Performance Analysis of a Specially Designed Flow Heat Exchanger Used in Hybrid Photovoltaic/Thermal Solar System

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Abstract- Solar Photovoltaic module converts the light component of solar radiation into electrical power and, heat part is absorbed by module increasing its operating temperature. Elevated module temperature reduces the electrical efficiency of modules by 10 to 35%. Cooling of module using external cooling system called as photovoltaic heat exchanger can improve its electrical power efficiency. This cooling system attached at backside of module produces thermal power in terms of hot water, which can be used for low temperature applications. Combined PV module and heat exchanger generating both electrical and thermal power is called as hybrid Photovoltaic/Thermal (PV/T) solar system. A performance of a specially designed flow heat exchanger called as spiral flow PV absorber and its effect on hybrid PV/T system is studied in the current paper. The experimental results like performance efficiencies of Photovoltaic, thermal and PV/T system over a range of working conditions were discussed and evaluated for latitude of Mumbai. The results at solar radiation of 892 W/m^2 and water mass flow rate of 0.042 kg/sec through heat exchanger showed significant improvement in combined PV/T efficiency of 68.2 % with PV efficiency of 12.9 % and performance ratio of 80 %.

Keywords- Photovoltaic module; electrical efficiency ; PV heat exchanger ; hybrid PV/T solar water system; spiral flow PV absorber; combined PV/T efficiency.

1. Introduction

Solar Photovoltaic (SPV) module utilizes solar radiation to generate electricity raising its operating temperature. Cooling of 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. In a hybrid PV/T solar water system, PV module and thermal unit are mounted together to enable simultaneous conversion of solar energy in to electricity and thermal energy. 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 thermal component is minimum.

Heat exchangers namely, direct flow, oscillatory flow, serpentine flow, web flow, spiral flow, parallel-serpentine flow, and modified serpentine-parallel flow, were designed to be used as PV hybrid systems and their performances were studied using different simulation techniques [1]. This simulation studies revealed that heat exchanger with spiral flow arrangement produced thermal efficiency of 50.12%; and PV module efficiency of 12.8% respectively which was significantly more than other types of designs.

Kostic et al. [2] carried out experimental studies using sheet and tube type of device fitted with a pair of flat aluminium concentrators. This study revealed that with aluminium sheet concentrators mounted at 10^0 and 56^0 to the vertical plane of PV module, the electrical and thermal energy output improved by 8.6% and 39% , compared to simple PV module. Aluminium foil concentrators used in the system produced 17.1% additional PV energy and 55% higher thermal energy compared to conventional PV module.

Jin-Hee Kim and Jun-Tae Kim [3] studied two hybrid PV/T water collector systems with different arrangements namely, sheet and tube and fully wetted absorber surfaces. Combined PV/T efficiency of these systems observed was 65% and 60.6% respectively. The comparison of performance of the absorber surfaces using unglazed and glazed PV module designs revealed that an unglazed PV module produced more electrical energy and the glazed PV module generated more thermal energy because of its more efficient ways of absorbing solar energy.

Investigational study on oscillatory flow heat exchanger fitted with hybrid PV/T water system was performed by Palaskar and Deshmukh [4] to predict its performance for Mumbai latitude. In the studies, the combined performance efficiencies of PV/T hybrid water system for different ranges of operating conditions were determined and examined with actual experimental work. The results of this system at solar radiation of 918 W/m^2 and cooling water flow of 0.035 kg/sec showed considerable improvement in performance of the system with its combined efficiency of 53.7 % and PV performance efficiency of 11.7 %. This study also revealed that operating temperature of cooled module decreased by 27% as compared to un-cooled PV module.

The overall performance of a conventional PV module improved when cooled directly by passing water over its top surface [5]. This study showed that the operating temperature of a PV module in a combined system was lower than in a conventional module. With PV module heat absorbed by the film of flowing water and which was utilized for low temperature applications, the overall combined efficiency of system was higher than conventional module. The experimental results showed that electrical output of this system increased by 33% compared to conventional module when the PV modules was cooled during its working.

