Thermal Management of PV Panels using Passive Cooling Approaches

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ABSTRACT

Due to rising global warming and increased energy security around the world, there is an ever-increasing need for transition towards more cleaner and renewable energy sources around the world in place of conventional energy sources including fossil fuels such as coal, oil and Natural gas. Solar power among renewables is by far a promising solution in terms of cleaner and greener energy production and utilization, owing to its cheap cost, reliability and sustainability in the recent years. But there are still few challenges faced by researchers and engineers around the world in the field of solar power. Particularly, the inherent low efficiency due to absorption of only a portion of solar spectrum that can be converted into electricity. Furthermore, environmental factors such as temperature, humidity and dust also contribute towards the power degradation and thus, in turn, a low conversion efficiency.

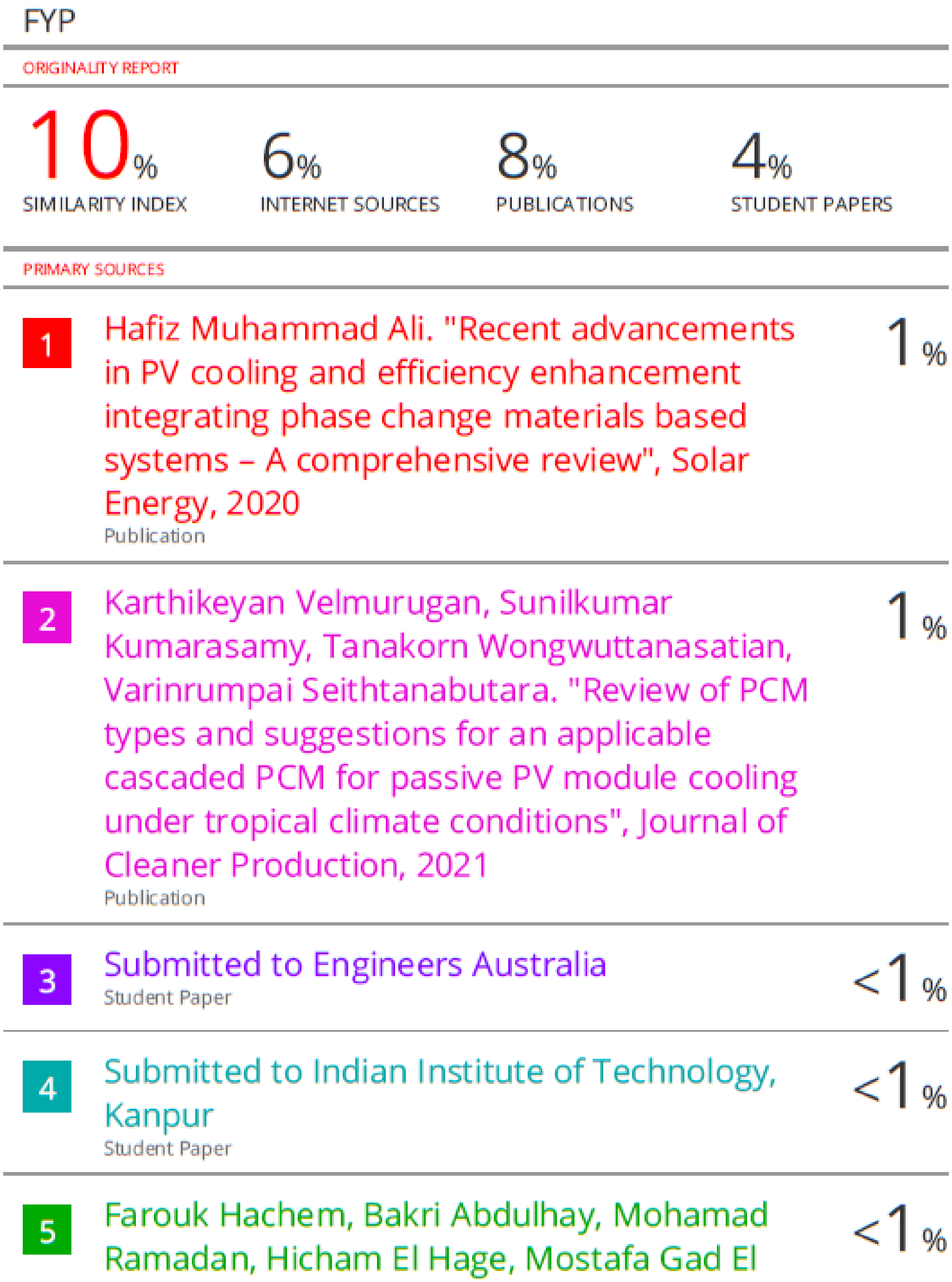
This project is aimed at utilizing the potential of various passive cooling approaches suggested by researchers to develop a working physical prototype of PV-PCM system which provides higher overall efficiency compared to the conventional PV Panel. Small scale 4 watts panels were obtained and phase change materials were utilized at the PV panel back to reduce their operating temperature and hence, to increase overall conversion efficiency. Phase change materials utilize their latent heat capacity to absorb large amounts of heat from panel back and change their phase from solid to liquid, resulting in reduced panel temperature due to increased heat transfer from panel back surface towards the ambient through PCM.

Two different designs were tested for various electrical and thermal parameters: One with rectangular PCM containment and the other with tubular design. Both the systems showed significant reduction in panel temperature up to 5-6 degree Celsius. Container Design has an average relative efficiency increase of 1.55 % while tubes modification has an average efficiency improvement of 1.1 %. Similarly, 10 % improvement in terms of output power is observed for tubes modification and 15 % improvement in power output, at average, is observed compared to the conventional PV Panel.

ACKNOWLEDGMENTS

First of all, we would like to thank Allah Almighty for giving us the courage to keep working on this project in these challenging times. Next, we would like to thank our project supervisor, Dr. Muhammad Sajid, for his continuous support and motivation on this project. Then we would like to acknowledge the efforts and support of Sir Hafiz Saeed Iqbal from USPCASE who not only assisted us in instrumentation required for the project but also provided us with the data of solar irradiance, wind speed and ambient temperature without which this project would not have been possible. We also acknowledge all the help and support offered by Sir Abdul Naeem Khan relevant to their field of Heat and Mass Transfer. Finally, we are humbled for the help offered by Sir Afnan during the design phase of our project.

ORIGINALITY REPORT



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1	Hafiz Muhammad Ali. "Recent advancements in PV cooling and efficiency enhancement integrating phase change materials based systems – A comprehensive review", Solar Energy, 2020 Publication	1%
2	Karthikeyan Velmurugan, Sunilkumar Kumarasamy, Tanakorn Wongwuttanasatian, Varinrumpai Seithtanabutara. "Review of PCM types and suggestions for an applicable cascaded PCM for passive PV module cooling under tropical climate conditions", Journal of Cleaner Production, 2021 Publication	1%
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ABBREVIATIONS

PV	Photovoltaics
PCM	Phase change material
TCE	Thermal conductivity Enhancers
CdTe	Cadmium Telluride solar cell
FF	Fill Factor

NOMENCLATURE

Q	Heat transfer Rate
K	Thermal conductivity (W/(m.K))
A	Area(m^2)
T_s	System Temperature(^oC)
T_a	Atmospheric temperature (^oC)
Q_{gen}	Heat generated due to light (J)
Q_{res}	Residual heat (J)
I_{sc}	Short circuit current (A)
V_{oc}	Open circuit voltage (V)
P_{out}	Output Power
P_{in}	Input Power
P_m	Maximum power

CHAPTER 1: INTRODUCTION

In this era of energy production by the means of conventional energy sources i.e. fossil fuels such as coal, oil and natural gas, there is a rising demand for the implementation of green and clean technologies for energy production. Renewable energy technologies such as Solar, wind, geothermal etc. are gaining traction, in the recent years, due to their reduced environmental and carbon footprints. However, there are still some technical and economic challenges that hinders their implementation on mass-consumer market. Particularly, In the field of solar power, Photovoltaic cell is one such invention that has to potential to change the global energy landscape. However, technical improvements and research is still required to improve their efficiencies, as right now, conventional PV cells are only about efficient in the range of 12-15%.

Apart from that, there are other environmental factors that hinders the full-scale implementation of this technology including uncertain weather patterns, Solar Intensity variations, dust, humidity and temperature. One of these parameters, temperature, has an adverse effect on the efficiency of the cells. On average, the efficiency of the solar cell drops by 0.5% for every 1-degree Celsius rise in temperature.

This Project aims to explore the possibilities of implementation different passive cooling methodologies to improve the overall conversion efficiency of the cells, and ultimately for the solar power station on a large scale. Cooling the PV cells/Panels will also help in reducing the degradation over time for the system, due to excessive heat absorbed by the system.

This Project aims to experimentally test the available passive cooling methodologies including the application of fins and Phase change Materials (PCM’s) to check for the performance enhancement of the panel. A comparative study is also done on similar panels with multiple designs for PCM containment and Fins to indicate the performance improvement for the parameters like power output and electrical conversion efficiencies.

CHAPTER 2: LITERATURE REVIEW

With the rising demand of clean energy through green technologies including renewables, there is a need to look for more cheaper, economical and efficient energy systems in the world. According to world energy outlook report 2020 by International Energy Agency, Solar is by far the cheapest option available among the renewables surpassing oil and natural gas and is expected to grow by 13% each year in the next decade of 2020-2030 meeting one-third of electricity growth demand [1]. Furthermore, renewables are expected to take up 30% of the total share of electricity production globally in 2021. It is evident from the facts and figures quoted by IEA, that solar is the technology that's going to change energy landscape globally; Solar PV expansion is going to reach 145 GW in 2021 and 162 GW in 2022, accounting for 55% expansion in renewables in these 2 years [2]. Among the renewables, Solar is going to be the future of electricity supply globally. In the context of the climate of Pakistan, Solar is the best energy option among renewables in terms of various factors like setup and maintenance cost, life span and environmental conditions according to researchers [3].

