Development and Performance Analysis of Photovoltaic Thermal Hybrid Solar Collector

Abdul Haseeb[a], Hassan Nazir[a], Hamza Saeed[a], Majid Ali[a], Nadia Shahzad[a], Adeel Waqas[a,]*

[a]*US-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, Islamabad 44000, Pakistan*

Abstract

Exposure of Photovoltaic (PV) module to insolation raises its surface temperature resulting in the efficiency drop of the PV panel. PV panel's efficiency can be improved by lowering its surface temperature. PV and solar thermal collector system were incorporated in one-unit photovoltaic thermal (PVT) system to harvest the heat from the PV module consequently lowering its temperature. PVT system was designed and fabricated by directly pasting the PV cells on the copper absorber plate and copper piping arrangement was coupled at the bottom side of the absorber plate providing both electricity and heat from a single module. Experiments were performed at the outdoor conditions to analyze the performance of PV cells and study the effect of temperature on its performance and PVT efficiency was calculated for various flowrates of heat transfer fluid. The experimentation was performed under climatic conditions at US-Pakistan Center for Advanced Studies-Energy NUST, Islamabad, Pakistan. Electrical, thermal, and PVT efficiencies were calculated for different time points and their average maximum were determined as 16.53, 49.91, and 66.44% respectively at a flowrate of 0.81 l/min. This PVT system successfully ascertained the electrical and thermal performance of the PVT collector with good adherence to the literature.

Keywords: *Photovoltaic Thermal Collector; PVT Efficiency; Performance Analysis; Solar Energy Conversion Efficiency.*

1. Introduction

Solar energy is one of the most valued sources of energy, accounting for a large share of global energy demand. Solar energy comes in two forms: photons, which are light particles, and solar thermal energy, which is heat from the sun. Their uses are determined by the energy forms. Photovoltaic (PV) panels employ photons to generate electricity, whereas soler thermal collectors use heat to generate thermal energy. PV systems do not convert the complete range of incoming photons into current generation; instead, a significant amount of insolation are absorbed and converted to heat, resulting in increased PV module temperature. When compared to the nominal temperature of 25° C output, this results in a 0.08-0.1% reduction in PV module conversion efficiency and a 0.45% reduction in output power [1]. Several studies have been published that use various cooling techniques to regulate the temperature of PV modules for improved efficiency [2]. In the mid-1970s, photovoltaic thermal (PVT) collectors were designed and reported. PVT collectors, as mentioned above, use both kinds of solar radiation to produce both heat and electricity from a single module. Flat plate photovoltaic thermal (FPVT) collectors combine the characteristics of a flat plate collector and a PV module into a single hybrid collector that collects heat and lowers the PV module utilizing water and air as primary accessible fluids [3]. The performance of the PVT collector is better to that of stand-alone PV and flat plat collectors [4]. Like flat plate collectors, FPVT also experiences different losses including conductive, convection and radiative losses. The cause of these losses are different such as radiative heat losses occurs mainly from the continuous exposure of the absorber plate increasing the collector temperature which increases the radiative losses. These losses can be reduced by selective absorber coating [5]. Non radiative losses including conduction losses can be suppressed by insulating the sides and back of the collector while increasing the air gap between the absorber plat and glazing will lead to lower the convective heat losses [3].

This survey involved designing and fabricating a lab-scale model of a flat-plate photovoltaic thermal (FPVT) collector that can deliver both electricity and heat under real ambient conditions. At various mass flow rates, several characteristics were studied in outdoor conditions at the US-Pakistan Center for Advanced Studies in Energy, NUST, Islamabad, Pakistan.

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*Corresponding author. Tel.: +92 5190855101; fax: NA
E-mail address: adeel@uspcase.nust.edu.pk

2. Experimental Setup and Procedure

The PVT collector is made up of an exterior box that houses the PVT portion of the collector. The PVT part of the collector consists of a copper absorber plat that serves as the collector's thermal component. Ethylene Vinyl Acetate (EVA) sheet is used to adhere the PV cells to the absorber sheet. Copper pipes in a serpentine form are attached to the back side of the absorber plat. Fig. 1 shows the schematic of the fabricated PVT collector.

