Renewable Energy 90 (2016) 95–104

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Fabrication, experimental study and testing of a novel photovoltaic module for photovoltaic thermal applications

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A R T I C L E I N F O

Article history:
Received 16 March 2015
Received in revised form
15 December 2015
Accepted 26 December 2015
Available online 2 January 2016

Keywords:
PV testing
Thermal resistance
Solar PV/T system
PV cooling

A B S T R A C T

Solar Photovoltaic Thermal (PV/T) System is the integration of Solar Photovoltaic (PV) module and thermal system to serve the dual purpose of providing electricity and hot water/air simultaneously. But the high thermal resistance in a PV/T collector due to the thermal conductive adhesive, sheet and tube metal absorber reduces the heat transfer from the PV cells to the fluid and increases the overall cost of the system. This causes non-uniform and inefficient cooling of the PV cells. Hence, in this paper, a solar photovoltaic thermal module was developed by laminating a thin, flat copper sheet instead of Tedlar as the bottom layer. This modification is then integrated to a single water channel to make a PV/T collector. Primary energy saving efficiency of 35.32% was obtained at 0.01 kg/s mass flow rate, whereas the reference PV module attained only 20.87%. Theoretical calculations using material properties of the different layers of PV/T module and PV module showed a decrease in thermal resistance and an increase in thermal capacitance compared to the PV module. Also discussed in this paper was the positive results of few conformance tests conducted on the PV/T module according to IEC standards.

1. Introduction

Solar energy is available abundantly and its utilization in modern life is getting prominence across the world due to depleting fossil fuels, increasing industrialization, rising fossil fuel prices, growing climate change and frequent power outages. One hour of solar energy reaching the earth is more than the total world energy consumption for a year, yet the capture of solar energy is mostly limited to solar PV modules and solar water heaters. The low efficiency of PV modules and low exergy of solar water heaters can be coupled to make a PV/T system for a higher combined efficiency per unit area. Many research, developments and commercialization of different PV/T systems have taken place worldwide since 1976. However, the PV/T system still faces a few hurdles to overcome for widespread consumer acceptance.

Only 13%–20% of the incident solar energy is converted to electrical energy by the silicon PV cells and the remaining is converted to heat [1], due to the infrared part of the solar spectrum [2]. Alternate materials like low refractive index transparent layer and low UV absorbing encapsulating layer showed a 2 mA/cm^2 electrical output enhancement [3]. Further, the electrical efficiency of the PV module depends on the PV cell temperature, which in turn depends on the PV cell encapsulation and material properties, atmospheric parameters like solar intensity, ambient temperature and wind speed [4]. Also, high thermal capacity and heat extraction are necessary to maintain a low PV cell temperature [2], hence the heat transfer between the bottom surface and the fluid underneath should be improved [5,6] to prevent short term efficiency loss and long term irreversible damage to the photovoltaic modules [7]. The heat transfer coefficient and thermal resistance of a PV/T collector fabricated by attaching a commercially available solar PV module with metal absorber using an expensive thermal conductive adhesive [8], causes non-uniformity of adhesive layer and formation of micro-air bubbles which increases the thermal resistance causing higher heat loss and higher PV cell temperature [9,10], which can be addressed with a single package lamination [11,12]. The PV cell is encapsulated inside the EVA in a solar PV module, hence it is difficult to measure the cell temperature, but can be estimated based on four different methods [13].

Several experimental and theoretical investigations performed by researchers all over the world contributed to present success

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http://dx.doi.org/10.1016/j.renene.2015.12.064
0960-1481/

and future scope of the PV/T technology. The use of air for drying applications and low cost modifications has improved the overall efficiency in a PV/T air collector [14–18] by cooling the PV cells and helps in the ventilation application in buildings [19]. The higher thermal properties of water compared to air makes its use in water heating applications. A 45% thermal efficiency and a 12% electrical efficiency in a 10 kW_p PV/T system for simultaneous production of hot water and electricity have reduced the auxiliary electric energy by 94% [20]. Similarly, a 51% thermal efficiency and 11.6% electrical efficiency were obtained for building integrated applications [21]. A few modifications were done to maximize the electrical or thermal efficiency of a PV/T collector, such as a PV/T collector partially covered with PV module produced higher thermal energy compared to fully covered with a PV module, but less than a flat plate collector [22,23], further the outlet temperature of water was 0.5 °C to 2.5 °C higher in parallel configuration than series configuration [24]. Similarly, a PV/T system with and without glass cover produced thermal and electrical efficiencies of 41.3%, 9.4% and 37.1%, 11.5% respectively [25]. Another design of implementing a water channel below a transparent PV module gave the best efficiency while a conventional PV module on sheet and tube design was considered as the second best [26]. A solar PV module attached to an aluminum absorber produced higher output density [27], while the use of copper radiator to attach a smaller PV module to a larger metal absorber produced a 10% increase in power output [28]. Higher electrical performance in a PV/T system can be obtained by cooling the PV cells [29], by positioning it at the inlet of the flat plate collector [30] and by using reflectors [31]. In India, the overall thermal energy and exergy gain are highest for Bengaluru [32], while the energy payback time (EPBT) and CO_2 emissions of a 1 m^2 PV/T water collector were analyzed to be 7.54 years and 37.24 kg/year respectively [33].

