PERFORMANCE INVESTIGATION OF PHOTOVOLTAIC MODULES BY BACK SURFACE WATER COOLING

by

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The temperature of the photovoltaic module has an adverse effect on the performance of photovoltaic modules. The photovoltaic module converts a small portion of energy from solar radiations into electricity while the remaining energy wastes in the form of heat. In this study, water cooled photovoltaic/thermal system was analyzed to enhance the efficiency by absorbing the heat generated by the photovoltaic modules and allowing the photovoltaic module to work at comparatively low temperature. For this system, four photovoltaic modules of two different types were used. To investigate the cooling effect, two modules were modified by making ducts at their back surface having inlet and outlet manifolds for water-flow. The measurements were taken with cooling and without cooling of photovoltaic modules. The temperature was measured at inlet, outlet, and at different points at the back of photovoltaic modules. It was found that there was a linear trend between the module efficiency and temperature. The average module temperature of c-Si and p-Si modules without cooling was 13.6% and 7.2% lower, respectively, than the same modules without cooling. As a result of temperature drop, the average module electrical efficiency of c-Si and p-Si was 13% and 6.2% higher, respectively, compared to the modules without cooling. Flowing water also gains useful heat from photovoltaic module so the resultant overall energy of the system was much higher.

Key words: *hybrid photovoltaic/thermal system, module efficiency, thermal efficiency, performance ratio*

Introduction

In last decade, usage of solar energy has been increased in many countries due to the increase in fuel prices and limited conventional resources. Photovoltaic (PV) is most prominent solar energy technology for conversion of solar radiations directly into electricity. In Pakistan, due to the electricity shortfall, the use of PV technology has been greatly increased during the recent years.

It is a well-documented fact that increase of PV module temperature causes the decrease of module efficiency. Many scientists and researchers worked on the performance of the

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PV modules at different climatic conditions and found that PV efficiency has an inverse relation with PV module temperature. Bashir *et al.* [1] investigated the performance of different PV modules in Taxila Pakistan. The study showed that with the increase of module temperature from 22 °C to 33 °C, the efficiency of monocrystalline and polycrystalline modules was decreased 8.9% and 5.3%, respectively. Ali *et al.* [2] worked on the PV module performance during peak summer months and found that module efficiency was much lower compared to the module efficiency at the same site in January. It was found that average efficiency of monocrystalline and polycrystalline PV module was 19.8% and18.7% lower than the module efficiency of the same site at peak winter month. Many other researchers [3-5] reported the effect of module temperature on the output of PV modules.

As silicon PV modules convert about 13% to 15% of solar radiations into electricity and remaining are wasted in form of heat. Therefore, to enhance the efficiency and performance of PV modules, it is required to use a mechanism to reduce the temperature of PV module. Rosa *et al.* [6] worked on the performance of PV module submerged in water. It was found that electrical efficiency was increased about 11%. Bahaidarah *et al.* [7] experimentally found the behavior of water cooled photovoltaic/thermal (PV/T) system. The water was allowed to flow on the back surface of the module. To predict various electrical and thermal parameters affecting its performance, a numerical model was developed using engineering equation solver (EES) software. It was found that PV module efficiency was increased by 9% by dropping module temperature of about 20%. Krauter [8] enhanced the PV module efficiency by allowing a thin film of water to flow over the front surface of PV module. It caused the reduction of Sun rays reflection from the surface and decrease of cell temperature. An increase of 10.3% electrical efficiency was reported. A PV hybrid system was used by Erdil *et al.* [9] to improve the output efficiency. The water first preheated by absorbing the heat from PV module and then entered into a solar collector. There was a considerable increase of module efficiency and also produce about 2.8 kWh of daily thermal energy. Amori and Al-Nijjar [10] analyze the electrical and thermal performance of single glass hybrid PV/T air collector. The measurements were taken on peak summer and peak winter seasons in Baghdad city and Fallujah city, respectively. It was found that electrical, thermal and overall efficiencies of PV/T system were higher in winter compared to summer. Teo *et al.* [11] used an active air cooling PV/T system to analyze the enhancement in the efficiency of PV modules. The air was allowed to flow in a duct in the back surface of PV module. Results demonstrated that significant decrement of module temperature caused the efficiency of PV modules to increase between 12% and 14%. Al Harbi *et al.* [12] investigated the efficiency of PV/T water cooled hybrid system. It was found that, in summer, high ambient temperature cause the drop of PV module efficiency up to 30% while the thermal efficiency was good. The PV performance was found to improve in winter season but thermal efficiency was very low. Bahaidarah *et al.* [13] evaluated the performance of silicon type solar module numerically and experimentally. The electrical model was developed using EES software. The numerical results showed close agreement with the experimental result with a correlation coefficient of 0.98. It was found that efficiency reduced considerably with module temperature. In another study Bahaidarah *et al.* [14] used V-trough integrated PV system to investigate the effect of active cooling on the optical, thermal and electrical performance. A comparison was made between flat PV panel and V-trough PV system. It was found that by applying cooling the power of the simple PV panel was increased by 22.8% and for the V-trough by 31.5%. Some other researchers [15-18] worked on the water cooled and air cooled PV/T systems and found significant efficiency enhancement. Some of the literature survey related to the efficiency enhancement using PV module cooling at different regions is presented in tab. 1.

