Waste Heat Recovery Study of Spiral Flow Heat Exchanger Used in Hybrid Solar System with Reflectors

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Abstract

The combined efficiency of simple hybrid photovoltaic/thermal (PV/T) solar water system is less due to its low concentration ratios and, non-standardization of PV heat exchanger surfaces. The simple and cost effective technique to increase PV/T efficiency is the use of reflectors which will boost solar radiation on PV module surface. Flat reflectors fitted to sides of PV module of hybrid system helps in improving the concentration of solar radiation on it. This paper provides design and performance analysis of spiral flow heat exchanger used in hybrid system with flat reflectors of aluminum sheets. The experimental results like performance efficiencies of photovoltaic, thermal, and combined photovoltaic/thermal system over a range of actual working conditions are discussed and evaluated for latitude of Mumbai. The results at solar radiation of 950 W/m² and water mass flow rate of 0.042 kg/sec through heat exchanger with reflectors showed combined PV/T efficiency of 71.40 % with PV efficiency of 12.40%.

Keywords

Low Concentration Ratio; Combined PV/T Efficiency; Flat Reflectors; Spiral Flow Heat Exchanger; Actual Working Conditions

Introduction

Solar photovoltaic (SPV) module absorbs solar radiation generating electricity while its temperature increases during the service. Cooling of module improves generation of electrical power, efficiency and its operational life. In general, module is cooled by supplying cold water through heat exchanger attached at bottom side of simple module. This heat exchanger is called as PV absorber surface that absorbs heat from module, cooling it at reasonable temperature. In hybrid PV/T solar system, simple PV module and thermal solar collector unit are mounted together to facilitate simultaneous conversion of solar radiation to electrical and thermal energy from single integrated unit. This conversion has showed that, hybrid solar system generates higher combined energy per square meter area of module, and could improve cost effectiveness of simple PV modules if the cost of thermal element is kept low. In the present scenario, materials cost of photovoltaic cell constitutes 50 % to 60% of total cost of commercial PV module (Solanki C.S. 2010). As a result of technological developments and market competition, PV module prices have started declining since the last few years (Solanki C.S. 2010). Currently, the cost of mono crystalline PV module is as high as US dollar of 1.12/watt to 1.70/watt. Significant measures are required to reduce the cost of PV power, for the widespread commercialization of PV technology, by reducing cell material. Various techniques such as use of thinner wafer, thin-film solar cell technologies, and concentrator techniques have been incorporated by many module-manufacturing companies to reduce the overall price of commercial modules. As per information obtained from manufacturing companies, these techniques are found useful to reduce PV cell material consumption per watt of generated output power. In the concentrator technology, optical reflectors could replace expensive PV cell area by the use of cheaper reflector materials such as glass mirror, aluminum sheets or foils, and acrylic mirror sheets. Implementing these techniques, performance of simple module will be enhanced due to more solar radiation striking module surface during day time when the system generates the electrical and thermal power. The idea to use solar concentrator with modules is simple, but it is difficult to achieve high level of
concentration ratio using this technology throughout the day. The high concentration ratio puts stringent constraints on solar cell’s heat dissipation capacity during its service life. However, it is possible to use low concentration optics with modules in static mode to eliminate continuous module tracking. Based on this idea, flat reflectors are found attractive to reduce price of solar photovoltaic output power. Flat reflectors are static concentrators, where solar intensity has been enhanced by adding reflectors to module sides.

