An Expermental Study of Solar Panel Performance Using Heat Pipe and Thermoelectric Generator

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Abstract- A system consisted of solar panel using a micro flat heat pipe (HP) and thermoelectric generator (TEG) is proposed and experimentally investigated in this paper to study its performance. In order to operate HP and TEG at highest possible efficiency, the condensation section of HP is innovatively cooled by utilizing the condensed water inside the evaporator of the air conditioner (which is usually between 5-7 °C). Two different types of silicon solar panel are used in this study, mono- and polycrystalline solar panel. The results showed that a reduction in average solar panel temperature up to 25% is obtained. In addition, the produced power was increased by as much as 50% when the solar panel was cooled by the heat pipe. Moreover, feasibility study and cost analyses are carried out by using SAM software to test the performance of the cooling system combined with the solar panel.

Keywords: PV performance, micro flat heat pipe, thermoelectric generators, cooling system

1. Introduction

Solar energy is the main source of energy that is expected to play a vital role in fulfilling the future global demand for electricity. Design of advanced photovoltaic (PV) system with high electric conversion efficiency is the key for collecting solar energy. The major obstacle hindering useful PV utilization is the high irradiance which increases the operating temperature point of solar panel and degrades its efficiency. The efficiency of the commercial solar cell is in the range of 15-18 % under Standard Test conditions (1000 W/m^2 and the panel is operating at 25°C). A large portion of the radiation falling on the solar panel is converted into heat, which leads to an elevated temperature of the solar cell and reduced its efficiency. Thus, the temperature of the panel is the main issue and needs to be considered in its design. Air-cooling and water-cooling methods were both commonly used for solar cell cooling. A recent technology used heat pipe cooling can be a promising cooling technology since it has higher heat transfer efficiency and a uniform temperature distribution that can solve the drawbacks of the air and water cooling methods. A heat pipe is a vacuum tight device filled with the liquid working fluid. It is divided mainly into 2 sections (Figure 1).

The first section is called evaporator section and it is bought in thermal contact with a hot point to be cooled. The second section, is called condenser section and it is connected to the cold point where the heat can be dissipated. There is a section between the evaporator section and the condenser section, and is called adiabatic section. The liquid working fluid is vaporized in the evaporator section by the input heat, converted to vapour and then follows toward the cooler condenser section via the adiabatic section. In the condenser section, the vapour condenses and gives up its latent heat. Then the condensed liquid returns to the evaporator. As long as the temperature gradients between the evaporator and condenser are maintained, the two-phase flow circulation and the phase change processes are continued. The working fluid and its pressure should be chosen in such a way that its saturation temperature is between the evaporator temperature and the condenser temperature [1].

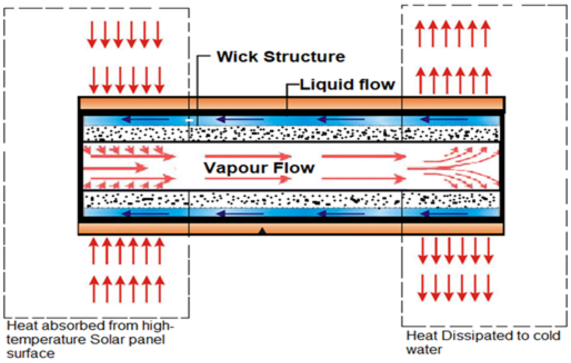


Fig. 1. Working principle of heat pipe cooling system.

Thermoelectric generators (TEGs) are solid-state devices that convert heat into electricity. TEGs do not contain moving parts and are completely silent. The efficiency of TEGs is lower compared to large and traditional heat engines, but they can be competitive for small applications. TEGs are compact, inexpensive, scalable and can be easily designed to operate with small heat sources and small temperature differences. TEGs produce electrical power from heat flow across a temperature gradient. A free charge carriers in the material are driven to the cold end when the heat flows from hot to cold (Figure 2). The resulting voltage is proportional to the temperature difference.

The use of heat pipe technology in solar systems has been studied extensively in recent years as an advanced cooling technique. A review of the development and advances of heat pipes, including numerical modeling, analysis and experimental simulation has been done by Faghri, A. [2]. The performance of a novel flat heat pipe based thermal and solar PV/T (photovoltaic and thermal systems) has been investigated by Jouhara et al. [3]. The results showed that the novel flat heat pipe could be an efficient thermal absorber from the ambient temperature to the intermediate fluid. A study of the effect of using finned heat pipe in reducing the operating temperature of a solar panel has been carried out by Sandeep, K. [4]. The results indicated that a maximum decrease of 13.8K can be achieved by using this technique. Recently, a study of the performance of a heat pipe based solar PV/T roof collector has been conducted by Jouhara and et al.[5]. In Jouhara's study, six experimental configurations of solar thermal collectors has been tested and showed that the conversion efficiency of solar to thermal energy for the integrated heat pipe solar collector with PV panels was between 35 to 52% . The results also indicated that the temperature of the solar panel with and without heat pipe reach up to 35 °C and 60 °C, respectively. In another study, the cooling design that uses a copper/water heat pipe with aluminium fins to cool a concentrator photovoltaic (CPV) cell by natural convection is discussed by Anderson, W. and et al. [6].

