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Article

Investigation of performance of polycrystalline PV module by using hybrid cooling technique

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Abstract: This study aims to investigate the enhancement in electrical efficiency of a polycrystalline photovoltaic (PV) module. The performance of a PV module primarily depends upon environmental factors like temperature, irradiance, etc. Mainly, the PV module performance depends upon the panel temperature. The performance of the PV module has an inverse relationship with temperature. The open circuit voltage of a module decreases with the increase in temperature, which consequently leads to the reduction in maximum power, efficiency, and fill factor. This study investigates the increase in the efficiency of the PV module by lowering the panel temperature with the help of water channel cooling and water-channel accompanied with forced convection. The two arrangements, namely, multi-inlet outlet and serpentine, are used to decrease the temperature of the polycrystalline PV module. Copper tubes in the form of the above arrangements are employed at the back surface of the panel. The results demonstrate that the combined technique is more efficient than the simple water-channel cooling technique owing to multi-heat dissipation and effective heat transfer, and it is concluded that the multi-inlet outlet cooling technique is more efficient than the serpentine cooling technique, which is attributed to uniform cooling over the surface and lesser pressure losses.

Keywords: polycrystalline PV module; fill factor; forced convection; hybrid cooling technique; solar energy

1. Introduction

With the discovery of electrical current, electrical energy has become a means to do work in every field of life. With the increase in demand for global energy, the production need is also increasing. There are two main sources of energy, i.e., non-renewable and renewable sources of energy. Fossil fuels and nuclear energy are the main sources of non-renewable energy. The global energy demand has been fulfilled by fossil fuels for a long time, which affects the environment and has become a major cause of an increase in global temperature. The disadvantages of fossil fuels are global warming caused by pollution and that form of energy is unsustainable. The consumption of fossil fuels has become a major source of emission of greenhouse gases (GHG). The energy produced by fossil fuels has become the largest contributor to CO_2 emissions. Nearly 75% of the emission of GHG is through the energy sector [1].

Nuclear fuel is where the risk of mishandling can lead to disasters. Working with radioactive elements is dangerous for workers and their surroundings. Handling waste material is also quite expensive and dangerous. In the USA alone, the cost to dispose of the high-level waste of the Manhattan Project was about 6 billion dollars.

Wind, tidal, hydro and solar energy are sources of renewable form of energy. These have approximately no contribution to pollution and have a practically unlimited supply in comparison with fossil fuels. These sources also produce more economical energy. Consumption of energy is central to a country's economic development and renewable sources of energy are the most reliable sources of energy, which increase the growth rate without harming the environment.

The renewable form of energy from the photovoltaic system is one of the most prevalent technologies that convert sunlight into electrical energy. Solar energy is one of the most abundant sources of energy. Around 84 terawatts of solar energy are received by the earth every day [2]. Solar energy is a major energy source in space, i.e., the energy used in space to operate the robots and space stations.

A solar cell consists of three main parts, which are further divided into layers. The first one is the top antireflective layer. This is commonly constructed from oxides of silicon and titanium, etc. The main purpose of this layer is to minimize any kind of reflection and ensure that as much as possible light falls on the energy conversion layer. The energy conversion layer mainly consists of three different layers, i.e., a top junction layer, a bottom junction layer, and a central core layer. The third part is of contact layers, one on the top and the other on the extreme bottom.

Generally, a solar panel is categorized into three types based on the structure of the material, namely amorphous, monocrystalline, and polycrystalline. Polycrystalline solar cells consist of several crystals in a single PV cell. The formation of a polycrystalline solar cell of silicon is achieved by cooling it abruptly, which results in multiple crystals. This construction produces different shades of blue color on top, and, due to the blue color, the rise in temperature of polycrystalline solar cells is relatively less than that of a monocrystalline solar cell. These types of cells have lower costs, are quite durable, produce fewer electric bills, and in some specific panels, lead is minimized to keep the environment pollutant-free. The efficiency of polycrystalline solar cells is less due to manufacturing processes, as there is more than one crystal, so the flow of electrons is difficult due to more resistance to the flow of electrons.

Though polycrystalline solar panels are excellent candidates for electricity generation, there are some avenues that need to be addressed. For instance, one main reason due to which a solar panel's efficiency decreases is because of increased temperature, as only a specific amount of energy is required by electrons to get excited, and the energy above that limit is of no use. All the excess solar energy received by the cell is transformed into heat and results in decreased performance of the solar panel. As the temperature rises, both the produced current and voltage behave differently, i.e., the voltage starts decreasing at a higher rate as compared to the increase in current. Eventually, the power output decreases. To evaluate this effect, standards are set by manufacturers, i.e., 25 °C temperature and 1000 watts per meter square irradiance. A temperature coefficient of 0.4%–0.5% is associated with silicon-made solar panels, which means for every 1 °C increase in temperature, the assigned percentage of total power will drop [3]. In this backdrop, there are many different cooling techniques utilized to reduce the panel's temperature, thus improving the performance.

In passive cooling, a cooling medium is circulated without the use of an external source of energy to lower the panel temperature. The cooling medium that is mostly used is water, as it is easily available and cheap. Some additives, like nanoparticles for improved heat absorption, can also be added to the cooling medium. In the case of solar panels, water is either sprayed on top or passed through pipes of copper, aluminum, PVC, etc., attached to the back of the panel. The disadvantage of spraying water is that it does not cover the whole area properly, and leftover droplets on top may act as a lens for light concentration, leading to the damaging of cell material. Thus, the back channel is preferred. Also, the cross-section of the pipe is crucial to the amount of heat absorbed [3].