Table 1. Efficiency improvement with cooling from the literature at different climatic conditions

Authors	PV module type	Climatic conditions	Results
Irwan *et al.* [22]	50 W Monocrystalline PV panels	Perlis Malaysia	Water was sprayed on the front surface of PV module. The decrement of temperature was around 5-23 °C and increase in the power output with water cooling was 9-22%.
El-Seesy *et al.* [23]	Polycrystalline silicon module (total area of 0.260 m^2)	Cairo Egypt (30º latitude north)	About 19% increase of relative efficiency after water cooling.
Chandrasekar *et al.* [24]	Monocrystalline PV module, (0.36 m^2)	Tiruchirappalli, India	The PV module temperature was reduced to about 45 ºC when cooling is provided with cotton wick with water. The efficiency was increased up to goes up to 10.4%.
Han *et al.* [25]	Concentrated monocrystalline silicon cells (300 µm thick 100 mm diameter)	Zhenjiang, China	Relative efficiency increase goes up to 15% with cooling.
Wu *et al.* [26]	Heat pipe PV system	Chongqing, China	The maximum reduction in the temperature of the cells reaches 19 ºC and overall thermal and electrical yield of PV/T system were 63.65%, and 8.45%, respectively.
Kalogirou *et al.* [27]	Four monocrystalline PV panels	Cyprus	Cooling cause increase of average annual electrical efficiency from 2.8-7.7%.
Abdolzadeh and Ameri [28]	Two polycrystalline PV cells (45×2 W) with 13.5% efficiency	Mahan (Kerman) Renewable Energy (MRE) Lab, Iran, July 2006	Water was sprayed to cool the PV modules and efficiency was increased by 3.26-12.5%.
Kolhe *et al.* [29]	Concentrated single crystalline silicon PV module	Nanjing, Jiangsu, China	The output of the concentration PV with cooling was 4.7-5.2% higher than the fixed PV module

Pakistan has great solar potential having high solar insolation in most part of the country [19-21] so the cooling of PV module is very effective in this region. The aim of this experimental research work is to design a water cooled hybrid PV/T system and to investigate the effect of passive cooling in the electrical and thermal efficiencies of the system. The system will be suitable for the standalone PV systems at homes.

Experimental set-up and methodology

A PV/T set-up was used to investigate the effect of module temperature on the electrical and thermal performance of PV modules by water cooling. The set-up was placed at the roof top of Mechanical Engineering Department, Mirpur University of Science and Technology (MUST), Mirpur AJK, Pakistan (33.2 N, 73.7 E). Experimental set-up and schematic diagram of the set-up is shown figs. 1(a) and 1(b).

