

Research article

Performance enhancement of PV cells through micro-channel cooling

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Abstract: Efficiency of a PV cell is strongly dependent on its surface temperature. The current study is focused to achieve maximum efficiency of PV cells even in scorching temperatures in hot climates like Pakistan where the cell surface temperatures can even rise up to around 80 °C. The study includes both the CFD and real time experimental investigations of a solar panel using micro channel cooling. Initially, CFD analysis is performed by developing a 3D model of a Mono-Crystalline cell with micro-channels to analyze cell surface temperature distribution at different irradiance and water flow rates. Afterwards, an experimental setup is developed for performance investigations under the real conditions of an open climate of a Pakistan's city, Taxila. Two 35W panels are manufactured for the experiments; one is based on the standard manufacturing procedure while other cell is developed with 4mm thick aluminum sheet having micro-channels of cross-section of 1mm by 1mm. The whole setup also includes different sensors for the measurement of solar irradiance, cell power, surface temperature and water flow rates. The experimental results show that PV cell surface temperature drop of around 15 °C is achieved with power increment of around 14% at maximum applied water flow rate of 3 LPM. Additionally, a good agreement is also found between CFD and experimental results. Therefore, that study clearly shows that a significant performance improvement of PV cells can be achieved through the proposed cell cooling technique.

Keywords: micro-channel cooling; heat transfer; performance enhancement; PV cells; renewable energy; live testing

1. Introduction

With an ever increasing demand for energy, research in the renewable energy sector is significantly increasing. PV Cells have gained more attention than any other source in the past

couple of years. The cumulative PV capacity for all major countries increased from about 40 GW to 100 GW during 2010–2012 [1]. With increasing energy demand and environment pollution, better utilization of solar energy is considered to be the best way for energy generation [2,3].

There are some methods and technologies that can improve the energy utilization efficiency; like multi-junction cells [4], optical frequency shifting [5], multiple exciton generation cells [6], hot carrier cells [7] and concentration photovoltaic system [8]. However, because of the extraordinary cost and complex service conditions these alternatives require, they have not been made commercial yet.

PV panels absorb around 80% of the solar irradiation whereas the maximum conversion efficiency that a single crystalline and single junction silicon cell can provide is not more than 30% [9,10]. Major component of the losses being heat dissipation; this heat significantly increases PV cells temperature resulting in decreased power output and hence the efficiency. In order for PV cells to work most efficiently; the cell temperature must be around 25 °C [11]. Therefore, a proper heat sink is required to get maximum power output.

A study was based on the effect of temperature on PV Cells efficiency. The study was aimed to make an empirical equation of efficiency dependent on the temperature of PV cells only. The developed equation clearly showed a negative gradient between conversion efficiency and the temperature [11].

A research was focused on the design and analysis of a PVT (photo voltaic thermal) system in which heat dissipated in PV panels is used to raise the temperature of water which can be used for different purposes. It was concluded that total efficiency of PVT system is higher than the sum of the efficiencies of separate PV and solar thermal systems [12].

Another research was intended to enhance the heat dissipation from PV cells by modifying EVA encapsulates. It was analyzed that photovoltaic cell efficiency has a negative gradient with temperature (about -0.4 to -0.5 %/K). They experimented by adding fillers of different compounds in EVA and the thermal conductivity was enhanced up to 3.0 W/mK by adding 60% volume fraction of SiC fillers [13].

Numerical analysis of heat transfer in photovoltaic cells using a mathematical model derived from energy conservation was performed in a research [14]. It was observed that the temperature at which a PV module works is at the equilibrium point between the heat generated by the solar panel and the heat loss to the surrounding environment through conduction, convection and radiation.

A research was based on the study of both parallel longitudinal and transverse micro channels [15]. The heat spreader was bonded to silicon substrate through eutectic-bonding to ensure a sealed micro-channel system. De-ionized water was used for as a coolant. The temperature distribution for the steady state silicon substrate was measured. They observed redeveloping of boundary layer through the transverse channels.