In forced air convection, the air is passed or sprayed on the backside of the panel, and heat is absorbed by passing air through convection. Air is forced by using fans that are operated by an external power source or by taking power from the panel itself. This additional use of power will lower overall power output, but the performance and power gains compensate for this decrease because when air is forced at high velocity, the heat-absorbing ability also increases significantly.

For instance, Odeh et al. [4] experimented to improve the efficiency of the photovoltaic module through water cooling methods. They found an effective way to decrease the operating temperature of the photovoltaic module surface by front surface cooling. In this study, the rig was tested for the desert condition in Jordan. The findings show that the efficiency increases because of the straight contact between water and the surface of the panel. The irradiance is increased due to refraction in the layer of water on the solar panel. There is no dust due to the front surface's continuous water flow. It is also concluded that 15% output is increased at the highest radiation conditions in experimental performance. The simulation results show that 5% energy is increased during dry and warm conditions.

Similarly, Bahaidarah and co-workers studied the performance of monocrystalline PV module numerically and experimentally through rear surface water cooling in hot climatic conditions. This experiment was performed in a period between 9 a.m. and 4 p.m. in Dhahran, Saudi Arabia. The findings show that due to the gain of temperature, the efficiency of the panel is decreased. The 20% managing temperature of the module is decreased, and 9% electrical efficiency is increased by using an active cooling technique. It is also concluded that when the flow rate of the water is increased, then the temperature rise is hindered [5].

Bhattacharjee and his team investigated the back surface cooling technique with variant designs (semi-over serpentine, serpentine, circular, circular spiral-shaped semi-flattened copper-shaped pipes) for photovoltaic panels to reduce temperature and enhance efficiency. It was found that circular spiral semi-flattened design showed a prominent performance increase among all arrangements. The increase in efficiency was 4.32%, in power 16.77%, and in the infill factor 19.80%. The worst performance recorded was for semi-oval serpentine arrangement [6]. Likewise, Bashir et al. [7] conducted an experimental study on different commercially usable photovoltaic modules (mono-crystalline, poly-crystalline, and single-junction amorphous silicon). Based on solar irradiance and temperature of the module, a comparison was carried out among the power output efficiency, performance ratio, and module efficiency of every module. An amorphous solar module laid out better output in the low amount of solar irradiance because of its improved light digestion properties. Monocrystalline and polycrystalline demonstrated better performance in higher irradiance, and a sudden decrease occurred with a decrement in irradiance. Monocrystalline showed the best monthly average module efficiency and showed that it is best for such sites. The average module efficiency for monocrystalline, polycrystalline, and amorphous silicon modules was decreased by about 8.85%, 4.5%, and 26%, respectively, by an increase of 11 ℃ in module temperature, and the decrease in performance ratio was about 5.6%, 4.8%, and 25.8%, respectively.

In another work, Smith and his team examined the field-mounted, insulated, and concentrating photovoltaic panels by the water cooling method to improve their performance. The chilled water at a temperature of 2.5 °C flowed as a cooling fluid on the front of the surface. It was found that the panel temperature remained below 40 ℃ due to this cooling technique, and, without this cooling technique, the module temperature was about 55 ℃. By using this technique, the panel remained clean and dust-free and efficiency increased. It is also concluded that an effective efficiency-increasing technique is water channel cooling [8]. Similarly, Hasanuzzaman et al. [9] presented an overview of different studies regarding cooling techniques for the photovoltaic and thermal systems. The heat was removed through natural convection alongside forced convection of air. It was concluded that passive cooling techniques are more suitable for small usage power requirements, whereas active cooling techniques are effective for large commercial scales but have issues of extra power requirements and are unable to properly use thermal energy for domestic and commercial purposes.

Cabo and his co-workers presented the overview of different cooling techniques comprising active and passive ones regarding the temperature control of photovoltaic panels. Passive water cooling proved to be more efficient than heat pipe and phase change material cooling. In the case of water active cooling, the respected increase in the electrical efficiency of 14.8%, 19.1%, and 20.4% was observed for the backside, front side, and simultaneous back and front cooling and resulted in more efficient cooling than nanoparticles and thermoelectric active cooling techniques. It concluded that active cooling techniques had higher electric efficiency in contrast to passive cooling techniques and also had more installment costs because of the usage of the external power device [10].

In another work, Sargunanathan and team members explained the enhancement of the performance of commercially available photovoltaic module cells through effective cooling techniques. Different experiments were performed employing passive and active cooling over the front and backside of panels. The experiments showed that when the intensity of solar irradiance and ambient temperature on the photovoltaic module cells increased, operating temperature also increased, which resulted in the reduction of fill factor, power output, and open-circuit voltage of both mono-crystalline and poly-crystalline photovoltaic modules. It is concluded that when 700 suns single cells are used through heat pipe passive cooling, the temperature drops to 30 ℃–40 ℃, where one sun is equivalent to 1000 W m^{-2}. Active front surface cooling through spraying water could reduce the temperature up to 26 ℃; moreover, the addition of phase change material over the backside of the panel and the bionic method of evaporation could also prove helpful to increase the electrical efficiency [11].