In this set-up, four commercially available PV module of two different types were used (two monocrystalline and two polycrystalline). The specifications of the PV modules are given in tab. 2. One module of each type was kept as it is for comparison purpose while modifications were made in other two modules of different types. In order to allow the water to flow from the back

Figure 1(a). Experimental set-up; PV modules with cooling and without cooling

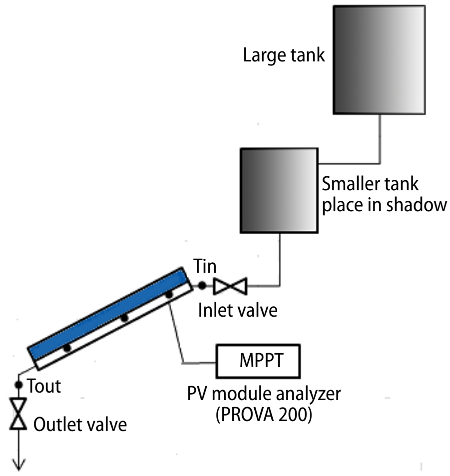

Figure 1(b). Schematic diagram of experimental set-up

surface of PV modules, a duct was made at the back surface having insulation at its outer surface. The K-type thermocouples were used for the measurement of temperature at the inlet, outlet and at different points on the back surface of the PV modules. To extract the maximum power of PV module and I-V curve at any specific time, PV module analyzer (PROVA 200) was used which measures the output parameters of PV modules. A pyranometer was used for the measurement of global solar radiations in W/m^2, placed in a plane with the PV modules. The PV modules were faced toward the south and were tilted at an angle 15 °C with horizontal.

Table 2. Specifications of the PV modules used in the experiment

PV modules	P_m [W]	I_{sc} [A]	V_{oc} [V]	I_m [A]	V_m [V]	Temp. coefficient of I_{sc} [%°C^{-1}]	Temp. coefficient of V_{oc} [%°C^{-1}]	Temp. coefficient of P_m [%°C^{-1}]	Total cells area [m^2]	Duct dimension [mm]
Monocrystalline (GE-m-40)	40	3.06	19.2	2.57	15.5	+0.05	–0.35	–0.45	0.29	690×495
Polycrystalline (ASL 40-12)	40	2.70	21.6	2.16	18.5	+0.06	–0.36	–0.5	0.26	690×455

To allow the water to flow and absorb heat from the back surface of the PV module a duct was made at the back surface of the PV modules. The back surface of PV module was covered with insulation material in such a way that at one side of the duct was tedler surface of PV module and other three sides were made insulated. The cross-sectional view is shown in the fig. (2). The duct behaves as the solar collector, absorb the waste heat of the module from the tedler surface and enable the PV module to work at a lower temperature. An insulated tank is used as cool water storage and PV/T system connected to tank through PVC pipes. The inlet and outlet ports of the duct were carefully designed to ensure the uniform water-flow. It is assumed that system is perfectly insulated and no heat loss to the environment. The mass-flow rate was 0.02 kg/s.

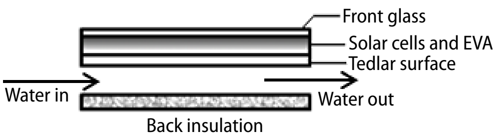

Figure 2. Cross-section of the PV module with duct

The data were measured for 11 different sunny days of peak summer months (July and August). The readings were taken hourly from 8:00 a. m. to 5:00 p. m. The days of measurement were sunny days having average solar irradiance more than 500 W/m^2.

Mathematical formulation

Designed PV/T system has electrical as well as thermal energy. The amount of energy absorbed by single solar cell is [11]:

$$E_c = P_c \alpha_c \tau_g I_{(t)} \tag{1}$$

Electrical efficiency of solar cell in term of temperature of the cell is given:

$$\eta_e = \eta_o \left[1 - \beta\left(T_c - 25\right)\right] \tag{2}$$

where η_o is cell efficiency at STC ($I_{(t)}$ = 1000 W/m^2, T_c = 25 °C, Air Mass = 1.5). The β is the electrical efficiency thermal coefficient.