With the rising demand and need for renewable technologies particularly Solar PV, there is also a huge concern regarding the sustainability and efficiency of this technology over the long period of time. Solar Photovoltaics based on silicon technology can convert 8-20% of the incoming solar radiation into electricity while the largest percentage is ultimately manifested in the form of heat which increases the PV surface temperature and thus the electrical efficiency drops [4]. Thus, the efficiency of solar PV having crystalline silicon reduces by 0.4-0.5% for every 1-degree Celsius rise in temperature [5]. Thus, there is a need for efficiency improvement of the solar PV in order to increase its overall conversion efficiency as well as to increase the life span of the PV Module, which in turn further increases the power over PV Module life span.

Researchers have developed and tested different cooling systems and methods; namely classified as active and passive cooling approaches. Passive cooling approaches requires no additional energy input and thus, are inexpensive and simple to use while Active approaches requires some form of energy input such as fan, blower etc.[6]. A lot of researchers are trying PCM and fins for PV panel cooling as they can absorb large amounts of latent heat without changing the operating temperature of the panel; making them a suitable and effective technique for PV cooling. Kumar et al has done a comparative study of PV and PV-PCM systems along with fins. It is determined that the PV-PCM with external Al fins greatly reduced the surface temperature of the module by 22.3 ºC which in turn translates to an efficiency increase of around 6.59 % [7]. Mahamudul, Rahman et al. did numerical investigation of attaching a PCM layer of RT35 on the performance enhancement of PV module in terms of temperature reduction of around 10 ºC for extended period of 4-6 hours. The study is also validated by experimental comparative study of developed prototypes [8].

Peter Atkin and Muhammad M. Farid tested and compared four systems: first simple PV, second with graphite infused PCM layer, the third with fins/heat sink and fourth with both PCM and fins. It is found that the last system is most effective for thermal management of the PV panel as efficiency improvement of 12.97% is recorded [9].

Qasim, M. A., et al. did experimental work for comparative study of PV-PCM system using hybrid PCM's. They achieved a maximum temperature drop of 26.5 ºC with the insertion of 11 fin with the parafin based PCM. Also, it was found out that the suitability of using two PCM's simultaneously is based on their melting point [10].

Hasan, McCormack et al. also conducted experiments on PV-PCM systems in two different climatic conditions of Dublin, Ireland and Vehari, Pakistan. They have utilized two PCMs: $CaCl_2.6H_20$ and capric palmitic acid. It was found out that the $CaCl_2.6H_20$ performed better in reducing the panel operating temperature in both environmental conditions. In Vehari-Pakistan, it was observed that both PCM's achieved higher drop in temperature with 13% power savings but compared to capric-palmitic acid, $CaCl_2.6H_20$ performed better with 3% more savings [11]. Wongwuttanasatian, T., et al. Utilized finned container heat sink with palm wax for thermal regulation and efficiency improvement. Temperature drop was found out to be 6.1 ºC which enhanced efficiency by 5.3% [12].

As far as PCM containment at the panel back is concerned, there is a rising concern of low thermal conductivty of PCM which slows down the whole process of heat transfer. Thus, Researchers have tried to use nano-particles as thermal conductivity enhancers to improve the overall heat transfer characteristics. Abdelrahman, H. E., et al. have used nanoparticles Al_2O_3 as TCE. The PV-PCM system having RT-35HC as PCM and cylindrical shaped fins achieved reduction of 20-46.3 % on the front surface of the panel which increases to 52.3 % along with Al_2O_3 nanoparticles at ambient conditions of around 20 ºC and heat flux range 279-820 W/m^2 [13].

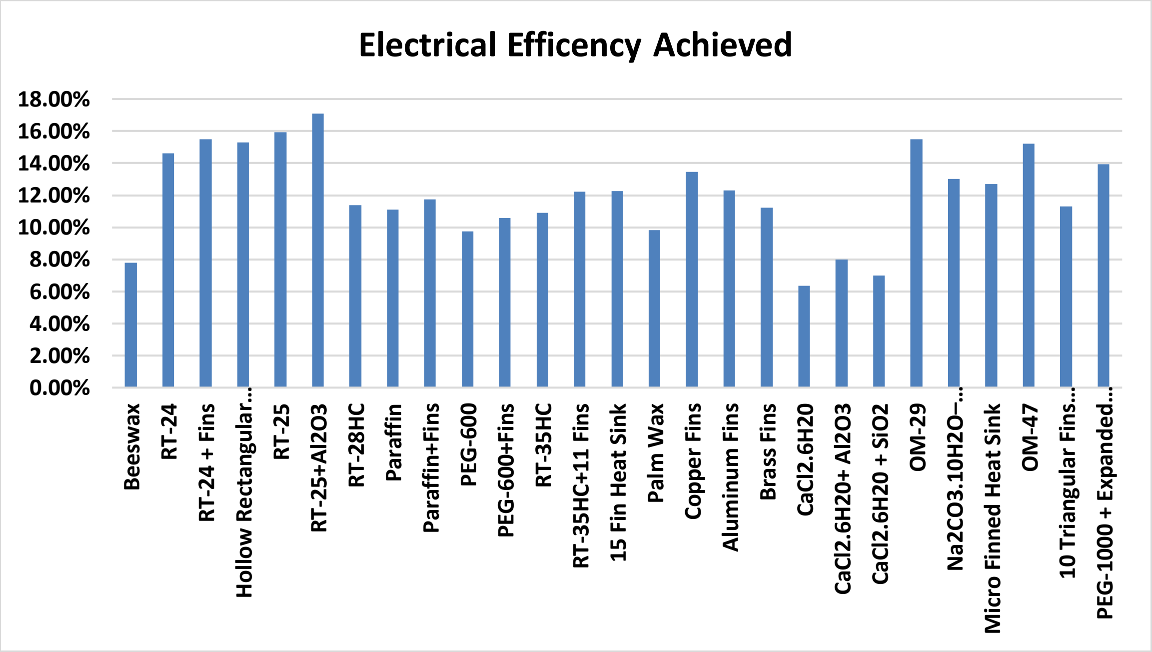

Figure 1: Efficiency Improvement Results achieved by different researchers published in literature.

In the context of Pakistan, few governmntal organiations are working in the field of solar cell manufacturing and panel assembling industry. One example is the is that of Pakistan Council of Renewable Energy Technologies under the ministry of science and tecchnology of government of Pakistan.

They are working on various solar enrgy/power applications including but not limited to:

Solar powered driven devices including geysers, greenhouse solar tunnel dryer, cooker, stove to be utilized in backward areas, solar driven rickshaw but it wasn’t up to the standards to be commercialized due to its high cost and ineffectiveness on implementing the technology on a large scale. Also, facility houses the Pakistan’s first solar cell manufacturing facility according to international standards. But there is still a lot of work and improvement required to improve the existing solar technology and to help us understand the underlying mechanism at the very basic level to enhance and discover the untapped potential present in the solar technology especially photovoltaics.

Table on the next page summarizes some of the efficiency and temperature reduction results using different passive cooling techniques.

Table 1: Summary of efficiency and temperature reduction results.

Serial No.	**Research Paper Title**	**Parameters**	**Conclusions**
1	Performance enhancement of photovoltaic cells by changing configuration and using PCM(RT35HC) with nanoparticles Al_2O_3 (Abdelrahman, Wahba et al. 2019)	- Heat Sink Configuration - Applied Heat Flux - PCM-Nano particles mixture with varying volume fractions	-Predicted Free Surface Temperature (74.5 degree Celsius at 850 W/m^2) -Temp Reduction of 21.5 % (16 degrees) with fins application (21 fins in staggered configuration) -Temp drop by 34.5 degree Celsius by employing RT35HC + Fins (Heat Flux: 820 W/m^2) -Using Al_2O_3 with above system, Temp drop of 1 to 4.5 degree Celsius using concentrations of 0.11 % and 0.77 % respectively -Finally, overall drop of **36.9-52.3 % (29.8 degree Celsius)** in the front panel surface temperature and efficiency improvement of 14.9 % for the above approach.
2	Improving the efficiency of photovoltaic cells using PCM infused graphite and aluminum fins (Atkin and Farid 2015)	-4 cases for thermal regulation -None -30 mm thick PCM Infused graphite -Aluminum Heat Sink 30 mm thick PCM -Infused graphite and aluminum heat sink -Point Based Efficiency, Thermal Regulation and overall efficiency is measured and compared in all 4 cases	-Case D found out to be most effective with overall efficiency increase of **13 %** -Economic Analysis of the system shows that the whole thermal regulation setup is **10 %** of the total cost of commercial PV Panel. -Overall efficiency of case D is **14.38 %**, an improvement of 9.69 % compared to case A for 18 h operation.