Experiments were performed on different PV/T water systems namely; direct flow, parallel flow and split flow system and their performances for thermal energy output were studied for various tilts of PV/T system by Kamaruzzaman [5]. This work revealed that the split flow PV/T system with 51.4% thermal energy output found producing marginally higher power compared to other two systems.

Experiments were performed by Tripanagnostopoulos et al. [7] on such type of hybrid PV/T systems with and without Glazing, using system with and without reflectors, operating at temperatures of 25^0C, 35^0C, and 45^0C respectively. It was found that system, with glazing and flat reflectors and operating at 25^0C temperature, generated maximum 167.98 kWh/ m^2 electrical energy per year at 10.21% of electrical efficiency and, 831.75 kWh/m^2 of thermal energy per year with of 50.57% thermal efficiency.

In a review articles of [8, 9], Palaskar and Deshmukh have extensively reviewed various literatures available on research, development and selection of PV absorber types, materials of its construction and use of concentrators for improvement in energy output of hybrid solar systems. The article shows that the overall performance of hybrid system improved considerably using above-mentioned techniques. It was also noticed that the spiral flow type of system fabricated from copper tubes with reflectors work with higher combined PV/T efficiency compared to hybrid systems. It was also revealed that such system has better commercial viability in future.

The performance evaluation of a hybrid photovoltaic thermal double pass facade for space heating was developed using the energy balance equations for the climate of New Delhi by Tiwari G N et al. [10]. In this study, from numerical results, it was observed that the yearly thermal and electrical energy generated by the façade system were 480.81 kWh and 469.87 kWh respectively. It was also observed that thermal energy generated by the system was 1729.84 kWh per year.

In the current research, performance analysis of simple PV module and hybrid PV/T solar hybrid system are compared with various technical parameters at ATC for latitude of Mumbai. For this work, commercial PV module was converted to hybrid PV/T system adding spiral flow type heat exchanger at its back surface. This heat exchanger was designed and fabricated using hollow square copper tubes. Copper tubes are used for fabrication of the device due to its better thermal conductivity and ease in fabrication. Square cross-sectioned hollow tubes were used to fabricate hybrid system increasing its surface contact with back surface of PV module. Increase in photovoltaic output power, thermal output power, photovoltaic, thermal and combined PV/T efficiency and decrease in top and back surface temperatures of module at different flow rates of cooling water for highest PV power condition are discussed and analysed. Performance ratio of the simple PV module and hybrid system were calculated and compared with each other.

2. Experimental

2.1. Commercial PV module with stand

A TATA BP commercial PV module with rated capacity of 180 watts having area 1.25 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 were mounted on mild steel stand facing due South with slope designed for latitude of Mumbai on the terrace of the main building of the Institute.

Table 1. Technical data of PV module

Module	I_{SC} (A)	V_{OC} (V)	I_{MP} (A)	V_{MP} (V)	η_{mod} (%)
Tata Bp Mono Crystalline	5.4	44.8	4.99	36.6	14.52

2.2. PV heat exchanger design and its fabrication

With detailed literature studies and its analysis, simulation results of stainless steel square spiral flow PV absorber surface were analysed [1] with experimental work by using tube of different materials and thickness to compare the performance parameters of both systems. Selected square section copper pipe provides good surface contact and thermal conductivity to absorb heat from module and cooling it at reasonable temperature level. To achieve maximum combined PV/T output, spiral flow PV absorber was fabricated with hollow tubes of square cross section. The manufacturing and assembly of copper spiral flow PV absorber surface was simple and cost effective compared to other types of flows and its materials. The detailed heat exchanger dimensions are given in Table 2. Figure 1 shows the detailed drawing of PV module and heat exchanger assembly with important dimensions and necessary features such as water inlet, outlet etc. The hydraulic test was conducted on heat exchanger using water pump to locate and eliminate minute leakages in joints and passages of water flow, before it was finally assembled to perform experimental work. This test was necessary, as hybrid system was required to circulate cooling water under certain pressure and flow rates. The installed spiral flow PV absorber surface on the back side of PV module is shown in Figure 2.