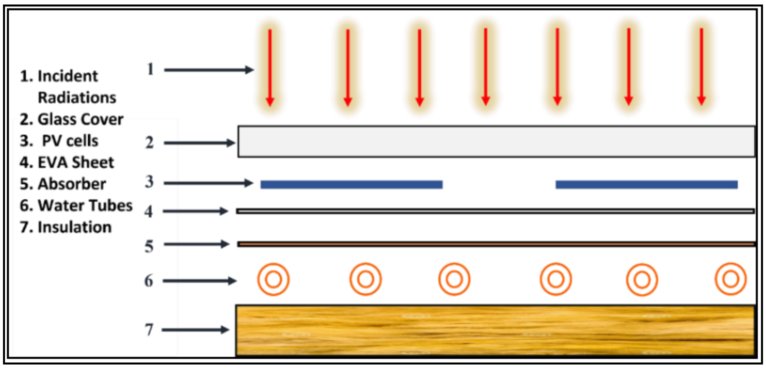

Fig. 1: Schematic Diagram of FPVT collector

The PV part of the collector comprises of four 156 x 156 mm polycrystalline PV cells, specification are listed in Table 1, pasted directly to the copper absorber sheet of 430 x 400mm. the copper was selected mainly because of high thermal conductivity (385 W/m.K). To minimize the conduction losses from backside of the collector, fiberglass thermal insulation of 2.54 cm thickness was used mainly because of its lower thermal conductivity i.e., 0.040 W/m.K

The experimental setup consists of the PVT collector, storage tank, water pump, k-type thermocouples (TC), data logging device (Extech TM500) used to log data of the TCs, Pyranometer; Hukseflux Model LP02-LI19, and an anemometer with data logger was used to record solar radiations and wind speed at the experimental setup respectively. Fig. 2 shows the fabricated setup.

Table 1: Characteristic of a single PV Cell used in the study

Efficiency %	18.9
Peak power output (W) P_{max}	4.644
Maximum power Voltage (V) V_{mp}	0.543
Maximum Power Current (A)I_{mp}	8.552
Open circuit voltage (V) V_{oc}	0.641
Short Circuit Current (A) I_{sc}	9.065

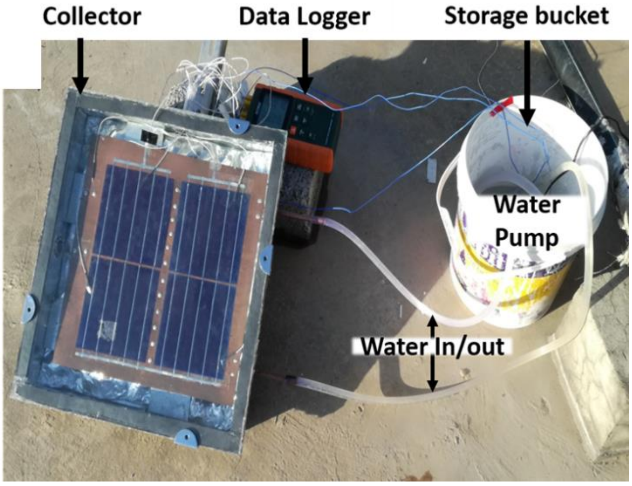

Fig. 2: A view of the experimental setup Flat plate PVT solar system

3. Calculations

Using law of conservation of energy for steady-state conditions, the total amount of useful energy gain is derived by using Eq. (1),

$$Q_u = A_{abs}F'\left[I\tau\alpha - U_l\left(T_{fm} - T_{amb}\right)\right] \tag{1}$$

where I represent incoming solar radiations and $\tau\alpha$ is the absorption-transmittance of the FPVT collector. The collector efficiency factor F' is calculated using Eq. (2),

$$F' = \frac{1}{W\left[\frac{1}{D_o+(W-D_o)F}+\frac{U_l}{C_b}+\frac{U_l}{\pi D_i h_{fi}}\right]} \tag{2}$$

