Effect of Cooling on Solar Panel Performance

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Abstract. One of the main problems in using the photovoltaic system is the low energy conversion efficiency of photovoltaic cells and, furthermore, during the long operational period of solar cells, their energy conversion efficiency decreases even more due to increase in operating cell temperature over a certain limit. One way of improving the efficiency of photovoltaic system is to cool it during its operation period. This study compares the effects of cooling on the performance of photovoltaic system. Experiments are performed on the photovoltaic system without cooling initially to have a set of reference performance parameters for comparison. Air and water are the fluids used in cooling of the system. I-V tests and temperature tests, for all the cases, are performed for comparative analysis. The energy balance calculations showed that the experimental results are in conformity with the theoretical results. The results further showed that the cooling of photovoltaic system using water over the front surface enhances the performance even more as compared to air cooling of solar panel.

Keywords: solar panel, cooling, efficiency, thermal analysis

1. Introduction

Solar cell performance is affected by factors such as crystalline structure, intensity of sunlight, angle of sunlight irradiation, and surface temperature. The main factor which significantly affects the efficiency of a solar cell is its operating temperature.

Different studies and research have been performed to enhance the electrical efficiency of solar panel. Tonui et al. [1] presented two low cost techniques, one with thin metal sheet suspended at the middle and other, fins attached to the back wall of the air channel to improve the heat transfer to air stream. Modified systems give better electrical efficiency, with the fin system giving better performance than the thin metal sheet system. Teo et al. [2] developed hybrid PV/T system having parallel array of air ducts, attached to the back of PV panel. This system increased electrical efficiency of PV panel from 8-9% to 12-14%. Krauter [3] cooled down PV module’s surface temperature by flowing of water over its front surface. He observed that reflection of sunlight reduced by 2-3.6% while decreasing the solar cell temperature up to 22°C and increasing electrical yield by 10.3%. Bahaidarah et al. [4] developed a hybrid water cooled PV system which incorporated a heat exchanger on the rear surface of the panel. The hybrid system reduced module temperature by 20% leading to an increase in PV module efficiency by 9%. Kordzadeh [5] cooled PV cells using thin film of water flown over PV surface. He observed that panel temperature decreases approximately by 40% and efficiency increases along with pump flow rate up to certain point. Eveloy et al. [6] investigated the effects of cooling the module using water flow experimentally. He concluded that incorporation of sun tracking system and water cooling with the PV module increases the power output by up to 40% as compared to passively cooled stationary PV module.

Cooling of solar panel using air and water has been studied separately so far and no study has been performed that compares the effect of cooling using air and water. The scope of this research is to study the effect of cooling of solar panel using two fluids, air and water. Furthermore, in case of cooling using water, performance of solar panel is evaluated at different water flow rates. Energy balance analysis has also been carried out for all the cases as a part of this study.

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2. Experimental Setup

Experiments were performed at room conditions under a 1000 W flood lamp. Figures 1 and 2 illustrate the schematic of the experimental setup and the main components of the setup during testing, respectively.

![Fig. 1: Schematic of the experimental setup](image1)

![Fig. 2: Experimental setup](image2)

A fan was installed at a distance behind the solar panel for cooling the surface of PV solar module by blowing air on its backside. Along with the air cooling, the solar panel was also cooled down by flowing water over its front surface. A piping system was used which consisted of a half inch diameter PVC pipe with 3 mm holes drilled along the length of the pipe. The pipe was firmly fixed at the top edge of the solar panel with the help of duct tape. Flexible transparent pipe was connected with the PVC pipe to direct the water flow from tap. A rotameter was connected in between the flexible pipe to measure the water flow rate through the pipe.

2.1. I-V Curve

I-V curve plots the variation in current and voltage produced by the solar panel when the resistance is varied. I-V curve was obtained in the room conditions using a flood lamp of 1000W power. The flood lamp is placed in front of the solar panel at a particular distance, and height of the flood lamp head is adjusted and tilted so that it gives maximum current and voltage through the solar panel.