Fibber glass wool insulation blanket with thermal conductivity of 0.04 W/m ^{0}k was used to ensure proper thermal insulation the PV absorber surface for reducing temperature loss from the back and other sides of the heat exchanger. A blanket of fibber glass wool with 50 mm thickness and 24 Kg/m^3 density was fitted to the backside of the heat exchanger. An aluminium sheet of 16-gauge thickness was used for covering and protection of the glass wool to form a complete assembly of hybrid PV/T solar system.

2.3. Measuring instruments

To measure global and diffuse solar radiations on horizontal surface a pyranometer made by Dynalab, India was used during experimental process. K-type thermocouples were used to measure ambient temperature and temperatures on the top and backside of PV module during experiments. A 16-channel temperature data logger was used to scan and record thermocouple temperatures at specified time interval. Output voltage and current at various loading conditions for a day were measured using DC voltmeter and ammeter respectively. A 36 Volts and 180 Watt direct current load bank was used to measure voltage and current load on PV module during experiments. A 500 LPH rotameter was arranged on the water line to measure flow rate of inlet water of the spiral flow PV absorber surface. Temperature gauges of dial types were used to measure inlet and outlet water temperature of the heat exchanger. Electrical water pump was used to ensure proper supply of cooling water through heat exchanger at variable flow rates reducing working temperatures of system. The complete, assembled experimental setup with all components is shown in Figure 3.

Table 2. Heat exchanger characteristics

Size of square Copper tube	Pitch between two consecutive tubes	Length of heat exchanger	Module back area occupied by heat exchanger
12x12x1.25 mm thick	37 mm	31.5 mts.	32 %

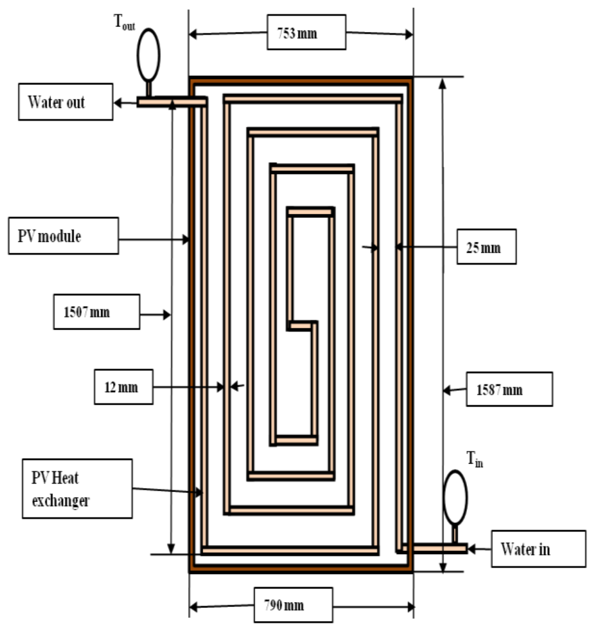

Fig. 1. Module and heat exchanger assembly with important dimensions and necessary features

Fig. 2. Installation of spiral flow heat exchanger at bottom side of PV module

Fig. 3. Hybrid PV/T solar water system with measuring instruments

2.4. *Experimental observations procedure*

The important purpose of this experimental work was to study and compare performance of conventional PV module and hybrid PV/T solar system using spiral flow type heat transfer system at ATC condition for Mumbai latitude. All experiments were conducted during month of March 2014. The electrical and thermal energy produced by the solar equipments were measured daily for 7 hours. Performance of the un-cooled and cooled PV module was studied with daily experiments conducted between 9.30 AM and 4.30 PM on distinct days for peak PV power point condition. As explained below, the entire experimental work was divided in two parts.

Initially, experiments were conducted on simple PV module determining its performance at actual test conditions (ATC) for selected slopes at peak PV power point. For these experiments, different observations such as global radiation, voltage, and current at corresponding loading conditions were recorded manually at every 30 minutes time interval. K-type temperature sensors with data logger were used to scan and record automatically ambient temperature and the temperatures at top surface of the PV module and its back side at an interval of one minute. During second observation set, experiments were performed on hybrid solar system with spiral flow heat exchanger attached at back side of module. For this setup, different readings were recorded manually and automatically as per the procedure explained above for peak PV power point. Readings of water flow rate, and its inlet and outlet temperatures flowing through heat exchanger were collected manually at every 30 minutes of time interval. These readings were used to calculate the thermal power, combined PV/T efficiency and performance ratio of hybrid system.

