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Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: An experimental study

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ABSTRACT

This paper aims to investigate the electrical, thermal and exergy efficiencies of a photovoltaic/ thermal (PV/T) system cooled by Ag/water nanofluid. The utilized nanofluid was prepared by a one-step method of electrical explosion of wire (EEW) and was tested for long-term stability and uniformity. The performance of the PV/T system was measured by considering a wide range of parameters to determine key performance indicators such as electrical and thermal energy efficiency as well as exergy efficiency of the system. The effects of mass flow (i.e. different flow regimes of laminar, transient, and turbulent) on efficiencies were studied. The results showed that using nanofluids for cooling of the PV/T system can enhance both the energy and exergy efficiencies of the system significantly. It was also found that this positive impact is more pronounced by increasing the concentration of the nanofluid and increasing the flow rate (i.e. moving towards a turbulent flow). By using 4 wt% nanofluid (with turbulent flow) the power output of the panel increased by ~35% and ~10% compared to when no cooling and water cooling were applied respectively; and the exergy efficiency was also determined to be 50% and 30% higher than when no cooling and water cooling were used, respectively.

1. Introduction

International agreements, which are aiming to control the level of greenhouse (GHG) emissions, have been greatly appreciated by countries around the world in recent years. This matter receives increasing attention even in oil-rich countries in Middle East such as Saudi Arabia, United Arab Emirates and Iran with significant investments on development of their solar energy capacity (Al-Maamary et al., 2017; Al-Maamary et al., 2016). According to the World Bank's reports (The World Bank), this international organization has been committed to finance renewable energy projects (e.g. solar photovoltaic electricity) in countries that suffer from lack of electricity and high level of GHG production. Examples of these are, $2.8 m, $1 bn, $519 m, $49 m, and $480 m have been granted for developing solar energy projects in Zambia, India, United Arab Emirates, Jordan and Argentina, respectively in recent years (The World Bank).

Among different renewable energy technologies photovoltaic (PV) technology (for generating electricity) is best known for its maturity and growing economical attractiveness. The penetration of this technology grew significantly from 400 billion kilowatthours in 2010 to 600 billion kilowatthours in 2017, showing 50% of increase (Annual Energy Outlook, 2018). The efficiency of PVs can be in the vicinity of 10–30% and significant part of inefficiencies appear in the form of heat that leads to increase in the temperature of the panel (i.e. can reach up to over 70 °C) and hence decrease the efficiency. The first pioneers in developing a theoretical model and finding a relation between the photovoltaic efficiency and its operation temperature were Hendrie (1865) and Fslorchuetz (1979). They suggested that the efficiency of PVs drops linearly as their temperature increases.

A properly-design cooling system can maintain the temperature of PVs at lower levels and prevents reduction in the efficiency. On the other hand, the heat collected from the PVs can then be used in certain applications. The PV system that also includes a heat recovery arrangement is known as photovoltaic/thermal system (PV/T) Farahat and Mahdavi, 2014. PV/T systems have attracted the researchers' attention in recent years and many experimental studies have been carried out to date for evaluating their performance.

The type of fluid that is used in PVs heat recovery system is a key topic of interest in designing PV/T systems. Cox and Raghuraman (1985) developed a computer simulation on the absorption of solar radiation and the emission of infrared rays in PV/T systems, and concluded that the overall efficiency of the system in which air is used as

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Nomenclature

A	area (m^2(
P	electrical power (W(
I	current intensity (A)
V	voltage (V)
Q	heat (W)

Greek symbols

ρ	density (kg m^{-3})
η	efficiency
τ	average local airtime)s(

Subtitles

th	thermal
el	electrical
in	input
out	output
s	sun
mp	maximum power
a	ambient
c	collector
u	useful energy
Eta	efficiency
Lam	laminar
Tra	transient
Tur	turbulent

working fluid is less than that in those using water as coolant (i.e. for heat recovery). Joshi and Tiwari (2007) investigated the energy and exergy efficiencies of PV/T collectors and reported 55% and 12–15% for energy and exergy efficiencies, respectively. Sarhaddi et al. (2010a), (2010b), Sobhnamayan et al. (2011) developed an electric and thermal model for air-based and water-based photovoltaic thermal collector to calculate electrical and thermal parameters, and optimize the system from the exergy perspective. Al-Nimr and Al-Ammari (2016) have developed a mathematical model to evaluate the concept of using PV/Ts for water distillation. The impact of solar radiation, ambient temperature, wind speed, and condensing chamber on the performance of the system were studied and the system total efficiency was reported to be 57%.