An electric circuit was formed as sketched in Fig. 3 to get an I-V curve for no cooling, air cooling and water cooling cases of solar panel.
2.2. Thermal Measurements

The next step of the study is to see the temperature pattern of solar panel while it achieves steady state during operation of lamp. Thermocouples were labeled first with their respective slot number as in the 20 channel multiplexer. This labeling would ease the process of tracking the temperature readings of specified points on the solar panel.

Thermocouples were then placed on the back side and front side of the solar panels. For backside, each thermocouple is affixed to the solar panel surface using a duct tape while keeping an insulating material in between the thermocouple and the tape. The purpose of using an insulating material is to enable the thermocouple to accurately measure the desired panel surface temperature without the influence of outside ambient temperature. For the placement of thermocouples on front surface of solar panel, caulking was done around the insulation to avoid water seepage through it.

3. Theoretical Analysis

The theoretical analysis of the PV system is based on its energy balance equations. For all three cases; (a) no cooling, (b) air cooling, and (c) water cooling of solar panel, the energy balance analyses are presented as follows:

a) No cooling analysis

\[ \alpha F_{lp} G = \dot{E}_{PV} + q''_{conv.free(fr)} + q''_{conv.free(bk)} + q''_{rad(fr\&bk)} \]

<table>
<thead>
<tr>
<th>Components</th>
<th>Details</th>
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<tbody>
<tr>
<td>( \alpha F_{lp} G )</td>
<td>( F_{lp} = \frac{1}{2} \left[ S - \left( S^2 - 4 \left( \frac{\tau}{\nu} \right)^2 \right)^{1/2} \right] ) [7] ; ( S = 1 + \frac{1+R_t \nu}{R_l \nu} ) [7]</td>
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<tr>
<td>( \dot{E}_{PV} )</td>
<td>Area under the I-V curve</td>
</tr>
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<td>( q''<em>{conv.free(fr)} = h(T_s - T</em>\infty) )</td>
<td>( Nu_L = 0.14 \left[ (Gr Pr)^{1/3} - (Gr_cr Pr)^{1/3} \right] + 0.56 (Gr_cr Pr cos \theta)^{1/4} ) [8]</td>
</tr>
<tr>
<td>( Gr = g cos \theta (T_s - T_\infty) L^3/\nu^2 )</td>
<td></td>
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\[ q''_{conv.free(bk)} = h(T_s - T_\infty) \]

\[ Nu_L = \frac{0.825 + \frac{0.387 Ra^{4/5}}{1+\left( \frac{0.492}{Ra} \right)^{9/16}}}{T^2} \] \[7\]

\[ Ra = \frac{g cos \theta (T_s - T_\infty) L^3}{\nu \alpha} \]

\[ q''_{rad(fr\&bk)} = \epsilon_\sigma F(T_s^4 - T_\infty^4) \]

\( \epsilon_{fr} = 0.91 \) \[8\] ; \( \epsilon_{bk} = 0.85 \) \[8\] ; \( \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \)

\( F_{fr} \) assumed to be 1 ; \( F_{bk} \) was calculated \[9-11\]

b) Air cooling analysis

\[ \alpha F_{lp} G = \dot{E}_{PV} + q''_{conv.free(fr)} + q''_{conv.free(bk)} + q''_{rad(fr\&bk)} \]
c) **Water cooling analysis**

\[
\frac{\alpha F_{l_p} G}{E_{pv}} = q''_{\text{conv,free}(bk)} + q''_{\text{conv,force}(fr)} + q''_{\text{rad}(fr\&bk)}
\]

**Components**

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<td>(q''<em>{\text{conv,free}(bk)} = h(T_s - T</em>\infty))</td>
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<td>(N_u = 0.14\left[(Gr Pr)^{1/3} - (Gr_{cr} Pr)^{1/3}\right] + 0.56(Gr_{cr} Pr cos \theta)^{1/4}) [8]</td>
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<tr>
<td>(h = 5.7w + 11.4) [8]</td>
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4. **Results**

4.1. **I-V Curves**

The current and voltage values of the solar panel, operating in the indoor environment under a flood/spot lamp, were calculated by varying the resistances connected within the closed circuit. The current and voltage values were obtained after the surface temperature of the solar panel reached a steady state. Fig. 4 shows the I-V curve for solar panel without cooling, air cooled solar panel, and water cooled solar panel using water flow rates of 1 gpm and 2 gpm.