During experiments, it was found that the electrical energy produced by the PV module during the day depended on two key factors, namely, intensity of solar radiation, and rise in module temperature. The intensity of solar radiation mainly depends on the time of the day and always fluctuates during the day. İt is maximum at noon and minimum at early morning and during sun sets. The rise in module temperature was directly proportional to solar radiation falling on the surface of the PV module. Experiments on PV module, with and without heat exchanger were performed by maintaining same slopes of hybrid system for all experimental days. These slopes were determined for the maximum output of the solar PV module by performing related experiments. The experimental setup was arranged at these slopes without any tracking mechanism of the module. For water-cooled system; experiments were conducted for different water flow rates to determine the exact performance of hybrid system in terms of electrical; thermal; combined power etc. at peak PV power point.

2.5. Calculations of technical parameters

Equations used to calculate output photovoltaic and thermal power, input solar power, performance ratio, photovoltaic, thermal and combined PV/T efficiency at ATC for Mumbai latitude [11, 12, 13] are as explained below.

Electrical power (P_{PV}) generated by un-cooled and cooled module and thermal power (P_T) produced by the hybrid system at ATC condition are given by:

$$P_{PV} = V \times I \quad (1)$$

$$P_T = \dot{m} \times C_P \times (T_{wo} - T_{wi}) \quad (2)$$

Total solar radiation (I_T) on normal to module surface (W) and solar radiation (I_t) calculated on normal to module surface (W/m^2) are calculated by using following formulas:

$$I_T = I_t \times A_{PV} \quad (3)$$

$$I_t = I_g \times r_g \quad (4)$$

The tilt factor (r_g) for global radiation and elevation angle (α) are calculated as under:

$$r_g = \sin(\alpha + \beta)/\sin\alpha \quad (5)$$

$$\alpha = 90 - \Phi + \delta \quad (6)$$

The electrical efficiency (η_{PV}) of PV module and thermal efficiency (η_T) of hybrid system (%) are found by following equations:

$$\eta_{PV} = P_{PV} / I_T \quad (7)$$

$$\eta_T = P_T / I_T \quad (8)$$

Combined photovoltaic and thermal (PV/T) efficiency and performance ratio (P_R) of hybrid solar system are calculated as under:

$$\eta_{PV/T} = \eta_{PV} + \eta_T \quad (9)$$

$$P_R = P_{PV}/P_{STC} \quad (10)$$

Where: P_{STC} is the electrical power produced by module (W) at STC condition.

3. Results and Discussion

3.1. Performance analysis of un-cooled PV module

At the time of experiments, amount of solar radiations and ambient temperatures were significantly higher compared to its values in the winter as majority of the reading were recorded during summer. Due to this, highest operating temperature of module was at 61.80 ^{0}C as shown in Figure 7. At 12.30 PM, the output voltage and current produced by the un-cooled module at highest PV power was 29.7 Volts and 4.37 Amps respectively. For highest PV power, the electrical power and efficiency generated by simple module were 129.8 W and 11.70 % respectively, with the performance ratio of 72 % as shown in Figures 4 and 5. The electrical power generating capacity of module was decreased by 0.4% for every 1°C raise in temperature of PV module above 25 ^{0}C at ATC. Figure 4 has shown that module could produce highest power of 129.8 W at 61.8 ^{0}C module temperature at solar radiation of 893 W/m^2. With increase in temperature of module, open circuit voltage decreased drastically to 38.2 Volts. The temperatures at the top and back of the un-cooled PV module (below the heat exchanger) were 61.8 ^{0}C and 39 ^{0}C as shown in Figures 7 and 8 respectively.

