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Experimental investigation of an optical water filter for Photovoltaic/Thermal conversion module

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ABSTRACT

This paper presents an experimental investigation of a novel optical water filter used for Photovoltaic/Thermal and Concentrating Photovoltaic/Thermal modules. A water layer is used as a spectrum splitter of solar radiation placed above the photovoltaic cells and as a thermal working fluid simultaneously. The water layer absorbs the ultraviolet and part of infrared, which are not used by the photovoltaic, but transmits the visible and some of infrared to the solar cell surface which are used by the photovoltaic. In this work, the transmittance of the optical water filter was measured for different water thicknesses (1, 2, 3, 4, and 5 cm) and radiation wavelength ranging from 0.35 to 1 μm. Results show that there is a significant effect of the water layer thickness on the transmittance of the spectra where the transmittance decreases as the water layer increases. Moreover, energy conversion rate of photovoltaic with the optical water filter at different water layer thicknesses has been determined.

1. Introduction

There has been significant growth in using Photovoltaic (PV) cells to convert solar energy to electrical power. At the end of 2013, the amount of global PV power generation capacity was about 139 GW which presents more than 97% of the total power generation capacity of solar energy systems [1]. However, the main disadvantage of PV is its low efficiency (10–20%) [2] compared with other renewable energy-generation systems. Many researchers studied the effects of various parameters on the performance of the PV. Al-Nimr and Al-Shohani [3] studied the performance of a PV module with generation capacity of 215 W at various sites with different solar radiation levels. Their results showed that for radiation level of 2308 kW h/year, the PV module produced 462 kW h/year, while it produced 377 kW h/year in the site which has 1815 kW h/year solar radiation. Radziemska [4] investigated the effect of temperature on the output of a PV module and showed that the PV efficiency decreased from 13.3% to 10.3% as the PV temperature increased from 25 °C to 60 °C. Consequently, the PV output current is directly proportional to the intensity of solar radiation where increasing the solar irradiance from 100 W/m^2 to 1000 W/m^2 leads to increasing the cell output current from 0.35 A to 3.4 A [5]. Also, the cell output voltage is inversely proportional to its temperature whereas the cell temperature increases from 25 °C to 85 °C the cell output voltage decreases from 0.6 V to 0.45 V [5]. Therefore, increasing solar radiation input to the cell increases the power output, but increasing its temperature reduces the power output. At constant solar radiation, increasing the cell temperature leads to decreasing the output voltage as well as the power output by −0.4%/K to −0.5%/K [5].

To enhance the performance of PV cells, researchers used three enhancements techniques. Firstly, many types of concentrators were attached to the PV module in order to increase the incoming solar radiation to the PV surface thus enhancing the PV current output [6], and consequently increasing the overall power output [7]. This combination of concentrator and PV module is named Concentrating Photovoltaic (CPV) system. In CPV systems, different types of concentrators are used with PV solar cells. Huang and Sun [8] used low concentration ratio flat reflectors with PV. Their results showed that power output of the PV module increased by around 23% when integrated with 2× concentrator reflectors. Wang et al. [9] used two-stage concentration system (up to 200×) with triple junction solar cell. A parabolic dish concentrator was used to collect and reflect the solar radiation into second compound parabolic concentrator which was fixed at the focal point of the dish concentrator. The results showed that the average efficiency of the system was 29.3% which is higher than the single stage concentrator by 9.1%. Hatwaambo et al. [10] analysed PV

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Nomenclature

Symbols

T	transmittance (%)
k	extinction index (–)
L	thickness of the layer (metre)
n	refraction index (–)
R	reflectance from incidence side (%)
R'	reflectance from non-incidence side (%)

Subscripts

1	first layer
2	second layer
i	bottom layer
j	top layer

Abbreviations

CPV	Concentrating Photovoltaic
CPVT	Concentrating Photovoltaic/Thermal
DHW	Domestic Hot Water
IR	Infrared
NOCT	Normal Operation Cell Temperature
PV	Photovoltaic
PVT	Photovoltaic/Thermal
SWH	Solar Water Heater
UV	Ultraviolet
VIS	Visible

Greek letters

λ	Wavelength (μm)

cells integrated with 3.6× compound parabolic concentrator with different reflective materials. Their results indicated that the power increased by 2.5 times when using the concentrator with Miro aluminium as a reflective material. Kuo et al. [11] tested a high concentration photovoltaic system consisting of Fresnel lens and triple junction solar cells. Their results showed that the maximum PV efficiency is around 26.1% with a geometrical concentration ratio of 476×. Also the concentrators are categorised according to the concentration ratio between the received and delivered solar radiation (low concentration 1–10, medium concentration 10–100, and high concentration 100–1000) [12]. Using concentrators result in increasing the input solar radiation, power output leading to increasing the cells temperature that adversely affect the PV performance and working life. For example, Gajbert et al. [13] investigated the performance of a PV module with a parabolic concentrator having concentration ratio of 4.65× and total reflectance 83%. Results showed that the power output per cell area increased by 72% compared to PV module without concentrator.