In another research the same transverse micro-channels were simulated. It was determined that maximum heat flux input of these heat sink was 75% more than the conventional ones [16].

The performance of PV solar cell at elevated temperature was theoretically studied [17]. Their study confirmed that the temperature decreases the open-circuit voltage and fill factor; hence the main reason for the decrease in efficiency is the rise in temperature.

In the current study, the heat sink is an open feed water cooled micro channeled system attached on the bottom side of PV Cells. The study is based on the numerical and experimental analysis of the system that used grooved micro-channels on a 4 mm thick aluminum plate which was then sealed

with a 1 mm Aluminum base plate. These plates were attached at the bottom of PV Cells, after a couple of layers of EVA, instead of TPT (Tedlar Polyester Tedlar). The purpose to use this type of system for cooling of PV cells is that its ratio of temperature drop to the flow rate is quite low compared to other systems currently being used. If such a system are manufactured on a large scale then its cost can also be significantly reduced to make it commercial.

2. Materials and Method

2.1. Nomenclature

FF fill factor [---]

V_{norm} normalized open circuit voltage to thermal voltage

K Boltzmann constant [1.38×10^{-23} J/K]

T average surface temperature of PV panel

V_{OC} open circuit voltage [V]

I_{SC} short circuit current [A]

P maximum power output [W]

η efficiency [%]

E solar irradiance [W/m^2]

A total surface area of PV cells for each panel [m^2]

Q̇ heat removed by the water circulating through the heat sink [W]

ṁ mass flow rate of water circulating through the heat sink [kg/s]

C_p specific heat [$\text{kJ}/\text{kg}\cdot^\circ\text{C}$]

T_{OUT} temperature of water at heat sink outlet [$^\circ\text{C}$]

T_{IN} temperature of water at heat sink inlet [$^\circ\text{C}$]

EVA ethylene vinyl acetate

w groove width [mm]

h groove height [mm]

S groove spacing [mm]

D sheet height [mm]

L sheet width [mm]

2.2. Theoretical Analysis

For theoretical analysis, the following desired performance parameters are determined through various mathematical and empirical relationships.

Fill factor is evaluated by using a graph which allows fill factor to be determined for any combination of the parameters used to characterize cell performance. Fill factor significantly affects the efficiency of the solar panel along with the maximum power output of the system. In this study, Fill factor is determined by Equation 1 [18]:

$$FF = \frac{V_{norm} - \ln(V_{norm} + 0.72)}{(V_{norm} + 1)} \quad (1)$$

where V_{norm} is the open circuit voltage per cell normalized to the thermal voltage “ kT/q ” [18]. Assuming each cell produces approximately the same voltage, the open circuit voltage is divided by the total number of cells i.e. 14 to get the voltage per cell as shown in Equation 2.

$$V_{norm} = \frac{(V_{oc}/14)}{\left(\frac{k \times T}{q}\right)} \quad (2)$$

Product of the open circuit voltage, short circuit current and the fill factor provides the value of the maximum power output of the system. As described in Equation 3 [18].

$$P = V_{oc} \times I_{sc} \times FF \quad (3)$$

The efficiency of the system then is computed by using equation 4 which gives us the ratio of the maximum power output to the total power the sun provides [19],

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{E \times A} \times 100 \quad (4)$$

The heat removed by the water circulating through the heat sink is calculated through Equation 5 by applying the conservation of energy principle to control volume with one inlet and one exit, with no work interactions and assuming negligible changes in kinetic and potential energies. [20]

$$\dot{Q} = \dot{m} \times C_p \times (T_{out} - T_{in}) \quad (5)$$

2.3. Numerical Analysis

To determine a suitable range of flow rates and groove spacing to use and design the proposed system accordingly to the desired specifications, a 3D mesh of width equal to the cell, height of 5mm and depth of 1.3m (length along the panel) was developed. Symmetry condition was applied to the right and left walls of the model. Then a 3D numerical analysis was performed using the commercial solver “Fluent” for solving “Navier-Stokes” and “Energy” equations for steady-state analysis at a solar irradiance of 1000 W/m^2 and water temperature of $30 \text{ }^\circ\text{C}$.

