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Performance analysis of flat plate hybrid PV/T solar water collector system

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ABSTRACT

Solar Photovoltaic module converts the light component of solar radiation into electrical output measured in watts and heats part is absorbed by module increasing its operating temperature which reduces the electrical efficiency of the module by 10 to 35%. Hence by using the external cooling system, the module temperature can be reduced to improve electrical power efficiency. This cooling system is called a photovoltaic heat exchanger. The cooling system fitted to the backside of the PV module produces thermal power (in terms of hot water), can be used for low-temperature applications. Combined PV module and heat exchanger generating both electrical and thermal power are called as hybrid Photovoltaic/Thermal (PV/T) solar system. Performance of a direct flow heat exchanger and its effect on the hybrid PV/T system is studied in the current paper. The experimental analysis and results like performance efficiencies of Photovoltaic, thermal and PV/T system at different loading conditions were discussed and evaluated for the latitude of Kalyan, Mumbai. The results at solar radiation of 6.52 kWh/m2/day and water mass flow rate of 0.04 kg/sec through heat exchanger showed improvement in combined PV/T efficiency of 73.7% with PV efficiency of 12.7% and performance ratio of 70.5%.

Keywords*— Photovoltaic module, Direct flow, Electrical efficiency, Thermal efficiency, PV heat exchanger, Hybrid PV/T solar water system, Combined PV/T efficiency*

1. INTRODUCTION

Silicon and Germanium are two semi-conductors which are used in making of Solar Cells. As we already know, the electrical efficiency of Solar Panel/Module ranges from 12% to 16% under standard testing condition (solar spectrum of AM 1.5, the irradiance of 1000 W/m2 and module temperature of 25˚C. For mono and poly-Silicon solar panels, the electrical efficiency decreases about 0.45%/˚C. For amorphous Silicon, the electrical efficiency decreases about 0.25%/˚C. It is because the temperature of the PV module is increased by absorbed radiation which is not converted into electricity resulting in a decrease in electrical efficiency.

The main problem is in the semi-conductor because an increase in temperature decreases the band gap of a semiconductor the distance between the valence band and conduction band decreases. So, there is an increase in the flow of electrons as they require lower energy to break the bond. This results in an increase of short circuit current whereas the decrease in the open circuit voltage which decreases the maximum power output.

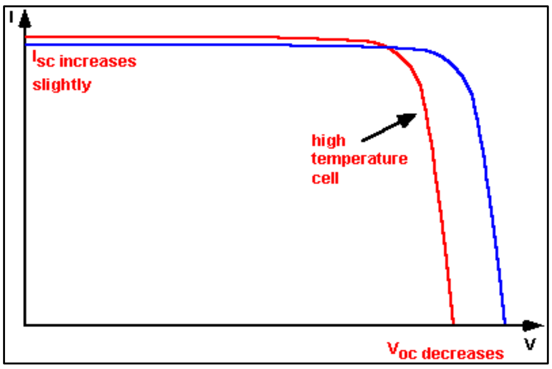

Fig. 1: Effect of Temperature on the IV characteristics of a Solar Cell [3]

The blue curve in the graph is at the normal condition whereas the red curve shows the temperature rise effect on the maximum power output. It clearly shows the decrease in maximum power output.

Cooling of the PV module improves its electrical power output and efficiency reasonably. PV module can be cooled by circulating cold water through the heat exchanger fixed at the backside of the commercial PV module. Such heat exchanger is called as PV absorber surface [2]. In a hybrid PV/T solar water system, PV module and thermal unit are mounted together to enable simultaneous conversion of solar energy into electricity and thermal energy as shown in. The hybrid PV/T solar system generates higher combined energy output per its square meter area making it cost effective compared to conventional PV module if the cost of the thermal component is minimum.