In recent years also the use of nanofluids attracted some attention due to the fact that such fluids offer better heat transfer capacity, making them appealing for systems operating at relatively low temperature. Al-Waeli et al. (2017a) conducted a comprehensive review on the effect of different working fluids/techniques to collect the heat generated by PVs, including the use of air, water, air/water, phase change materials (PCMs) and nanofluids. They suggested that the use of water based nanofludis improved the overall system efficiency of the PV/T systems.

Yousefi et al. (2012) examined the effect of 2 wt% and 4 wt% of aluminum oxide/water nanofluids on a flat solar panel collector's efficiency. Experimental studies were carried out at different flow rates with and without the presence of surfactants (i.e. used to stabilize the nanofluids). They reported that by using surfactant the working fluid (i.e. coolant) remains more stable and performs better in collecting heat. They reported a collector's efficiency improvement of 28.3% when 2% wt of nanofluids is utilized compared to that can be achieved by using pure water. Saidur et al. (2012) studied the effect of using nanofluid as working fluid in a PV/T collector and compared the efficiency of the PV/T system when different coolants including aluminum nanofluid, water and air were used. They analyzed the energy absorption at different wavelengths by varying the size of nanoparticles and volume fraction of nanofluids. They concluded that the use of nanofluid at an optimal wavelength increases the efficiency of the system by 11% in comparison with the case of water used as working fluid. Crisostomo et al. (2017) recently reported a study on Ag/SiO_2 hybrid nanofluid effects on PV/T system indicating 12% of enhancement in weighted energy output compared with a stand-alone PV system under the same illumination. Soltani et al. (2017) carried out experiments on a PV/T system using Fe_3O_4/water nanofluid and showed that the total efficiency and power production enhanced by 3.13% and 52.4%, respectively when the above-mentioned nanofluid replaced water. They also reported the results of using SiO_2 and the enhancements in total efficiency and power production were measured to be 3.35% and 54.29%, respectively, that was very close to those obtained for Fe_3O_4/water nanofluid. Hussien et al. (2015) conducted an experimental study using 0.1–0.5 wt% Al_2O_3/water nanofluids and forced convection. They measured the PV module temperature to be 79.1 °C when the using water alone and under the same condition (i.e. input radiation, ambient temperature, and etc.) they could achieve a significantly lower temperature for the PV module (e.g. 42.2 °C by using 0.3 wt% Al_2O_3/water nanofluid).

Al-Waeli et al., (2017b) published a comparative study on the effect of using water based Al_2O_3, CuO, and SiC nanofluids on thermal and electrical efficiencies of photovoltaic thermal collectors. They first examined the stability of nanofluids and reported that SiC nanofluid showed better thermal conductivity and stability compared with Al2O3 and CuO nanofluids. Al-Waeli et al. (2017c) recently published their work by focusing on evaluating the efficiencies of a PV/T system in which SiC/water nanofluid was used in the heat recovery system. They reported that the electrical and thermal efficiencies improved by up to 24.1% and 100.19% respectively, when water as coolant was replaced with SiC/water nanofluid. They also reported that the PV/T system in which nanofluids are used as coolant had a higher overall efficiency of about 88.9% compared to a PV system used in power generation mode only. In another work, Al-Waeli et al., (2017d) reported the applicability of a new hybrid nanofluid of SiC- Paraffin-PCM nanofluid in improving electrical and thermal efficiencies of a PV/T collector tested in Selangor, Malaysia. They observed 13.7% enhancement in electrical efficiency and a significant increase of 72% in thermal efficiency of their newly-designed system (i.e. compared to that using pure base fluid for heat recovery). Assessing the annual yield factor, capacity factors (CFs), the cost of energy, payback period, and efficiency of a grid connected PV/T using nanofluid and water as the working fluid, is one of the other recent studies carried out by Al-Waeli et al. (2017e). They indicated that the grid connected PV/T (GCPVT) system with nanofluid improved the PV technical and economic performance.

Mohammad Sardarabadi et al. (2014) experimentally studied the effect of silica/water nanofluid on overall efficiency and exergy of a PV/T system. They reported enhancements of 7.9% and 24.3% in overall efficiency and exergy, respectively, with the nanofluid used with a maximum volume fraction of 3 vol%. In another work done by Hassani et al. (2016), environmental and exergy benefits of a hybrid nanofluid PV/T system have been studied. They reported that the exergy payback time of nanofluid-based hybrid PV/T system is about two years in Malaysia. They also suggested that it is not only a reliable solution for pollution prevention, but also can be highly recommended at high solar concentration.

The literature clearly confirms the advantages that can be offered by