3	Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates (Hasan, McCormack et al. 2015)	-Reference PV -PV-PCM 1 -PV-PCM 2 -Power Savings, Voc, Isc are compared in three system	Peak PV-temperature reduced from 49 °C to **43 °C & 40 °C** with **PCM1 & PCM2**, respectively in Dublin. While in Vehari, it dropped from **63 °C to 51 °C& 42 °C** with **PCM1& PCM2**, respectively. Results revealed higher cost-effectiveness of PV-PCM systems in Vehari than Dublin
4	Photovoltaic module temperature stabilization with the use of phase change materials (Klugmann-radziemska and wcisło-kucharek 2017)	N/A	The best results were obtained for the PV/PCM configuration of a PV module with a steel tank filled with PCM1 (42–44 paraffin) with a thickness of 2 cm and water cooling, for simple PCM system, temperature drop of **7 K** was achieved.
5	Efficiency gains of photovoltaic system using latent heat thermal energy storage (Tan, Date et al. 2017)	Examining 4 different PV configurations i.e. finless, 3, 6 & 12 fins-PV/PCM under real outdoor conditions	Maximum drop (15 °C) in PV-temperature was found in PV/PCM with 12 fins, with **5.39%** enhancement in PV-efficiency. Reason was maximum PCM contact with metal surface leading to increased PCM melting rate

6	Improving the performance of photovoltaic cells using pure and combined phase change materials – experiments and transient energy balance (hachem, abdulhay et al. 2017)	Pure (White petroleum jelly) and combined PCM (white petroleum jelly, copper, and graphite) on the thermal behavior and electrical performance of a PV panel	The electrical efficiency has been increased by an average of 5.8% when using combined PCM.
7	Thermal management of conventional PV panel using PCM with movable shutters–A numerical study (Waqas and Ji 2017)	N/A	Reduction in PV Temperature of 22 degree Celsius. Efficiency can be improved up to 9% during peak summer season for the PV panel.
8	Improving photovoltaics performance by using yellow petroleum jelly as phase change material	2 10W monocrystalline panels with two configurations: one on stand and other on roof.	5.7-degree Celsius decrease in PV operating temperature

CHAPTER 3: METHODOLOGY

The project under consideration is mainly divided into two parts: first is the design and development of prototype of PV-PCM system and second is the experimental testing work undertaken to generate the real time data for various parameters including temperature, voltage, current, irradiance, wind speed, humidity etc.

Different Thermal management approaches were taken under consideration including fins, Phase change materials or both.

Upon considering the experimentations and research done previously for advancements in the field, there’s still room for improvement by implementing updated techniques and materials to achieve desired results. Our approach revolved around systematically evaluating the solar panel system, figuring out what possible modifications could lead to improved efficiency. The designed setup involves achieving the outcome by varying multiple parameters involved, along with using sensor technology and chemicals (PCMs) for testing. There are certain factors which influence the results. This section covers the testing parameters, design selection and design of data acquisition system. The factors involved are as following:

3.1 PV PANELS SELECTION

The 4W solar panels were chosen for testing such that any progress could then be replicated on a bigger panel. Therefore, the testing was initiated under the direct sunlight. However, due to changing weather conditions the results achieved were inconsistent to some extent. A varying angle stand was designed in order to attain the precise results and vary the position as required. The angles can be set at 15, 20, 25, 30 and 45 degrees for convenient positioning of the panel such that it can work more efficiently by absorbing most of the light from the sun. However almost complete testing was done for an angle of inclination of 15 degrees with the horizontal.

3.2 EXPERIMENTAL SET UP

A complete setup was installed to initiate the testing phase which consisted mainly of electrical equipment including Arduino, sensors, data logger, multimeter, a rheostat and K-type thermocouples. The modified and general PV panel were tested simultaneously so the deviation can be evaluated as both were subjected to similar direct normal irradiance (DNI). The direct dependance of performance on DNI also impacts other parameters such as temperature, humidity and PCM heat absorption rate. The experimental data collected was further used to calculate the system's efficiency by comparing the performance of both panels.

The panel designs proposed to be implemented were based on multiple factors such as:

- Material availability
- Material characteristics
- Heat transfer rate
- Types of PCMs being used.

The Figure 2. over the next page shows the physical setup for the experimentation and testing of various performance parameters including the :

- Temperature.
- Current.
- Voltage.
- Power (P=IV).

The Rheostat is used as a variable load to change the resistance values and ultimately the current and the voltage for the tracing of current-voltage (IV) and Power-voltage (PV) curves. Furthermore, thermostats, voltage sensors and current sensors can be seen in the figure attached with the PV panel for recording parameter values after fixed time intervals.

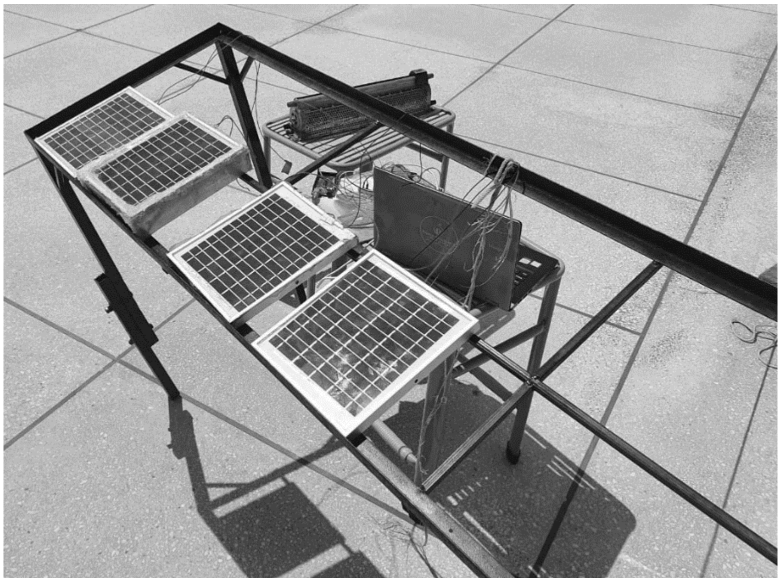

Figure 2. Experimental Setup

The Experiments were conducted at Islamabad, Pakistan with the coordinates of (33.6844° N, 73.0479° E). For the conditions of summer, the optimum tilt angle for the PV Panel was set at 15 degrees for maximum insolation absorption onto the panel surface.

3.3 MATERIAL SELECTION

Among a range of materials, the material selection involved several factors to be considered. Initially, the thermal conductivity co-efficient (k) played a vital role as considerably high “k” is required such that more heat from the panel escapes to the surroundings.

The heat transfer rate is given by:

$$Q = kA(T_s - T_a)$$

Where T_s is system temperature and T_a is temperature of the atmosphere.

Therefore, some potential materials considered are as follows:

Table 2. Some Potential Materials

MATERIAL	THERMAL CONDUCTIVITY (W/m.k)
Copper	401
Aluminum	250
Steel	50.2
Brass	109

Being easily accessible in the market, these materials were considered for use. Another major constraint that needed to be taken under consideration was cost effectiveness. Since we need to ensure the usage of end-product as a better version thus, low-cost manufacturing is required. For that purpose, we ended up selecting aluminum as it has high conductivity along with low cost as compared to others.

3.4 THERMAL MANAGEMENT

Different methods of thermal management techniques are employed by researchers to improve power and efficiency of solar cell. These methods include phase change materials, water and air cooling, usage of fins and cooling using nano-fluids. Before applying any of the following techniques, a steady state thermal analysis was performed which showed temperature variation at different parts of the panel under variable solar irradiance as it varies day to day. For the month of April, the maximum temperature reached was 57.75 ^{o}C as shown in the figure 2.

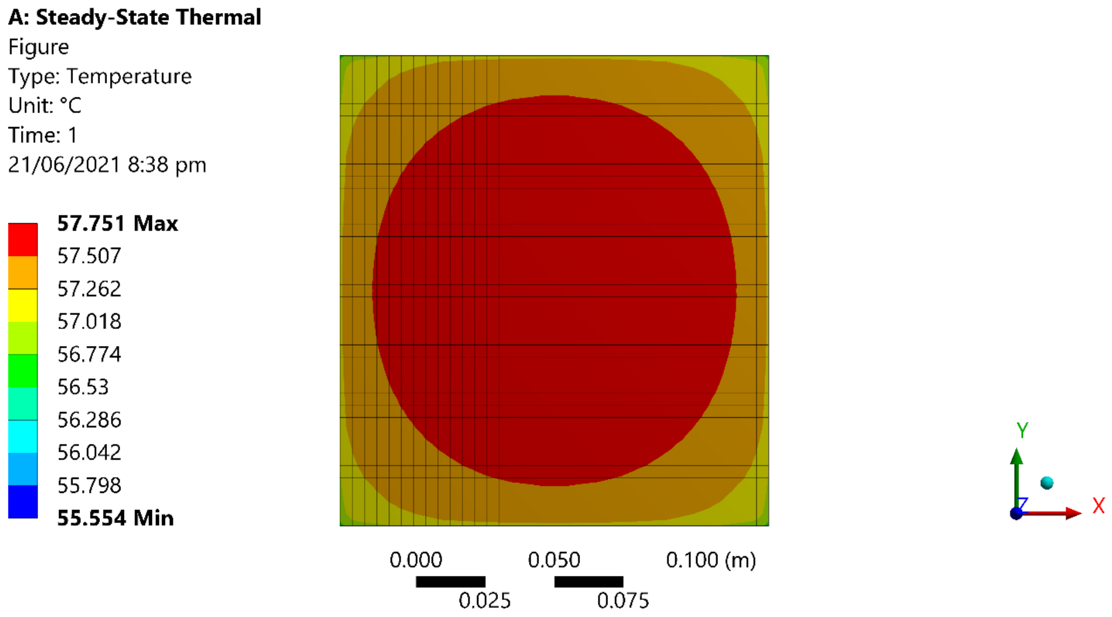

Figure 3. Simulation in ANSYS for a Conventional Panel

The most effective technique hence deployed is the use of phase-change material for maintaining the temperature of panel through effective heat absorption. The phase change materials exhibit high latent heat of fusion per unit volume, high specific heat, high density, and high thermal conductivity. Thus, being the perfect selection for achieving the desired results. There were certain potential PCMs selected based upon their melting temperature. However, the selection was restricted due to unavailability in the market.

3.5 DESIGN SELECTION

The first design consisted of a container attached to the back of the panel which had a cavity for the containment of PCM as shown in figure 4. An aluminum sheet was used since the thermal conductivity is higher as compared to other materials. That is our prime purpose to expel the heat in the atmosphere such that the panel temperature doesn’t exceed a limit where it compromises its output. The heat transfer rate is given by:

Q_{gen} is the total light energy available to solar cell which is converted into heat. Its mathematical formulation is given as follows:

$$Qgen = Irradiance * surface\ area\ of\ cell * efficieny\ of\ cell$$

Q_{res} is the rest of the heat which remains in solar cell after some of its heat energy has been removed by PCM.

$$Q_{res} = h * A * \Delta t * (T_{cell} - T_{atm})$$

Figure 4. and 5. below shows an isometric view of the containment and tubular designs developed for the PCM attached at the back of the modified PV Panel.