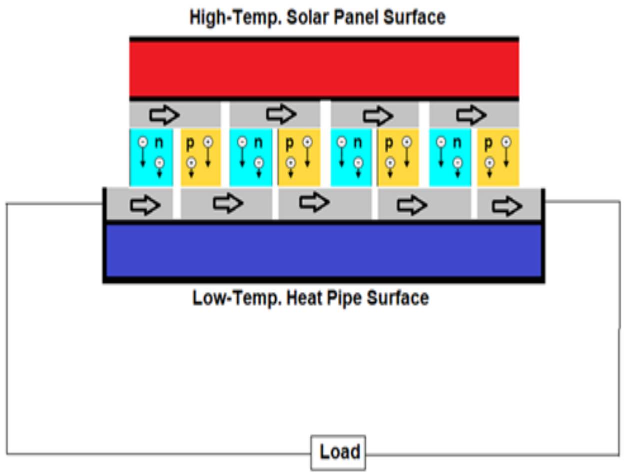


Fig. 2. Working principle of TEGs.

A prototype of heat pipe heat sink was designed, fabricated, and tested. It has been found that with an input heat flux of 40 W/cm2, the heat pipe rejected the heat to the environment by natural convection. Charaf Hajjaj et al. [7] presented a new design of a Photovoltaic-Thermal hybrid solar collector system with a sheet of flowing water as a cooling device with several inputs/outputs (I/O) of the coolant. The thermal performance of the heat pipe cooling system with the thermal resistance model has been studied by Chang, Y. et al.[8]. A novel micro heat pipe array used in solar panel cooling was investigated for both of air-cooling and water-cooling conditions under nature convection condition by Tang. X. et al.[9]. The results indicated that under cooling condition, the temperature can be reduced to effectively increase the photoelectric conversion efficiency of solar panel.

Application of TEGs for solar energy conversion has been studied both theoretically and experimentally by Omer and Infield [10]. A detailed experimental and theoretical analysis of solar concentration system using TEG including the selection of the concentration ratio and the cooling method for different thermoelectric materials has been conducted by Li, Cai et al.[11]. A study on the use of thermoelectric generators in solar hybrid systems has been conducted by Chávez-Urbiola, E. et al.[12]. Results indicated the inclusion of Temperature will enhance the thermal stability of system's electrical efficiency reducing its loss with an increase of temperature. Dilek et al. [13] investigated experimentally thermoelectric cooling with solar panel. In Dilek study, the effect of thermoelectric cooling (TEC) on the coefficient of performance (COP) was evaluated. In another study, the performance of thermal-concentrated solar thermoelectric generators (TEGs) at three different geometric types has been investigated by Chen, W. et al.[14]. Results indicated that water cooling is better than air cooling for the net output power of the TEG. These publications show the importance of heat pipes and TEG in increasing the efficiency of solar system.

The characteristics of heat pipes for suppressing of heat leakage in thermoelectric generation is presented in [15]. The results show that by increasing the number of heat pipes, the output of thermoelectric generation was stable during the experiment.

This paper aims to study the performance of solar panels with and without using a cooling system. It details the use of the state-of-the-art of micro flat heat pipe to cool the solar panel by absorbing the heat from its aluminium back plate. Moreover, a part of the absorbed heat is utilized to generate extra electricity by using a thermoelectric generator while the remaining heat is absorbed by flowing water. Instead of using regular tap water, an idea of using low-temperature water that condensed inside the evaporator of the air conditioner is also utilized to absorb the remaining of heat from HP enhancing its performance. Furthermore, T-flex is used as an adhesive which is an exceptionally soft and highly conductive gap filling material. This makes a superior thermal contact between the heat pipe, solar panel and TEG resulting in higher efficiencies.

2. Methodology and Materials

This experiment aims to study the impact of temperature on two types of solar panels, monocrystalline and polycrystalline, with and without cooling system. The used cooling system is heat pipes and TEGs. The first panel is a monocrystalline silicon solar cell with a surface area of 1.114m2 and a maximum power of 170W at standard test condition. The second panel is a polycrystalline silicon solar cell with a surface area of 0.105 m2 and a maximum power of 15W at standard test condition. Eight flat heat pipes and eight TEGs are used to study the effects of the cooling system on the monocrystalline solar panel, while four HP and 8 TEGs are used with the polycrystalline solar panel. In order to increase the efficiency of solar panels and TEGs, an innovative technique is used to cool the heat pipe by utilizing the condensed water inside the evaporators of air conditioners (which is usually at 5-7 °C). Solar simulator with adjusted individual halogen lights is used to give the required irradiance. The required irradiance is fixed by adjusting the distance between the solar panel and the solar simulator. A protractor was used to adjust the panel through the flexible support at an angle Zero degree. In order to negate the effect of the dust particle, a wet tissue was used to clean the panel from the dust. For data recording, data acquisition devices were used to measure the voltage, the current, the temperature and the variable resistance. The HP & TEG were fixed at the back of the panel with the help of adhesives material and any air-gap was filled with the aluminium plate. In the case of HP, the cooled water was supplied with the help of a chiller, where the temperature was fixed according to our requirements. Figure 3 shows the schematic geometry of the problem for the two solar panels while Figure 4 details the experimental setup and the measuring instruments. Before starting the solar simulator, the room temperature and the panel temperature were recorded and after turning on the lights the temperature of the panel increased initially very fast, thermocouple placed was fixed on the backside of the panel to measure the temperature. The steady state was achieved after 20 minutes as there was no more change noticed. In a steady state condition, the voltage and current values were recorded with the help of variable resistance. Thermal images were captured immediately with the help of infrared camera after reaching the steady state and turning off the lights so that the light rays could not affect the temperature distribution; the rationale behind this step was to get results for the panel output with different configuration and to repeat the experimentation under various configurations.