Minimum and maximum flow rates were chosen according to the difference between the surface temperature of PV panel near the outlet and inlet of heat sink. As it was not feasible to have very low temperature difference as it would mean that flow rate of water is quite high neither to have a very high temperature difference because that would keep the cells near the outlet at high temperatures. So hit and trial method was used, several flow rates were simulated starting from 0.05 LPM with an interval of 0.1 LPM.

Finally, the results were selected on the base of maximum temperature of the last cells near outlet and temperature difference between the surface near inlet and outlet. A minimum flow rate of 0.150 LPM was chosen to keep the temperature of cells above $40 \text{ }^\circ\text{C}$ approximately and 3.00 LPM to make sure that the temperature drop is not less than $2 \text{ }^\circ\text{C}$.

2.4. Experimental Procedure

The experimental investigation was performed under real conditions to check the practicality of

the proposed system. The testing site was at the roof of mechanical engineering department in University of Engineering and Technology Taxila, Pakistan (33.7660° N, 72.8250° E). Experimentation was performed during the months of June and July. To measure the enhanced performance, a comparison is made between the standard PV panel and the modified PV panel. Both the panels were fixed on a horizontal plane at about a distance of 2 feet from each other and the experimentation was performed.

Figure 1 shows the cross-section of both the modified and the standard PV panel. On the top layer, both the panels have the standard glass used in the manufacturing and PV cells sandwiched between two layers of EVA. The basic function of EVA is to fix the PV cells in their respective position and electrically insulate them. A total of 14 Mono-crystalline silicon cells having surface dimensions $125 \times 125\text{mm}$ were used in each panel.

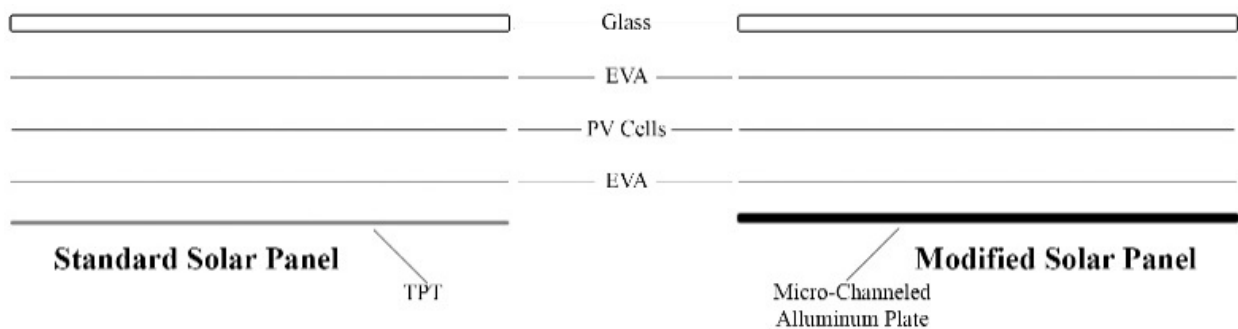


Figure 1. Cross-sectioned view of the standard and modified panel.

Figure 2 shows cross-sectioned view of the micro-channeled plate and its zoomed view to show a clear view of the micro-channels.