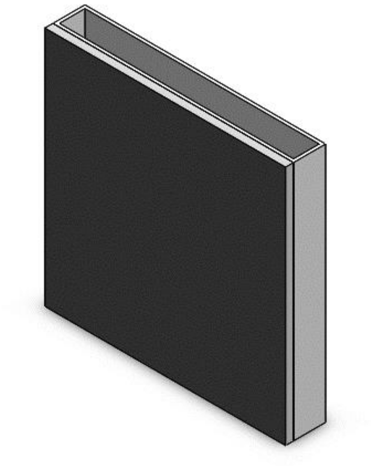

Figure 4. Isometric view of PCM container design.

Another design consisted of aluminum tubes (1.5cm x 1.5cm) attached to the back sheet of the panel. More the number of tubes attached, ensures more efficient heat transfer through them. These tubes were then filled with Petroleum jelly (PCM) and subjected to testing for several days consecutively. The design model is shown in figure 5.

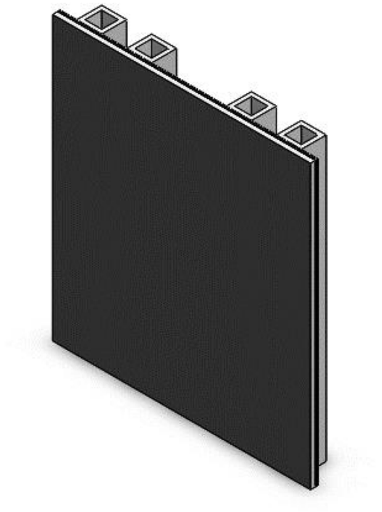

Figure 5. Isometric View of Tubular PCM Containment Design

3.6 PERFORMANCE PARAMETERS

Mentioned below are the measured parameters that were used to test the performance of the selected designs.

3.6.1 Temperature

Panels temperature at both the back and front sides were continuously being monitored throughout the test to check for the temperature reduction that was achieved against both of the designs. Temperature was measured using the temperature sensor DS18B20 and thermocouples as well.

Similarly, ambient temperature was also kept in check because different months had different peaks of temperature with more higher peaks observed at the end of May and start of June. The data for ambient temperature for the all the days of testing was taken from USPCASE, NUST.

3.6.2 Short Circuit Current

The amount of current that flows through the solar cell when the potential across it is set to zero i.e. solar cell is short circuited is called Short Circuit Current. Since there is no potential drop across the circuit, the value of current obtained is potentially the maximum value of current that is obtainable from the solar cell keeping the irradiance constant. The current was measured using a INA219 Current Sensor.

3.6.3 Open Circuit Voltage

The maximum value of voltage that is obtained from the solar cell in an open circuit (no current is flowing through the circuit) is called Open Circuit Voltage. It is potentially the maximum value that can be obtained from the solar panel keeping the irradiance constant. It was also measured using an Arduino Voltage Sensor (25V).

3.6.4 Maximum Power

The maximum amount of power that can be obtained from a solar cell under specific set of conditions is the maximum power for that solar cell.

$$P_m = FF(I_{sc})(V_{oc})$$

3.6.5 Irradiance

The data for irradiance is required for the calculation of efficiency, which was obtained from USPCASE, NUST.

3.6.6 Efficiency

The ratio of maximum power generated by the solar cell at the output to the total irradiance power incident upon the solar cell is the efficiency for that solar panel.

$$\text{Electrical Efficiency} = \frac{\mathrm{P_{out}}}{\mathrm{P_{in}}} = \frac{\mathrm{P_{max}}}{(\text{Solar intensity}) \times (\text{Panel Area})}$$

$$= \frac{(\text{Fill Factor}) \times \mathrm{I_{sc}} \times \mathrm{V_{OC}}}{(\text{Solar intensity}) \times (\text{Panel Area})}$$

3.6.7 IV and PV Curve Tracing

IV curves were plotted using a variable load (rheostat) across the PV panel by changing the load (resistance) from maximum (open circuit) to zero ohm (short circuit). The current and voltage were measured with INA219 Current Sensor and Voltage Sensor respectively and data was logged using Arduino. The circuit used is shown in figure 6.

The IV curves are further used to generate PV curves from which we get: maximum power point, fill factor and finally, the electrical efficiency.

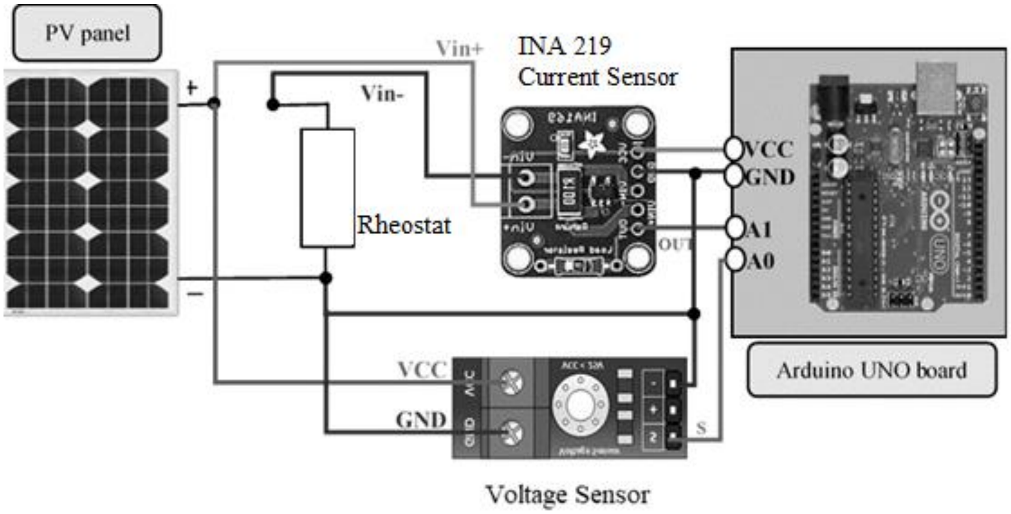

Figure 6. Circuit for IV Curve Tracing.

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter presents and discusses the outcomes of the rigorous testing done on the PV panels using passive cooling techniques. The complete testing of these techniques on the PV panels was done during the month of May 2021 under natural sunlight condition. However, results from a few particular days will be discussed here.

We have done a comparative study of the PV panels testing three PV panels at the same time; first one being a normal panel with no modifications, second one having PCM-filled tubes attached to its back and the third one having the PCM-filled container attached to the panel back. Relative results will be presented, showing comparison of improvement of a parameter relative to that of a normal PV panel.

We will discuss mainly the decrement of panel temperature using passive cooling techniques and its subsequent effect on the maximum power output and efficiency of the panel.

4.1 TEMPERATURE

The passive cooling techniques employed on the PV panels were successful in reducing the temperature of the panel during peak times. The temperatures were measured using DS18B20 water-proof temperature sensor attached to the front and back surface of the PV panel and interfaced using Arduino microcontroller which logged the data for every minute during the testing period.

A comparison of the temperatures on the front of three panels is shown in figure 7, for the testing period from 1000 to 1800 hrs. Lines for temperature of normal panel and two thermally managed panels along with the ambient temperature is shown by different colors. Further detailed data is given in Appendix I.

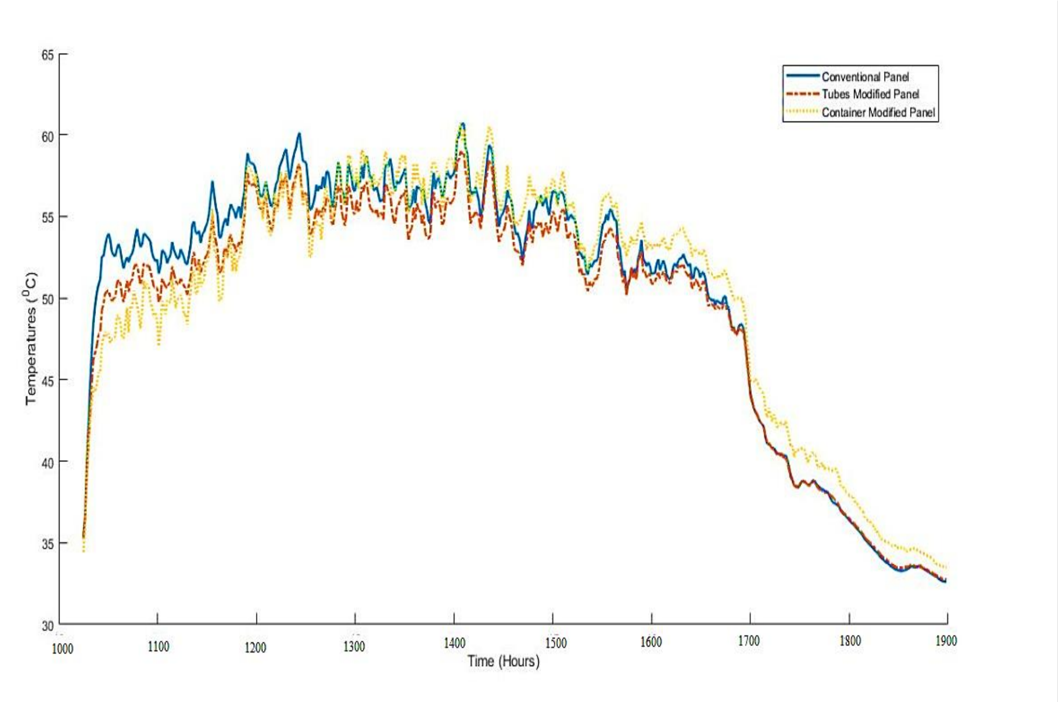

Figure 7. PV Panel Front Temperatures

The container modification to the PV panel achieved a maximum temperature drop of 6.5°C during the starting and kept an appreciable difference till 1300 hrs as compared to a normal panel. At this time the PCM has melted completely. After which its temperature became equal to that of the normal panel and later on, around 1530 hrs, the temperature became slightly hotter than normal panel till the end, since the PCM will require a larger amount of time to dissipate the heat it had absorbed. Overall, the PCM container acts an effective heat sink during the peak times of operation.