Different formulas were derived and applied analytically to calculate geometrical concentration ratios and irradiance distribution at the base of flat-sided linear trough configuration (Burkhard Donald G et al., 1978). In this study, the realistic concentration ratios were obtained in a range of 1.5 to 4 depending on geometry and coefficient of reflection. Low concentration solar energy configurations were investigated and studied to determine its effect on photovoltaic electrical output (Tripanagnostopoulos Y, 2002). During this work, it was found that the flat diffuse reflectors provided a uniform distribution of solar radiation on PV module surface and the linear Fresnel lenses were used to achieve additional solar control for interior spaces. The compound parabolic collector (CPC) with reflectors was effectively combined with PV strips to act as flat solar thermal absorbers. The absorbed solar radiation increased the cell temperature with reduced PV efficiency. Several modes were applied for efficient and cost effective heat extraction and the most appropriate one was selected according to required application. Tripanagnostopoulos et al. (2003) conducted experiments using hybrid PV/T systems, with and without glazing, and, with and without reflectors, operating at system temperatures of 25 °C, 35 °C, and 45 °C respectively. In the experiments it was found that system with glazing and flat reflectors operating at 25 °C system temperature, generated highest annual electrical energy (167.98 kWh/m²y) with electrical efficiency of 10.21%, and, maximum annual thermal energy (831.75 kWh/m²y) with thermal efficiency of 50.57%. An auxiliary mirror drive mechanism was designed and developed to track sun continuously and reflect solar radiation on stationary PV arrays to study its effect on electrical power output (Kulkarni et al., 2007). This mechanism consisted of five bar spherical linkage used for solar tracking, and two degrees of freedom mechanism was used for sun tracking along its azimuth and altitude direction. These experiments show that output power of the PV panel increased by 22% by fitting tracking mechanism to PV arrays. V-trough shape concentrators were designed and fabricated to evaluate the PV electricity cost ($/W) reduction as compared with one-sun concentration PV module for latitude of Mumbai (Sangani and Solanki, 2007). V-trough concentrator system with two-sun concentration was able to generate 44% more output power as compared with one-sun concentration for naturally cooled PV modules. The cost/unit watt of electricity generated from PV module was reduced by 24% from 7.72 to 5.88 $/W by using V-trough concentrators as compared with one-sun concentration PV module. Kostic et al. (2008) have carried out investigational studies using sheet and tube type heat exchanger as a hybrid system fitted with flat aluminum concentrators. It was concluded that with aluminum sheet concentrator, the electrical and thermal energy produced was 8.6% and 39% more than simple PV module, and aluminum foil concentrators produced 17.1% and 55% more PV energy and thermal energy respectively compared with PV module. Othman et al. (2008) designed and studied seven types of PV absorber, i.e., direct flow, oscillatory flow, serpentine flow, web flow, spiral flow, parallel-serpentine flow, and modified serpentine-parallel flow. Performances of these systems were studied using simulation methods. The spiral flow heat exchanger of the above systems produced highest thermal efficiency of 50.12%; and PV module efficiency of 12.8% compared with other types of PV absorber surfaces. Reflectors of different materials were designed and fitted to sides of simple PV module to investigate the performance of module for different reflector materials, and the best reflector which could generate highest electrical power (Djilali Rizk and Nagrial M H, 2009) was selected for the studies. Experiments were performed on aluminum; stainless steel, and chrome film reflectors to determine more efficient type of reflector producing highest PV power and less amount of excess heat. Finally it was observed that, chrome reflectors produced 27.65% additional PV power output against aluminum foil and 34.05% more PV power output against stainless steel reflectors respectively. Overall performance of simple PV module was also found to be improved when it was cooled by passing water over its top surface (Hosseini, et al., 2011). This test shows that the operating temperature of a PV module in a combined system was lower than that in a conventional module. As the heat of PV module is absorbed by the water film and utilized for low temperature applications, the overall efficiency of combined system was found to be higher than conventional module. The experimental results showed that electrical performance of the combined system was 33% higher than conventional
module. Three PV/T water collectors, namely direct flow, parallel flow and split flow were designed and their thermal performances were experimentally compared for various tilts of hybrid PV/T system by Kamaruzzaman, et al. (2011). In this study, it was found that split flow PV/T system produced 51.4% thermal power compared with that of 50.8 % and 50.6% by other two collectors respectively. The performance evaluation of a hybrid photovoltaic thermal double pass façade for space heating was developed by using the energy balance equations for the climate of New Delhi (Tiwari G N et al. 2011). In this study, from numerical results, it was observed that the annual 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 calculated as 1729.84 kWh on yearly basis. Palaskar and Deshmukh (2012, 2013-b) reviewed the literature on research, development and selection of various PV absorber designs, materials, and use of concentrators for higher energy output of hybrid solar systems. The review showed that the overall system performance of hybrid system could be improved by applying the above mentioned augmentation techniques. It was also found that the spiral flow heat exchanger made of copper and fitted with reflectors had higher combined PV/T efficiency than simple hybrid systems. This system will have better commercial viability in future than other systems. Experimental study was performed on specially design heat exchanger used in hybrid PV/T water system to predict its performance for latitude of Mumbai (Palaskar et al., 2013-a). The results of this hybrid system at solar radiation of 918 W/m² and cooling water mass flow rate of 0.035 kg/sec showed the combined PV/T efficiency of 53.7 % with PV efficiency of 11.7 %. Experiments on this system showed that the operating temperature of cooled module was decreased by 27% by fitting the heat exchanger to the bottom of the PV module. A pair of aluminum flat reflector was designed, and attached to sides of simple PV module to study its effect on performance of PV module for latitude of Mumbai (Palaskar and Deshmukh, 2014).The modified PV module at 25° tilt at south direction and 24° reflector orientations with vertical surface of module could generate more PV power and efficiency of 22 % and 21 % respectively as compared with simple PV module. The performance ratio of modified PV module was enhanced by 17 %.

