Study on PV Thermal Integrated systems for Rooftop Applications

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Abstract. Around 90% of the total solar wafers produced and deployed around the globe is primarily based either on mono or polycrystalline silicon cells. Majority of these are deployed for converting incoming insolation directly to electrical energy and are termed as photovoltaic systems (PV). Another application is to convert the incoming solar energy into thermal energy and termed as Thermal systems (T). The vital components for both the above conversions are their respective solar energy collection systems. As the temperature rises, the conversion efficiency of solar cells decreases. This is due to the fact that with increase in temperature, there will be a reduction in the mobility of charge carriers. When deployed in field, photovoltaic cells will heat up rapidly as they are good heat absorbers. In storage integrated solar installations, heat is considered as killer of all batteries and encapsulate. The work aims at design and development of an integrated PV thermal solar system to efficiently utilise the incoming solar energy. An efficient heat exchanger mechanism will help bringing in possibility of having a storage integrated solar module so that the final solution will have generation, storage and thermal evacuation in the same laminate. The integrated model when implemented gives enough room and a lower temperature chamber, where the batteries could be easily integrated without loss of cycle life and AH capacity loss.

1. Introduction

India accounts for 18% of the world’s population, but only uses 6% of the world’s primary energy. The energy consumption in our country has almost doubled since 2000 and the potential for further rapid growth is enormous. India’s economy, currently the world’s third largest, is scaled to grow rapidly in coming years. The Government of India has made it a priority to increase access to electricity for rural communities, emphasising renewable and decentralised sources. Unfortunately, there are a number of hurdles that are preventing solar mini-grids from becoming a large-scale reality in rural India.

The default technology for energy storage in developing countries i.e., Lead-acid batteries have significant technical challenges that limit their usability. The total energy conversion from the incoming solar insolation to output energy is low for an isolated system. A 250 W mono/poly crystalline module can only convert 20% of incoming solar radiation into electricity. Similarly, the conversion ratio for a solar thermal collector or a solar water heater is also low when each system is evaluated individually. Rooftop area of all residential/commercial spaces is now at a premium. When considering the economic factors, installation of a Solar PV system to generate electricity alone or a solar water heater to heat up your water supply is not considered efficient.

All these issues have led to more focus on development and deployment of hybrid/integrated systems by which maximum amount of energy can be extracted using minimal footprint area. In light of this, an integrated PV/Thermal sandwich can help bring in possibility of integrating storage to the entire system. Normally storage unit cannot be attached to the PV sandwich as the liquid electrolyte in batteries vaporise in process of solar module sandwich lamination. Also when kept in field, the storage unit is kept below the PV module. High temperature increases faster evaporation of the liquid electrolyte and therefore an
efficient and integrated PV/Thermal module can help in paving the way for attaching storage unit to the entire system.

1.1. Literature Review
To increase the efficiency, particularly at high irradiance, the PV module must be cooled and methods to do the same have to be studied. During the process of converting sunlight directly into electricity, most of the absorbed solar radiation is dumped to the PV modules as waste heat. This heat generated is transferred to the heat exchanger in thermal contact with PV modules in order to supply the heat demand [1]. The concept of flat-plate PV/T collector was first introduced by Kern and Russell [2] in 1978. Later a theoretical model for PV/T systems using conventional solar thermal collector techniques was presented by Hendrie [3]. Florschuetz [4] extended the well-known Hottel–Whillier model developed for the thermal analysis of flat-plate collectors to the analysis of hybrid PV/T collectors. Zondag et al. [5] analysed the different types of PV/T collectors (sheet and tube, channel, free flow and dual absorber). The best efficiency was observed for the channel-below-transparent-PV design. Air PV/T collectors are not efficient enough compared with the liquid ones. Hence majority of the work was based on water based PV/T. Temperature of the PV module will increase as a result of concentration and it should be kept as low as possible in order to achieve higher efficiency [6].