![Fig. 4: I-V curves](image)

4.2. **Thermal Measurements**

To analyze the effect of flood lamp on the surface temperature of the solar panel, thermocouples were affixed on front and back surface of the solar panel. As the lamp is turned on, the data acquisition unit is activated along with it to measure the temperature change of front and back surface of solar panel. Temperature readings were recorded until steady state was sustained. Fig. 5 illustrates the temperature variations at various locations for cases tested.

4.3. **Theoretical Results and Thermal Images**

Theoretical and experimental values along with calculated error are presented in Table 1.
Fig. 5: Front and back surface temperature variation for all cases.

Fig. 6: Thermal images of (a) no cooling, (b) air cooling, and water cooling cases at (c) 1 gpm and (d) 2 gpm.

Table 1: Theoretical analysis of no cooling, air cooling, and water cooling cases

<table>
<thead>
<tr>
<th>Solar panel tests</th>
<th>$q''_{PV}$ (W/m²)</th>
<th>$q''_{conv(fr)}$ (W/m²)</th>
<th>$q''_{conv(bk)}$ (W/m²)</th>
<th>$q''_{rad(fr)}$ (W/m²)</th>
<th>$q''_{rad(bk)}$ (W/m²)</th>
<th>$\alpha F L_p G$ (experimental) (W/m²)</th>
<th>$\alpha F L_p G$ (calculated) (W/m²)</th>
<th>Error (%)</th>
<th>Efficiency $\eta$ (%)</th>
</tr>
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<tbody>
<tr>
<td>a No cooling</td>
<td>31.5</td>
<td>39.3</td>
<td>80.7</td>
<td>128.8</td>
<td>58.8</td>
<td>339.0</td>
<td>339.3</td>
<td>0.1</td>
<td>9.28</td>
</tr>
<tr>
<td>b Air cooling</td>
<td>32.3</td>
<td>22.2</td>
<td>183.1</td>
<td>64.9</td>
<td>22.0</td>
<td>324.5</td>
<td>339.3</td>
<td>4.4</td>
<td>9.51</td>
</tr>
<tr>
<td>c Water cooling at 1 gpm</td>
<td>33.0</td>
<td>280.0</td>
<td>0.0</td>
<td>5.8</td>
<td>0.5</td>
<td>319.4</td>
<td>339.3</td>
<td>5.9</td>
<td>9.72</td>
</tr>
<tr>
<td>d Water cooling at 2 gpm</td>
<td>33.5</td>
<td>290.2</td>
<td>0.0</td>
<td>6.4</td>
<td>0.0</td>
<td>330.0</td>
<td>339.3</td>
<td>2.7</td>
<td>9.86</td>
</tr>
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5. Conclusions

I-V curve generated for each case demonstrates how the electrical power output is increasing as more heat is taken away from the solar panel. Based on the experiments performed in controlled environment, the power output of air cooled solar panel increased by 2.4% when compared to solar panel without cooling. It is worth noting that the solar panel was air cooled from the back surface only. When water is used as cooling fluid, the power output from the solar panel increased by 4.7% and 6.3% for water flow rate of 1 gpm and 2 gpm respectively. Water having higher heat capacity has the ability to draw more heat out of the solar panel as compared to air when it is operating at high temperatures. The use of water flow over the front surface of solar panel also reduces the irradiation losses due to reflection. Flowing water over the front surface of solar panel enhances the aesthetic view of solar panel and generates a pleasing effect along with the increase in electrical yield. Furthermore, the analysis of cooling of solar panel using water at different flow rates also has impact on its electrical output. It was noted that increasing the water flow rate reduces the surface temperature of solar panel which results in increase in electrical yield. The energy balance of solar panel for
no cooling case, air cooling case and water cooling case at flow rates of 1 gpm and 2 gpm was performed. The maximum error between the energy coming into the PV system due to irradiation from the lamp and the energy lost by the solar panel, through convection and radiation was calculated to be 5.9%. This shows that the experimental data is in good agreement with the theoretical results.

6. Acknowledgements

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7. References