3.2. Performance analysis of hybrid solar water system

Cooling of the module with spiral heat exchanger increases its open circuit voltage (40 Volts) and load voltage (31.5 Volts) at highest PV power of the module at 12.30 PM as compared to un-cooled module. It also leads to an increase in photovoltaic power (146.3W), performance ratio (80 %) and efficiency (12.9%) of the system as shown in Figures 4 and 5 respectively. This mainly reveals that the cooling of module improves its electrical output. Figure 5 shows low PV efficiencies in morning and late afternoon for both cooled and un-cooled cases. This mainly happens due to decrease in angle of incidence of solar rays from morning to noon and increases to late afternoon. At solar noon sun rays strike normal to module surface generating peak electrical power and efficiencies. The performance of the system can further be improved using mechanised sun tracking system. By utilizing waste heat, the hybrid solar system generated 616 W of additional thermal power at cooling water flow of 0.042 Kg/sec. The temperature measured at heat exchanger water outlet was 36.50 ^{0}C. This hot water is suitable for low temperature applications such as domestic use, swimming etc.

It was observed that the PV/T system could generate power with combined efficiency of 68.2 % as shown in Figure 6. During the experimental work, cooling water was continuously circulated through heat exchanger using electric pump from 10 AM to 3 PM. Due to this, system performances enhanced significantly and operating temperature of the system reduced considerably. By fitting copper spiral flow PV absorber surface to back surface of PV module and supplying cooling water through it continuously, the operating temperature of module dropped to 50.7^{0}C which was considerably lower than the peak temperature attained by module as shown in Figure 7. Use of thermal grease compound between top surface of absorber surface and lower surface of module will minimize the air gap between these surfaces, improving the rate of heat transfer between these surfaces. With cooling of module, its operating temperature decreases, improving the photovoltaic, thermal, and combined power and efficiencies of hybrid system. Figure 8 shows temperature attended by back surface sheet attached below absorber surface. The observation shows that, the temperature of sheet fitted below heat exchanger was equal to the ambient temperature. This shows that selected thickness of glass wool insulation was suitable for providing proper thermal insulation to the system.

The overall performance of the system improved due to the reflectors fixed to the sides of the module enhancing its concentration ratio. The operating temperature of cooled module can be further reduced providing inlet water at low temperature enhancing photovoltaic, thermal and combined PV/T power, and efficiencies of hybrid system. 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 pump for circulation of cooling water through heat exchanger. An autonomous hybrid system may be developed for above-mentioned applications for rural areas. At peak PV power point condition, the performance assessment of the simple PV module and hybrid solar system at ATC condition for Mumbai latitude is shown in Table 3.

Table 3. Performance comparison of simple PV module and hybrid solar system

Technical parameters	Performance of PV module	Performance of hybrid PV/T system
Open circuit voltage (V)	38.2	40
Voltage (V)	29.7	31.5
Current (A)	4.37	4.56
PV power (W)	129.8	143.6
PV efficiency (%)	11.70	12.9
Thermal power (W)	---	616
Thermal efficiency (%)	----	55.3
Combines PV/T efficiency (%)	---	68.2
Top module temperature (^{0}C)	61.8	50.7
Performance ratio (%)	72	80