In this study, performance analysis of cooled PV module and hybrid PV/T solar system with reflectors are compared with various technical parameters for latitude of Mumbai. Commercial PV module is converted to hybrid PV/T system by fixing spiral flow heat exchanger at bottom side of PV module. This heat exchanger was designed and fabricated using copper square tubes. Copper tubes were used for this study for its high thermal conductivity and ease of fabrication. A pair of aluminum reflector was designed, and fitted to the shorter sides of module of hybrid solar system. In this study, it was observed that there was considerable increase in solar radiation collection on surface of module. Increase in photovoltaic power, thermal power, photovoltaic, thermal, and combined PV/T efficiency and decrease in top and bottom side module temperatures at different flow rates for highest PV power point condition are discussed and analyzed in this work.

Nomenclature and Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>A refl</td>
<td>Area of any one reflector attached to module (m²)</td>
</tr>
<tr>
<td>A PV</td>
<td>Area of PV module (m²)</td>
</tr>
<tr>
<td>ATC</td>
<td>Actual Test Conditions of commercial PV module</td>
</tr>
<tr>
<td>C p</td>
<td>Specific heat of water (J/kg °K)</td>
</tr>
<tr>
<td>F CV</td>
<td>The View factor</td>
</tr>
<tr>
<td>I</td>
<td>Current produce by PV module (A)</td>
</tr>
<tr>
<td>I b</td>
<td>Beam radiation measured by pyranometer on horizontal surface (W/m²)</td>
</tr>
<tr>
<td>I d</td>
<td>Diffuse radiation measured by pyranometer on horizontal surface (W/m²)</td>
</tr>
<tr>
<td>I g</td>
<td>Global radiation measured by pyranometer on horizontal surface(W/m²)</td>
</tr>
<tr>
<td>I ref</td>
<td>Solar radiation reflected from one reflected surface on PV surface (W/m²)</td>
</tr>
<tr>
<td>I T</td>
<td>Direct solar radiation on PV module surface (W)</td>
</tr>
<tr>
<td>I r</td>
<td>Global radiation calculated on normal to PV module surface (W/m²)</td>
</tr>
<tr>
<td>I r ref</td>
<td>Total radiation on module surface by considering direct plus reflected radiation (W)</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate of water (kg/sec)</td>
</tr>
<tr>
<td>η PV/T</td>
<td>Combined PV/T efficiency (%)</td>
</tr>
</tbody>
</table>
\begin{equation}
\eta_T \quad \text{Thermal efficiency of hybrid (PV/T) solar water system (\%)}
\end{equation}

\begin{equation}
P_{PV} \quad \text{Electrical power produced by PV module (W) at ATC conditions}
\end{equation}

\begin{equation}
P_{R} \quad \text{Performance ratio of PV module (\%)}
\end{equation}

\begin{equation}
P_{STC} \quad \text{Electrical power produced by PV module (W) at STC conditions}
\end{equation}

\begin{equation}
P_T \quad \text{Thermal power produced by hybrid (PV/T) solar water system (W)}
\end{equation}

\begin{equation}
r_b \quad \text{Tilt factor for beam radiation}
\end{equation}

\begin{equation}
r_d \quad \text{Tilt factor for diffuse radiation}
\end{equation}

\begin{equation}
r_g \quad \text{Tilt factor for global radiation}
\end{equation}

\begin{equation}
\text{STC} \quad \text{Standard Test Conditions of commercial PV module}
\end{equation}