The gain of electrical energy by the solar cell is given [30]:

$$E_{ce} = \eta_e P_c \tau_g I_{(t)} \tag{3}$$

Expression for percentage electrical efficiency of PV module is represented:

$$\eta_m = \left(\frac{P_m}{A_a I_{(t)}}\right) \cdot 100 \tag{4}$$

where A_a is the actual area of PV module which converts solar radiations into electricity and P_m represents the maximum output power of PV module at any specific time. It depends upon the measured current and voltage:

$$P_m = V_m I_m \tag{5}$$

The expression of total electrical energy gain of the PV module is given:

$$E_{me} = \eta_m A_a I_{(t)} \tag{6}$$

Thermal energy of the system is given:

$$Q_{\mathrm{th}} = \dot{m} C_p \left(T_o - T_i\right) \tag{7}$$

The overall energy can be calculated:

$$Q_{\mathrm{overall}} = Q_{\mathrm{th}} + \frac{E_{me}}{0.38} \tag{8}$$

The electrical efficiency was converted into equivalent energy produced by a thermal power plant. Nuber 0.38 represents the conversion power of thermal power plant for good quality coal with low ash contents [31].

Thermal efficiency of the system can be calculated from the following relation:

$$\eta_{\mathrm{th}} = \left(\frac{Q_{\mathrm{th}}}{A_a I_{(t)}}\right) \cdot 100 \tag{9}$$

Performance ratio (PR) is the performance of PV module at any specific condition compared to its performance at STC. It can be calculated by following relation [32]:

$$PR = \frac{\dfrac{P_m}{P_{STC}}}{\dfrac{I_{(t)}}{1000}} \tag{10}$$

Next mathematical relation, eq. (11), was used to find percentage increase of any component.

$$X_{\text{increase}} = \left(\frac{X_{\text{cooling}} - X_{\text{without cooling}}}{X_{\text{without cooling}}} \right) \cdot 100 \tag{11}$$

Results and discussion

The experiment was performed on the top roof of the Department of Mechanical Engineering, MUST, for different sunny days of two months (July and August 2015). It was assumed that there was 1-D heat input (perpendicular to the front glass). The maximum power, electrical efficiency, thermal efficiency and overall efficiency of two different PV modules were measured and the comparison is presented here. The results showed that there is a considerable efficiency increment with back surface cooling of PV modules. Days of measurements were sunny. Figure 3 shows the hourly average solar irradiance from 8:00 a. m. to 5:00 p. m. The average solar radiations increased linearly up to 12 p. m. and then decreased after that. The highest average solar irradiance measured was 971 W/m^2.

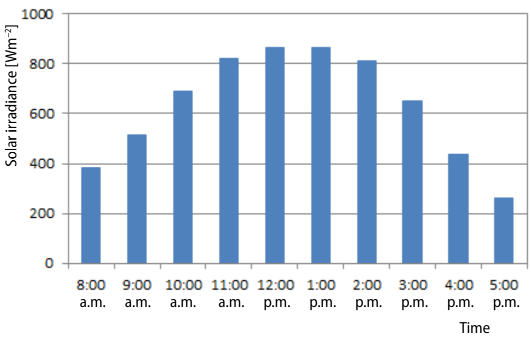

Figure 3. Variation of hourly average solar irradiance

Module temperature analysis

The module temperature affects the output parameters of PV modules. The cooling of PV module has a significant effect on PV modules temperature as shown in fig. 4. It can be seen that c-Si and p-Si modules with cooling has a lower temperature than the modules of the same type without cooling and is closer to the ambient temperature at morning. Figure 5 shows the average thermal energy absorbed by the flowing water. As module temperature increase, the voltage produces a negative temperature coefficient and current produces a small positive temperature coefficient. This effect is shown in the I-V curve of PV module, where there is a significant decrease of voltage with an increase of module temperature at same solar irradiance, fig. 6. Furthermore, module temperature varies linearly with the solar irradiance as shown in fig. 7. From the value of the coefficient of determination, a good relation can be seen. Figure 8 demonstrates that average module temperature of c-Si and p-Si modules with cooling was 13.6% and 7.2% lower than the same modules without cooling.