Where,

$$F = \frac{\tanh\left(\sqrt{\frac{U_l}{\lambda_p\delta_p}}(W-D_o)-2\right)}{\sqrt{\frac{U_l}{\lambda_p\delta_p}}(W-D_o)-2} \tag{3}$$

whereas the average convective heat transfer coefficient h_{fi} is calculated by Eq. (4),

$$h_{fi} = \left(1430 + 23.3\left(T_{fm} - 273.15\right) - 0.048\left(T_{fm} - 273.15\right)^2\right) V_f^{\,0.8} D_i^{\,-0.2} \tag{4}$$

Flow velocity V_f inside the tube is calculated from Eq. (5),

$$V_f = \frac{\dot{m}}{\frac{\pi D_i}{4}\times\rho_f\times int\left(\frac{W_2}{W}\right)} \tag{5}$$

To analyse the thermal and electrical performance of the FPVT collector, thermal and electrical efficiency are calculated using eq. (6) and (8) respectively,

$$\eta_T = \frac{Q_u}{Q_{in}} \tag{6}$$

Whereas

$$Q_{in} = I_s A_c \tag{7}$$

The electrical efficiency is calculated by using eq. (9), [6]

$$\eta_{PV} = \eta_r\left[1 - \beta\left(T_c - T_r\right)\right] \tag{8}$$

where η_r is the reference efficiency of the PV panel at reference temperature ($T_r = 25\ °C$), where T_c represents cell temperature. β is the temperature coefficient mainly dependent on the material of the PV module. Different modules such as monocrystalline, polycrystalline, and CdTe have β values of -0.44 %, -0.387 %, and -0.172 %/ºC, respectively [7]. The overall efficiency of the FPVT collector is calculated as the sum of thermal and electrical efficiency by eq. (9) [8].

$$\eta_{PVT} = \eta_T + \eta_{PV} \tag{9}$$

4. Results and Discussion

Experiments were performed at the rooftop of the US-Pakistan Centre for Advanced Studies in Energy-NUST, Islamabad, Pakistan (33°38’32.5” N,72°59’03.6” E). Different parameters were studied including the performance of PV cells and the effect of temperature on its performance and PVT efficiency was calculated for various flow rates of heat transfer fluid.

4.1. Meteorological Data

Fig. 3 (a-c) shows the meteorological data of the experimental site for various test days including irradiance at test site, ambient temperature, and wind speed. The irradiance data shows an increasing trend from sunrise till noon and a downward trend till sunset. The maximum irradiance was recorded 853.5 W/m^2 on 27th January 2021. FPVT efficiency is also linked to the ambient temperature and wind speed. Fluctuations in wind speed can be seen in Fig. 3(c) mainly because of the experimental site climate conditions.

4.2. Temperature Effect on PV Cells

Experiments were performed in January 2021 from 10:00 a.m. to 5:00 p.m. on two different days. To study the effect of temperature on the performance of the PV cells, the collector was exposed to solar irradiance and the temperature was allowed to rise. After reaching a maximum point the cooling mechanism was activated and was set on for the rest of the time, lowering both absorber and PV cells temperature. PV efficiency is calculated by using Eq. (8).