Likewise, Ali and co-workers analyzed the photovoltaic panels' outdoor testing in between the summer season. The performance of the monocrystalline module, polycrystalline module, and amorphous silicon module was studied for 3 months (May, June, and July) of summer. The findings show that the monocrystalline module had high average module efficacy, and the amorphous silicon had a better average performance ratio. It was found that when the module temperature was increased, then the performance ratio and module efficiency were decreased. So, the performance ratio and module efficiency have an inverse relationship with temperature. In summer the temperature of the module is increased; that is why the efficiency and performance ratio decrease as compared to winter [12].

Dwivedi et al. [13] presented some elevated cooling techniques and overviewed parameters related to module efficiency. After the application of these cooling techniques on PV modules, it is concluded that simple natural convection in the case of the passive cooling technique is not as efficient as the active ones because of its certain drawbacks. For the purpose of maintaining the panel temperature stable and low, active cooling techniques in addition to heat pipes and sinks should be prioritized.

Based on the literature review, a combination of passive (water channel cooling) and active cooling techniques (forced air convection) is investigated in this study, as there is no study on the aforesaid research direction according to the best of our knowledge. The serpentine and multi-inlet/outlet arrangement is used as it is easy to construct and covers all the cells of a panel in a better way.

2. Materials and methods

2.1. Experimental setup

The experimental setup consisted of energy source (Sun), solar panels (3 polycrystalline PV modules), adjustable stands, absorber (copper pipe of serpentine shape), water tank (17 L), cooling medium, DC fans, DC battery, wooden sticks, PVC pipe, valves (1/4 inch), and nozzles (8 mm outer-diameter).

2.2. Experimental procedure

The experiments were carried out in ambient conditions at the rooftop of the workshop of COMSATS University Islamabad, Sahiwal Campus, Sahiwal, Punjab, Pakistan (30.6506° N, 73.1158° E). This place was chosen as there were no barriers of shadow from trees or other buildings. In the experiment, three commercially available polycrystalline PV modules of 50 W each were used. The modules were placed at an angle of 45° from the roof as shown in **Figure 1**. Sahiwal is in the northern hemisphere, so the modules were faced towards the south.

$$\text{Angle of inclination (for winter)} = \text{Latitude} + 15°,$$

$$\text{Angle of inclination for Sahiwal} = 30.6506° + 15° = 45.6506°.$$

Figure 1. Experimental setup.

The calculated angle is approximately 45° with approximately 2° human error. However, such small variations in the angle of inclination could be negligible. First, a serpentine arrangement of copper pipes was mounted at the back of the two PV modules, and then multi-outlet copper pipes were mounted on the back. The copper pipes were fixed tightly with the help of wooden sticks for maximum contact. Thermal paste is used to ensure maximum conduction of heat. At the back of one PV module, a serpentine/multi-inlet-outlet pipe arrangement along with three fans (12 V) was installed to see the results of the combination of two techniques.

The water tank with an 8 mm valve attached at the end of it was placed higher than the PV modules. The water tank was placed higher, due to which the flow of water naturally occurred. PVC pipe with a diameter of 8 mm was used to join the outlets of valves to the inlets of the serpentines because PVC is not a good conductor of heat, and due to this, the heat transfer could not occur. For the first ten minutes of every hour from 8 am to 5 pm, the water flowed, and fans were switched on for cooling. A battery was used for powering the fans. The time was measured with the help of a stopwatch, with a tolerance of ±5 s.

The water flow rate was approximately 0.7 L/min (0.01162 L/s) throughout the experiments. Water was used as a cooling medium due to its conductivity of 0.609 W m^{-1} K^{-1}. It is cheap and easily available. The conduction from the back of PV modules to the copper pipes was due to the second law of thermodynamics, as it states that "heat transfer occurs spontaneously from higher to lower temperature bodies but never spontaneously in the reverse direction".

Once a day at 6:30 in the morning, the PV modules were cleaned with a damp cloth to remove dust from the glass of the modules. After running water and fans for the first ten minutes of each hour, the temperature of the inlet water was recorded, and then exactly one minute later, the temperature of the outlet water was recorded. After 10 min, the water and fans were turned off. Instantly after turning them off, the temperature of all PV modules was noted. The temperature was noted diagonally at three different points of each PV module, and their average was considered as a final value. At the same time, the solar survey 200R irradiance meter was placed on the lower-left corner of the first PV module to allow the reading to stabilize, and then the current irradiance was recorded.

Meanwhile, the PROVA 210A m was connected with the wires of one polycrystalline PV module for auto-scan of desired readings. After a few seconds, the PROVA 210A meter's screen would show the V_{open}, I_{open}, I_{short}, P_{max}, V_{max}, I_{max}, efficiency, and fill factor (FF) with the I-V curve graph. All the desired readings were obtained from the stored readings. The whole procedure was repeated for each hour. In the end, the data were extracted for the whole day from the PROVA 210A meter with the help of solar module analyzer software. An Excel sheet was generated to log the readings and plot the desired graphs.

2.3. Data collection

Manually, the below-mentioned formulas can also be used for calculating desired parameters.