Output power analysis

Figure 9 demonstrates the output power of PV modules with cooling and without cooling from 8 a. m. to 5 p. m. At high solar irradiance and module temperature, the cooling

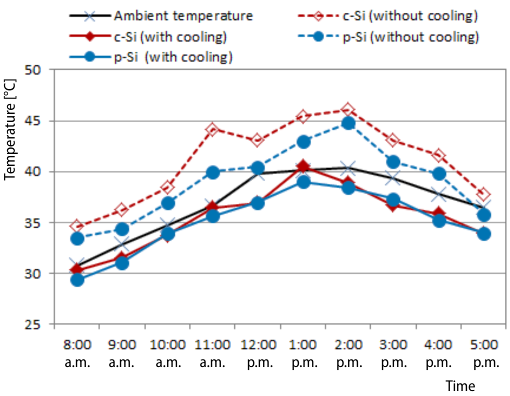

Figure 4. Hourly average temperature of PV modules with and without cooling

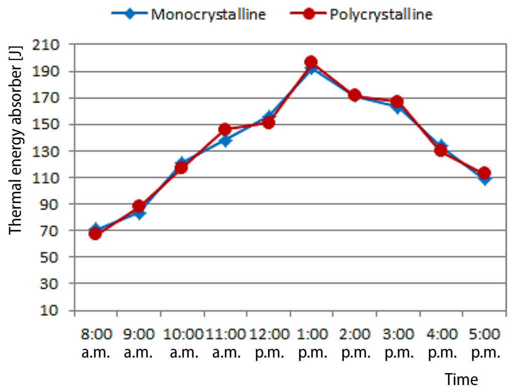

Figure 5. Hourly average thermal energy absorbed by the water flow in duct

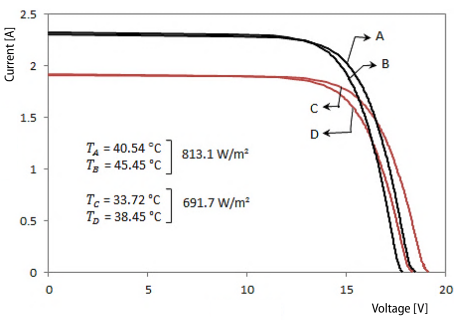

Figure 6. The I-V curve of PV modules at different module temperatures

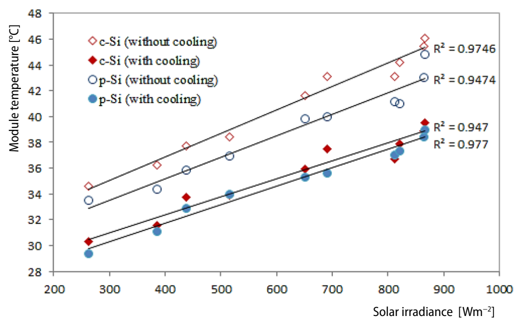

Figure 7. Relation between module temperature and solar irradiance of different PV modules

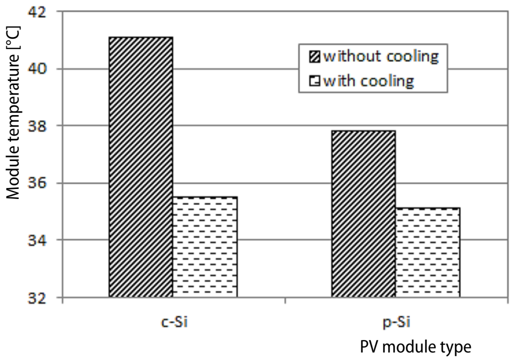

Figure 8. Average module temperature of PV modules with and without cooling

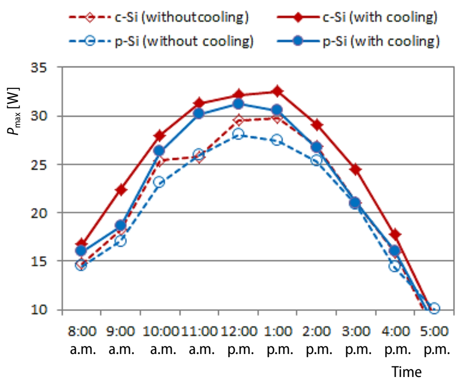

Figure 9. Variation of hourly average output power of different modules.

of PV module causes higher output power compare to the PV modules without cooling. At morning and evening, when module temperature was not much high, effect of cooling was not much significant. The output power increased linearly with solar irradiance as shown in fig. 10. At high solar irradiance (>800 W/m^2), the increase of output power was low and graph deviates from a linear trend. This is due to increase of module temperature at high solar irradiance.