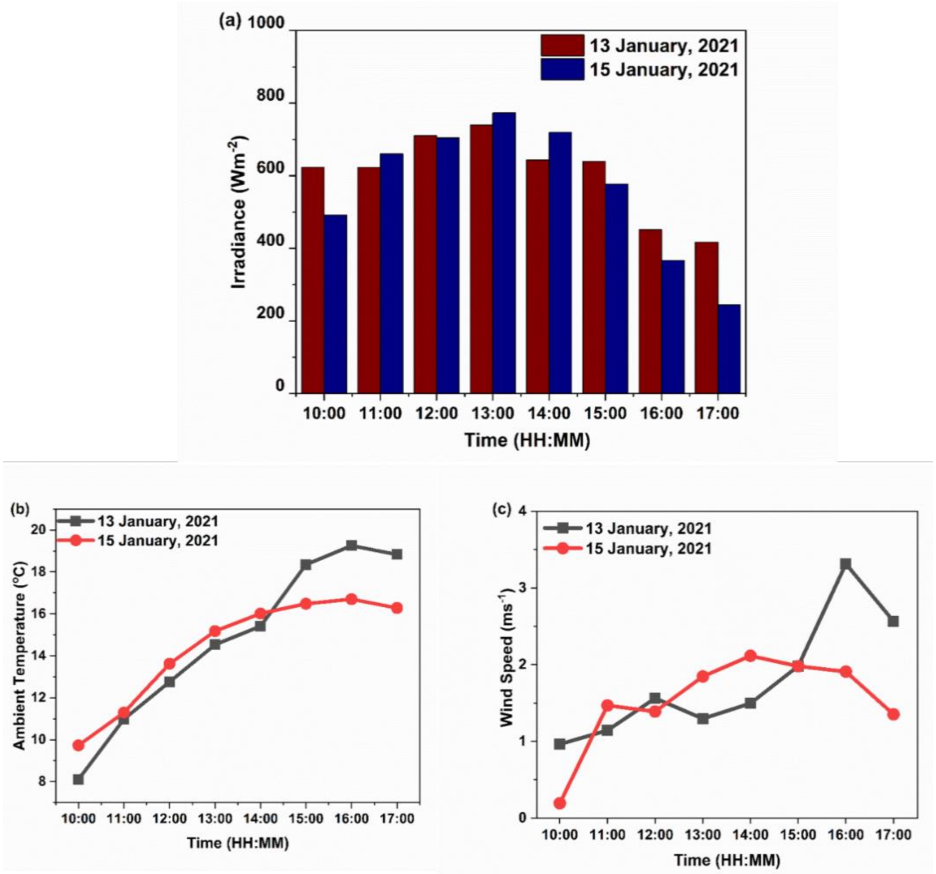

Fig. 3: Variation of meteorological data with time for test days, (a) Solar Irradiance on FPVT collector, (b) Ambient Temperature, and (c) Wind speed.

A maximum electrical efficiency of 17.15% against 31.58° C, and 25.60° C with an efficiency of 17.56% for the flow rates 0.6 and 0.8 l/min, respectively. The cooling mechanism was not activated in the start resulting in decreased PV efficiency at the start mainly due to increased temperature of the PV cells. Fig. 4(a-b) demonstrate the experimental results for the flow rate 0.8 l/min. Fig. 4(a) shows the temperature for the given flow rate where it can be seen in increasing trend in region-I where the cooling mechanism was set OFF. The region is linked to region-I of Fig. 4(b), which shows a declining trend in efficiency as temperature rises. Region-II depicts the section of the cooling mechanism that is activated, resulting in a drop in PV cell temperature and an increase in PV cell efficiency. Table 2 shows the maximum and minimum PV cells temperature along with respective efficiencies.

Table 2: PV Cell Temperature vs Efficiency

Flow rate (L/min)	PV Cell Temp (°C) Max/Min	Electrical Efficiency (%)
0.6	77.63/31.58	14.01 17.15
0.8	54.35/25.60	15.60 17.56