Maximum power can be calculated by:

$$Pm = Vm \times Im \tag{1}$$

Direct solar irradiance can be measured by:

$$\mathrm{Energy}_{Direct} = \mathrm{Energy}_{Hours} \times \mathrm{Airmass} \tag{2}$$

where Airmass = 1/Cosϑ.

$$E_D = E_H/\mathrm{Cos}\vartheta \tag{3}$$

Performance ratio is mainly a ratio of the actual and theoretically possible energy outcomes. It mainly depends upon the PV module orientation and the incident irradiance on the PV module. It can be calculated as follows:

$$P_r = E_{measured}/(Irrad \times A_m \times Eff_{PV}) \tag{4}$$

Fill Factor (F_c) measures the quality of a solar cell. It is the ratio of the maximum obtained power to the product of short-circuit current and open-circuit voltage. It can be calculated as;

$$F_c = (I_{mp} \times V_{mp})/(I_s \times V_o) \tag{5}$$

3. Results and discussion

3.1. Variation of irradiance

The experiments were conducted from 8 am to 5 pm. It is observed that the average maximum irradiance is 876 W m^{-2} at 12 pm. Then the average minimum irradiance is 104 W m^{-2} at 5 pm for the serpentine cooling technique. The average maximum irradiance is 842 W m^{-2} at 12 pm. The average minimum irradiance is 144 W m^{-2} at 5 pm for the multi-inlet outlet cooling technique, which is shown in **Figure 2**.

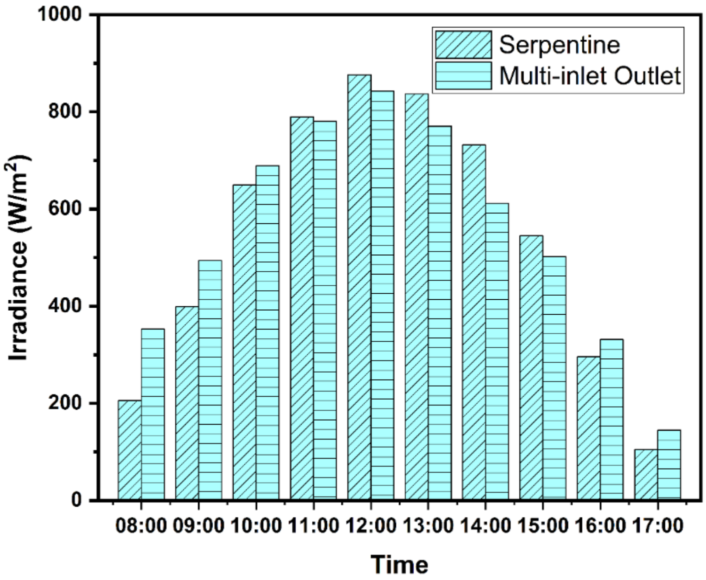

Figure 2. The average irradiance during different times.

The difference between the irradiances of experiments with serpentine cooling and multi-inlet outlet cooling is due to the fog and clouds [14]. The weather was not cleared during the serpentine cooling experiment from 8 am to 10 pm due to the fog that why the difference between the irradiance for both experiments is quite high.

3.2. Variation of panel temperatures

The average maximum panel temperatures for the simple panel, serpentine, and serpentine with fan are found to be 44.43 ℃, 37.87 ℃, and 37.8 ℃, respectively, at 1 pm. The minimum average panel temperatures are 16.27 ℃ for the simple panel, 15.38 ℃ for serpentine arrangement, and 14.56 ℃ for serpentine with the fan at 8 am.

In the multi-inlet/outlet arrangement, it is noticed that average maximum panel temperatures for the simple panel, multi-inlet/outlet arrangement, and multi-inlet/outlet with fan are 45.27 ℃, 42.40 ℃, and 38.32 ℃, respectively, at 1 pm. The minimum average panel temperatures are 27.14 ℃ for the simple panel, 26 ℃ for the multi-inlet/outlet arrangement, and 25.37 ℃ for the multi-inlet/outlet with the fan at 8 am.

For both cooling techniques, the overall temperatures of the simple PV panels are higher than the PV panels with serpentine/multi-inlet outlet arrangements and with serpentine/multi-inlet outlet and fan. The temperatures of PV panels with serpentine/multi-inlet outlet arrangements and fan cooling techniques are lower than PV panels with serpentine/multi-inlet outlets, as shown in **Figures 3** and **4**.

The panel temperatures are decreased due to the application of both cooling techniques simultaneously. The reason for this variation in panel temperatures is that in the simple panel, there is no cooling arrangement applied at the backside of the panel as compared to the other panels where serpentine or multi-inlet/outlet channel cooling techniques are applied. The most decrement in panel temperature is observed for panels that have serpentine or multi-inlet/outlet channels with fans due to forced air convection. This can be attributed to the effective heat transfer due to the multi-heat dissipation techniques [15].

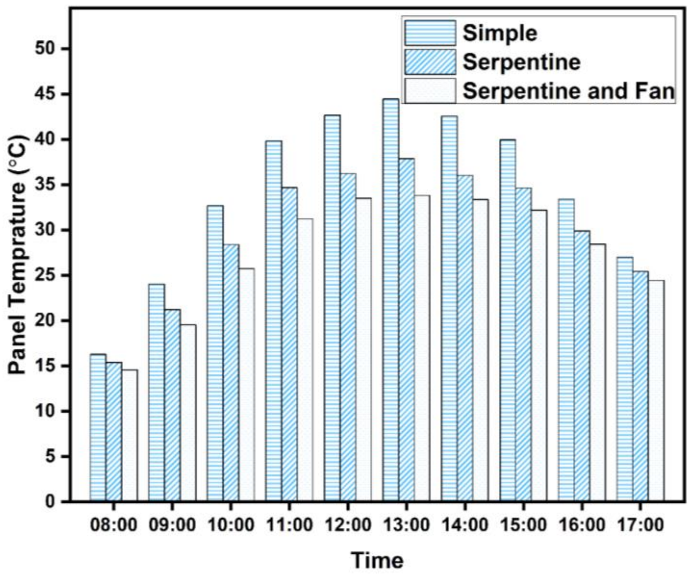

Figure 3. Comparison of average panel temperature for different serpentine arrangements.