Higher temperature can also result in localized stress concentration regions and increased stress levels in contacting interfaces [7-9]. Sharan et al. [10] carried out an analysis for the economic evaluation of concentrator-PV systems. Their results indicated that if both of electrical and thermal outputs are collected and used properly, the cost of unit of energy produced by the concentrator PV systems decreases with increasing concentration ratio (CR). Rosell et al. [11] investigated a water PV/T collector which was integrated with a linear Fresnel concentrator and a two-axis solar tracking system. From the results obtained, it was inferred that the total efficiency of the system is over 60% when CR > 6. Thermal conduction between PV cells and the absorber plate was found to be a crucial parameter in theoretical analysis. Li et al. [12] examined the performance of a trough concentrating PV/T system with an energy flux ratio 10:27. This was done using three different types of c-Si PV cell arrays and the GaAs cell array. The electrical performance of the system with the GaAs cell array was found out to be better than that of c-Si PV cell arrays. At the same time, better thermal output was shown by the system with crystal silicon PV cell arrays.

Water based PV/T collectors was first tested and analysed by Kern and Russell [13] at MIT. They analysed five different configurations of integrated solar heating and cooling system (baseline solar heating system, parallel heat pump system, series heat pump system, absorption-cycle chiller and high-performance series advanced heat pump) across four climatic regions in the USA. As per the results obtained, the greatest energy savings potential in all four geographic areas was provided by an advanced heat pump system. The analysis also indicated that integrated systems were quite effective in regions with high-heat demands. PV system was found to be most economical on areas with balanced heating and cooling loads or with dominant cooling loads.

Several researches were carried out on hybrid PV/T solar water heaters [14 – 16] in the Indian Institute of Technology. Their analysis indicated that the amount of water in the tank had a significant effect on the system performance. The efficiency increased a slight notch with increasing water mass [14]. Based on their field studies and data, it was also summarised that the hybrid PV/T solar water heaters would be suitable for rural areas since a PV/T collector of approximate 2 m² area can generate electricity to run two tube lights of 20 W each for 5 hours and one television of 30 W for 4 hours [16].
PV/T systems are especially appropriate for the applications where the available surface area is limited. It can also be inferred that the thermal efficiency of water PV/T collectors are higher than the air PV/T collectors. Since the basic objective of this work is to find out effective mechanism for draining out the waste heat and to pave way for integration of storage into a solar module, water based PV/Thermal technology is used for further analysis and evaluations.

While designing the storage integrated solar modules, it is important to make sure that the excess heat generated is not transferred to the battery module. Increases in temperature of the battery module can adversely affect the performance of the system. Hence, the excess heat generated in the solar module should be brought down by means of a cooling system. One of the simplest and effective methods is to introduce a flow of appropriate coolant to run through a cooling pipe. This brings in an additional advantage that if water is used as a coolant, the water gets warm and can be used for household applications. However, such a design demands the fundamental understanding of the mechanisms behind heating of solar modules.

Detailed real time experiments needs to be carried out to understand the solar irradiation with respect to the atmospheric conditions, solar flux on solar modules, rate of temperature rise between solar panel and storage system etc. Various methods are used in PV/Thermal technology to maximize the conversion efficiency. In this paper, different experiments are designed to evaluate the thermal characteristics of the PV module. The performance characteristics of a thermal system in PV module are studied in detail using Computational Fluid Dynamics (CFD) analysis.

2. Experiment Methodology

Design of a cooling system in solar modules demands detailed real time experiments to be carried out. Different types of experiments are conducted to obtain the thermal data associated with a 15W solar panel. The experiments are designed to understand the temperature gradient across different interfaces of the module and to identify a suitable heat transfer mechanism so that an optimal temperature is maintained between the panel and the storage. Four different sets of experiments are conducted and these can be broadly classified as i) Calibration of Data Acquisition Systems ii) Thermal Data Evaluation of Solar Cells iii) Experimental parameters from Simulated Irradiance iv) Thermal Data along Insulated Back Sheets.

2.1. Calibration of Data Acquisition Systems

The experimental evaluation of thermal data uses different types of data acquisition systems. Data acquisition systems includes NI 9178 DAQ chassis, NI 9191 Wi-Fi DAQ Chassis, NI9173 DAQ thermocouple module, NI MAX 12.0 software, NI Signal Express 12.0, IMT Mini-KLA handheld PV-IV analyser, Si 01 TCT Irradiance measurement module, MECO 9009 Solar Module Analyser, MATLAB- Simulink 2010, EES equation Solver. It is essential to calibrate these systems for the given condition and run trial tests to visualise the thermal data of a 15W solar panel.