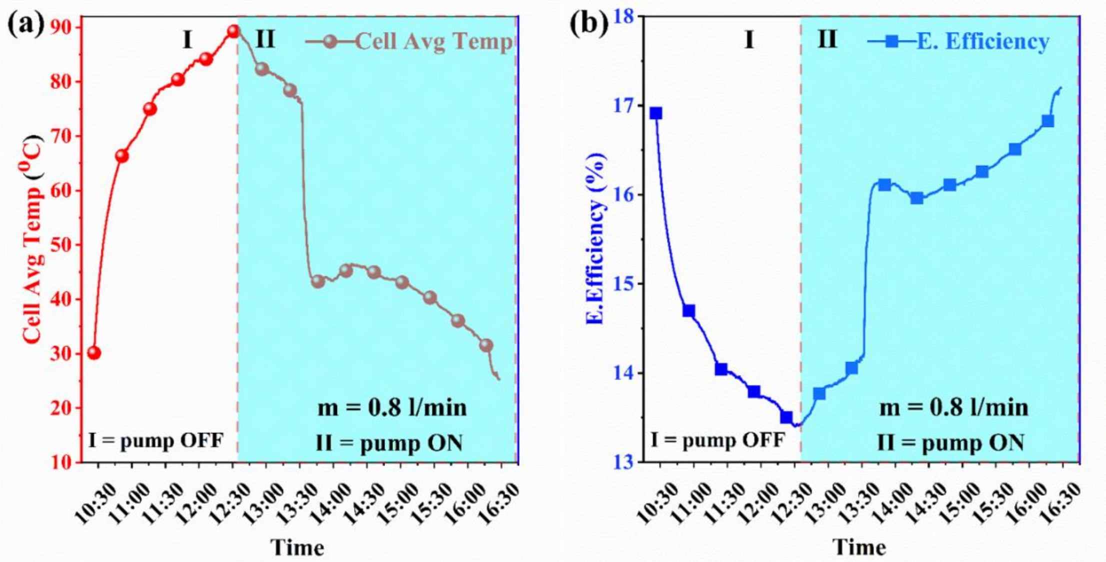

Fig. 4: PV cells parameters against flow rate 0.8 l/min, (a) Temperature, (b) Efficiency

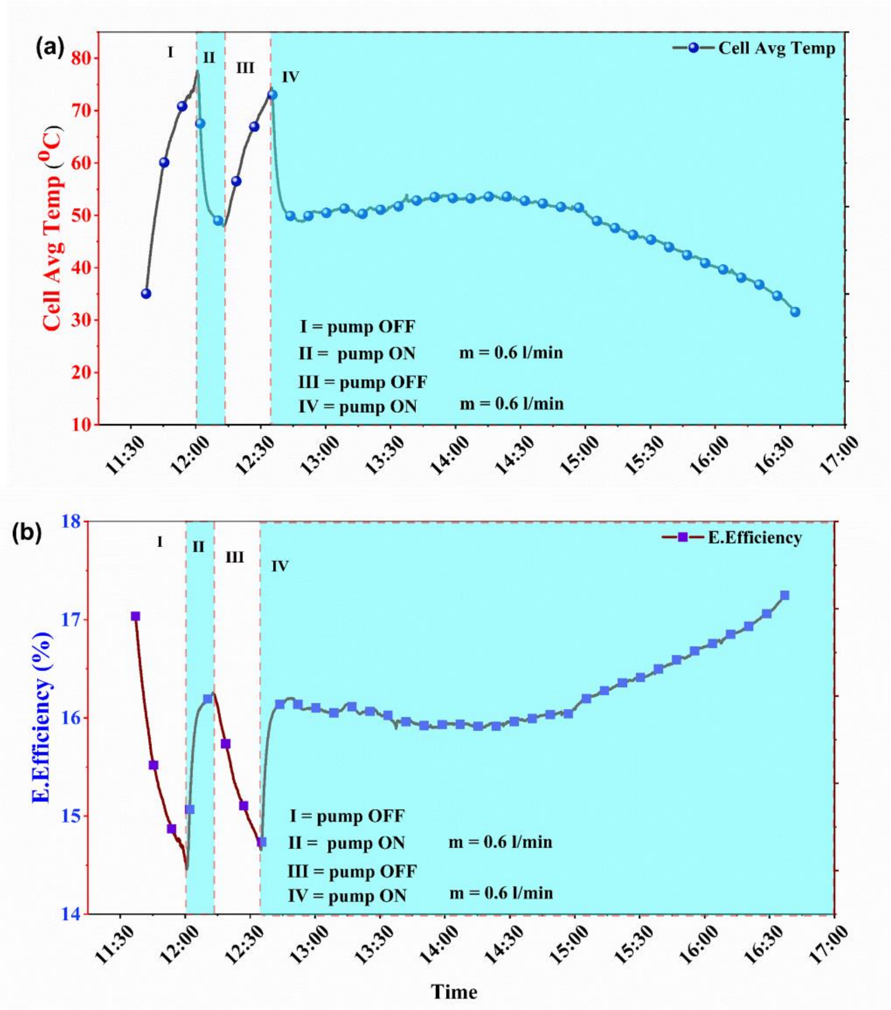

Fig. 5: PV cells parameters against flow rate 0.8 l/min, (a) Temperature, (b) Efficiency