\begin{equation}
T_{wi} \quad \text{Water inlet temperature (°K)}
\end{equation}

\begin{equation}
T_{we} \quad \text{Water outlet temperature (°K)}
\end{equation}

\begin{equation}
V \quad \text{Voltage produce by PV module (V)}
\end{equation}

\begin{equation}
\alpha \quad \text{Elevation angle (°)}
\end{equation}

\begin{equation}
\beta \quad \text{Slope of PV module at south direction (°)}
\end{equation}

\begin{equation}
\delta \quad \text{Declination angle (°)}
\end{equation}

\begin{equation}
\eta_{PV} \quad \text{Electrical Efficiency of PV module (\%)}
\end{equation}

\begin{equation}
\eta \quad \text{Reflectivity of reflectors (\%)}
\end{equation}

\begin{equation}
\Phi \quad \text{The latitude angle (°)}
\end{equation}

\section*{Materials and Methods}

\subsection*{Commercial PV Module and Heat Exchanger Design with Its Fabrication}

Tata Bp India made commercial PV module with rated capacity of 180 watts was used to conduct experiments on the simple and cooled module with flat reflectors. The rectangular module with its length and width of 1.587 m and 0.79 m respectively was used for this work. Open circuit voltage and short circuit current at STC of the module quoted by manufacturer were 44.8 volts and 5.40 amps respectively. As per technical specifications of the module at STC, its efficiency was found at 14.52%.

Detailed literature review and its analysis was carried out (Othman et al., 2008) and simulation based results of square spiral flow PV absorber surface were analyzed with experimental work using copper as a heat exchanger material. The copper square section tube provides good surface contact and high thermal conductivity compared with other materials to absorb heat from module cooling it at reasonable temperature. In present research work, tubes with different configuration of water flow were fitted as a heat exchanger from bottom side of module. To achieve highest combined PV/T efficiency of hybrid system, spiral flow PV absorber arrangement was used with square hollow tubes. The manufacturing and assembly of copper spiral flow PV absorber surface was simple compared with other types of flows and its materials. With the detailed design and its calculations, heat exchanger specifications are shown in table 1. 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 helped to ensure proper circulation of water at certain pressure and flow through the heat exchanger sealing the leakages of the heat exchanger. Actual installation of spiral flow PV absorber surface on bottom side of PV module is shown in figure 1. Fiber Glass wool blanket with thermal conductivity of 0.04 W/m\(\cdot\)k was used to insulate the PV absorber surface for reducing the overall temperature loss from the bottom and sides of the heat exchanger. Blanket of fiber glass wool with 50 mm thickness and 24 Kg/m\(^3\) density was fitted at the bottom of the heat exchanger. An aluminum sheet of 16-gauge thickness was used to cover and protect the glass wool to form a complete assembly of hybrid PV/T solar system.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Size of square Copper tube} & 12x12x1.25 mm thick \\
\hline
\textbf{Pitch between two consecutive square tubes} & 37 mm \\
\hline
\textbf{Total length of heat exchanger} & 31.5 mts. \\
\hline
\textbf{PV module bottom side area occupied by heat exchanger} & 32 \% \\
\hline
\end{tabular}
\end{table}
Design and Fabrication of Aluminum Flat Reflectors

The maximum electrical power output and generation efficiency of any commercial module normally depend on local climate, season of year, ambient temperature, wind velocity, latitude of location, tilt of module and solar radiation. At actual test condition (ATC), the performance of module is strongly influenced by solar radiation striking normal to its surface. The intensity of solar radiation varies constantly over a day. Its value is less in morning and afternoon and maximum at solar noon. Due to fluctuation of solar radiation over a day, power produced by module varies at different period of a day. Therefore, module generates power inconsistently as compared with rated power specified by manufacturer. Different methods can be used to enhance electrical power of commercial module as stated in introduction section. In the current studies, simple and cost effective methods were used to increase concentration ratio of module by fitting flat reflectors to its shorter sides. An anodized aluminum sheet of 0.5 mm thickness, available in market was used for fabrication of flat reflectors. The reflectivity of the sheet was measured by using Albedo meter and found to be 82%. The amount of solar radiation reflected from reflectors on module surface was strongly influenced by its concentration ratio and, reflector angle normal to module surface. Due to improved concentration ratio, electrical power and efficiency of module were found enhanced drastically over a day. The concentration ratio and reflector slant height were calculated as per formulas discussed in introduction section (Burkhard Donald G et al., 1978). Using these data, a pair of reflector was fabricated from Aluminum sheet with its size equal to module dimensions and fitted to shorter sides of module as shown in figure 2. Experiments were conducted on modified PV module by changing orientations of reflectors.
manually from 100° to 135° (90°-45°) normal to PV surface with an interval of 5° on distinct days (Palaskar and Deshmukh, 2014). This was done to determine the optimum orientation of reflectors generating highest electrical power and efficiency. The highest photovoltaic power and efficiency was able to be generated at 24° orientations of reflectors normal to module surface. The modified PV module includes simple PV module with pair of reflector and other measuring instruments as shown in figure 2.