The specifications of HP and TEG are presented in Tables 1 and 2, respectively.

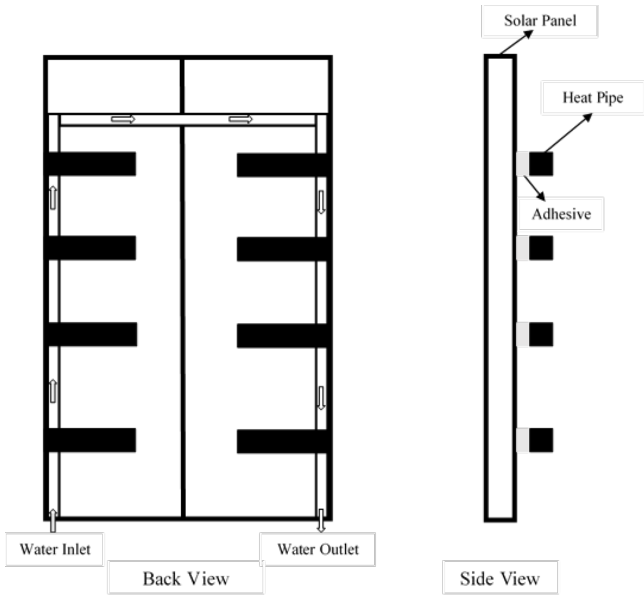


Fig. 3a. The schematic geometry of monocrystalline solar panel with HPs.

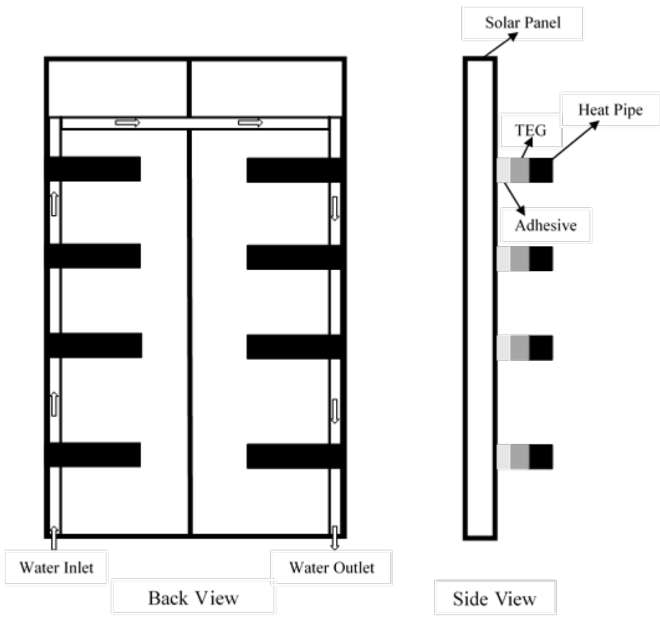


Fig. 3b. The schematic geometry of polycrystalline solar panel with HPs and TEGS.

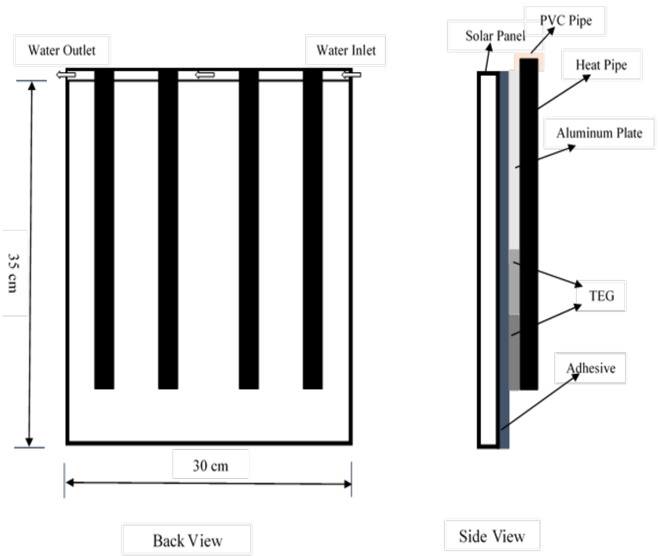
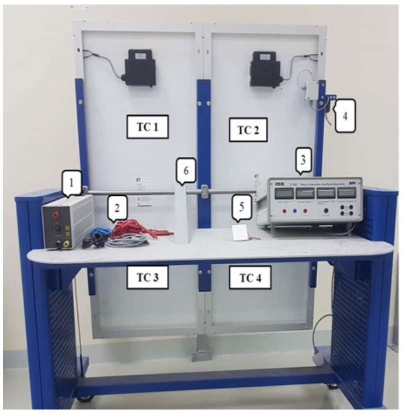


Fig. 3c. The schematic geometry of polycrystalline solar panel system with HPs and TEGS.



Accessories and components

1. Slide resistor
2. Cable sets
3. Measuring unit
4. Illuminance sensor
5. TEG
6. Heat pipe

TC Thermocouples

Fig. 4. The experimental setup for the solar PV modules.