Efficiency analysis

The PV module temperature has a significant effect on the module efficiency [32]. Figure 11 shows that module electrical efficiency varies inversely with the module temperature. The PV module with cooling has lower temperature and high electrical efficiency as compared to the same module without cooling. It can also be seen from figs. 12 and 13, that PV modules with the cooling system have higher hourly average electrical efficiency compared to the PV module of same types without cooling from 8 a. m. to 5 p. m. Furthermore, module electrical efficiency of c-Si and p-Si modules was lower at peak solar hours due to high module temperature. The thermal efficiency of PV modules was much higher at evening due to the high temperature difference between input and output but lower solar irradiance at that time. Using the hybrid system, the overall efficiency of the system became much higher, figs. 12 and 13. Figure 14 shows the average module efficiency of 11 days of study. The average module electrical efficiency of c-Si and p-Si modules with cooling was 12.7% and 6.2% higher than the modules of same types without cooling. This increase in efficiency of c-Si and p-Si modules was due to a decrease of module temperature as previously described.

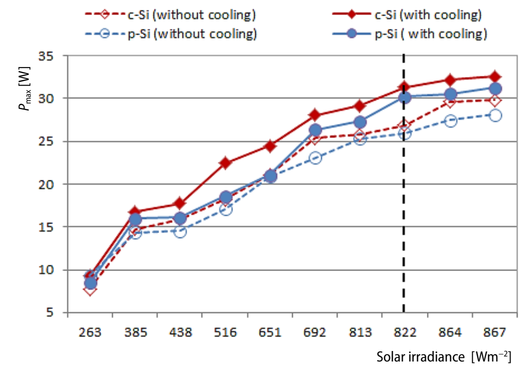

Figure 10. Relation between maximum output power and solar irradiance

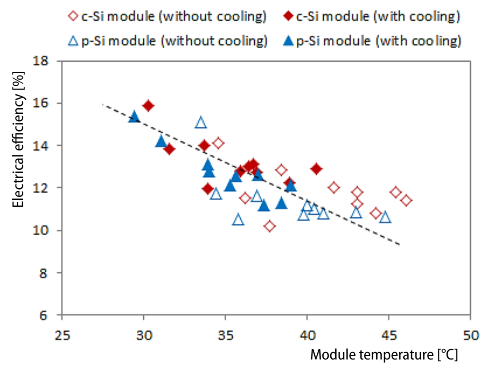

Figure 11. Relation between electrical efficiency with module temperature

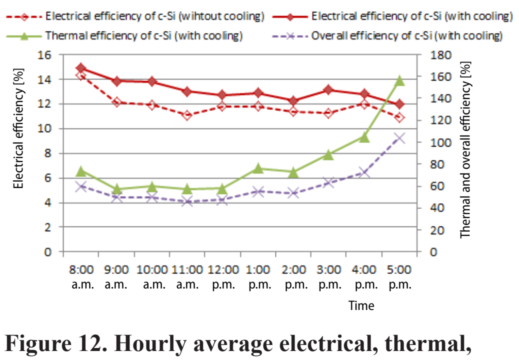

Figure 12. Hourly average electrical, thermal, and overall efficiencies of c-Si modules with and without cooling

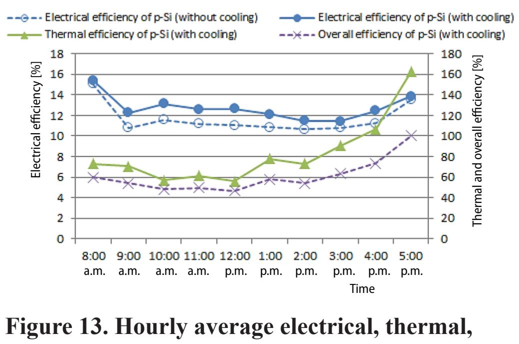

Figure 13. Hourly average electrical, thermal, and overall efficiencies of p-Si modules with and without cooling