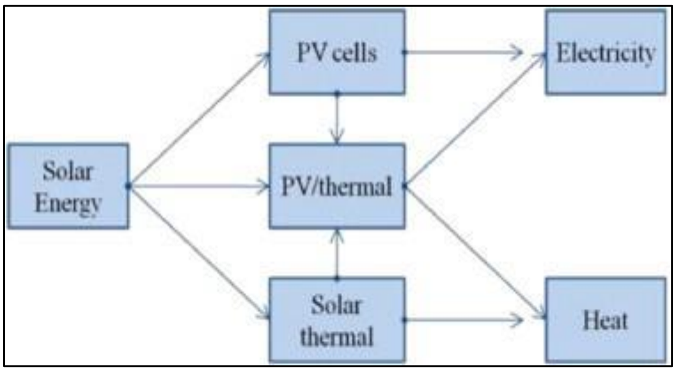

Fig. 2: Solar energy conversion paths

In this paper, commercial PV module was converted to a hybrid PV/T system adding a heat exchanger unit at its backside. This heat exchanger was designed and fabricated using hollow copper tubes. Copper tubes are used for fabrication of the device due to its better thermal conductivity and ease in fabrication. Then electrical as well as thermal performance analysis of the experimental work is further discussed and evaluated.

2. EXPERIMENTAL

2.1. Commercial PV module with stand

A Prashant Solar commercial PV module with a rated capacity of 50 watts having area 0.4288 m^2 was used to conduct experiments on un-cooled PV module and hybrid solar system. The technical specifications of the module at STC as per manufacturer's data are given in Table1. Commercial PV module with heat exchanger was mounted on mild steel stand facing south. The angle provided for a solar panel is 10^0 for the month of April according to the optimum tilt angle for Kalyan city.

Table 1: Technical data of PV module

Module	Vmp	Imp	Isc	Voc	Fill Factor (F.F.)	η
Prashant Solar Multi Crystalline	18 V	2.8 A	3.17A	22 V	75.75 %	12.89 %

2.2. PV heat exchanger design and its fabrication

Firstly a stool was constructed using aluminium angles and steel plates which were joined using nut and bolts. The stool is made to rest the whole assembly. The front part consist of solar panel with a heat exchanger (as a copper tube) and the back part consisted of two desks to keep water tank and electrical setup. Plywood of size 27 x 28 inches was used to design heat exchanger which was to be fitted at the backside of the solar panel. The layout of whole copper tube bent was drawn on plywood which helped in calculating the exact copper tube length required for the project. On the basis of this, a 28 ft. (including wastage) of a copper tube of diameter 12 mm was bought. Then adhering to the layout, copper tubes were bent with the help of pipe bender. The bent pipes were fitted onto the backside of the solar panel but it was not in the same plane. To combat this, m-seal (solid as well as liquid) was used at various places so that the whole length of copper tube was in contact with the backside of the solar panel. Finally, a glass fitted in aluminium frame was made attached to the solar panel with heat exchanger fabrication.

The manufacturing and assembly of copper direct flow PV absorber surface were simple and cost-effective compared to other types of flows and its materials. The detailed heat exchanger dimensions are given in Table 2. Figure 3 shows the detailed drawing of the PV module and heat exchanger assembly with important dimensions and necessary features such as water inlet, outlet etc.

Table 2: Heat exchanger characteristics

The diameter of the Copper tube	The pitch between two consecutive tubes	Length of the heat exchanger
12 mm	75 mm	8.5 meters.

2.3. Measuring instruments

Table 3: Measuring instruments

Multi-meter	To measure current (0-10A range)
Clamp meter	To measure voltage
k-type thermocouple with the probe as lead wire	To measure panel temperature
Rheostat	35Ω, 5A

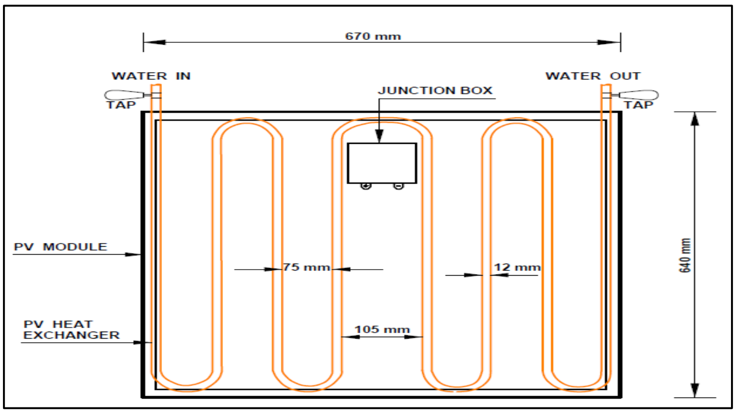

Fig. 3: Module and heat exchanger assembly with important dimensions and necessary features