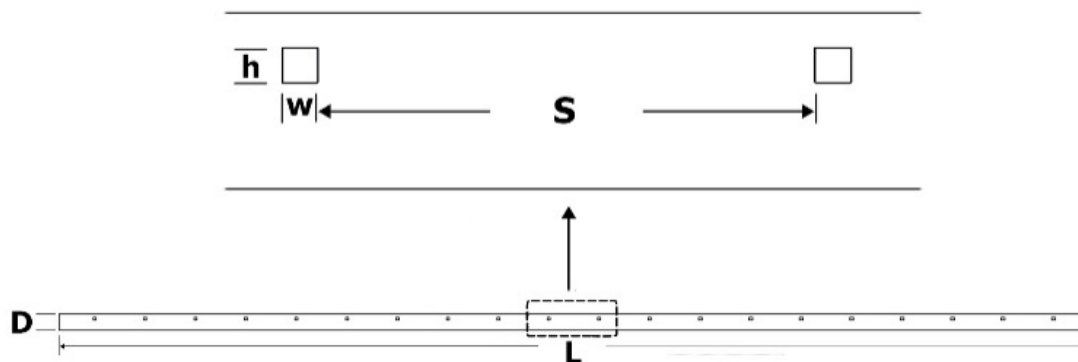


Figure 2. Cross-sectioned micro-channel setup.

Complete specifications of the micro-channeled plate are defined in Table 1.

Table 1. Dimensions of micro-channeled plate.

Parameters	Dimensions (mm)
Groove width, w	1
Groove height, h	1
Groove spacing, S	15
Sheet length	1070
Sheet height, D	5
Sheet width, L	305

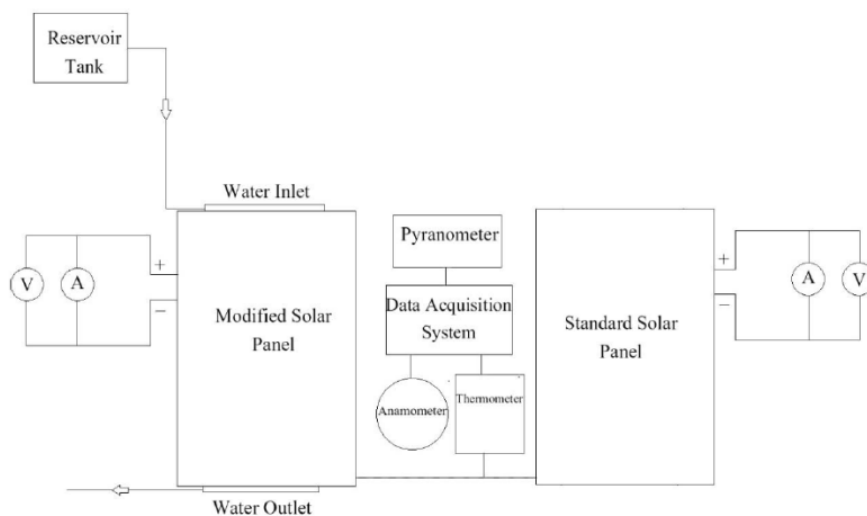
In the current study, the flow of water during the experimentation was kept open cycle to maintain a constant inlet temperature for water as shown in Figure 2. The required maximum water flow rate of 3.0 LPM is achieved through a head of 3 meters without using a pump, thus the flow is under gravity with no water circulation. Therefore, no power is consumed during experimentation. However, in other case, the required power consumption can be calculated through pressure drop. The pressure drop through channels due to friction is determined by Equation 6.

$$\Delta P = f_D * \left(\frac{L}{D}\right) * \frac{\rho v^2}{2} \quad (6)$$

where the friction factor for a square channel is found by Equation 7.

$$f_D = \frac{56.92}{Re} \quad (7)$$

Here, L/D is $(0.875/0.001 = 875)$ and $v = 0.0035$ m/s which results the pressure drop of 1.1 kPa for 16 channels. Thus, the power required a single PV cell against this pressure drop is very nominal of about 0.1 W for the flow rate of 0.00005 m³/s. However, the power saved through this approach is 4.9 W i.e. 14% of 35 W (section 3).

**Figure 3. Schematic and flow diagram of the experimental setup.**

The short circuit currents were noted at the same instant for both the panels and then quickly after switching off the ammeter, the open circuit voltages were taken using the same method. While the values for solar irradiance, wind speed and ambient temperatures were calculated for the instant the short circuit current was noted.