Secondly, researchers investigated ways of decreasing solar cells temperature by removing the accumulated heat and using this heat for thermal applications [14]. This co-generation system of electrical power and thermal energy named Photovoltaic/Thermal (PVT) systems. In PVT systems [15], water is pumped through pipe network attached behind the PV cells, to absorb the unwanted heat and make the PV cells working under Normal Operation Cell Temperature (NOCT) which is 47–50 °C for silicon solar cells [16]. This thermal energy can be used for different applications. Dupeyrat et al. [17] studied the performance of the PVT system used for Domestic Hot Water (DHW) in three cities in France (Paris, Lyon, and Nice). Their results showed that the PVT system produces up to 12.7% higher power than the PV system. Fang et al. [18] studied experimentally the performance of PVT system coupled with heat pump air conditioning system. Their results showed that the efficiency of PV in the PVT heat pump system and the COP of the heat pump are 10.4% and 2.88 respectively. In addition, they found that the efficiency of the PV in the PVT system is more than the efficiency of conventional PV by 23.8%. Also, air has been reported to be used to cool the PV cells where air is passed through ducts welded to the back side of the PV cells. Sarhaddi et al. [19] presented a simulation study for PVT air system. Their results showed that the electrical and thermal efficiencies of the PVT air collector are around 10.01% and 17.18%, respectively. PVT systems not only improves the thermal performance of the PV [20], but also increases the overall efficiency and reduces the required area to half that with separate PV module and Solar Water Heater (SWH) [21]. For example, Rommel et al. [22] experimentally tested a PVT flat system to produce electricity and heat for DHW. Their results showed that the electrical gain of the PV module in PVT – water system is higher than PV module without cooling by 4%. Furthermore, the yearly electrical gain of PVT module is 150 kW h/m^2, and the yearly thermal gain of PVT is about 330 to 230 kW h/m^2.

Thirdly, combing CPV and PVT in one system named Concentrated Photovoltaic Thermal (CPVT) system increases both electrical and thermal efficiencies, reduces the energy cost, and produces thermal energy with high temperature that can be used in different applications [23]. Kerzmann and Schaefer [24] simulated a CPVT system for DHW applications consisting of Fresnel lens integrated with triple junction solar cell and mounted on a dual-axis solar tracking system. They concluded that a 6.2 kWp system can save annually about $1623 in the cost of electricity and water heating for residential user, and save 10.35 tons of CO_2 yearly. Al-Alili et al. [25] presented a theoretical analysis of a CPVT system used in air conditioning application where the CPVT system was integrated with a solid desiccant wheel cycle and a conventional vapour compression cycle. Their results showed that the COP of the CPVT air conditioner is higher than that of a solar absorption cycle and a vapour compression cycle powered by PV module where the COPs are 0.68, 0.29 and 0.34, respectively. Ong et al. [26] presented a CPVT system used in the water desalination application where a high concentration CPVT system was coupled with multi-effect membrane distillation unit. They concluded that the CPVT – desalination system is able to convert about 85% of the solar energy into useful energy used to generate electricity and fresh water.

For both PVT and CPVT systems which used water as a thermal working fluid, water is pumped behind the PV cells. In this configuration, PV cells receive the whole of the solar radiation spectrum consisting of: Ultraviolet (UV), Visible (VIS), and Infrared (IR) radiation. According to the physical properties of the conventional silicon solar cells, any solar radiation with wavelength of 0.37–1.18 μm can be converted to electricity and the remaining solar radiation will be converted to heat which increases the cell temperature. Then, the water absorbs this heat from the back side of the PV. This technique makes the PV cells working under acceptable cells temperature, but suffers from cyclical thermal stresses caused by the periodic heating and cooling processes. These thermal stresses lead to reducing the working life of the PV cells, and the rate of power generation with the time.

Otanicar et al. [27] tested experimentally the optical properties of the water and compared the results with other optical fluids which are used in solar thermal energy applications. The tests were carried out for water, ethylene glycol, propylene glycol, and Therminol VP-1 with fluid thickness of 10 mm. The results indicated that the water has good transmittance value (about 90%) at