**Measuring Instruments and Experimental Observations**

The measuring instruments with technical specifications used in the present experimental work are given in table 2. The complete; assembled experimental setup with all instruments is shown in figure 2.

<table>
<thead>
<tr>
<th>Name of the measuring instruments</th>
<th>Specifications</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyranometer</td>
<td>Sensor: 72 element thermopile. Spectral range: 0.3 to 3 μ meters. Time constant: &lt; 30 seconds. Range: 0 – 1500 W/m² Output: 0 to 25 milli volts.</td>
<td>To measure global and diffuse radiations on horizontal surface</td>
</tr>
<tr>
<td>Thermocouples</td>
<td>0- 600 °C (Leaf shaped Temp sensor ‘K’ type thermocouple)</td>
<td>To measure ambient temperature and temperatures on the top and rear side of PV module during experimental process</td>
</tr>
<tr>
<td>Temperature data logger</td>
<td>16 channel input thermocouple with RS-485 port</td>
<td>To scan and record thermocouple temperatures at specified time interval</td>
</tr>
<tr>
<td>DC volt meter</td>
<td>0-50 V</td>
<td>To measure voltage at various loading conditions</td>
</tr>
<tr>
<td>DC ammeter</td>
<td>0-6 Ams</td>
<td>To measure current at various loading conditions</td>
</tr>
<tr>
<td>DC load bank</td>
<td>180 Watts</td>
<td>To measure voltage and current across load applied to PV module during experiments</td>
</tr>
<tr>
<td>Rota-meter</td>
<td>500 LPH</td>
<td>To measure flow rate of water at the inlet of the spiral flow PV absorber surface</td>
</tr>
<tr>
<td>Temperature gauges</td>
<td>0- 120°C</td>
<td>To measure water temperature at the inlet and exit of the heat exchanger of hybrid system</td>
</tr>
</tbody>
</table>

The entire experiments were performed during months of April-May 2014. Experiments were conducted on simple cooled module and cooled module with reflectors to determine and compare their overall performances with system operated for 7 hours per day between 9.30 AM and 4.30 PM. The slope for both configurations was selected and maintained 20° for all experimental days for latitude of Mumbai. Different experiments were performed on distinct days for peak PV power point condition. Entire experimental work was divided in two parts as explained in following paragraph.

In the preliminary stage of work, experiments were performed on simple cooled module or hybrid solar system with spiral flow heat exchanger attached at bottom side of module as shown in figure 1. This was done to determine different performance parameters such as electrical and thermal power and efficiency of simple cooled module at actual test condition (ATC). During these tests, different observations such as global and diffuse radiations on horizontal surface, voltage, and current at corresponding loading conditions at every 30 minutes time interval were recorded manually. Readings in terms of water flow rate, and inlet, and outlet water temperatures flowing though heat exchanger at every 30 minutes of time interval were also collected manually. K-type temperature sensors with data logger were used to scan and record the ambient temperature and the temperatures at top and bottom of the PV module automatically at an interval of one minute. During the second stage of observations, trials were conducted on heat exchanger used in hybrid system fitted with a pair of flat reflectors to shorter sides of module as shown in figure 2. At water flow rates for peak PV power point on distinct days, different readings were recorded manually and automatically as per procedure explained in the first stage of experimental work.