Back panel of the module was peeled off at 5 spots at random from the back side of the panel and thermocouples were embedded underneath and above the back panel layer and sealed using duct tape. Each thermocouple wire was labelled and connected to Ni 9173 DAQ module.

Back side of the module along with the thermocouple arrangements are shown in figure 1. Module along with the setup was placed under the sun for duration of 2 hrs. Using the Ni signal express software, data was logged. Thermocouples were fixed to a plastic block at measured heights (0.5, 1.5, 2, 2.5 cms) from its base and the block was stuck to the backside using glue stick. A thermocouple was also connected to DAQ module and left open for measuring the ambient temperature. The irradiance was measured using Mini KLA PV-IV analyser at every 10 min interval.
2.2. Thermal Data Analysis of Solar Modules

These experiments are done to evaluate the temperature trends among adjacent cells in the solar panel. The experiment is planned from 10.30am to 3.30pm so as to get the full range readings of temperatures. Thermocouples were stuck to the back of the panel using duct tape at measured points in the form of a 3x3 matrix. Thermocouples connected at 9 different parts of the module are shown in figure 2. Each thermocouple wire was labelled and connected to Ni 9191 Wi-Fi DAQ module. Just above cell 6, a small piece of aluminium foil (10 microns, food grade) was stuck using heat sink compound and another thermocouple was stuck over it with the help of another piece of aluminium foil and Atlas super glue. Module along with the setup was placed under the sun for duration of 5hrs. Using the Ni signal express software, data was logged. Thermocouples were fixed to a plastic block at measured heights (0.5, 1.5, 2, 2.5 cms) from its base and the block was stuck to the backside using glue stick. A thermocouple was also stuck on the top end of the glass surface. A thermocouple was also connected to DAQ module and left open for measuring the ambient temperature. Angle was measured using a surface angle gauge instrument and the panel was tilted at regular intervals according to the position of the sun such that maximum irradiance incidents on the surface. The irradiance was measured using Mini KLA PV-IV analyser at every 10 min interval. Wind speed was also measured along with it.

![Figure 1. Thermocouples connected at the back side of the solar module for calibration.](image1)

![Figure 2. Thermocouples connected at the back side of the solar module for temperature gradient studies.](image2)

2.3. Experimental Parameters for Simulated Irradiance

This experiment is devised to simulate the outdoor sun irradiance under laboratory conditions so that a range of parameters can be evaluated under controlled conditions. Here, thermocouples were stuck to the back of the panel using duct tape at measured points in the form of a 3x3 matrix. Each thermocouple wire was labelled and connected to Ni 9173 DAQ module. Just above cell 6, a small piece of aluminium foil (10 microns, food grade) was stuck using heat sink compound and another thermocouple was stuck over it with the help of another piece of aluminium foil and atlas super glue. The module along with the setup was placed in a controlled environment and the sun was simulated using four 300W ELH lamps. The sun simulator was fixed at an angle of 40 degrees while the panel was tilted to an angle of 35 degrees. Using the Ni signal express software, data was logged and a temperature-time plot was generated. Thermocouples were fixed to a plastic block at measured heights (0.5, 1.5, 2, 2.5 cms) from its base and the block was stuck to the backside using glue stick. A thermocouple was also stuck on the top end of the glass surface. A thermocouple was also connected to DAQ module and left open for measuring the ambient temperature. The irradiance was measured using Mini KLA PV-IV analyser at each designated points on the panel. I-V values were recorded frequently using MECO solar analyser.
2.4. Temperature evaluation with insulated back sheet on solar modules
This experiment is designed to establish a condition of complete blocking of fresh air onto the back side of the panel to visualise the effect of directly mounting the storage on the back side of the panel. Thermocouples were stuck to the back of the panel using duct tape at measured points in the form of a 3x3 matrix. Each thermocouple wire was labelled and connected to Ni 9173 DAQ module. The panel is covered using hardboard at 1.5 cm from the back panel surface. It was riveted to the frame using 4mm aluminium rivets and reinforced using aluminium tape.