The PCM-filled tubes modification shows a maximum temperature drop of about 4°C in start and later on it stays a little cooler than normal panel throughout the testing period. This due to the tubes acting as fins at the back of the panel and are increasing the effective surface area of the panel back to be cooled by the natural air convection.

A comparison of the temperatures on the back of three panels is shown in figure 8. for a similar testing period.

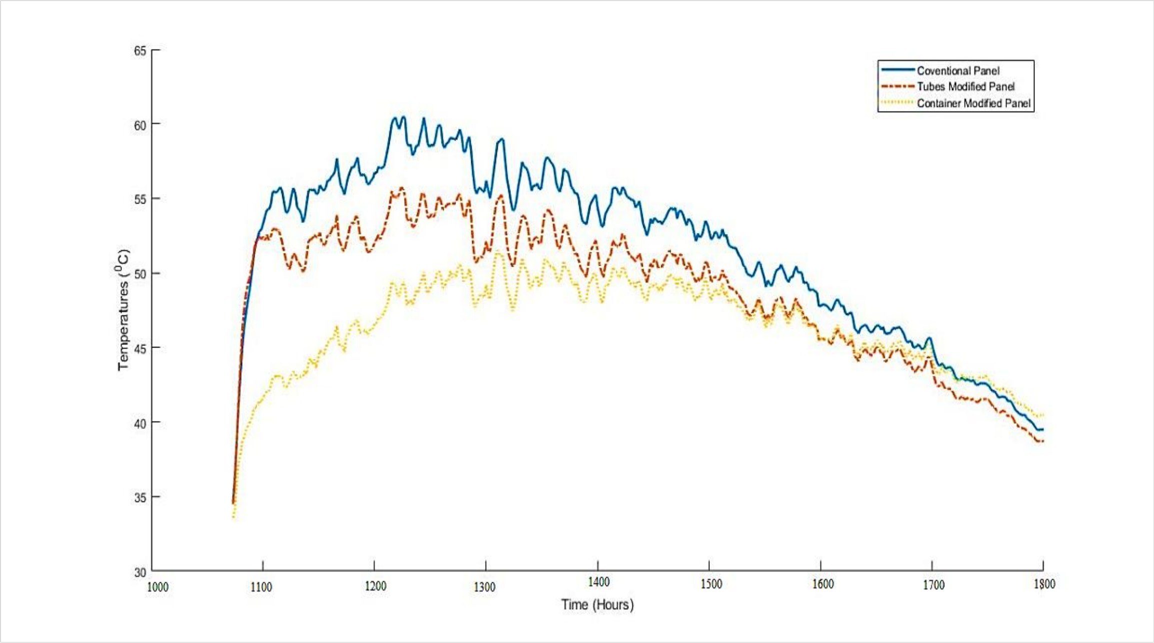

Figure 8. PV Panel Back Temperatures

The container modification to the PV panel achieved a maximum temperature drop of 12.6°C during the starting and kept an average difference of 5.2 °C compared to a normal panel. The PCM container acts an effective heat sink absorbing the heat from the PV panel.

The PCM-filled tubes modification shows a maximum temperature drop of about 5°C at the back of the panel and maintains a good difference of average of 2.7°C during the testing period as compared to normal panel throughout the testing period. This due to the tubes acting as fins at the back of the panel an increasing effective surface area to be cooled.

4.2 MAXIMUM POWER OUTPUT

The effect of the two cooling techniques on the maximum power output of the panels at a particular time will be discussed here. These maximum power values are calculated using the data from IV-curve to generate the PV-curve getting the maximum power point at various intervals during the testing period.

Table 2 provides a detailed comparison of the maximum power output of the PV panels after employing the cooling techniques and compared to normal panels in the graph shown in Figure 9. More data is given in Appendix II.

Table 3. Power Output Comparison on 22nd May

Power Output (W)					
	Panels			**Improvement (%)**	
Time	**Conventional**	**Tubes**	**Container**	**Tubes**	**Container**
10:30	2.82	3.12	3.33	10.64	18.09
11:00	2.74	3.02	3.37	10.22	22.99
11:30	2.94	3.2	3.38	8.84	14.97
12:00	**2.73**	**3.22**	**3.42**	**17.95**	**25.27**
12:30	2.88	3.14	3.2	9.03	11.11
13:00	2.7	2.97	3.07	10.00	13.70
13:30	2.64	2.95	3.16	11.74	19.70
14:00	2.56	2.83	2.99	10.55	16.80
14:30	2.4	2.57	2.64	7.08	10.00
15:00	2.09	2.44	2.07	16.75	-0.96
15:30	1.4	1.35	1.54	-3.57	10.00
			Average	**9.93**	**14.70**

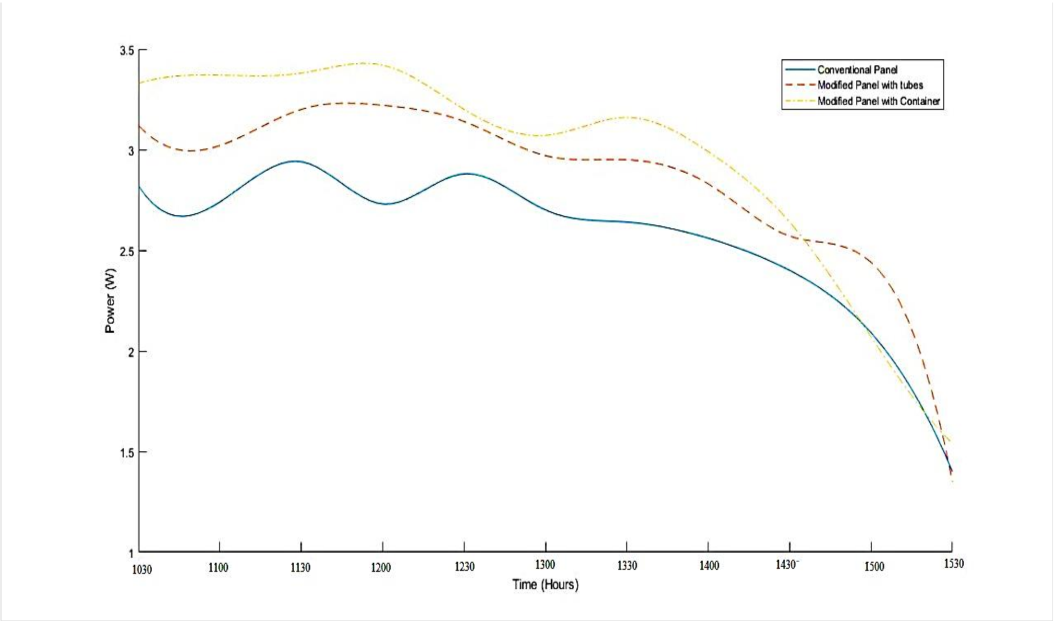

Figure 9. Power Output Comparison on 22nd May

The maximum power obtained was 3.42 w and this was for container modification. This shows that the container modification is an overall better enhancement.

The tubes modification produces a maximum improvement in power of 18% from 2.73W to 3.22W and 25% improvement from 2.73W to 3.42W for the container modification is observed. An average improvement in power output of about 10% for tubes and 15% for container modification is obtained from the testing done. The improvement is due to the use of cooling techniques.

4.3 ELECTRICAL EFFICIENCY

The effect of the two cooling techniques on the electrical efficiency of the panels at a particular time will be discussed here.

These the electrical efficiency values are calculated using the maximum power point and the solar intensity at various intervals and during the testing period using the formulae already discussed in methodology section.

Table 3 provides a detailed comparison of the Electrical efficiency of the PV panels after employing the cooling techniques and compared to normal panels in the graph shown in Figure 10. More data is given in Appendix III.

Table 4. Electrical Efficiency Comparison for 22nd May, 2021

Efficiency (%)					
Panels				**Difference Achieved**	
Time	**Conventional**	**Tubes**	**Container**	**Tubes**	**Container**
10:30	11.08	12.25	12.98	1.17	1.90
11:00	10.75	11.84	13.2	1.09	2.45
11:30	11.5	12.6	13.25	1.10	1.75
12:00	**10.72**	**12.64**	**13.4**	**1.92**	**2.68**
12:30	11.3	12.32	12.6	1.02	1.30
13:00	10.5	11.67	12.02	1.17	1.52
13:30	10.33	11.55	12.4	1.22	2.07
14:00	9.96	11.1	11.74	1.14	1.78
14:30	9.16	10.08	10.34	0.92	1.18
15:00	8.2	9.6	8.1	1.40	-0.10
15:30	5.5	5.3	6.06	-0.20	0.56
	Average			**1.09**	**1.55**

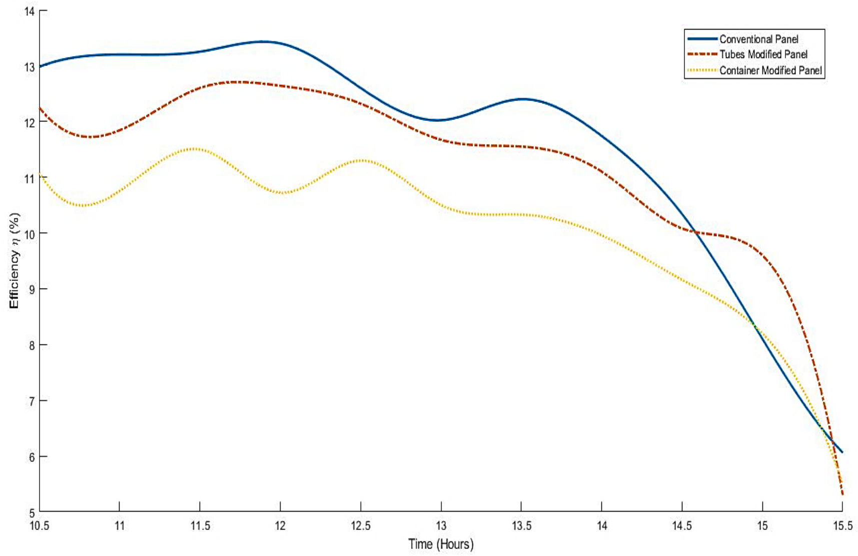

Figure 10. Electrical Efficiency Comparison for 22nd May

The maximum electrical efficiency obtained was 13.4% and this was for container modification indicating that it is a better enhancement to the PV panel.