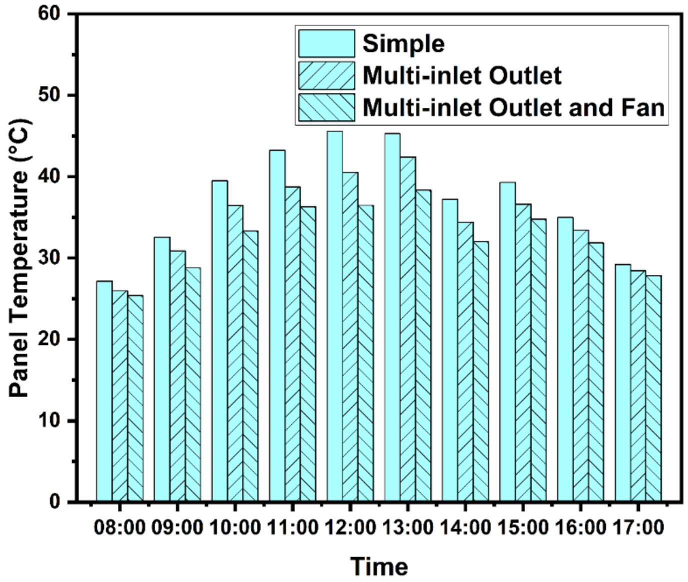

Figure 4. Comparison of average panel temperature for different multi-inlet outlet arrangements.

3.3. Open circuit voltage

The average maximum open circuit voltage (V_o) for the simple panel, serpentine arrangement, and serpentine with fan are 20.2 V, 20.5 V, and 21.1 V, respectively, at 9 am. The minimum average (V_o) is 17.35 V for the simple panel, 18.51 V for serpentine arrangement, and 18.9 V for serpentine with the fan at 5 pm.

In the multi-inlet/outlet arrangement, the average maximum (V_o) for the simple panel, multi-inlet/outlet arrangement, and multi-inlet/outlet with fan are 19.87 V, 20.29 V, and 21.01 V, respectively. The minimum average is 17.92 V for the simple panel, 18.28 V for the multi-inlet/outlet arrangement, and 18.46 V for the multi-inlet/outlet with the fan at 5 pm.

For both cooling techniques, the overall (V_o) of the simple PV panels is lower than the PV panels with serpentine/multi-inlet outlet arrangements and with serpentine/multi-inlet outlet and fan. The (V_o) of PV panels with serpentine/multi-inlet outlet arrangements and fans are higher than PV panels with serpentine/multi-inlet outlets, as shown in **Figures 5** and **6**.

The open-circuit voltage is inversely proportional to the panel temperature. So, for both cooling techniques, the overall (V_o) of the simple PV panels is lower than the PV panels with serpentine/multi-inlet outlet arrangements and with serpentine/multi-inlet outlet arrangements and fan. The (V_o) of PV panels with serpentine/multi-inlet outlet arrangements and fans is higher than PV panels with serpentine/multi-inlet outlets. This can be ascribed to the lowering of panel temperature, which resists the narrowing of the band gap and leads to the improvement in the open circuit voltage. Furthermore, thermogeneration of electron-hole adds to it [16].

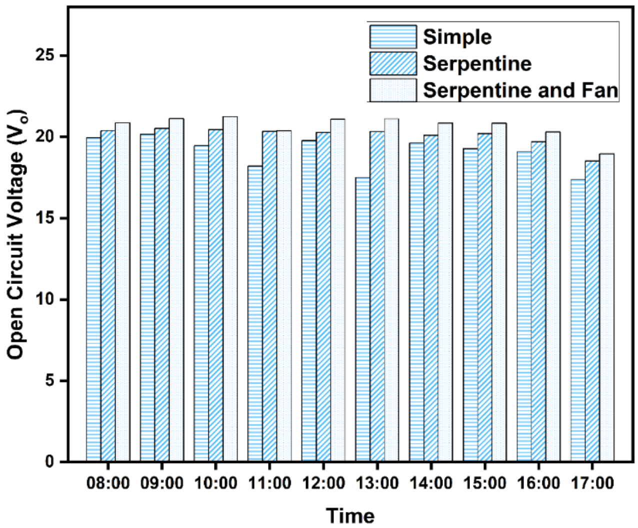

Figure 5. Comparison of average open circuit voltage for different serpentine arrangements.

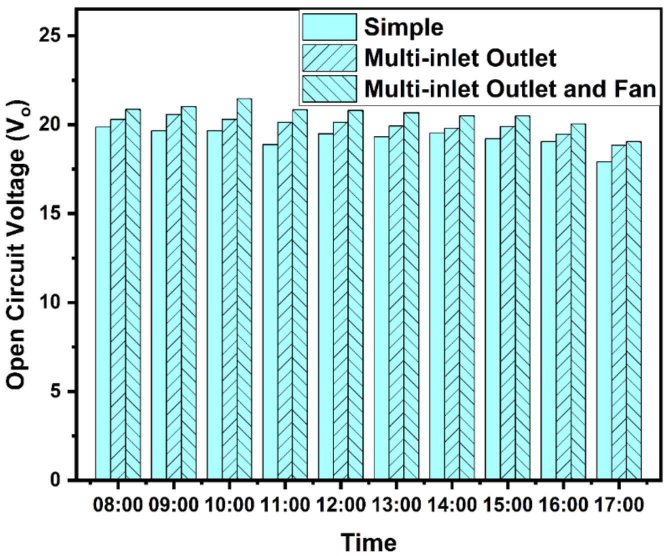

Figure 6. Comparison of average open circuit voltage for different multi-inlet outlet arrangements.