The module along with the setup was placed in a controlled environment and the sun was simulated using four 300W ELH lamps. The sun simulator was fixed at an angle of 40 degrees while the panel was tilted to an angle of 35 degrees. Using the Ni signal express software, data was logged and a temperature-time plot was generated. A thermocouple was also stuck on the top end of the glass surface. A thermocouple was also connected to DAQ module and left open for measuring the ambient temperature. The backside was covered with hard board at a distance of 1.5 cm (the value obtained from previous tests). The irradiance was measured using Mini KLA PV-IV analyser at each designated points on the panel. I-V values were recorded frequently using MECO solar analyser. On similar lines quantification of the reduction in temperature with natural convection through slotted frames and back side of the panel insulated with hard board is studied.

3. Thermal Data from Experimental Results
This experiment is designed to understand the temperature trend among adjacent cells in the panel. Temperature gradient versus time data is shown in figure 3. From this experiment, it is clear that no specific trend is seen in the temperature. The temperature of aluminium shot up and was leading till the end of the test. But the cell just under the aluminium foil showed low temperature as compared to other cells. This shows that there is better heat rejection on the surface of aluminium, which leads to a hypothesis that on covering the backside with aluminium completely would reduce the panel temperature.

3.1. Experimental parameters from Simulated Irradiance
This test is conducted to understand the effect of irradiance under solar simulator. The rate of temperature rise in panel is measured when the panel is subjected to 1000 W/m². Thermal trend of the solar simulator was similar to that of test case in section 3.1. This proves that the setup is equivalent to that of natural daylight and therefore all future tests can be conducted under the sun simulator.

3.2. Temperature evaluation with insulated back sheet on solar module
This experiment is conducted to establish a condition of complete blocking of fresh air onto the backside of the panel. This would give a visualization of the effect of directly mounting the storage on the backside of the panel. During this experiment, highly elevated temperatures (approx. 14°C) were observed (figure 4). This brings in a caution that there should be free flow of air between the storage and the panel. An improper design of such insulations will definitely lead to thermal failure and therefore the electronics will shut down on prolonged use. On similar lines, solar module is illuminated with 1000 w/m² flux from solar simulator in a controlled environment. Thermocouples were placed on top of the panel and in between battery and panel. The air gap between the panel and battery is meant to insulate the heat flow. Initially the ambient temperature of the surroundings is 30°C. The tilt angle of the module was 0° degrees and the wind velocity was also zero. Similar set of experiment is conducted to compare the performance of different materials like wood pulp and ABS (Acrylonitrile Butadiene) in intermediate layer of solar module to restrict heat flow towards the back panel. The thermocouple readings with a time interval of one minute each is shown in the temperature pattern (figure 5). This experiment clearly reveals that there should be a mechanism to bring down the temperature at the back panel. Though one can initially think of a good insulating material, there is lot more one can benefit from if it is a liquid cooled system.
From the previous experimental data, it is clear that one should have a proper heat transfer mechanism to bring down the excess temperature at the back side of the panel. Here we consider a flow induced cooling system by which one can also utilize the increase in temperature of the coolant. If one use water as a coolant, this brings in additional usage as this could be effectively used for household applications. However, the performance of the cooling system depends on several parameters.

One of the main challenges is in optimizing the parameters such that one could extract maximum temperature difference between the inlet and outlet of the cooling tube. This is in fact important as the increase in fluid temperature needs more energy and this will be taken out from the system which will result in better thermal enhancement at the back side of the panel. One has to simulate different conditions before arriving at the design of such heat transfer mechanisms. With the data from the experiments detailed, it is amenable to do a CFD analysis on the heat transfer mechanism of the cooling system. This would help to understand the influence of different parameters including mass flow rate, tube length, tube diameter etc. on the heat transfer mechanism of the cooling system.

The solar module considered in this study has a maximum length of 1.6 m along its width. Further the thickness of the backing panel is close to 7 mm. This factors brings in additional constrains over the dimensions on the cooling tube which can be selected for the given application. Hence, the cooling tube dimensions are selected as 5 mm in diameter and having a length of 1 m. From the sun simulator experiments, the solar irradiance is found to be in the range of 800 w/m². A constant heat flux is assumed throughout the periphery of the tube and the corresponding mass flow rate is taken as 0.3 Kg/s, the CFD analysis has been carried out. As the water flows through the pipe, the temperature would increase.
However, it is interesting to note that there is no perceptible difference between the inlet and outlet temperature contours. However, on a closer look and inspection from the probe values at the centre, it is observed that, though minimal, temperature did increase to a mean value of 30.46°C at the exit.