The tubes modification produces a maximum difference in efficiency of 1.9% from 10.72% to 12.62%. A maximum difference of 2.6% from 10.72% to 13.4% for the container modification is observed. An average difference of about 1.1% for tubes and 1.55% for container modification is obtained during the testing period.

The increase in electrical efficiency is observed due to the decrease in PV panel and cells' temperature due to the application of cooling techniques already discussed.

It is to be noted that the container modified design showed a percentage enhancement of 25 % in terms of output power compared to tubular design which showed a percentage increase of about 18% . The difference can be explained since the tubular design allows for the increased space for utilizing Phase change material (PCM) at the panel back. This, in turn, translates into an increased contact area of PCM with the PV panel back, allowing larger percentage of heat to be rejected into the ambient. Also, when the PCM inside the PV panel back container starts melting, it further enhances the convection currents inside the PCM container which further enhances the rate of heat transfer from the back surface of the panel.

The container design has an inherent disadvantage of lower heat transfer coefficient values for natural convection but the added advantage of using larger amount of PCM offsets that disadvantage and turns out to be efficient in terms of power output and efficiency increase.

In contrast, for the case of the tubular design, tubes act not only as a PCM containment for heat absorption but also as fins which further increases the rate of heat transfer. In the tubular design, a large portion of back panel area is left open to the ambient for the natural convection currents. This has an added disadvantage of not utilizing the whole panel back area for heat transfer into the PCM and then, towards the ambient environment.

This explains the nature of results obtained for efficiency as it shows that the quantity of PCM utilization and its contact area with the PV Panel back surface.

Furthermore, it is to be noted that that the experimental data for power output from which electrical efficiency is obtained is reported for one day in the report for showing the overall variational trend. If other environmental factors were held constant including irradiance, ambient temperature etc., the pattern obtained will be similar for remaining days as our setup geometrical parameters are same.

The data of electrical efficiency for conventional and modified PV panel systems for remaining days of experimental testing is attached with the appendix IV for the reference.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Thermal management of conventional 4-watt PV panels were performed using different fins configuration including multiple phase change materials including Candle wax and petroleum jelly which has a primary hydrocarbon: 1,1,2-Trimethylbenzeindole ($C_{15}H_{15}N$). Two different designs were developed and tested under real time environmental conditions using different combinations of two PCMs, by employing different data acquisition systems including thermocouple for temperature measurement, Voltmeter and Ammeter sensors for the acquisition of electrical performance parameters including current and voltage.

Using container design, we were able to achieve a maximum power increase of 25.3% and a maximum efficiency increase of 2.7% while tubular design, on the other hand, was able to achieve a maximum power increase of 18% and a maximum efficiency increase of 2%. From the data obtained it was observed that the tubular design was more suitable for environments with lower temperatures due to the fact that it has less amount of PCM for heat absorption as compared to the container design which has relatively much more PCM for heat absorption. However, despite having less PCM in the tubular design, it radiated the absorbed heat more swiftly to the environment due to the presence of more surface area per the amount of PCM used.

For future work, effect of adding internal fins should also be explored in conjunction with external fins. Also, fins optimization should be done to determine the number of required fins and fin interspacing for the given panel area, in order to efficiently and effectively transfer the heat from the panel structure (back) toward the ambient environment.

Another important development that can be pursued in this course is the use of composite PCMs that can be utilized in the container due to their increased thermal conductivity. The PCMs being used should have two different melting point which will affect in the melting of the second PCM after the first has almost finished melting thus offering heat absorption at a much wider range of temperature. Also, the addition of nano particles in PCMs can greatly help enhance their conductivity.

As far as economic viability of the system is concerned, low cost PCM’s should be selected along with better thermal properties after rigorous real time environmental testing on PV-PCM systems. Payback period for the initial costs incurred during the installation of PV-PCM system can be reduced by employing highly efficient design with maximum heat transfer towards the ambient environment and the deciding factor in this is the PCM with better thermal characteristics such as latent heat capacity, thermal conductivity etc.

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APPENDIX I: PANEL FRONT TEMPERATURES

The data given below is only for the temperatures recorded on 29th May, 2021.

Time	Normal Panel	Tubes Modified Panel	Container Modified Panel	Difference Tubes Modified Panel	Difference Container Modified Panel
10:15	35.44	35.25	34.44	0.19	1
10:16	36.63	36.5	36	0.13	0.63
10:17	39.88	39.13	39.38	0.75	0.5
10:18	42.13	40.88	41	1.25	1.13
10:19	44.69	42.88	42.44	1.81	2.25
10:20	46.75	44.75	43.56	2	3.19
10:21	48.5	46.25	44.56	2.25	3.94
10:22	49.56	46.63	44.31	2.93	5.25
10:23	50.31	47.06	44.69	3.25	5.62
10:24	50.81	47.75	45.44	3.06	5.37
10:26	51.13	47.88	45.44	3.25	5.69
10:27	52.56	49.25	47.19	3.31	5.37
10:28	52.56	49.63	47.63	2.93	4.93
10:29	53.19	50.31	47.94	2.88	5.25
10:30	53.69	50.38	47.63	3.31	6.06
10:31	53.94	50.5	47.81	3.44	6.13
10:32	53.56	50.06	47.25	3.5	6.31
10:33	52.81	49.81	47.44	3	5.37
10:34	52.63	50	47.56	2.63	5.07
10:35	52.56	50	47.63	2.56	4.93
10:36	53	50.88	48.88	2.12	4.12
10:37	53.31	51.13	48.94	2.18	4.37
10:38	53	50.94	48.56	2.06	4.44
10:39	52.31	50.19	47.63	2.12	4.68
10:40	51.81	49.75	47.5	2.06	4.31
10:41	52.25	50.38	48.44	1.87	3.81
10:42	52.5	51.06	49.38	1.44	3.12
10:43	52.19	50.38	47.88	1.81	4.31
10:44	52.56	51	49.5	1.56	3.06
10:45	52.69	51.06	49.38	1.63	3.31
10:46	53.06	51.75	50.44	1.31	2.62
10:47	53.75	52.06	50.06	1.69	3.69
10:48	54.25	52	49.56	2.25	4.69
10:49	53.63	51.5	49.06	2.13	4.57
10:50	53.13	50.81	48.13	2.32	5
10:51	53.25	51.19	49.13	2.06	4.12
10:52	53.94	52.13	51.06	1.81	2.88
10:53	53.88	52	50.56	1.88	3.32
10:54	53.75	51.94	50.88	1.81	2.87
10:55	53.63	52	50.69	1.63	2.94
10:56	53.44	51.63	49.75	1.81	3.69
10:57	52.75	51.19	49.44	1.56	3.31
10:58	52.44	50.69	48.88	1.75	3.56
10:59	52.25	50.63	49.13	1.62	3.12
11:00	52.38	50.63	48.56	1.75	3.82
11:01	51.5	49.75	47.06	1.75	4.44
11:02	51.94	50	48.13	1.94	3.81
11:03	52.94	51.19	49.81	1.75	3.13
11:04	52.81	50.94	49.5	1.87	3.31
11:05	52.63	50.69	49	1.94	3.63
11:06	52.13	50.63	49.88	1.5	2.25