In comparison to the previous graph, Fig. 5(a-b) displays a different approach. The fact that PV efficiency reduces with increasing temperature is examined in detail in the graph. The cooling mechanism was turned on and off at different intervals for this. The shaded region depicts the activated cooling mechanism section, whereas the unshaded region depicts the switched OFF cooling mechanism section. The plotted graph clearly shows an increasing and decreasing pattern in PV efficiency as a function of temperature.

4.3. Effect of flowrates on efficiency

Thermal, electrical, and PVT efficiency was calculated by using eq. (6),(8), and eq.(9) respectively and plotted against flow rates. average efficiencies against each flow rate is listed in Table 3. While Fig. 6 show the plot of these efficiencies. At a flow rate of 0.8 l/min, overall PVT efficiency was achieved to be 66.44%, maximum against the other PVT efficiency.

Table 3: Thermal, Electrical and Overall Efficiency at different flowrates

m (l/min)	η_{th} (%)	η_{PV} (%)	η_{PVT} (%)
0.60	48.56	15.92	64.48
0.80	49.91	16.53	66.44

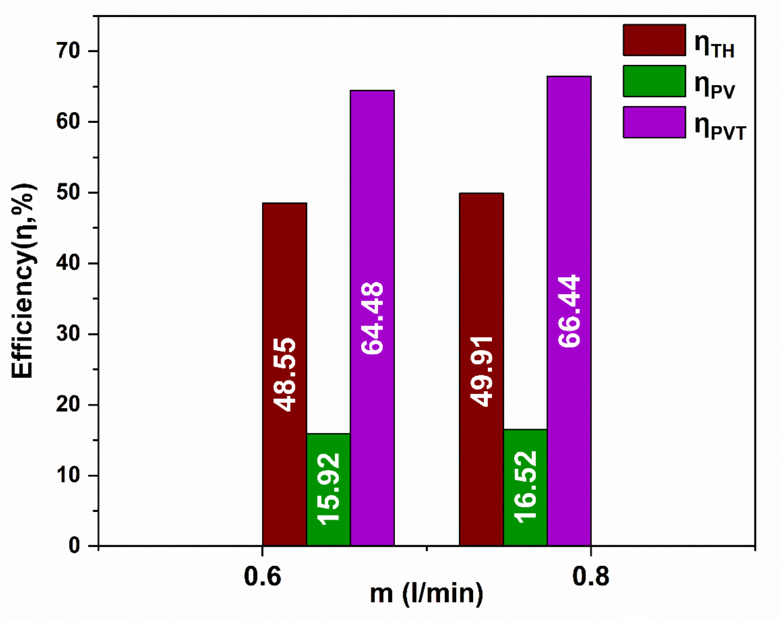

Fig. 6: Thermal, PV, and overall PVT Efficiencies for flow rates of 0.6 l/min and 0.8 l/min

5. Conclusion

In this study a flat plate photovoltaic thermal collector was designed and fabricated. Solar PV cells were directly pasted onto the copper absorber sheet and were tested under real climatic conditions. The temperature of the solar PV cells was allowed to rise and at a point maximum the colling mechanism was turned ON to lower the temperatures. The PV efficiency was calculated by the temperatures noted during the experiment and efficiencies were derived. On the flow rates of 0.6 l/min and 0.8 l/min, the efficiencies at the later were observed high with values of 49.91%, 16.52%, and 66.44% for thermal, electrical, and overall PVT efficiencies respectively. The results derived from the experiment sowed an increase in electrical and thermal efficiency after the coolant circulation was activated, lowering the solar PV cells temperature.

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