Afterwards the values of the rapidly varying parameters were taken. The surface temperature was measured at 6 strategic points (two in each; beginning, center and end) as shown in Figure 2 for both the panels along with the inlet and outlet temperatures of water in the heat sink.

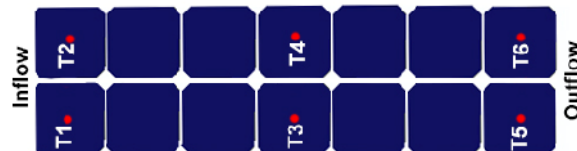


Figure 4. Temperature measuring points on PV Panel.

The instruments listed in Table 2 were used to collect values of the short circuit current, open circuit voltage, ambient temperature, surface temperature, solar irradiance and wind speed.

Table 2. Instruments used.

Name of Instrument	Model No. (Made)
Humidity Meter	37003-10 (Singapore)
Thermocouple Probe	K type, 08516-60 (USA)
Pyranometer	TBQ-2 (China)
Anemometer	EC95 (China)
Ultrasonic Flow Meter	EW-05613-65 (USA)
Multi-meter	Fluke 28 II Ex (USA)

A total of ten readings for all the require values were noted after every five minutes for each flow rate. The flow rate was measured using a high accuracy ultrasonic meter through the inlet. After the desired flow rate was achieved, the valve was fixed in its position and the readings were taken after the reached steady state condition of temperature difference no more than ± 0.1 °C in 2 minutes.

To begin, the comparison between the panels was done without any water flow to make sure that having aluminum on the back of PV Cells instead of TPT does not have any negative effects on the performance of solar panel. No deficiency of output power was observed and almost equal power output was calculated from both the panels.

In experimentation water is used as a cooling medium. The surface temperature values for all the 6 points were averaged out to get the mean surface temperature of the panels for each reading. After getting all the values required, the empirical relation in Equation 1 was used to calculate the fill factor. Using the fill factor, maximum power output and efficiency were then calculated.

3. Results and Discussion

It can be observed from Figure 5 that by providing a flow rate of 3LPM, numerical analysis resulted in a difference of about 2 °C between the inlet and outlet surface temperature of PV panel. During real-time testing, a temperature difference of about 1.9 °C was observed. Therefore the resulted error was 5% and this shows a good agreement between numerical and experimental work.

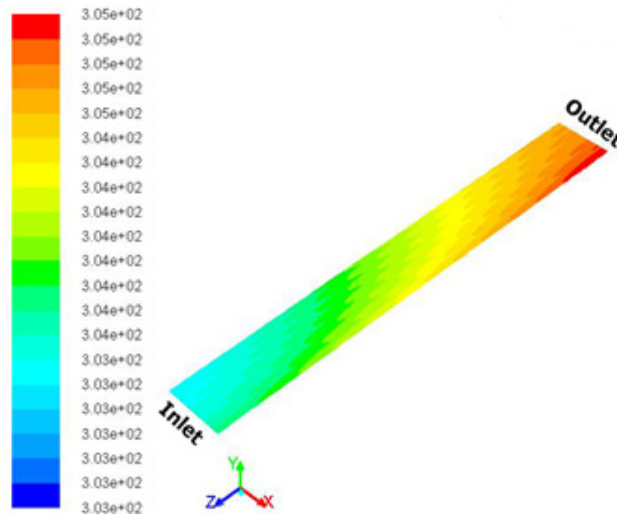


Figure 5. PV cell surface temperature distribution at 3.00LPM.

At minimum flow rate, the simulations resulted in a minimum and maximum temperature of 31 °C and 41 °C respectively as shown in Figure 6. However, the experimentation resulted to be 37 °C and 45 °C as their minimum and maximum temperature respectively. There is a difference of about 6 °C between the actual and simulated values; an error of about 19%. This can be justified because of the neglected factors in the simulated model i.e. ambient temperature.