11:07	52.44	50.88	49.75	1.56	2.69
11:08	52.63	50.94	49.75	1.69	2.88
11:09	53.44	51.94	51.19	1.5	2.25
11:10	52.94	51.5	50.5	1.44	2.44
11:11	52.69	51.06	49.38	1.63	3.31
11:12	52.44	50.88	49.88	1.56	2.56
11:13	52.44	50.81	50	1.63	2.44
11:14	53	51.19	50.19	1.81	2.81
11:15	52.75	51	49.81	1.75	2.94
11:16	52.5	50.75	48.94	1.75	3.56
11:17	52.13	50.56	49.06	1.57	3.07
11:18	52.06	50.19	48.38	1.87	3.68
11:19	52.63	50.88	49.75	1.75	2.88
11:20	53.25	51.25	50.38	2	2.87
11:21	54.56	52.5	51.63	2.06	2.93
11:22	54.69	52.81	51.63	1.88	3.06
11:23	54	51.81	50.31	2.19	3.69
11:24	53.94	51.75	50.25	2.19	3.69
11:25	54.13	52.38	52.25	1.75	1.88
11:26	53.38	51.56	50.69	1.82	2.69
11:27	53.94	52	51.06	1.94	2.88
11:29	54.06	52.19	51.13	1.87	2.93
11:30	54.38	52.56	52.25	1.82	2.13
11:31	54.63	52.69	52.19	1.94	2.44
11:32	55.19	53.19	52.69	2	2.5
11:33	56.19	54.06	53.94	2.13	2.25
11:34	57.19	55.13	55.5	2.06	1.69
11:35	56.38	53.94	52.81	2.44	3.57
11:36	55.56	53.5	52.81	2.06	2.75
11:37	55.13	53	51.81	2.13	3.32
11:38	53.75	51.56	49.81	2.19	3.94
11:39	53.69	51.63	49.94	2.06	3.75
11:40	54.25	51.94	50.31	2.31	3.94
11:41	54.69	52.94	52.63	1.75	2.06
11:42	54.88	53.13	52.75	1.75	2.13
11:43	54.44	52.5	52.44	1.94	2
11:44	55.31	53.63	53.81	1.68	1.5
11:45	55.75	53.88	53.19	1.87	2.56
11:46	55.5	53.25	51.63	2.25	3.87
11:47	55.31	53.31	52.81	2	2.5
11:48	54.88	52.81	51.63	2.07	3.25
11:49	55.38	53.13	52.38	2.25	3
11:50	55.63	53.44	52.5	2.19	3.13
11:51	54.88	53	52.94	1.88	1.94
11:52	55.88	54	54.25	1.88	1.63
11:53	56.44	54.81	55.31	1.63	1.13
11:54	57.94	56.63	57.19	1.31	0.75
11:55	58.88	57.69	58.31	1.19	0.57
11:56	58.38	56.94	57.94	1.44	0.44
11:57	58.25	56.88	57.81	1.37	0.44
11:58	58.25	57	57.56	1.25	0.69
11:59	58.13	56.94	57.06	1.19	1.07
12:00	57.69	56.88	57.63	0.81	0.06
12:01	57.19	56.25	56.75	0.94	0.44
12:02	56.44	55.5	55.75	0.94	0.69
12:03	56.19	55.5	56.06	0.69	0.13
12:04	56.25	55.19	54.81	1.06	1.44
12:05	56.75	55.94	56.44	0.81	0.31
12:06	57.13	56.31	57.13	0.82	0
12:07	56.44	55.13	54.31	1.31	2.13

12:08	56	54.75	54	1.25	2
12:09	55.63	54.19	53.81	1.44	1.82
12:10	55.63	54.31	54.5	1.32	1.13
12:11	56.44	55.5	56.44	0.94	0
12:12	57	55.88	55.94	1.12	1.06
12:13	57.19	55.63	55.31	1.56	1.88
12:14	58	56.63	57.13	1.37	0.87
12:15	58.31	57.25	57.75	1.06	0.56
12:16	58.56	56.88	56.06	1.68	2.5
12:17	58.94	57.25	57.13	1.69	1.81
12:18	59.13	57.63	57.81	1.5	1.32
12:19	58.13	56.44	56	1.69	2.13
12:20	57.25	55.38	54.75	1.87	2.5
12:21	57.81	55.94	55.25	1.87	2.56
12:22	58.5	56.88	56.69	1.62	1.81
12:23	58.94	57.19	56.63	1.75	2.31
12:24	59.25	57.56	57.31	1.69	1.94
12:25	59.88	58.06	58.13	1.82	1.75
12:26	60.13	58.19	57.88	1.94	2.25
12:27	59.19	56.94	56.69	2.25	2.5
12:28	58.38	56.13	55.63	2.25	2.75
12:29	58.38	56.38	56.13	2	2.25
12:30	58.25	56.44	56.31	1.81	1.94
12:32	57.19	55.38	55.06	1.81	2.13
12:33	55.44	53.94	52.56	1.5	2.88
12:34	55.44	53.94	52.56	1.5	2.88
12:35	55.75	54.38	54	1.37	1.75
12:36	56.19	54.88	54.31	1.31	1.88
12:37	56.94	55.5	54.75	1.44	2.19
12:38	56.56	55.06	54.44	1.5	2.12
12:39	56.88	55.38	54.56	1.5	2.32
12:40	56.69	54.94	53.56	1.75	3.13
12:41	57.44	55.56	55	1.88	2.44
12:42	56.75	55.25	56.56	1.5	0.19
12:43	57.75	56.19	56.88	1.56	0.87
12:44	57.75	56	56	1.75	1.75
12:45	57.13	55.88	56.25	1.25	0.88
12:46	55.88	54.63	54.94	1.25	0.94
12:47	55.56	54.5	54.81	1.06	0.75
12:48	56.44	55.31	55.75	1.13	0.69
12:49	57.25	56	56.94	1.25	0.31
12:50	58.31	56.88	58.19	1.43	0.12
12:51	58	56.81	58.19	1.19	-0.19
12:52	56.63	55.38	56.69	1.25	-0.06
12:53	56.5	54.88	55.88	1.62	0.62
12:54	55.75	54.44	55.63	1.31	0.12
12:55	56.5	55.19	57	1.31	-0.5
12:56	58.25	56.88	58.75	1.37	-0.5
12:57	57.81	56.63	58.69	1.18	-0.88
12:58	57.44	56	57.88	1.44	-0.44
12:59	56.63	55.25	57.19	1.38	-0.56
13:00	56.56	55.13	57.06	1.43	-0.5
13:01	57.25	56	57.94	1.25	-0.69
13:02	57	55.31	56.69	1.69	0.31
13:03	57.06	55.5	57.56	1.56	-0.5
13:04	58.13	56.81	59.06	1.32	-0.93
13:05	57.31	56.5	58.88	0.81	-1.57
13:06	58.44	57	58.25	1.44	0.19
13:07	58.69	57.13	58.63	1.56	0.06
13:08	58.06	56.31	57.56	1.75	0.5

13:09	57.38	55.56	57	1.82	0.38
13:10	57.44	55.44	56.69	2	0.75
13:11	56.63	55.25	57.69	1.38	-1.06
13:12	56.63	55.19	56.94	1.44	-0.31
13:13	56.81	55.5	57.13	1.31	-0.32
13:14	56.38	54.94	56.81	1.44	-0.43
13:15	55.88	55.19	57.38	0.69	-1.5
13:16	56.06	55.19	57.38	0.87	-1.32
13:17	55.94	54.81	57.88	1.13	-1.94
13:18	58	56.88	58.94	1.12	-0.94
13:19	58.19	56.94	58.75	1.25	-0.56
13:20	58	56.38	57.56	1.62	0.44
13:21	58.56	56.38	57.19	2.18	1.37
13:22	58	55.44	56.38	2.56	1.62
13:23	57	54.75	56.44	2.25	0.56
13:24	56.56	54.56	56.69	2	-0.13
13:25	57.19	55.56	57.88	1.63	-0.69
13:26	57	55.63	57.44	1.37	-0.44
13:27	57.13	56.06	58.56	1.07	-1.43
13:28	57.44	56.31	58.75	1.13	-1.31
13:29	57.63	56.25	58.38	1.38	-0.75
13:30	57.94	56.63	58.75	1.31	-0.81
13:31	56.38	54.56	55.56	1.82	0.82
13:32	55.31	53.5	55.19	1.81	0.12
13:33	55.63	54.13	56.19	1.5	-0.56
13:35	55.75	54.31	56.44	1.44	-0.69
13:36	56.69	55.56	58.25	1.13	-1.56
13:37	55.81	54.81	57.19	1	-1.38
13:38	56.88	55.81	58.25	1.07	-1.37
13:39	56.69	55.31	57.13	1.38	-0.44
13:40	56.75	55.38	57.13	1.37	-0.38
13:41	56.5	54.5	55.69	2	0.81
13:42	56.69	55.13	57.38	1.56	-0.69
13:43	55.81	54	56.19	1.81	-0.38
13:44	55.44	53.69	56	1.75	-0.56
13:45	54.69	53.63	56.56	1.06	-1.87
13:46	54.56	53.88	57	0.68	-2.44
13:47	56.56	55.81	58.19	0.75	-1.63
13:48	57.69	56.5	58.38	1.19	-0.69
13:49	56.69	55.5	58.19	1.19	-1.5
13:50	57.25	55.88	57.69	1.37	-0.44
13:51	57.38	55.94	57.56	1.44	-0.18
13:52	56.88	55.5	57.25	1.38	-0.37
13:53	56.19	54.5	55.38	1.69	0.81
13:54	56.38	54.63	55.81	1.75	0.57
13:55	57.13	55.56	57.06	1.57	0.07
13:56	57.81	56.13	58.31	1.68	-0.5
13:57	57.56	56	58.5	1.56	-0.94
13:58	57.31	55.75	58.56	1.56	-1.25
13:59	57.56	55.94	58.56	1.62	-1
14:00	57.56	56.06	57.94	1.5	-0.38
14:01	58.19	56.81	58.63	1.38	-0.44
14:02	59.75	58.38	59.88	1.37	-0.13
14:03	59.88	58.44	60.31	1.44	-0.43
14:04	60.44	59	60.75	1.44	-0.31
14:05	60.69	58.81	59.56	1.88	1.13
14:06	60.69	58.94	60.31	1.75	0.38
14:07	59.19	57.75	59.44	1.44	-0.25
14:08	58.94	57.31	58	1.63	0.94
14:09	57.56	55.75	56.63	1.81	0.93