*Equations Used to Calculate Technical Parameters*

Different equations used to calculate photovoltaic power, thermal power, input solar power, performance ratio,
photovoltaic, thermal and combined PV/T efficiency for Mumbai latitude (Sukhatme and Nayak, 2008; Solanki, 2011; Duffie and Beckman) are as given below.

\[
\begin{align*}
P_{PV} &= V \times I \\
P_T &= I_{th} \times C_r \times (T_{sw}-T_{hi}) \\
I_T &= I_r \times A_{PV} \\
I_{th} &= I_r \times r_g \\
r_g &= \sin(\alpha + \beta)/\sin\alpha \\
\alpha &= 90-\Phi + \delta \\
I_{2ref} &= 2 \times I_{ref} \times A_{PV} \\
I_{ref} &= [(I_r \times r_g + (1-F_{C,s}) I_d) \times q \times A_{ref} \times F_{C,s})] / A_{PV} \\
I_{Tr} &= I_T + I_{2ref} \\
\eta_{PV} &= P_{PV} / I_{Tr} \\
\eta_I &= P_T / I_{Tr} \\
\eta_{PV/T} &= \eta_{PV} + \eta_I \\
PR &= P_{PV}/P_{STC}
\end{align*}
\]

Results and Discussion

The cooling of module with spiral heat exchanger resulted in the increase of open circuit voltage (40 Volts) and voltage (31.5 Volts) at highest PV power point of the module at 12.30 PM. With its cooling module, produced photovoltaic power (146.3W), performance ratio (80 %), and efficiency (12.9%) as shown in figures 3 and 4 respectively. Figure 4 shows low PV efficiencies in the morning and late afternoon for both uncooled and cooled module with reflectors cases. This mainly happens due to decrease in angle of incidence of solar rays from morning to noon and its increase to late afternoon. At solar noon sun rays strike normally to module surface generating peak electrical power and efficiencies. By utilizing waste heat, the hybrid solar system generated 616 W of surplus thermal power at flow rate of 0.042 Kg/sec as shown in figure 5. As shown in figure 7, the system worked with combined PV/T efficiency of 68.2 % observed for the hybrid system. The force circulation system was in operation from 10 AM to 3 PM to supply tap water to hybrid system. This lead to enhancement in system performances and reduction in operating temperature for the experiments conducted between 10.30 AM to 3 pm.

The hybrid solar water system with spiral heat exchanger and flat reflectors resulted in the increase in open circuit voltage (39.70 Volts), voltage (34.78 Volts) and current (4.8 A) at highest power point of the module at 1 PM. Due to this configurations, there was increase in module photovoltaic power (166.9W), performance ratio (92.70%) and efficiency (12.40%) as shown in figures 4 and 5 respectively. These figures show that cooling of the module increased the output voltage drastically. At the same time due to concentration effect, module generated more current compared with module without reflectors. Due to these effects, the overall performance of the simple module is improved substantially. By utilizing waste heat of module, the hybrid solar system generated 791.9 W of surplus thermal power at flow rate of 0.042 Kg/sec as show in figure 5. The combined PV/T efficiency of system was 71.40 % as shown in figure 6. The force circulation system was in operation from 10 AM to 3 PM to supply cooling water to hybrid system. Enhancement in system performances and reduction in operating temperature of the hybrid system were observed from 10.30 AM to 3 pm. The performance of the spiral flow heat exchanger for cooled module and cooled module with reflectors for peak PV power condition is shown in table 3. Figure 4 shows that the PV efficiency produced by the cooled module with reflectors is lower than that by cooled module. This had happened, as the total radiation measured by pyranometer for cooled module experiment was lower than cooled module with reflectors for peak PV power condition.
TABLE 3 PERFORMANCE OF THE HEAT EXCHANGER FOR COOLED MODULE AND COOLED MODULE WITH REFLECTORS