This simulation clearly brings in an understanding that these parameters are not sufficient for an effective cooling system. As the second step, the tube length is arbitrarily increased to a value of 17 m. All the other input parameters and boundary conditions including the mass flow rate kept constant. The exit temperature result is shown as a contour plot in figure 6. Figure 6 clearly brings in the understanding that the temperature has showed noticeable increasing trend and the mean temperature at exist is close to 34.7°C. Further, the temperature profile shows that the maximum value of the fluid temperature is close to the wall and towards the centre of the tube the fluid temperature is close to the inlet temperature. This simulation clearly shows that one can get high temperature difference if the tube length is sufficiently high.

![Figure 7. Variation of exit temperature with respect to tube length for a fixed mass flow rate of 0.3 kg/s and tube diameter of 5 mm.](image)

![Figure 8. Variation of exit temperature with respect to tube diameter for a fixed mass flow rate of 0.3 kg/s and tube length of 1 m.](image)

![Figure 9. Variation of exit temperature with respect to mass flow rate for a fixed length of 1 m and tube diameter of 5 mm.](image)

![Figure 10. Exit temperature for different mass flow rate and tube diameter.](image)

From the CFD simulation, it is shown that the tube length needs to be higher. However, this may not be possible as many will not have that much dimension for the solar module. In order to circumvent this issue, it is to be understood that one has to have a coiled type of arrangement of the tubes so that sufficient tube length can be achieved with in the panel itself. Further investigation on the parameters, which could be influential in the heat transfer mechanism demands more CFD simulations to be done in similar procedures. Initially, the model is investigated for different tube length for a constant mass flow rate of 0.3 kg/s for a tube diameter of 5 mm. Variation of exit temperature with the change in tube length is shown in figure 7. From figure 7, it can be seen that the exit temperature increases from 30°C to 35°C
with an increase in tube length of 17 m. The model is investigated for different tube diameters for a constant mass flow rate of 0.3 kg/s and a constant length of 1m. Variation of exit temperature with the change in tube diameter is shown in figure 8. As the tube diameter increase from 5 mm to 195 mm, the exit temperature varies from 30.48°C to 39°C. However, for problems like solar module panels, one cannot go beyond a limiting value for the diameter as the pack panel channels would demand a minimum value and hence this would be a constraint to increase the diameter. Mass flow rate is one of the key parameters in thermal performance of the fluid. Here, CFD analysis is utilized to study the tube flow for different mass flow rates starting from 0.1 kg/s to 2 kg/s. All the input parameters are kept constant other than the mass flow rate. Exit temperature variation with change in mass flow rate is shown in figure 9. From figure 9 it is clear that, mass flow rate has a reverse trend on exit velocity when compared to that of tube length and tube diameter. This is clearly brought by the figure 10 where it shows the exit temperature for different mass flow rates and tube length. These simulations bring out the fact that, if one has to decide on a proper cooling system, optimum value of mass rate and tube length is essential. This will change according to the real time situations and one has to consider all these parameters while designing the heat transfer system for the solar panel modules.

5. Conclusion
The heat transfer mechanisms are crucial in performance optimisation of solar modules. This work was focused on understanding the heat transfer mechanism and influence of temperature profiles in the solar modules. Initially, different experiments were conducted to acquire all the relevant data from a thermal point of view. Experimental investigations on solar modules have shown that the temperature gradients and higher temperature in the module interface may pose serious problems for both modules as well as for storage integration. It is found that the insulating or blocking the natural convention at the backside can pose serious issues on the system over a period of time. Effective methodology to bring down the temperature at the back panel is investigated. From the relevant experimental data, CFD models are constructed to understand the heat transfer mechanism for different configurations. Role of tube length, mass flow rate and the size of the tubes in the heat transfer mechanism is studied. It is found that increasing the tube length and the diameter of the tube can enhance the effective heat carrying capacity. However, the trend for the mass flow rate is found to be opposite. Lower mass flow rate is desirable for proper heat intake. From a design point of view, one has to select a proper combination of the tube length, mass flow rate and diameter of the tube for a given situations.

6. References
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