Table 1. The heat pipe specifications

1	Packages cooled	LED
2	Thermal Resistance	0.2 ºC/W
3	External Height	2.5 mm
4	External Width	50 mm
5	External Length	300 mm
6	Heat Sink Material	Aluminium
7	Working fluid	Acetone

Table 2. Specification of TEGs

1	Maximum cooling capacity	128.7 W
2	Maximum temperature difference	+74 K
3	Maximum current	13.1 A
4	Maximum voltage	15.7 V
5	Active Area	55*55 mm
6	Active Area Length	55
7	Active area Thickness	4.6 mm
8	Active Area Width	55

3. Validation of the results

There is no available published study to validate the present results of the proposed design. Therefore, the measurement for the two solar panels were validated by:

For the monocrystalline panel, the experimental setup is validated with the specification and guidelines details provided by the panel Manufacturer. 1.3 m between the panel and the solar simulator has been considered to get an irradiance of 460 W/m2. The results obtained for the power output curve and the current-voltage characteristics matches very well with the characteristics mentioned in the catalogue of the manufacturer as shown in Figure 5. This validates the output of sun simulator and solar panel.

For the polycrystalline panel, the results validation is performed by having the specification of the panel and output power at an Irradiance of 1000W/m^2. The output power is 15 W at an Irradiance of 1000W/m^2 with the same Short Circuit current and open circuit voltage as mentioned on the panel by manufacture.

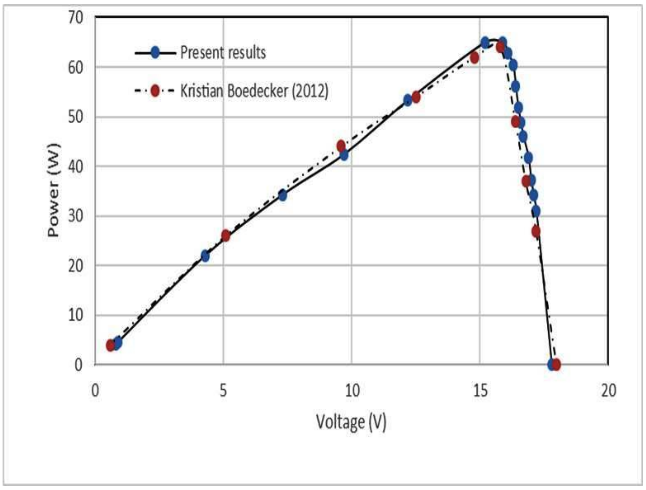


Fig.5. Comparison of the Power-voltage characteristic curve of solar panel in the current study and in the manufacturer' catalogue.

4. Results and Discussion

The obtained results for monocrystalline panel and polycrystalline panel are presented here below:

4.1 Monocrystalline solar panel

For the monocrystalline solar panel, the experiments were carried out for two different cases. The first case is for the solar panel without cooling (i.e., no HPs or TEGs are attached to the surface of the cell). The second case is when the back surface of the solar panel is attached to 8 heat pipes and 8 thermoelectric generators. Figure 5 shows the variation of solar cell temperature with time for the monocrystalline solar cell at radiation of 460W/m2 and an ambient temperature of 22°C. It can be noticed from Figure 6 that the temperature increases dramatically then gradually until reaches its steady state condition.

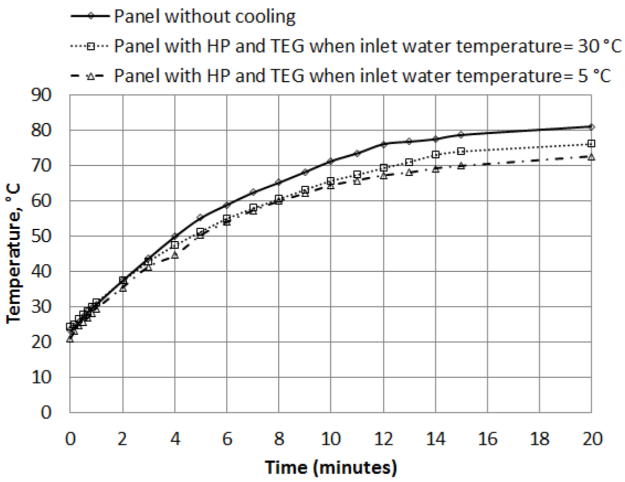


Fig.6. Variation of the temperature of monocrystalline solar panel versus time at irradiance of 460W/m^2.

The steady-state surface temperature distribution obtained of the solar cell in the three studied cases, without cooling system, with a cooling system coupled with an inlet water temperature of 30°C and with a cooling system coupled with an inlet water temperature of 5°C are presented in Figures 7, 8, and 9 respectively. The two values of the inlet water temperature are selected to simulate the temperature of the condensed water inside the evaporator of the air conditioner (~5°C) and the temperature of the regular tap water (~30°C).

When light strikes the surface of the solar panel, small part of light converted to electricity, while the major part converted to heat; increasing temperature of the solar panel. When heat pipes were integrated to the solar panel, their evaporator sections absorb heat from the solar panel surface; turning the acetone fluid from liquid to gas. The gas then turned to the condenser sections and condenses back to the liquid-rejecting its latent heat to the flowing water. Since heat pipes utilize evaporative cooling to transfer thermal energy from the solar panel to the flowing water, temperature of the heat pipe surfaces maintains almost constant near the boiling point of the working fluid (acetone). Reducing the inlet temperature of flowing water allows the heat pipes to operate in a lower temperature which in turn enhances the heat transfer from the solar panel. This makes the proposed design a very effective cooling system when compared to the conventional water active cooling and can reduce the temperature of the solar panel significantly as can be shown in Figure 6.

