Studies on the performance of 150W solar photovoltaic module with evaporative cooling

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Abstract. The increase in surface temperature of solar photovoltaic module due to incident solar radiation has an adverse impact on its performance, reducing its electrical output power and efficiency. Proper cooling can improve the electrical efficiency, and decrease the rate of cell degradation with time, resulting in maximization of life span of photovoltaic modules. Various methods like active cooling, passive cooling and heat pipe cooling are employed to cool the module. In the present work, water passive cooling technique has been used since this method is preferred for small modules and is more efficient because of higher thermal capacity of water. evaporative cooling is one such technique. Numerical and experimental investigations have been carried out to study the effect of evaporative cooling on the performance of solar photovoltaic module. A two dimensional, steady state, cross flow, heat and mass transfer model has been developed and temperature distribution of air and water across a cooling pad has been studied. An evaporative cooling pad is incorporated at the bottom surface of solar photovoltaic module. Experiments are conducted to evaluate the performance of solar PV module and the results are compared with that of numerical simulation.

1. Introduction
Solar photovoltaic (PV) modules technology has grown rapidly since researchers shifted their attention to the generation of electricity from renewable energy sources. PV modules are highly reliable, durable, silent and pollution-free devices. A typical photovoltaic cell efficiency is about 15%, converting approximately 1/6 of solar energy into electricity. Wind speed, ambient temperature, relative humidity, accumulated dust and solar radiation are the most common natural factors which influence the surface temperature of a PV module. Every 1°C surface temperature rise of the PV module causes a reduction in efficiency of 0.5%. Cooling the panel surface is a key operational factor to achieve higher efficiency when operating solar photovoltaic systems. Proper cooling can improve the electrical efficiency, and decrease the rate of cell degradation with time, resulting in maximisation of their life span. Most of the research work reported in the literature, employ active, passive and heat pipe cooling methods for the PV modules.

Siecker et al. [1] have carried out an exhaustive review on the cooling technologies employed for PV modules. Bottom surface of the panels shall be water sprayed, immersed in water, fitted with heat sinks, circulated with water as well as air, provided with phase change materials and thermoelectric systems. Benefits and limitations of each method has been discussed in detail. Peng et al. [2] investigated the performance of the modules by spreading ice at their bottom surfaces. The system performance improved by 47% at an optimum panel temperature when the efficiency was maximum.
This system was found to be unsuitable on the basis of cost analysis. Popovici et al. [3] investigated the performance of PV panels using air cooled heat sinks at the bottom surface and carrying out numerical simulations. Results showed a 10°C reduction in surface temperature and power generation increased by 7 to 8%. However, turbulent air flow in the heat sink caused a highly unstable performance. Akbarzadeh and Wadowski [4] introduced a passive method of panel cooling by incorporating a thermosyphon cooling system. Refrigerant R11 was used as thermosyphon working fluid. When PV module was tested, surface temperature reduced by 30 to 35°C and module performance increased by 50%. However, this system is too costly and make it commercially unviable. Du et al. [5] employed a novel approach by integrating a nano-coated heat pipe plate with the solar cell and carried out indoor-experimental studies on a commercial solar cell fitted with heat pipe plate. A plasma lighting system was used to simulate the sun light. Degassed water was used as the working fluid in the heat pipe plate. Results showed 50% reduction in surface temperature and 50% increase in solar cell efficiency. Also a prolonged cell life is implied. But thermal management of these types of systems is complex and commercially not attractive. Klemm et al. [6] evaluated a new concept of combining a phase change material (PCM) with metallic fibre structure in a PCM module and mounting it at the backside of the PV module.

The system performance was assessed by carrying out numerical simulations using commercial finite element software. Though the numerical results show a better performance, these systems become inefficient without the inclusion of metallic fibre structure in the PCM. Also, if the thickness of PCM is insufficient, it results in reduced thermal capacity and performance cannot be enhanced by increasing the PCM size. Alami [7] investigated the performance of PV modules by using a passive evaporative cooling technique. In this method, a layer of synthetic clay was incorporated at the backside the module and thin film of water was allowed into the clay. A set of experiments were conducted with clay layers of different thicknesses 2, 4 and 6 mm, to evaluate system performance. Results showed that clay layer of thickness 2 mm was effective and module output power was enhanced by around 20%. Limited work has been reported in the literature on evaporative cooling techniques employed for cooling of solar PV panels.

Few authors have developed theoretical models based on heat and mass transfer between air and water. However these models have been useful for improving the performance of fin and tube heat exchangers and cooling towers.