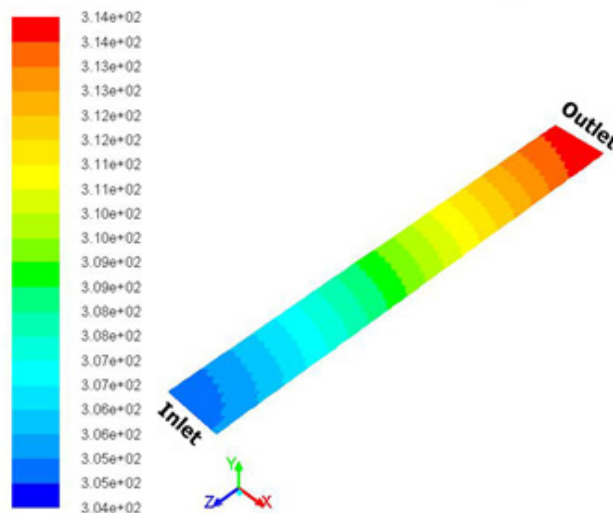


Figure 6. PV cell surface temperature distribution at 0.15LPM.

Variation of surface temperature is plotted with the flow rate of water in Figure 7. No fluid was passed through the standard PV panel, however the projections are shown against the flow rate for the purpose of comparison between both stations. The general trends between these two parameters are inversely related and as the flow rate increases, the gradient of the curve decreases. The difference between the temperature of standard and micro-channeled PV panel is about $-8\text{ }^{\circ}\text{C}$ without cooling as Aluminum gets heated up much quickly than TPT. But the difference changes to about $+15\text{ }^{\circ}\text{C}$ at the flow rate of 3LPM. It can also be observed that if flow rate of more than 0.1LPM is passed through the heat sink, the temperature of the modified panel remains below the standard PV panel.

The abnormality in the graph at the flow rate of 0.150LPM is because of the significant change in ambient temperature and decrease in solar irradiance. This change can also be observed in Figure 8, which shows a sudden drop for the power output at 0.150 LPM and in turn a decrease in solar irradiance can be interpreted. Apart from the abnormality, there exists a 3% power increment at 0.150LPM. The power increment also keeps on increasing up to about 14% at the flow rate of 3LPM.

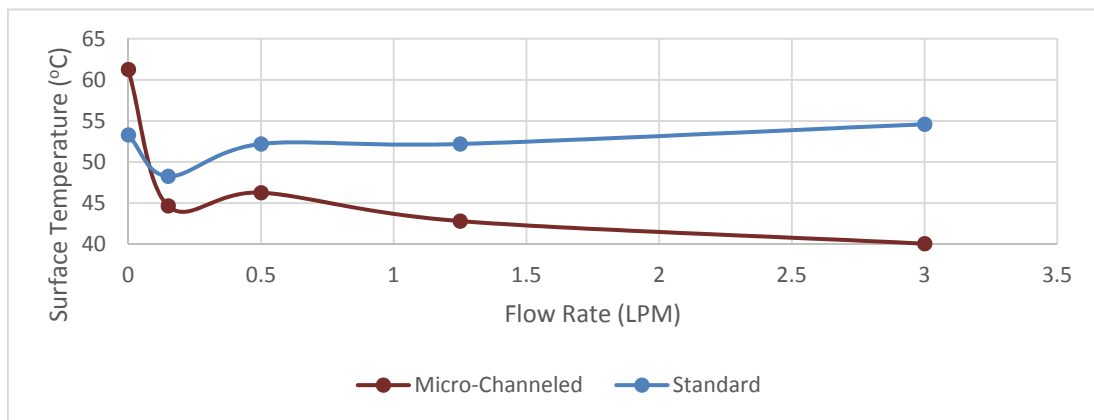


Figure 7. Average surface temperature against flow rate.