In this paper, to reduce the thermal resistance between the PV cells and the fluid, a copper sheet is laminated in direct contact with the PV cells, thereby attaining fin efficiency of unity. This modification eliminates the need for a Tedlar (Poly Vinyl Fluoride) backsheet and thermal conductive adhesive, to bind the PV module to the metal absorber. Also, this modification enables for a single lamination of the electrical and thermal components of the PV/T collector, providing better heat transfer from the PV cells to the fluid. This modified PV/T module was integrated to a single water channel and the overall performance was studied. Few tests performed to conform to the IEC standards followed for a conventional PV module were also presented.

2. Methodology

In this section, the construction of the PV/T module, thermo-physical properties of the PV/T module, PV/T collector experimental construction, uncertainty analysis and the conditions used in the testing of the PV/T module and PV/T collector are discussed. Generally, a PV/T collector is constructed by attaching a commercially available PV module to a metal thermal absorber using mechanical or chemical bonding. Thereafter, different methods of fluid flow arrangement design, namely serpentine flow, spiral flow, parallel tube flow, channels are made.

The measuring instruments and location of the experiment are listed in Table 1. The pyranometer is placed in the same plane of the solar collector. The ambient temperature and wind speed were measured at the location of the experiment. All temperature measurements were carried out using Resistance Temperature Detector (RTD) PT100 temperature sensors. The voltage and current were measured using the inbuilt voltmeter and ammeter of data acquisition system. The water flow was maintained at 0.01 kg/s using a booster pump connected to a rotameter. The solar collectors were tilted corresponding to the latitude of the location using manual single axis tracking mechanism.

Table 1
Measuring instruments and location of experiment.

Solar radiation	Pyranometer (Hukseflux LP02)
Ambient temperature	Spectrum Technologies WatchDog 2000
Wind speed	
Temperature	RTD PT100
Voltage	Agilent 34970A
Current	
Water flow	Rotameter
Latitude	13 °N
Longitude	80 °E
Tilt angle	13° facing South
Location	Institute for Energy Studies, Anna University

2.1. PV/T module

The PV/T module discussed in this paper can be manufactured in a conventional PV module manufacturing facility. A 0.2 mm thickness copper sheet is bonded to the PV cells in a PV module lamination chamber. Therefore the PV/T module layer arrangement comprises the glass, Ethylene Vinyl Acetate (EVA), PV cells, EVA and copper sheet as shown in Fig. 1. The high temperature and pressure inside module lamination chamber, remove any air present and for the polymerization reaction of EVA to take place. The high electrical resistivity and high elongation property of the EVA layer acts as a buffer layer between the PV cells and the copper sheet. The electrical terminals of the PV/T module are taken from the side of the PV/T module with sufficient electrical insulation from the copper sheet.

The thermo-physical properties of each layer of the module are given in Table 2. Temperature measurements taken on the glass layer, EVA layer and Tedlar layer reveal that the EVA layer has the highest temperature, because of the low thermal conductivity as given in Table 2 [34]. The temperature of the PV cell can be calculated using the following formula [35].

$$T_{cell} = T_{back} + \frac{E}{1000}\Delta T \tag{1}$$

where T_{cell} is the PV cell temperature in °C, T_{back} is the measured bottom surface of module temperature in °C, E is the measured solar irradiance incident on the module in W/m^2, and ΔT is the temperature difference between the PV cell and the module bottom surface.

2.2. PV/T collector

The tests were conducted by comparing a PV module and the PV/T collector of the technical specification as shown in Table 3.

The PV/T collector is attached to a 100 L thermal storage tank with internal heat exchanger. Water is the heat transfer fluid in the primary and secondary circuit. The flow of water is augmented by the use of a booster pump. The experimental setup and schematic diagram of the PV/T collector are shown in Fig. 2.

2.3. Uncertainty analysis

A solar PV/T water heating system has electrical and thermal efficiencies. The electrical efficiency of the solar PV/T water heating system is directly proportional to the voltage, current and inversely proportional to the area of the solar collector and incident solar radiation falling on the solar collector. The thermal efficiency of the solar PV/T water heating system is directly proportional to the mass