Two dimensional steady state model considering cross flow of water and air has been developed in the present work for the specific application of solar PV panel cooling. Also, a cellulose cooling pad has been incorporated at the bottom of the PV panel and experimental studies have been carried out in the present work to assess the performance of 150 Watts solar PV panel.

2. Numerical Simulation
Numerical simulation of air and spray water flowing in cross direction across the cooling pad, for the purpose of studying evaporative cooling has been carried out in the present work. A two dimensional, steady state, cross flow, heat and mass transfer model has been developed, based on theoretical studies carried out by Jiang et al. [8] on cross flow closed wet cooling tower. Governing equations for the air and water interaction have been discussed in [8].

3. Experimentation
Initially a solar PV panel of 150 Watts capacity was tested without incorporating evaporative cooling technique (Fig. 1). Specifications of PV panel have been given in Table 1. The positive and negative terminals of PV panel were connected to a charge controller and power generated was measured using a multimeter. Ambient and surface temperatures were measured using temperature sensors. Next, the panel was tested by fitting honeycomb type cooling pad made of cellulose material, at the bottom of panel surface. A PVC pipe with multi-point water inlet nozzles, was attached to the panel to supply water for the purpose of initiating evaporative cooling (Fig. 2). Water flow rate was measured using a measuring jar and stop watch.
Figure 1. Solar PV panel without incorporating evaporative cooling technique.

Figure 2. Solar PV panel fitted with cooling pad and PVC pipe with water inlet nozzles.

Table 1. Solar PV panel specifications.

| PARAMETERS                        | SPECIFICATIONS |
|-----------------------------------|----------------|
| Dimensions (in cm) – L x W x T    | 148 X 68 X 3.4 |
| Voltage at Max Power ($V_{max}$)  | 18.3 V         |
| Open Circuit Voltage ($V_{oc}$)   | 22.0 V         |
| Current at max power ($I_{max}$)  | 7.0 amps       |
| Short Circuit Current ($I_{sc}$)  | 8.9 amps       |
| No. of cells                      | 60             |
| Output Power                      | 150 Watts      |
| Operating Voltage                 | 12 Volt        |
| PV Panel Type                     | Poly Crystalline |

4. Results and Discussion
4.1. Numerical simulation
The model has been simulated for the following inlet conditions:

- Air flow rate : 0.2 kg/s
- Air temperature : 35°C
- Air relative humidity : 60 – 70%
- Spray water flow rate : 0.0015 – 0.03 kg/s
Spray water temperature : 33°C

The model comprising a system of ordinary differential equations has been solved using Runge-Kutta method with a variable time step. Results have been obtained by means of a computer code written in MATLAB. Temperature and absolute humidity profile of air across cooling pad along cooling pad for varying inlet conditions of air and water have been studied. Simulation results are shown in Fig. 3, 4 and 5.

![Figure 3. Absolute humidity profile for varying air relative humidity across cooling pad.](image)

![Figure 4. Air temperature profile for varying air relative humidity across cooling pad.](image)
Figure 3 shows the absolute humidity profile of air across cooling pad for varying inlet conditions of air relative humidity. Figures 4 and 5 show the temperature profile of air across cooling pad for varying inlet conditions of air relative humidity and water spray flow rate respectively. For all the cases, air temperature decreases and humidity increases across the cooling pad.

During air-water interaction, water is evaporated and added to the air as water vapour. During this interaction, sensible heat transfer takes place from air to water and latent heat transfer takes place from water to air. Due to sensible heat removal, air temperature decreases and due to addition of latent heat, absolute humidity of air increases. This process is called cooling and humidification. The decrease in temperature is more and increase in humidity is less, at lower values of air relative humidity, water spray flow rate, water spray temperature and air temperature. The reasons are discussed below:

- At lower relative humidities, rate of evaporation is faster due to the presence of lesser moisture content in the air. At lower water spray flow rates, interaction between air and water is better due to the availability of more time. At lower water spray temperatures, sensible heat transfer is better than latent heat transfer resulting in decrease of air temperature faster and increase of humidity slower. At lower air temperatures, temperature air reduces to further lower values due to evaporative cooling.