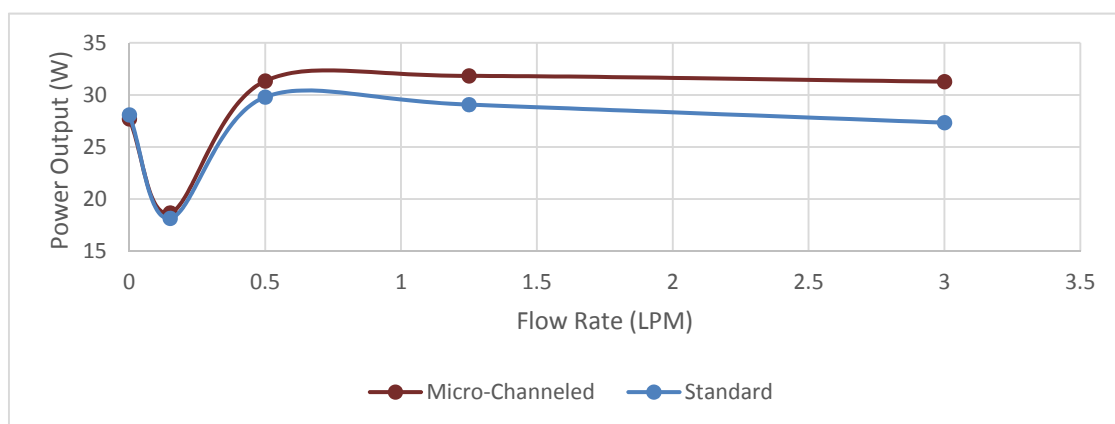


Figure 8. Maximum power output against flow rate.

It is already determined in various research activities that the efficiency of the solar panel is substantially decreased by the increase in temperature. The comparison in Figure 9 shows us an exact

graphical representation and perfectly fits the descriptions of the Figure 7 and 8 as well. The efficiency of the cooled panel again increases around the flow rate of 0.1LPM; when the temperature of the micro-channeled panel becomes less than the standard one.

The difference between both the panel's efficiency also shows us an increasing trend with increase in flow rate which again can be also interpreted as a direct relationship between temperature and PV panel's efficiency. At the minimum flow rate we find more than 1% increase in the efficiency while for the maximum flow rate, an increase of up to 3% is observed.

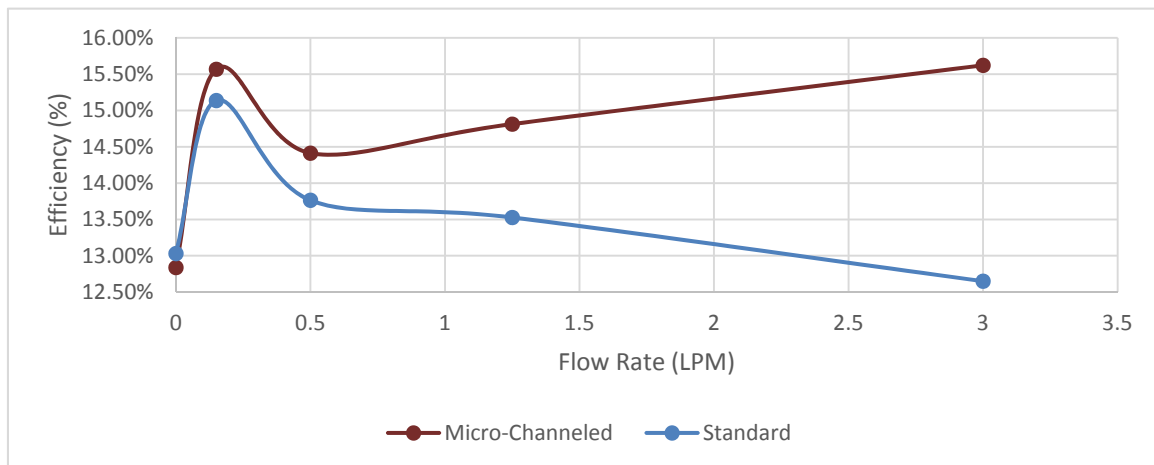


Figure 9. Efficiency against flow rate.