It can also be noticed from Figure 6 that the temperature increases dramatically then gradually until reaches its steady state condition. Figures 7, 8, and 9 show that the average temperatures of the solar panel at the steady state conditions are 74.3°C, 67.7°C and 63.8°C for no cooling, cooling at 30°C, and cooling at 5°C, respectively. It can be concluded that the present cooling system can reduce the average temperature by 6.6 °C in the case of cooling system coupled with an inlet water temperature of 30°C (8.9 %) and by 10.6°C (14.3%) in the case of cooling system coupled with an inlet water temperature of 5°C.

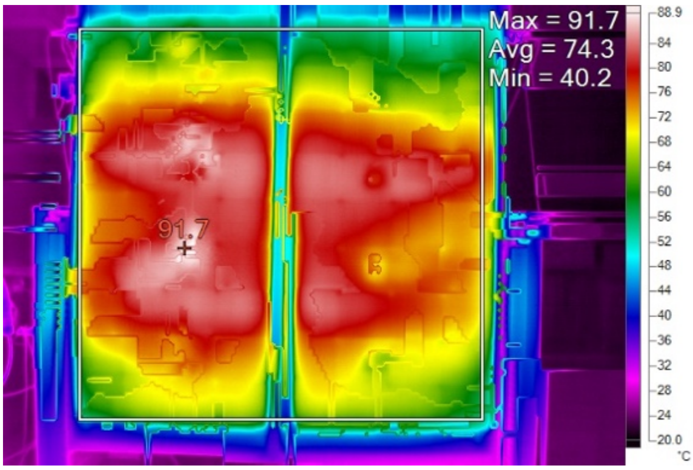


Fig.7. Temperature distribution of monocrystalline solar panel distribution without cooling

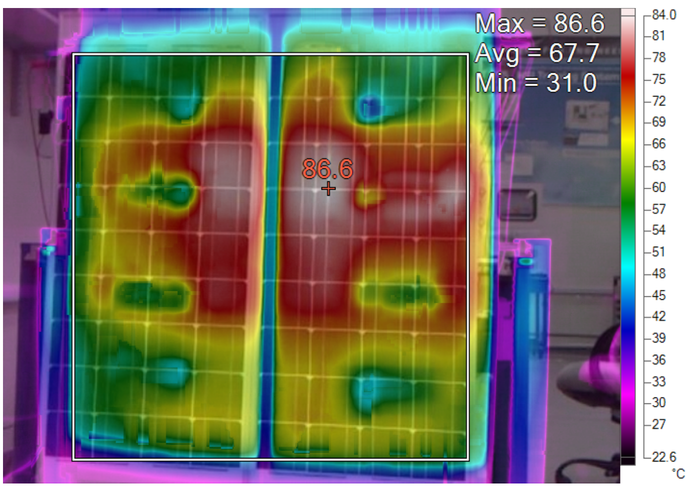


Fig.8. Temperature distribution of monocrystalline solar panel with HP and TEGs at 30°C

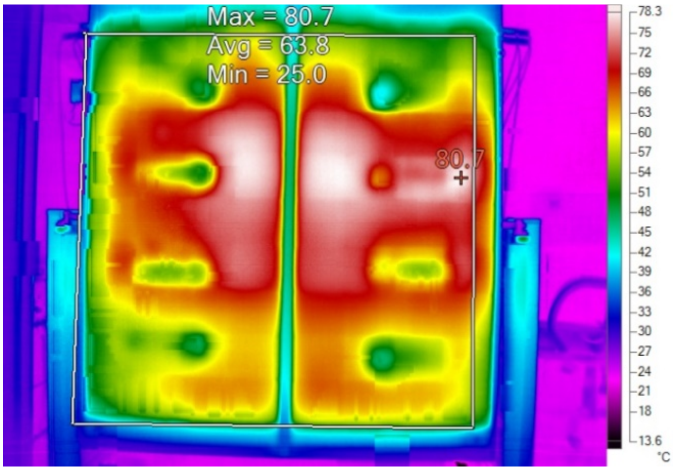


Fig.9. Temperature distribution of monocrystalline solar panel with HP and TEGs at 5ºC

The power characteristic curve of the monocrystalline solar panel for three studied cases is presented in Figure 10. It can be seen from the Figure 10 that the maximum power of the solar panel without cooling is 68.4W; while the maximum power of cooled solar panel at 30°C and 5°C are 71.2W and 73.3W, respectively. It can be concluded that there are increments in the maximum power by 4% and 7.2% for 30°C and 5°C, respectively. In addition, the thermoelectric generators (8 TEGs) produce an extra power of about 2 W. Thus, the total amount of power produced by the integrated system is 75.3W (10.1% increment comparing to regular solar panel).

