 450 and 350 mT, respectively.

2.2. Preparation of ferrofluids

The nanofluid was formed from Fe_3O_4 nanoparticles with diameter of less than 25 nm (purity, 99.5%, supplied by US Research Nanomaterials Inc. (Houston, TX)) suspended in deionized water. In order to break down the nanoparticle agglomerations and to form a homogeneous and stable suspension, the prepared nano-suspension was sonicated by an ultrasonic homogenizer (Hielscher UP400S, Germany). The sonication was performed at a frequency of 24 kHz and a nominal power of 400 W at the controlled temperature of 293–298 K. During the sonication, the temperature of nano-suspension was controlled such that the suspension container surrounded by water–ice cooling bath. It took 90 min to prepare a stabilized ferrofluid. This method was used to prepare nanofluids with different concentrations of 0.01, 0.02, 0.03, 0.04 and 0.05 (w/v).

2.3. Experiment procedures

The reservoir at the backside of PV cell was full filled of about 2 L of working fluid. The temperatures of 12 points on the surface of PV cell were recorded by a thermometer (Lutron, BTM-4208SD). During the experiments, the radiation intensity was equal to 1000 W/m^2 and the PV electrical output was connected to an electrical load system. As soon as the steady-state condition was established, I–V values were recorded in order to determine the maximum power point (P_{max}), the values of current I (I_{max} in A) and voltage V (V_{max} in V) at maximum power of the PV module. All the experiments were performed at room temperature (17 °C). Dilute concentrations of ferrofluid (φ = 0.01, 0.02, 0.03, 0.04, 0.05 (w/v)) were prepared by dispersion of the MNPs in the pure water. The measurements were repeated three times in order to ensure reliable and repeatable results.

3. Results and discussion

As it was explained previously in Section 2.3, the temperatures of twelve measuring positions of the PV cell were recorded in each 5 min till the system reaches a steady-state condition (after nearly 40 min). The average of these 12 temperature data was considered as the average temperature of the PV cell surface. In this study, two types of working fluids were used: pure deionized water and ferrofluids with five different volume fractions (0.01–0.05 (w/v)). Using ferrofluid as working fluid was evaluated in two conditions: one without a magnetic field and the other in the presence of RMF with different rotational speeds (ω) of the permanent magnet.