Figure 10 shows increase in the heat removed as the flow rate is increased. But also indicate a decreasing gradient at higher flow rates. The reason lies in the concept that as we move towards larger flow rates, the efficiency of heat dissipation starts to decrease because of the low temperature difference across both ends of the PV panel.

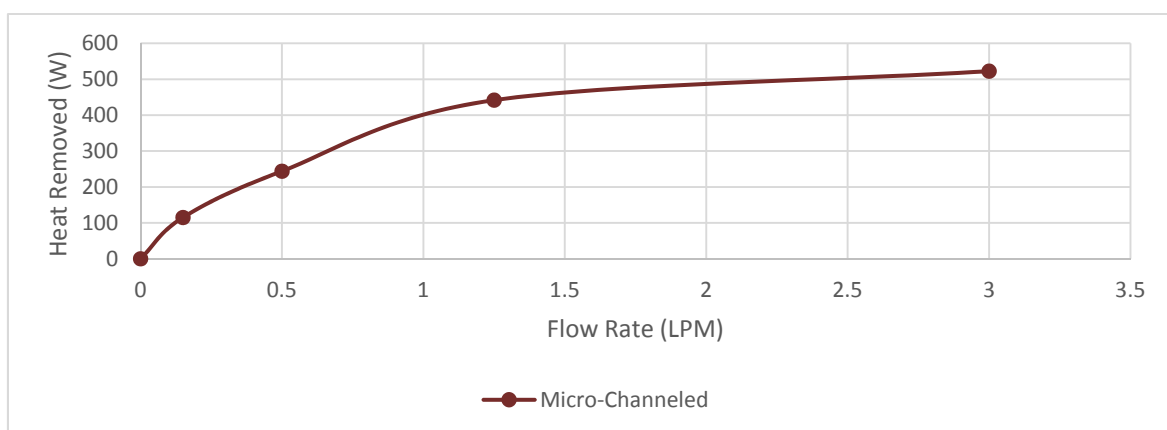


Figure 10. Heat removed by heat sink against flow rate.

All the graphs and contours shown above greatly justifies the authenticity and preciseness of the results carried out during the live experimentation. Solid evidence is present that we can harness

great amount of energy just by flowing very little amount of water using micro-channels.

4. Conclusions and Future Work

Comparison of a water cooled micro-channeled PV panel was done with the standard PV panel at flow rates of 0, 0.15, 0.55, 1.25 and 3 LPM under real-time conditions of varying solar irradiance, ambient temperature and wind speed.

A maximum average temperature difference of 15 °C was observed at a flow rate of 3 LPM during an average irradiance and ambient temperature of 915 W/m² and 39.3 °C respectively. This resulted in about 14% increase in the power output and 3% increase in the efficiency of the PV panel.

Even at the lowest flow rate of 0.15 LPM, 3% increase in power output and 0.43% increase in efficiency was observed. Also a temperature drop of about 4 °C was observed under an average irradiance and ambient temperature of 548 W/m² and 37.3 °C respectively.

Even without providing any cooling, however, the temperature of micro-channeled PV panel was greater, its power output and efficiency was approximately same as that of the standard panel. It can be deduced from the above justification that using Aluminum instead of TPT did not result in any significant deficiency even if not cooled.

The research shows that using micro-channels is an effective way of cooling solar panels and the amount of water used in cooling the system is feasible if considered the amount of power gain achieved by it.

Further research can be carried out in this area by increasing the scale of the experimental setup and trying to manufacture the micro-channels as economically as possible. This research can also be used for the study of hybrid heating systems and efficiency enhancement during winters and summers respectively. Instead of using water as a cooling agent, air can be used by attaching fins to the aluminum sheet instead of micro-channeled plate.

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Conflict of Interest

There is no conflict of interest among authors and with any other organization.

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