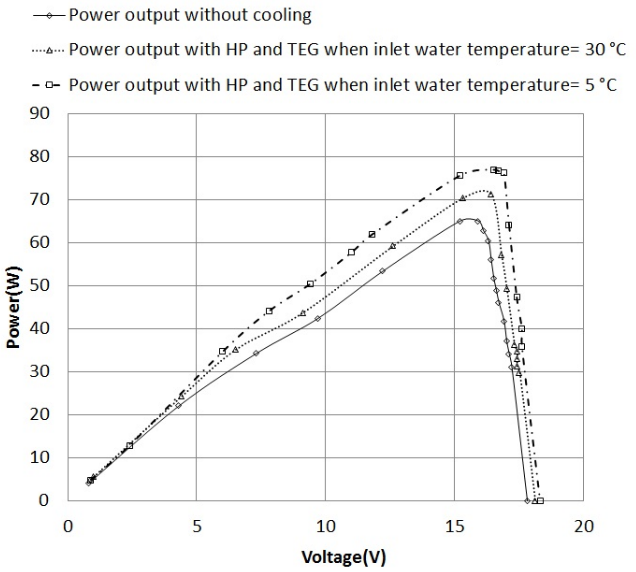


Fig.10. Power curve characteristic of the monocrystalline solar panel with and without cooling

4.2 Polycrystalline solar panel

For polycrystalline solar panel, three experiments have been done. The first experiment tested the performance of the solar cell without cooling (without adding HP and TEGs). The second experiment tested the performance of solar panel with cooling system by attaching four heat pipes to the solar panel. The third experiment test the performance of solar panel with cooling system by attaching eight TEGs between the HP and the solar cell in order to produce an extra power.

Effect of adding HP without TEGs

The variation of the polycrystalline solar cell with the time at irradiance of 1000 W/m2, an ambient temperature of 22°C and water flow rate of 4 l/m is presented in Figure 11. It can be seen that, the temperature increases sharply then gradually until reaches its steady state condition. Also, the temperature when the solar cell was cooled by HP is less than that without HP.

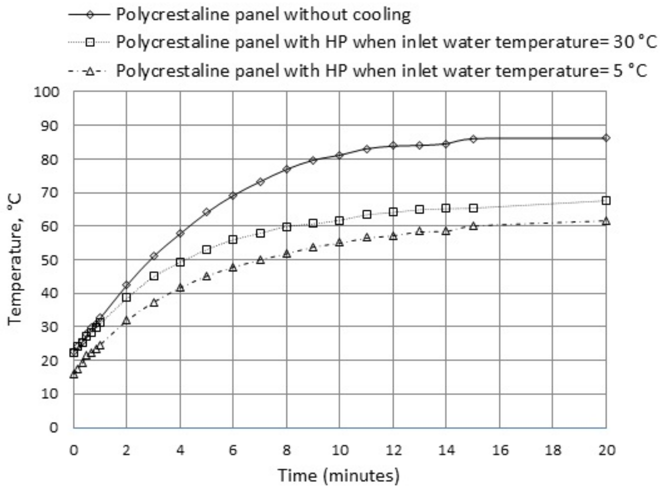


Fig.11. Polycrystalline solar panel temperature variation with time at irradiance of 1000W/m^2

The steady-state surface temperature distribution of the polycrystalline solar cell for the three studied cases, without cooling system, with cooling system based on HP and an inlet water temperature of 30°C, and with cooling systems based on with HP and an inlet water temperature of 30°C are presented in Figures 12, 13 and 14. It can be seen that the average temperatures of the solar cell are 75.5°C, 63.6°C , 56.3°C, for no cooling, cooling at 30°C, and cooling at 5°C, respectively. Therefore, the present cooling system can reduce the average temperature of the solar cell by 11.9 °C in the case of cooling system with an inlet water temperature of 5°C (15.8 %) and by 19.2 °C (25.4%) in the case of cooling system with an inlet water temperature of 30°C.

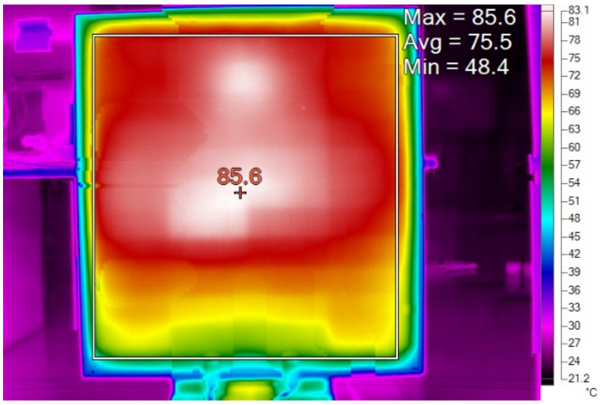


Fig.12. Temperatures distribution of polycrystalline solar panel distribution without cooling.

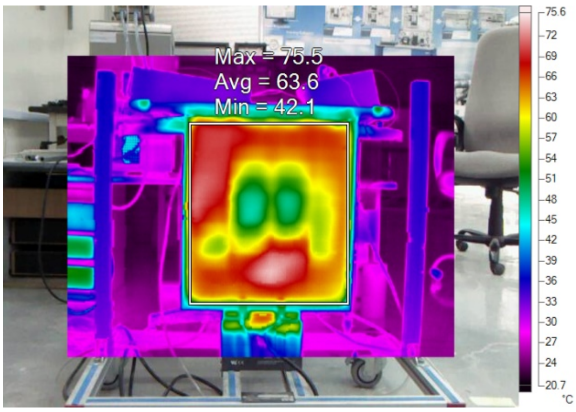


Fig.13. Temperatures distribution of polycrystalline solar panel with heat pipes at 30 ^{0}C.