3.4. Maximum power (Pm)

In case of serpentine arrangement, it is observed that the average maximum output power for the simple panel, panel with the serpentine channel, and panel with serpentine channel and fan are 25.34 W, 27.42 W, and 38.21 W, respectively. The minimum average output power is 7.37 W for the simple panel, 7.98 W for the panel with the serpentine channel, and 9.53 W for the panel with the serpentine channel and fan, as demonstrated in **Figure 7**.

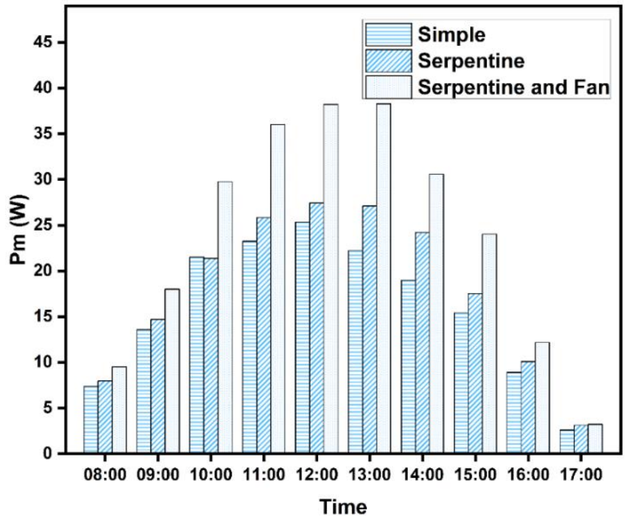

Figure 7. Comparison of average maximum power for different serpentine arrangements.

In the multi-inlet/outlet cooling technique, it is noticed that the average maximum output power for the simple panel, multi-inlet/outlet arrangement, and multi-inlet/outlet with fan are 22.67 W, 26.57 W, and 37.69 W, respectively. The minimum average output power is 3.98 W for the simple panel, 4.79 W for the multi-inlet/outlet arrangement, and 4.994 W for the multi-inlet/outlet with the fan. The comparison of average maximum power for different multi-inlet outlet arrangements is presented in **Figure 8**.

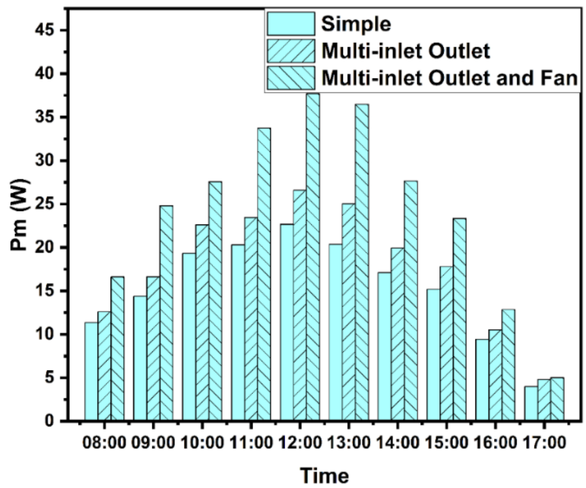

Figure 8. Comparison of average maximum power for different multi-inlet outlet arrangements.

For both cooling techniques, the overall Pmax of the simple PV panels is lower than the PV panels with serpentine/multi-inlet outlet arrangements and serpentine/multi-inlet outlet arrangements and fan. The (Pm) of PV panels with serpentine/multi-inlet outlet arrangements and fans is higher than PV panels with serpentine/multi-inlet outlets.

The output power of PV panels is directly proportional to the open-circuit voltage (Vo). So, for both cooling techniques, the overall Pmax of the simple PV panels is lower than the PV panels with serpentine/multi-inlet outlet arrangements and serpentine/multi-inlet outlet arrangements with a fan. The Pmax of PV panels with serpentine/multi-inlet outlet arrangements and fans is higher than PV panels with serpentine/multi-inlet outlets. The combination of both cooling techniques addresses the issue of high panel temperature thus, improving open circuit voltage and consequently the output power of PV modules [17].

3.5. Efficiency

For the serpentine arrangement, it is found that the average maximum efficiency for the simple panel, panel with the serpentine channel, and panel with serpentine channel and fan are 12.28%, 13.30%, and 15%, respectively. The minimum average efficiency is 8.56% for the simple panel, 10.24% for the panel with the serpentine channel, and 9.98% for the panel with the serpentine channel and fan. The comparison of average efficiency for different serpentine arrangements is presented in **Figure 9**.