<table>
<thead>
<tr>
<th>Time slot</th>
<th>Performance of the heat exchanger for cooled module (°C)</th>
<th>Performance of the heat exchanger for cooled module with reflectors (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T_{sw}</td>
<td>T_{sw}</td>
</tr>
<tr>
<td>10:30</td>
<td>32.25</td>
<td>35.00</td>
</tr>
<tr>
<td>11:00</td>
<td>32.25</td>
<td>35.50</td>
</tr>
<tr>
<td>11:30</td>
<td>32.50</td>
<td>35.75</td>
</tr>
<tr>
<td>12:00</td>
<td>32.75</td>
<td>36.00</td>
</tr>
<tr>
<td>12:30</td>
<td>32.75</td>
<td>36.25</td>
</tr>
<tr>
<td>13:00</td>
<td>32.75</td>
<td>36.25</td>
</tr>
<tr>
<td>13:30</td>
<td>32.75</td>
<td>36.25</td>
</tr>
<tr>
<td>14:00</td>
<td>32.75</td>
<td>36.00</td>
</tr>
<tr>
<td>14:30</td>
<td>32.75</td>
<td>36.00</td>
</tr>
<tr>
<td>15:00</td>
<td>33.00</td>
<td>35.75</td>
</tr>
</tbody>
</table>

The temperature of water at the outlet of heat exchanger measured was 36-37°C for both systems, which was suitable for low-grade applications such as domestic use; to heat water in swimming pool, etc. It was found that sunrays striking on reflectors were not fully reflected on module surface over a day, due to fixed position of reflectors with respect to module surface. Between 11:30 AM to 2 PM when angle of incidence of sunrays was nearly normal to PV surface and reflectors reflecting all receiving rays on module surface the system produced highest PV power of 166.9W. For other timings, missed reflections did not hit the module surface and directly went to atmosphere. To utilize these missed reflections, reflectors are required to be tracked continuously from morning to evening along East-West direction. Due this, angle of incidence may maintain constant over a day, producing PV power and efficiency equal to or more than its rated output power quoted at STC condition. Use of thermal grease compound applied at top side of heat exchanger and bottom side of module could minimize the air gap between these surfaces, improving the rate of heat transfer between them. Due to this effect, the operating temperature of module falls, photovoltaic, thermal, and combined power and efficiencies of hybrid system are improved respectively. It was also observed that, the temperature attended by bottom side sheet attached below heat exchanger was equal to the ambient temperature for both configurations. This observation showed that selected thickness of glass wool insulation was precise for this application. The operating temperature of cooled module may further be reduced by lowering inlet water temperature; enhancing photovoltaic, thermal and combined PV/T power and efficiencies of both systems. Sufficient water head maintained in storage of cooling water can lead to use of thermo siphoned hybrid PV/T system added with reflectors. This will be the ideal solution for electrical power generation and hot water production used for low temperature applications. By using this system, an autonomous hybrid system may be developed which can be used in rural areas.

![FIG. 3 PHOTOVOLTAIC POWER PRODUCED BY COOLED MODULE AND COOLED MODULE WITH REFLECTORS](image-url)
FIG. 4 PHOTOVOLTAIC EFFICIENCY PRODUCED BY COOLED MODULE AND COOLED MODULE WITH REFLECTORS

FIG. 5 THERMAL POWER PRODUCED BY COOLED MODULE AND COOLED MODULE WITH REFLECTORS

FIG. 6 THERMAL EFFICIENCY PRODUCED BY COOLED MODULE AND COOLED MODULE WITH REFLECTORS

FIG. 7 PHOTOVOLTAIC/ THERMAL EFFICIENCY PRODUCED BY COOLED MODULE AND COOLED MODULE WITH REFLECTORS
Conclusions

This study compares the performance of simple cooled module with hybrid solar system fitted with aluminum flat reflectors to module sides. The electrical power of the water-cooled module with reflectors compared with the simple cooled module was improved by 14 % at 1.00 PM by fitting reflectors with small increase in cost of the hybrid system. At the same time the thermal power and efficiency of water cooled module with reflectors increased by 29 % and 6% respectively. The performance ratio of cooled module with reflectors was increased by 20.70 %. The hybrid system produced 791.90 W of thermal power with 59% efficiency, achieving a combined efficiency of 71.40 %. The hybrid solar system exhibited a combined PV/T efficiency of 71.40 % as compared with that of 62.92 % obtained by simulation (Othman et. al., 2008). The experimental results make a good fit with the simulation results. The hybrid solar water system harnesses 71.40 % of total solar radiation falls on earth and converts 59 % of waste heat into thermal energy that could be used for low-grade temperature applications. Thus, on a yearly basis, the hybrid system can produce 1725.60 KWh of combined energy and 300.40 KWh of electrical energy. These experiments proved that the hybrid solar water system was a potential alternative for electrical power generation and hot water production use in rural areas.

REFERENCES