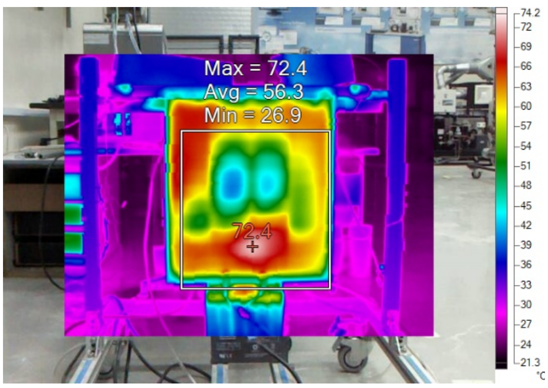


Fig.14. Temperature distribution of polycrystalline solar panel with heat pipes at 5^{0}C.

The effect of HP on the maximum power of the polycrystalline panel for the three studied cases is presented in Figure 15. In the case of the polycrystalline solar panel without cooling, it was found that the maximum power produced was 10.4W. In the case of the polycrystalline solar panel with cooling system with an inlet water temperature of 30°C and with an inlet water temperature of 5°C, it was found that the maximum power produced increases. The increment on the power was 13.44W (29.2%) and 15W (44.2%) for inlet water temperature at 30°C, and 5°C, respectively. Since the maximum power of the solar panel under the (STC) is 15W (as per manufacturer manual), it can be concluded that the suggested cooling system can operate the solar panel at its optimal.

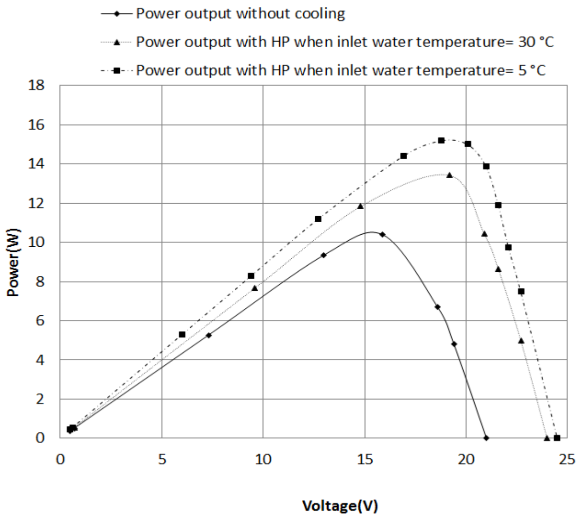


Fig.15. Power output of polycrystalline solar panel without HP and with HP vs temperature at Irradiance of 1000W/m^2

-Effects of adding micro flat heat pipe and thermoelectric generators

To study the effect of integrating thermoelectric generators to the system, eight TEGs are attached between the solar panel and the heat pipes. Figure 16 shows that there is a slight increase in the solar panel temperature when adding TEGs to the system. This is due to the increments in overall thermal resistance. However, TEGs produce 2W as an extra power.

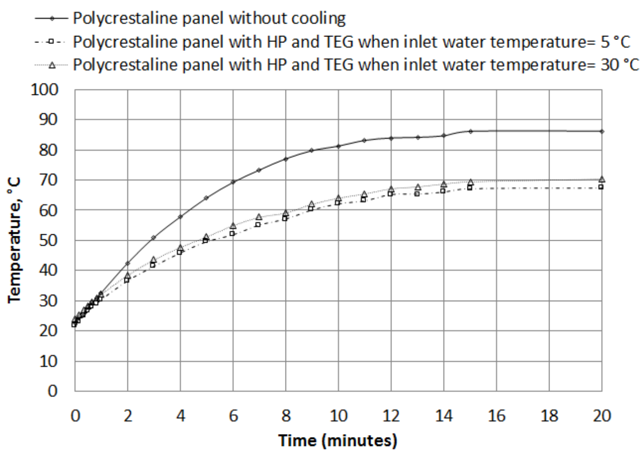


Fig.16. Variation of the polycrystalline solar panel temperature with HP and TEG and without cooling versus time at irradiance of 1000 W/m2.

5. Feasibility Study and Cost Analysis

In order to test the performance of the cooling system combined with the solar panel and to estimate the cost of installing it, two cases have been conducted. In these two cases, two solar panels are installed on the roof of a house located in Dammam city, the capital of the Eastern region of the Kingdom of Saudi Arabia. The difference between them is that a cooling system, heat pipes, is installed with the solar panel in the second case. The solar cells used in these two studies are monocrystalline.

The SAM software is used in this paper to design the PV system, to predict the performance and to estimate the cost. The SAM software makes performance predictions and cost of energy estimates for grid-connected power projects based on installation and operating costs and system design parameters that we specify as inputs to the model. SAM represents the cost and performance of renewable energy projects using computer models developed at NREL, Sandia National Laboratories, the University of Wisconsin, and other organizations.

The website pvwatts.nrel.gov is used in this paper to estimate the electricity production and the energy value of a grid connected roof-mounted PV system based on defined inputs about the system's location, basic design parameters. These inputs are presented in Table 3.

Table 3. Inputs to estimate the AC energy output of PV array

Parameters	**Values**
PV desire array size	7.5kWdc
Dc to AC Ratio	1.2
Graphic location and corresponding solar radiation	26.43 Latitude 50.1Longitude
Tilt angle of the PV array	23o
Operating temperature	45oC

The results obtained from the two cases are presented here below:

Case 1: PV solar panels without cooling system

The monthly solar irradiation, the PV array irradiance, and the estimated values of monthly DC energy output and AC energy output are presented in Table 4. It can be noticed from Table 4 that the annual AC output energy is 12908.3 kWh.