2.4. Experimental observations procedure

The important motive of this experimental work was to compare the performance of a simple PV module and hybrid PV/T solar system using direct flow type heat transfer system at ATC condition for Kalyan latitude. All experiments were conducted during the month of May 2019. Measurement was taken for both electrical and thermal energy produced by the solar devices and equipment's and hence the performance of the un-cooled and cooled PV module was studied at time 12:30 PM and 1:00 PM for peak PV power point condition. As explained below, the entire experimental work was divided into two parts.

The optimum tilt angle of 10^0 at peak PV power point was selected to determine the performance of a simple PV module at Actual Test Conditions (ATC). For these experiments, different observations voltage, and current at corresponding loading conditions were taken at 12:30 PM and 1:00 PM respectively. K- Thermocouples were used to measure ambient temperature and the temperatures at the top surface and back side of the PV module. Since the readings were taken in the month of May the solar irradiance taken was 6.52 KWh/m^2/day for Kalyan city. During the second observation set, experiments were performed on a hybrid solar system with direct flow heat exchanger attached at the back side of the module. For this setup, all readings were recorded manually for peak PV power point. Readings of the inlet and outlet temperatures, water flow rate flowing through heat exchanger were collected which were further used to calculate the thermal power, combined PV/T efficiency and performance ratio of the hybrid system.

During experiments, it was found that the electrical energy produced by the PV module depends on two main factors, namely, a rise in module temperature and intensity of solar radiation. The rise in module temperature was directly proportional to solar radiation falling on the top surface of the PV module. The intensity of solar radiation fluctuates at a different time of the day. İt is minimum at early morning and during sunset and maximum at noon. Fig.4. shows the electrical setup to measure voltage and current to plot I-V characteristics of the PV module.

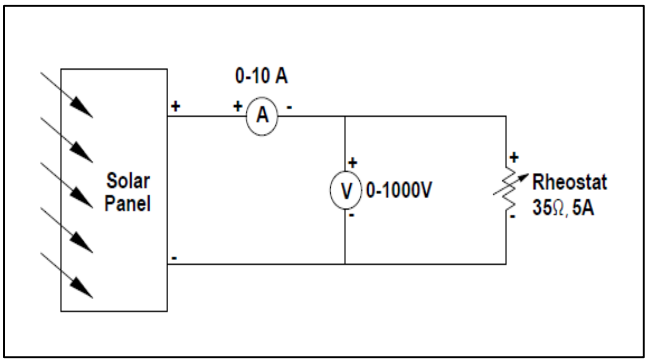

Fig. 4: Solar panel electrical setup to study I-V characteristics

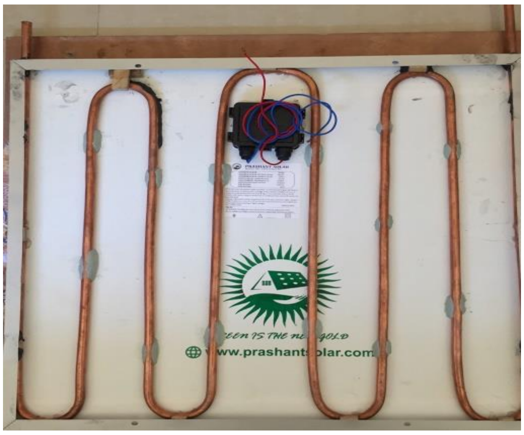

Fig. 5: Installation of the direct heat exchanger at the bottom side of the PV module

Fig. 6: Hybrid PV/T solar water system with measuring instruments

2.5. Calculations of technical parameters

2.5.1. Electrical Performance: Voltage and current readings were taken at 12:30 pm, and 1:00 pm. Then I-V characteristics were plotted for above time intervals as shown in Figures 7, 8, 9 and 10 respectively.