4.2. Experimentation
Solar PV panel was tested with and without incorporating evaporative cooling techniques. Experiments were conducted for 6 hours in a day. This procedure was repeated for several days and average values of readings were taken into consideration for analysis.
### Table 2 Test results – Solar PV module with and without evaporative cooling.

| Time of the day | Amb. temp. (°C) | Surface temp. without evap. cooling (°C) | Surface temp. with evap. cooling (°C) | Top surface temp. with evap. cooling (°C) | Bottom surface temp. with evap. cooling (°C) | Water temp. at panel top (°C) | Water temp. at panel bottom (°C) | Power generated without evap. cooling (W) | Power generated with evap. cooling (W) | % increase in power generation |
|-----------------|-----------------|----------------------------------------|---------------------------------------|------------------------------------------|-------------------------------------------|-------------------------------|-----------------------------------|------------------------------------------|------------------------------------------|---------------------------------------|
| 9.30            | 32              | 39.9                                   | 41.6                                  | 39.3                                     | 33                                        | 30                            | 114.6                            | 114.8                                    | 0.1                                      |                                       |
| 10.00           | 32              | 42.7                                   | 43.7                                  | 41.9                                     | 33                                        | 30                            | 133.3                            | 136.2                                    | 2.2                                      |                                       |
| 10.30           | 33              | 44.8                                   | 44.5                                  | 42.1                                     | 33                                        | 30                            | 133.7                            | 136.9                                    | 2.4                                      |                                       |
| 11.00           | 33              | 45.4                                   | 45.7                                  | 42.9                                     | 33                                        | 30                            | 139.7                            | 148.3                                    | 6.1                                      |                                       |
| 11.30           | 34              | 46.6                                   | 46.1                                  | 43.4                                     | 33                                        | 30                            | 143.9                            | 152.8                                    | 6.2                                      |                                       |
| 12.00           | 34              | 47.5                                   | 46.7                                  | 43.6                                     | 33                                        | 30                            | 144.9                            | 153.6                                    | 6.0                                      |                                       |
| 12.30           | 35              | 48                                     | 47.1                                  | 44.1                                     | 33                                        | 30                            | 146.0                            | 154.3                                    | 5.7                                      |                                       |
| 13.00           | 35              | 48.8                                   | 47.5                                  | 44.8                                     | 33                                        | 30                            | 146.6                            | 154.6                                    | 5.5                                      |                                       |
| 13.30           | 35              | 49.5                                   | 47.9                                  | 45.2                                     | 33                                        | 30                            | 134.5                            | 155.0                                    | 15.2                                     |                                       |
| 14.00           | 35              | 45.1                                   | 45.9                                  | 43.7                                     | 33                                        | 30                            | 128.6                            | 149.1                                    | 16.0                                     |                                       |
| 14.30           | 35              | 44.3                                   | 44.7                                  | 41.6                                     | 33                                        | 30                            | 119.7                            | 128.6                                    | 7.5                                      |                                       |
| 15.00           | 34              | 43.2                                   | 43.5                                  | 40.9                                     | 33                                        | 30                            | 115.9                            | 126.8                                    | 9.4                                      |                                       |

**Figure 6.** Panel surface temperature during the time of the day.
Figure 7. Power generation from the panel during the time of the day.

Table 2 shows test results for solar PV panel with and without incorporating evaporative cooling techniques. Increase in power generation for the panel with cooling pad varies from 0.1 to 16% during the time of the day. It peaks at 1.30 to 2.00 PM. From Fig. 6 and 7, it is observed that due to incorporation of cooling pad at the bottom of the solar PV module, surface temperature of module decreases compared to that of module without cooling pad. This results in improved power generation of solar PV module up to 10% increase in the morning/evening time and up to 16% increase in the afternoon time.

5. Conclusions
In the present work, effect of evaporative cooling on the performance of solar PV panel has been studied. Evaporative cooling has been adopted to reduce the temperature of the PV module. A numerical model has been developed for air-water interaction by considering a cellulose cooling pad at PV panel bottom surface and temperature distribution of air and water across the cooling pad have been studied. Experimental observations were made by testing a solar PV module with and without incorporating a cooling pad at the bottom of the module to compare the effect of temperature on the power conversion efficiency of the panel. The following conclusions are drawn from the investigations:

- At lower relative humidities, rate of evaporation is faster due to the presence of lesser moisture content in the air. So, humidity is less in the air. Due to this, latent heat transfer is more resulting in decrease in temperature of water. Faster evaporation leads to faster loss of water resulting in decrease in water flow rate along control volume.
- At lower water spray flow rates, interaction between air and water is better due to the availability of more time. Hence evaporation takes place at a better rate and as discussed above, temperature of spray water decreases faster.
• At lower water spray temperatures, sensible heat transfer is better than latent heat transfer. This leads to increase of humidity slower, resulting in decrease in water flow rate slower. This also results in decrease in water temperature slower.

• At lower air temperatures, rate of sensible heat transfer from air to water is less than that of latent heat from water to air. This results in faster rate of decrease in water flow rate and temperature.

• Due to incorporation of cooling pad at the bottom of the solar PV module, surface temperature of module decreases compared to that of module without cooling pad. This results in improved power generation of solar PV module up to 10% increase in the morning/evening time and up to 16% increase in the afternoon time.

6. References
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