Performance ratio analysis

To compare the performance of PV modules at a specific conditions PR was defined. The PR decreases with the increase of module temperature. Figure 15 demonstrates that PV

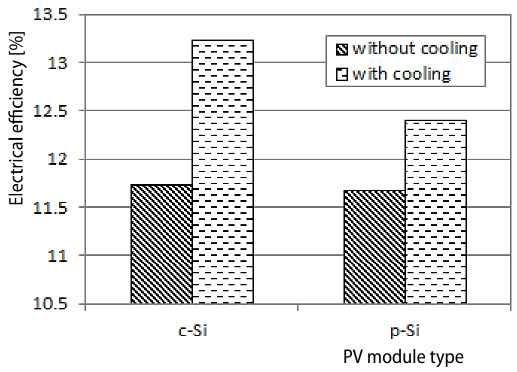

Figure 14. Average electrical efficiency of PV modules with and without cooling

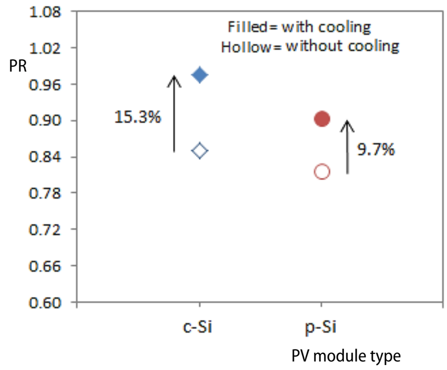

Figure 15. Average PR of PV module with cooling and without cooling

modules with cooling system perform better than the PV modules without cooling. The c-Si and p-Si modules with cooling have 15.3% and 9.7% higher PR compare to same modules without cooling.

Conclusions

The paper presented an experimental investigation of efficiency enhancement in PV/T systems with water cooling using monocrystalline and polycrystalline PV modules. The hybrid system produces electrical as well as thermal energy. A duct was made at the back surface of PV modules having insulation at its outer surface. The flowing water in the duct absorbs the heat of the solar cells causing it to cool and gain thermal energy. The results of PV modules with cooling were compared with the PV module of the same type without a cooling system. The measurements were taken on 11 sunny days of July and August.

Based on experimental results, it was found that there was a significant decrease of module temperature using a hybrid system. The decrease of module temperature results in the increase of output power. The decrease of average module temperature of monocrystalline of 13.6% results in an increase in average electrical efficiency 13%. Similarly, in polycrystalline PV module, 6.2% of average electrical efficiency was increased with the decrease of about 7% module temperature. With the gain of thermal energy, the overall efficiency of the system becomes higher. Furthermore, module temperature varied linearly with solar irradiance.

The performance of different PV modules was compared by PR. It was found that PR of monocrystalline and polycrystalline were 15.3% and 9.7% higher, respectively, using cooling system compared to the same module without cooling. The results show the feasibility of the system, indicating its good application prospects in Pakistan where solar insolation rate is high.

Nomenclature

A_a – aperture area of the PV module, [m^2]
C_p – specific heat capacity, [Jkg^{-1}K^{-1}]
E_c – energy gain by solar cell
E_{ce} – electrical energy of the cell
E_{me} – electrical energy of the module
$I_{(t)}$ – solar irradiance, [Wm^{-2}]
I_m – maximum current, [A]
I_{sc} – solar cell current
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
P_c – packing factor
P_m – maximum power, [W]
PR – performance ratio, [–]
Q_{overall} – overall energy, [J]
Q_{th} – thermal energy, [J]
T_c – cell temperature, [°C]
T_i – inlet water temperature, [°C]

T_o – outlet water temperature, [°C]
V_m – maximum voltage, [V]

Greek symbols

α_c – absorptivity of the cell
β – temperature coefficient, [°C^{-1}]
η_e – electrical efficiency
η_m – module efficiency
η_o – nominal efficiency of the cell
η_{th} – thermal efficiency
τ_g – fraction transmitted by glass surface

Acronyms

PV/T – photovoltac thermal
EVA – ethylene vinylacetate

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