The electrical efficiency of the PV panel is calculated by the following formula

$$\eta = \frac{Im * Vm}{Apvt * G}$$

η_{el} - *Electrical* efficiency
Apvt - *C*ollector area [m^2]
G - *Irradiance* on the collector surface [W/m^2]
Im – Current of PV module at max. Power
Vm – Voltage of PV module at max. Power.
Then according to I-V characteristics at every Maximum Power Point (MPP) with collector area as 0.4288 m^2 and solar irradiance is taken as 6.52 kWh/m^2/day for the month May, electrical efficiency was calculated.

2.5.2. Thermal Performance: The thermal performance is calculated by the following formula, which is a function of solar radiation (G), mean fluid temperature Tm, and ambient temperature (Ta).

$$\eta = \frac{\dot{m} * Cp * (To - Ti)}{Apvt * G}$$

η_{th} - *Thermal* efficiency
Apvt - *C*ollector area [m^2]
T_o - *C*ollector outlet water temperature [°C]
T_i - *C*ollector inlet water temperature [°C]
$\dot{m}$ - Mass flow rate [kg/s]
C_p - *Specific* heat of Water [J/kg K]
G - *Irradiance* on the collector surface [W/m^2]

3. RESULTS AND DISCUSSION

3.1 Performance analysis of un-cooled PV module

In summer the number of solar radiations and ambient temperatures are significantly higher as compared to its values in the winter. Due to this, the highest operating temperature of the module was at 71 ^{0}C. The maximum efficiency of the PV module was observed at 12:30 p.m. for the highest PV power 13.4 Volts and 2.5 Amps respectively. For the highest PV power, the electrical power and efficiency generated by simple module were 33.5 W and 12.07 % respectively. Figure 7 has shown that module could produce the highest power of 33.5 W at 71 ^{0}C module temperature at solar radiation of 6.52 KWh/m^2/day. With the increase in temperature of the module, the open circuit voltage decreased drastically to 18.59 Volts.

3.2 Performance analysis of hybrid solar water system

The cooling of the PV module with direct heat exchanger increases its open circuit voltage (19.4 Volts) and load voltage (14.3 Volts) at highest PV power of the module at 12.30 PM as compared to the un-cooled module. It also leads to an increase in performance ratio (70.5 %) and efficiency (12.7%) of the system as shown in Figures 8. This shows that the cooling of the module improves its electrical output at 12.30 PM because sun rays strike normal to module surface generating peak electrical power and efficiencies. The performance of the system can further be improved using a mechanised sun tracking system. By utilizing waste heat, the hybrid solar system generated 616 W of additional thermal power at a cooling water flow of 0.042 Kg/sec. The flow rate measured was 0.042 Kg/sec and the temperature measured at heat exchanger water outlet was 45.4 ^{0}C. This hot water is suitable for low-temperature applications such as domestic use, swimming pools, hotels, heat pumps and under floor heating etc.

It was observed that the hybrid PV/T system could generate power with a combined efficiency of 73.7 % as shown in Figure 8. By fitting copper direct flow PV absorber surface to back surface of PV module and supplying cooling water through it continuously, the operating temperature of module dropped to 62.9^{0}C which was considerably lower than the peak temperature attained by the module as shown in figure 7.

The thermal efficiency of the module can be increased by continuously circulating cooling water through heat exchanger using an electric pump. The overall performance of the system can be enhanced further by the use of reflectors fixed to the sides of the module to improve the concentration ratio. By providing inlet water at low temperature, the operating temperature of the cooling module can be further reduced enhancing the overall performance of the PV/T system.