Table 4. Monthly DC energy output and AC energy output

Month	Solar irradiation (kWh/m2/day)	Plane of Array irradiance (W/m2)	DC Array Energy Output (kWh)	AC System Energy Output(kWh)
1	5.66578913	175.6394653	1065.593262	1021.255188
2	6.14025879	171.9272461	1016.674805	974.463562
3	6.38678455	197.9903259	1164.271606	1115.999146
4	6.45321178	193.5963593	1103.083984	1056.696045
5	6.94987392	215.4460907	1178.437378	1128.685913
6	7.32614231	219.7842712	1187.130127	1137.272095
7	7.26340675	225.1656036	1219.314575	1167.875854
8	7.318501	226.8735352	1206.780762	1156.360596
9	7.39285469	221.7856445	1185.602905	1137.043701
10	7.16660118	222.1646423	1221.00354	1171.490112
11	6.05624199	181.6872559	1020.735291	978.9238281
12	4.80211258	148.8654938	900.6920166	862.2816162
Total	78.92177867	2400.925934	13469.32025	12908.34766

Table 5 represents the monthly average temperature, the AC energy output and the effect of variation of temperature on the AC energy output. It can be noticed from Table 5, that the AC energy output decreases with the increasing of the temperature. The AC energy output increases by 2.10 % when the temperature is 20.81 °C while the AC energy output decreases by 26.56 % when the temperature is 38.28 °C.

Table.5 Effect of temperature on AC energy output

Month	**Average of Temperature(°C)**	**Effect of Tem. On production**	**Ac Energy (kWh)**	**AC energy with the effect of Tem.**
January	20.81	2.10%	1021.255188	1042.701547
February	21.66	1.67%	974.463562	990.7371035
March	24.09	0.46%	1115.999146	1121.132742

April	28.62	-7.24%	1056.696045	980.1912513
May	33.67	-17.34%	1128.685913	932.9717758
June	36.47	-22.94%	1137.272095	876.3818762
July	38.11	-26.22%	1167.875854	861.6588054
August	38.28	-26.56%	1156.360596	849.2312215
September	36.42	-22.84%	1137.043701	877.3429198
October	32.51	-15.02%	1171.490112	995.5322974
November	27.52	-5.04%	978.9238281	929.5860672
December	23.12	0.94%	862.2816162	870.3870634
Total			12,908	11327.85467

The direct and indirect cost for installing the PV system on the roof of a house located in Dammam city is estimated by using the software SAM (A screen shot of the calculation is presented in the Appendix). Based on the estimation of the software SAM, the total cost (sum of the direct and the indirect cost) is $ 21885,47 which is equivalent to SAR 82070,52.

Case 2: PV solar panel with cooling system

In the second case, heat pipes are combined with the PV solar panel in order to decrease the effect of high temperature on the performance of the PV solar panel. 36 PV solar panels are used and five heat pipes are used for each panel. Therefore, 180 heat pipes are used in the second case.

For the estimation of the total cost, the cost of heat pipes, pumps and their installations should be added to the total cost estimated in case 1. Table 6 presents the cost of installing PV system with a cooling system.

Table.6 Cost of installing PV panel with a cooling system

	Cost ($)
Cost of installing the PV system	21885,47
Heat pipe cost ($180/ unit)	2400
Installation of cooling system with pump	1600
Total cost	25885,47

Table 7 presents the price of the output energy for the two studied cases during 7.5, 10 and 20 years. The calculation has been done based on an energy output unit price of 0.25 $/kWh.

Table.7 Energy output price for PV system with and without cooling system during 7.5, 10 and 20 years

	7.5 years	10 years	20 years
Energy output price in the case of PV system with cooling system	25526	33733	66090
Energy output price in the case of PV system without cooling system	21805	28697	54373

It can be noticed from Table 7 that the energy output price in the case of PV system combined with a cooling system is more than the energy output price in the case of PV system without cooling system. By comparing the results obtained in Table 7 and the cost of installing PV system in case 1 and the cost of installing PV system and a cooling system in case 2, it can be noticed that the payback of the system in the two cases is 7.5 years.

In the case of PV system with a cooling system, the profit gained during 20 years is SAR 40 564 while in the case of PV system without cooling system, the profit gained during 20 years is SAR 32568. Based on a census of 2014, there are 4 million houses in KSA, if all these houses installed the same system, the net profit is SAR 162,256,00000.

6. Conclusion and perspectives

In this paper, the performance of solar panels with and without cooling system is presented. The use of the state-of-the-art micro flat heat pipe to cool the solar panel by absorbing the heat from its aluminium back plate is detailed. In addition, the thermoelectric generator is used to generate extra power from the panel while the remaining heat is absorbed by flowing water. The idea of using low-temperature water that condensed inside the evaporator of the air conditioner is also utilized to absorb the remaining of heat from HP enhancing its performance. The experimental is carried out using a monocrystalline silicon solar cell with a maximum power of 170W and a polycrystalline silicon solar cell with a maximum power of 15W.

The results of the experiments have shown that for the monocrystalline solar panel, the present cooling system can reduce the average temperature by 14.3% and the total amount of power produced by the integrated system increase by approximately 10.1% compared to the regular solar panel. In addition, the results for polycrystalline solar have shown that the present cooling system can reduce the average temperature by 25.4%. It was found also that the cooling system can operate the solar panel at its optimal power. Finally, the feasibility study and cost analysis showed that the proposed PV system is more profitable than the PV system without cooling system in the long period while the payback of the two systems is 7.5 years.

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APPENDIX