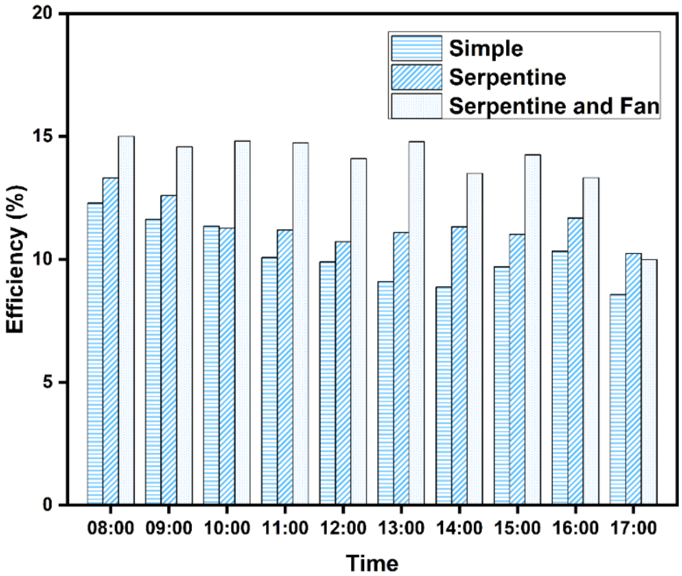

Figure 9. Comparison of average efficiency for different serpentine arrangements.

For the multi-inlet/outlet arrangement, it is noted that the maximum average efficiencies for the simple panel, multi-inlet/outlet arrangement, and multi-inlet/outlet with fan are 11%, 12.23%, and 16.22%, respectively. The minimum average efficiency is 8.90% for the simple panel, 10.29% for the multi-inlet/outlet arrangement, and 11.17% for the multi-inlet/outlet with the fan. This is exhibited in **Figure 10**.

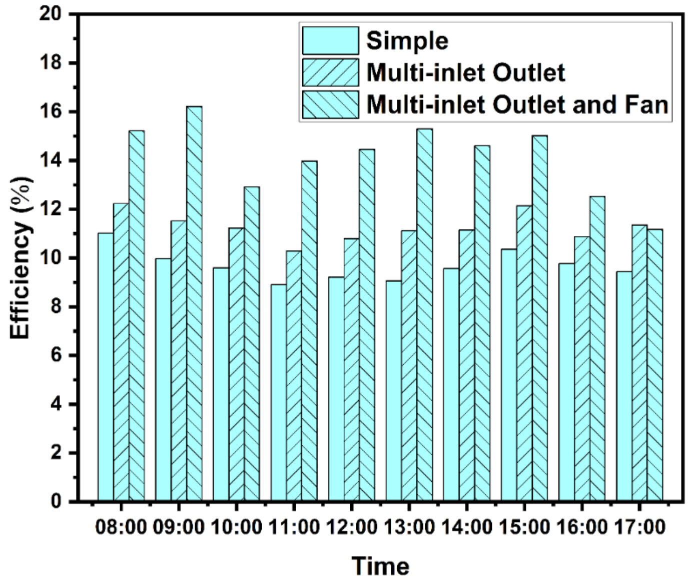

Figure 10. Comparison of average efficiency for different multi-inlet outlet arrangements.

For both cooling techniques, the overall efficiencies of the simple PV panels are lower than the PV panels with serpentine/multi-inlet outlet arrangements and serpentine/multi-inlet outlet arrangements with fan. The efficiencies of PV panels with serpentine/multi-inlet outlet arrangements with a fan are higher than PV panels with serpentine/multi-inlet outlet.

The efficiency of PV panels is directly proportional to the maximum output power, and panel temperature is inversely related to the maximum output power. For both cooling techniques, the overall efficiencies of the simple PV panels are found to be lower than the PV panels with serpentine/multi-inlet outlet arrangements and serpentine/multi-inlet outlet arrangements with a fan. The efficiencies of PV panels with serpentine/multi-inlet outlet arrangements and fans are found to be higher than PV panels with serpentine/multi-inlet outlets. The introduction of hybrid cooling techniques leads to an increase in overall efficiencies by reducing the panel temperatures and is in agreement with the previous studies [18].

3.6. Fill factor (F_c)

As far as serpentine arrangement is concerned, it is found that the average fill factors for the simple panel, panel with the serpentine channel, and panel with serpentine channel and fan are 0.62, 0.65, and 0.75, respectively. The minimum average fill factor is 0.46 for simple panel, 0.56 for panel with the serpentine channel, and 0.67 for panel with serpentine channel and fan. The comparison of average fill factor for different serpentine arrangements is exhibited in **Figure 11**.

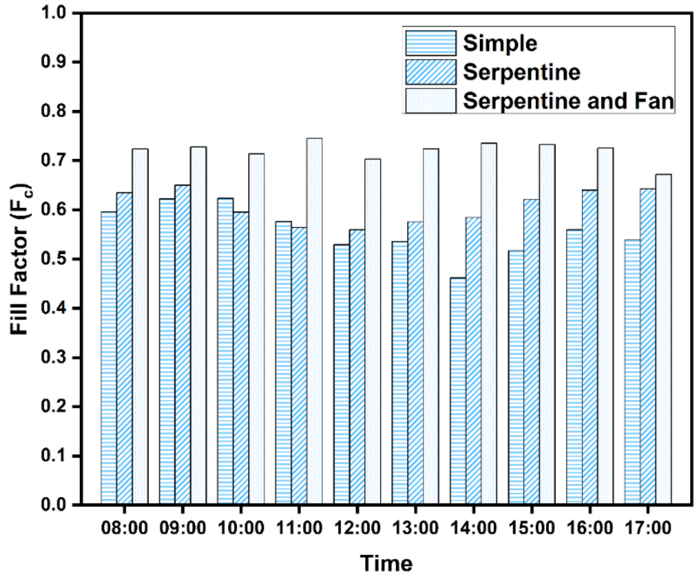

Figure 11. Comparison of average fill factor for different serpentine arrangements.