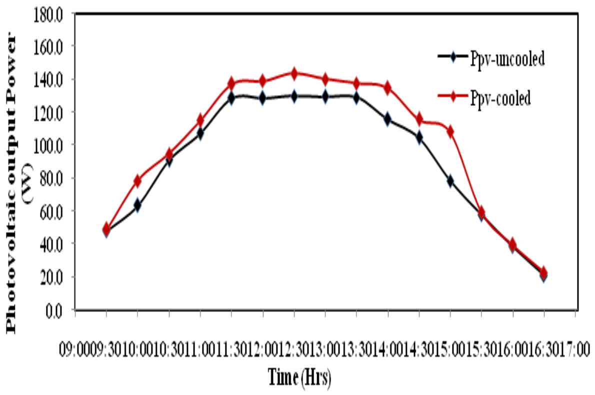

Fig. 4. Photovoltaic power produced by un-cooled and cooled PV module

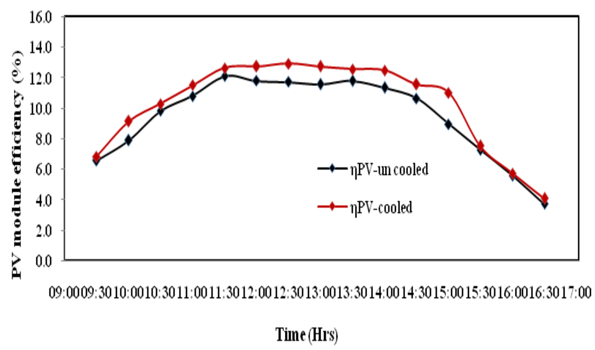

Fig. 5. Photovoltaic efficiency of un-cooled and cooled PV module

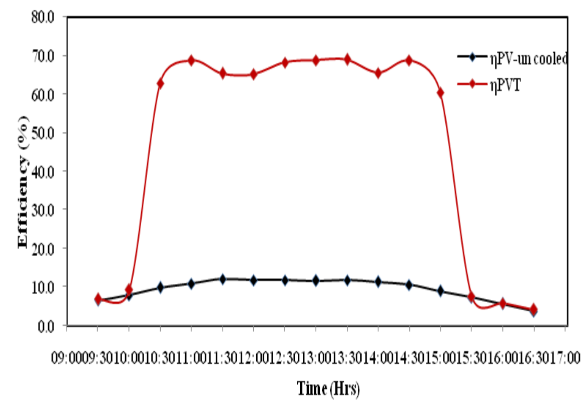

Fig. 6. Photovoltaic and combined efficiency of un-cooled/ cooled PV/T system

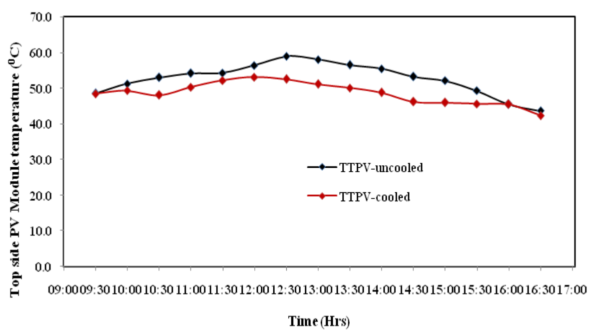

Fig. 7. Top side PV temperature (TTPV) attended by un-cooled and cooled PV module

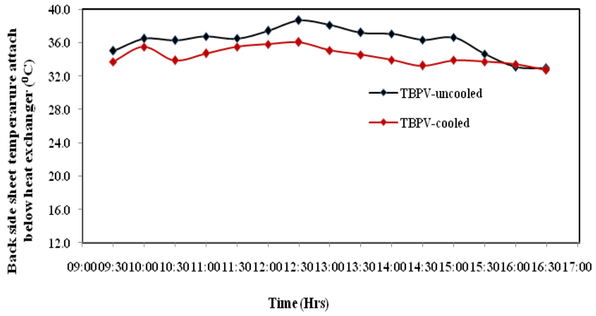

Fig. 8. Temperature attended by Backside PV sheet (TBPV) attached back side of heat exchanger for un-cooled and cooled PV module

4. Conclusion

Copper spiral flow absorber surface fitted at bottom surface of PV module supplying cooled water through it, reduced operating temperature of PV module by 18 % as compared to un-cooled module. Due to this reason, the photovoltaic power and efficiency of water-cooled module enhanced by 10.60% and 10.30% respectively at 12.30 PM as compared to un-cooled module. Using this system, the performance ratio of cooled module increased by 8 % . The hybrid system generated thermal power and efficiency of 616 W and 55.3 % respectively achieving combined PV/T efficiency of 68.2 % at highest PV power point. The hybrid solar water system used in this work harnessed 68.2% of solar radiation falling on earth using 55.3 % of waste heat to thermal energy enhancing the combined efficiency of the system significantly. The thermal energy thus generated in the form of hot water is suitable for low temperature applications. Thus, on a yearly basis, the hybrid system can produce 1368 KWh of combined energy with 259 KWh of electrical energy for module area of 1.25 m^2. The above results reveal that the hybrid solar water system can be used as a potential alternative for power production.

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