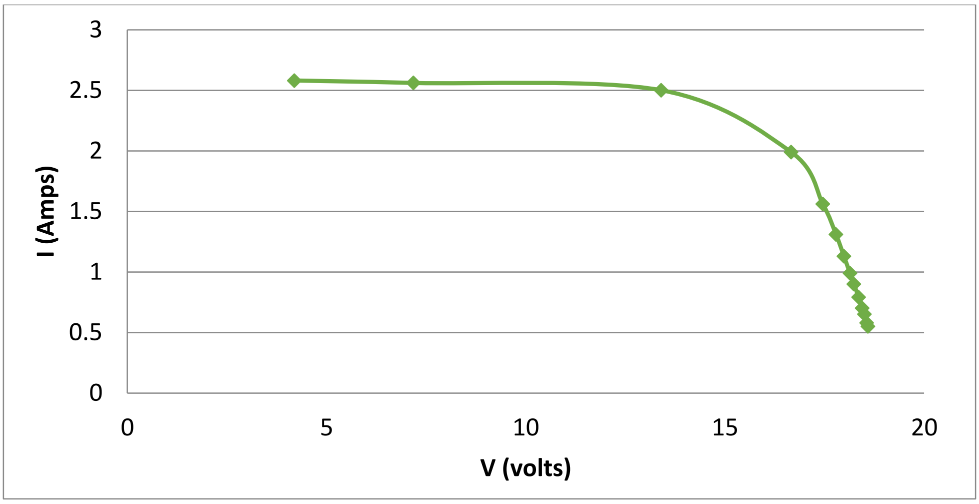

Fig. 7: Photovoltaic power produced by the uncooled PV module at 12:30 PM

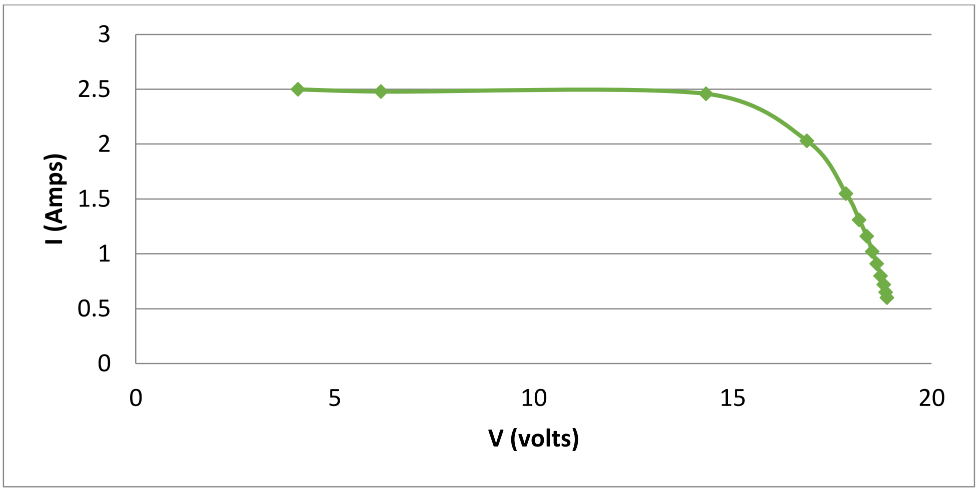

Fig. 8: Photovoltaic power produced by cooled PV module at 12:30 PM

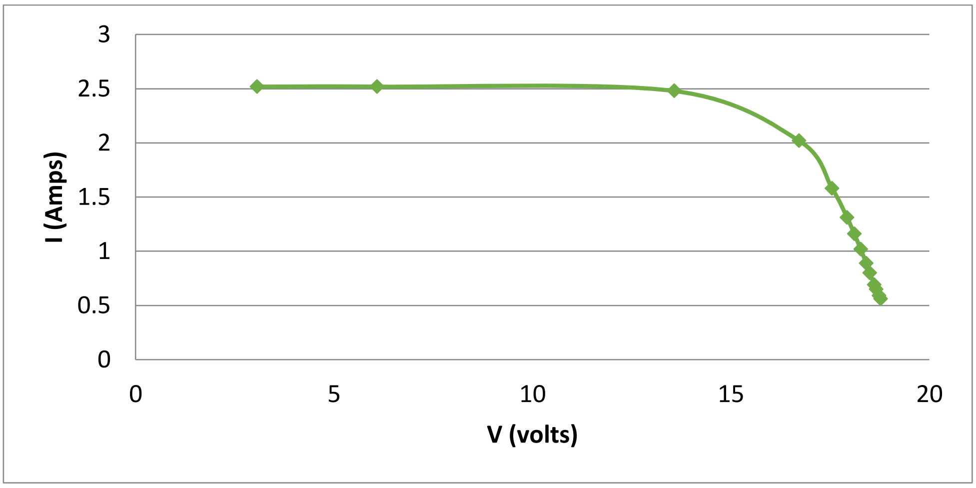

Fig. 9: Photovoltaic power produced by the uncooled PV module at 1:00 PM

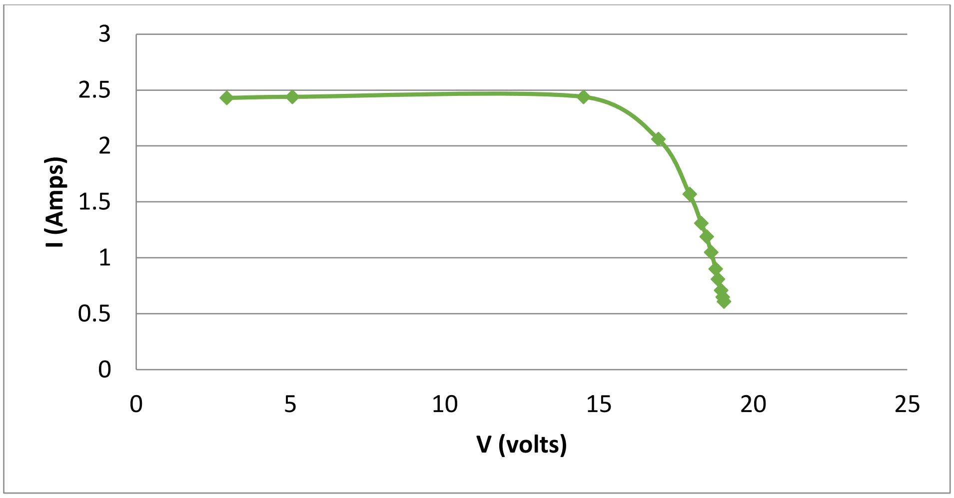

Fig. 10: Photovoltaic power produced by cooled PV module at 1:00 PM

At peak PV power point condition, the performance assessment of the simple PV module at ATC condition for Kalyan city latitude is shown in table 5.

Table 5: Performance of simple PV module

Technical parameters	Performance of PV module	Performance of hybrid PV/T system
Open circuit voltage (V)	18.59	19.38
Voltage (V)	13.40	14.33
Current (A)	2.5	2.46
PV power (W)	33.5	33.3
PV efficiency (%)	12.07	12.7
Thermal efficiency (%)	-	60.9
Combined PV/T efficiency (%)	-	73.7
Top module temperature (^{0}C)	71	62.9
Performance ratio (%)	67	70.5

4. CONCLUSION

The widespread adoption of solar energy systems requires low system costs and maximum high-quality energy to be generated per m^2 of roof coverage. Hybrid PV-T systems, which combine the basic principles of PV and solar-thermal collectors, generate both electricity and a useful thermal output from the same aperture area. By benefitting from integration synergies, a liquid PV-T collector can generate up to 40% more energy than PV and solar-thermal panels installed side by side over the same area, despite lower sun-to-electricity and sun-to-heat conversion efficiencies with respect to the separate panels. A PV-T module increases the longevity of the PV cells as these are operated at lower temperatures. These systems are best for small and weak roofs where installing two arrays side by side is not ideal, or applications where heat and electricity are required simultaneously.PV-T systems enable 'self-consumption' – the generation and use of electricity on site. Self-consumption is the cheapest way to generate energy with renewables and reduce the stress on the local grid at the same time. PV-T systems can be integrated with heat pumps or cooling systems and the electricity generated in excess could be stored in the integrated thermal store, or in the ground to be reutilised by ground-source heat pumps.

With sufficient water head of cooling water maintained during experiments, thermo syphon hybrid PV/T system will be the ideal solution for electrical power generation and hot water production used for low-temperature applications saving power to operate the pump for circulation of cooling water through the heat exchanger.

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