In the multi-inlet/outlet cooling configuration, it is noted that the maximum average fill factors for the simple panel, multi-inlet/outlet arrangement, and multi-inlet/outlet with fan are 0.56, 0.67, and 0.74, respectively. The minimum average fill factor is 0.47 for the simple panel, 0.55 for the multi-inlet/outlet arrangement, and 0.67 for the multi-inlet/outlet with the fan. The comparison of average fill factor for different multi-inlet outlet arrangements is presented in **Figure 12**.

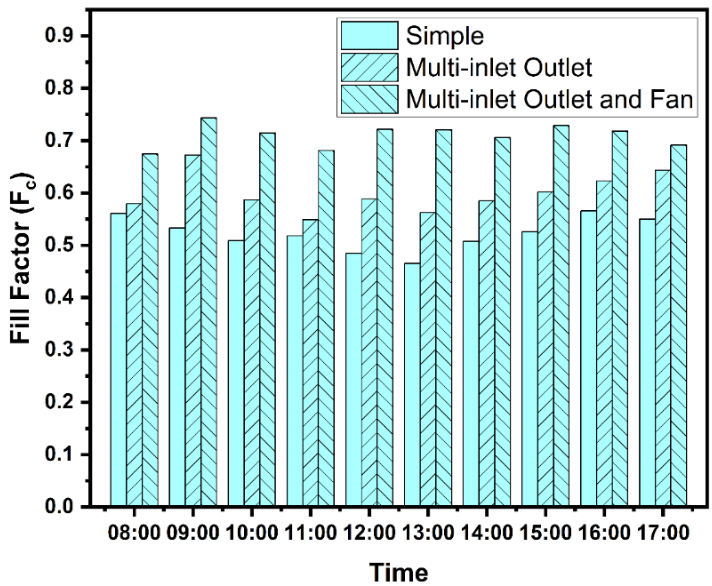

Figure 12. Comparison of average fill factor for different multi-inlet outlet arrangements.

It has been found that modern cooling methods lead to the reduction in panel temperature which is consequently in relationship with the improved open circuit voltage. This ultimately improves the fill factor and is in agreement with the previous studies [19,20]. The uncertainty analysis is provided in **Table 1**.

Table 1. Average fractional uncertainty.

Parameter	Unit	Serpentine	Multi Inlet	Overall Average fractional Uncertainty
Solar Irradiance	W/m^2	0.001	0.001	0.001
Panel Temperature	℃	0.003	0.003	0.003
Improvement in short circuit current	mA	0.015	0.011	0.013
Improvement in open circuit voltage	V	0.009	0.015	0.012
Improvement in fill factor	%	0.426	0.433	0.429
Improvement in power	% W	0.243	0.248	0.245

4. Conclusion

This study was conducted to reduce the temperature, enhance the efficiency, and power output of the PV module. The results show that for both serpentine and multi-inlet/outlet arrangements, the combination of the water channel cooling technique and the forced convection technique exhibits higher output power and efficiency as compared to the simple water channel cooling technique. The results are more pronounced at the 1 pm reading and are concluded below:

- In the multi-inlet/outlet cooling technique, the temperature of the polycrystalline panel with multi-inlet/outlet channel is decreased up to 2.86 ℃ approximately and the panel temperature with multi-inlet/outlet channel with fans is decreased up to 6.94 ℃ as compared to the simple panel. In the serpentine cooling technique, the temperature of the polycrystalline panel with the serpentine channel is decreased approximately up to 6.56 ℃ and the panel temperature with the serpentine channel and fans is decreased approximately up to 10.63 ℃ as compared to the simple panel. The decrease in temperature is attributed to the effective heat transfer and multi heat dissipation phenomenon.
- In the multi-inlet/outlet cooling technique, the maximum power of polycrystalline panel with multi-inlet/outlet channel is increased up to 4.66 W approximately and the maximum power with multi-inlet/outlet channel and fans is increased up to 16.1 W as compared to the simple panel. In the serpentine cooling technique, the maximum power of the polycrystalline panel with the serpentine channel is increased up to 4.9 W approximately and the maximum power with the serpentine channel with fans is increased up to 16.1 W approximately as compared to the simple panel. The improvement in power out put is ascribed to the increase open circuit voltage due to reduction in panel temperature.
- In the multi-inlet/outlet arrangement, the efficiency of the polycrystalline panel with multi-inlet/outlet channel is increased up to 2.06% approximately, and the efficiency of the polycrystalline panel with multi-inlet/outlet channel and fan is increased up to 6.23% approximately. In the serpentine cooling technique, the efficiency of the polycrystalline panel with the serpentine channel is increased up to 1.99% approximately, and the efficiency of the polycrystalline panel with the serpentine channel and fan is increased up to 5.69% approximately as compared to the simple panel. The hybrid cooling technique leads to increase in overall efficiencies by reducing the panel temperatures

- When the results of multi-inlet/outlet and serpentine arrangements are compared with each other based on the improved maximum power and efficiency of the polycrystalline PV module, it is concluded that the multi-inlet/outlet arrangement exhibited higher efficiency than the serpentine one. This can be due to the uniform cooling over the surface of the module and lesser pressure losses.

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