14:10	56.25	54.56	55.81	1.69	0.44
14:11	56.56	55	56.38	1.56	0.18
14:12	56.31	55	56.25	1.31	0.06
14:13	56.81	55.38	56.81	1.43	0
14:14	56.38	55.13	57.75	1.25	-1.37
14:15	55.94	54.94	57.56	1	-1.62
14:16	54.94	54.25	56.63	0.69	-1.69
14:17	55.44	55.13	57.56	0.31	-2.12
14:18	56.5	56.06	58.5	0.44	-2
14:19	57.56	57	59.38	0.56	-1.82
14:20	58.56	57.75	59.75	0.81	-1.19
14:21	59.38	58.44	60.5	0.94	-1.12
14:22	59.25	58.25	60.31	1	-1.06
14:23	58.88	57.75	59.81	1.13	-0.93
14:24	57.38	56.25	58.25	1.13	-0.87
14:25	56.06	55.31	57.5	0.75	-1.44
14:26	55.19	54.13	56.06	1.06	-0.87
14:27	54.38	53.44	56.06	0.94	-1.68
14:28	55	53.81	55.13	1.19	-0.13
14:29	55.13	53.94	55.81	1.19	-0.68
14:30	55.38	54.19	56.19	1.19	-0.81
14:31	55.75	54.63	56.69	1.12	-0.94
14:32	56.63	55.69	58.13	0.94	-1.5
14:33	56.13	55.13	56.69	1	-0.56
14:34	56.13	54.75	56.25	1.38	-0.12
14:35	55.5	54.06	55.19	1.44	0.31
14:36	54.5	53.06	54.56	1.44	-0.06
14:38	53.88	52.88	54.75	1	-0.87
14:39	54	52.88	54.44	1.12	-0.44
14:40	53.69	52.81	54.69	0.88	-1
14:41	53.19	52.38	54.88	0.81	-1.69
14:42	52.25	52	55.13	0.25	-2.88
14:43	53.06	52.69	55.44	0.37	-2.38
14:44	53.81	53.31	56.06	0.5	-2.25
14:45	54.25	53.75	56.31	0.5	-2.06
14:46	55.38	54.75	57.56	0.63	-2.18
14:47	54.38	53.75	56.94	0.63	-2.56
14:48	54.25	53.38	56.19	0.87	-1.94
14:49	55.38	54.44	56.75	0.94	-1.37
14:50	55.5	54.25	56.06	1.25	-0.56
14:51	56	54.63	56.25	1.37	-0.25
14:52	55.88	54.38	55.75	1.5	0.13
14:53	56.31	54.63	56.13	1.68	0.18
14:54	55.63	53.75	55.88	1.88	-0.25
14:55	55.88	54.13	56.25	1.75	-0.37
14:56	56.19	54.63	56.81	1.56	-0.62
14:57	55.5	54.13	56.06	1.37	-0.56
14:58	55.06	53.94	56.19	1.12	-1.13
14:59	56	54.75	56.94	1.25	-0.94
15:00	56.56	55.31	57.31	1.25	-0.75
15:01	56.5	55.13	57.19	1.37	-0.69
15:02	56.5	54.56	55.81	1.94	0.69
15:03	55.75	54.06	55.63	1.69	0.12
15:04	56.5	54.81	56.63	1.69	-0.13
15:05	56.5	55.25	57.31	1.25	-0.81
15:06	56.44	55.44	57.75	1	-1.31
15:07	56.13	55.31	57.19	0.82	-1.06
15:08	55.5	54.25	55.63	1.25	-0.13
15:09	54.75	53.56	55.38	1.19	-0.63
15:10	54.94	53.94	55.75	1	-0.81

15:11	55.13	53.94	55.63	1.19	-0.5
15:12	54.88	53.94	55.88	0.94	-1
15:13	54.88	53.81	55.25	1.07	-0.37
15:14	54.44	53.13	54.38	1.31	0.06
15:15	53.75	52.56	54	1.19	-0.25
15:16	52.69	51.56	52.88	1.13	-0.19
15:17	52.75	51.81	53.44	0.94	-0.69
15:18	52.38	51.31	52.75	1.07	-0.37
15:19	52.56	51.5	53.13	1.06	-0.57
15:20	51.69	50.81	52	0.88	-0.31
15:21	51.44	50.44	51.69	1	-0.25
15:22	52.13	51	52.5	1.13	-0.37
15:23	51.88	50.69	52.31	1.19	-0.43
15:24	52.06	50.81	52.75	1.25	-0.69
15:25	52.31	51.19	53.19	1.12	-0.88
15:26	52.25	51.13	53.19	1.12	-0.94
15:27	52.44	51.38	53.63	1.06	-1.19
15:28	53.25	51.94	54.44	1.31	-1.19
15:29	53.94	52.75	55.38	1.19	-1.44
15:30	54.56	53.38	56.13	1.18	-1.57
15:31	54.63	53.5	56	1.13	-1.37
15:32	55.13	54	56.31	1.13	-1.18
15:33	54.75	53.94	56.38	0.81	-1.63
15:34	55.38	54.25	56.38	1.13	-1
15:35	55.44	54.25	55.81	1.19	-0.37
15:36	55.06	53.81	55.38	1.25	-0.32
15:37	54.75	53.75	55.75	1	-1
15:38	54.81	53.88	55.81	0.93	-1
15:39	53.25	52.44	54.81	0.81	-1.56
15:41	53.13	52.31	54.25	0.82	-1.12
15:42	52.13	51.56	53.81	0.57	-1.68
15:43	51.38	50.94	53.06	0.44	-1.68
15:44	51.69	51.25	53.38	0.44	-1.69
15:45	50.38	50.19	52.56	0.19	-2.18
15:46	50.94	50.81	52.94	0.13	-2
15:47	51.13	51.13	53.25	0	-2.12
15:48	51.88	51.88	53.75	0	-1.87
15:49	51.5	51.25	53.31	0.25	-1.81
15:50	51.81	51.5	53.56	0.31	-1.75
15:51	51.38	51.13	53.31	0.25	-1.93
15:52	52.44	52.25	54.13	0.19	-1.69
15:53	52.75	52.44	54.19	0.31	-1.44
15:54	53.56	52.94	54.69	0.62	-1.13
15:55	52.38	51.56	54.06	0.82	-1.68
15:56	52.25	51.63	53.56	0.62	-1.31
15:57	51.94	51.25	52.94	0.69	-1
15:58	52.19	51.5	53.38	0.69	-1.19
15:59	52	51.44	53.38	0.56	-1.38
16:00	51.44	50.88	53.06	0.56	-1.62
16:01	51.56	50.88	53.06	0.68	-1.5
16:02	51.5	50.94	53.31	0.56	-1.81
16:03	52.06	51.38	53.31	0.68	-1.25
16:04	52.38	51.56	53.13	0.82	-0.75
16:05	51.69	51.19	53.25	0.5	-1.56
16:06	52.06	51.31	53.44	0.75	-1.38
16:07	52.31	51.69	53.69	0.62	-1.38
16:08	52	51.44	53.5	0.56	-1.5
16:09	51.44	51	53	0.44	-1.56
16:10	51.25	51	53.06	0.25	-1.81
16:11	51.13	50.88	52.94	0.25	-1.81

16:12	51.38	51.19	53.44	0.19	-2.06
16:13	51.94	51.69	53.81	0.25	-1.87
16:14	52.13	51.69	53.94	0.44	-1.81
16:15	51.88	51.56	53.88	0.32	-2
16:16	52.31	51.94	54.06	0.37	-1.75
16:17	52.44	51.94	54.19	0.5	-1.75
16:18	52.44	51.94	54.25	0.5	-1.81
16:19	52.69	52.13	54.31	0.56	-1.62
16:20	52.38	51.63	53.81	0.75	-1.43
16:21	52.13	51.5	53.63	0.63	-1.5
16:22	51.94	51.31	53.5	0.63	-1.56
16:23	52.13	51.5	53.44	0.63	-1.31
16:24	51.31	50.63	52.56	0.68	-1.25
16:25	51.19	50.63	52.69	0.56	-1.5
16:26	51.88	51.13	53.06	0.75	-1.18
16:27	51.81	51.06	52.88	0.75	-1.07
16:28	51.69	50.81	52.81	0.88	-1.12
16:29	51.25	50.44	52.63	0.81	-1.38
16:30	51.56	50.81	52.63	0.75	-1.07
16:31	51.56	51.06	52.94	0.5	-1.38
16:32	51.25	50.81	52.81	0.44	-1.56
16:33	50.63	50.06	52.19	0.57	-1.56
16:34	50	49.5	51.56	0.5	-1.56
16:35	50	49.69	51.5	0.31	-1.5
16:36	49.81	49.56	51.5	0.25	-1.69
16:37	49.94	49.56	51.38	0.38	-1.44
16:38	49.56	49.31	51.19	0.25	-1.63
16:39	49.88	49.5	51.25	0.38	-1.37
16:40	49.75	49.44	51.44	0.31	-1.69
16:41	49.69	49.31	51.25	0.38	-1.56
16:42	49.63	49.31	51.38	0.32	-1.75
16:44	50.06	49.69	51.63	0.37	-1.57
16:45	50.13	49.69	51.69	0.44	-1.56
16:46	49.56	49.19	51.25	0.37	-1.69
16:47	49.38	49.06	51.06	0.32	-1.68
16:48	48.69	48.5	50.63	0.19	-1.94
16:49	48.13	48	50.25	0.13	-2.12
16:50	48.25	48.13	49.94	0.12	-1.69
16:51	47.88	47.75	49.88	0.13	-2
16:52	47.81	47.75	49.94	0.06	-2.13
16:53	48.25	48.19	50.06	0.06	-1.81
16:54	48.38	48	49.94	0.38	-1.56
16:55	48.38	48.06	49.94	0.32	-1.56
16:56	48.06	47.75	49.38	0.31	-1.32
16:57	47.25	47.06	48.94	0.19	-1.69
16:58	46.19	46	47.25	0.19	-1.06
16:59	45.25	45.06	46.63	0.19	-1.38
17:00	44.13	44	45	0.13	-0.87
17:01	43.69	43.56	44.88	0.13	-1.19
17:02	43.25	43.25	44.88	0	-1.63
17:03	43	43.06	45.06	-0.06	-2.06
17:04	42.81	42.88	44.81	-0.07	-2
17:05	42.56	42.63	44.69	-0.07	-2.13
17:06	42.38	42.38	44.38	0	-2
17:07	42.25	42.25	44.25	0	-2
17:08	42.13	42.06	44.06	0.07	-1.93
17:09	41.44	41.5	43.06	-0.06	-1.62
17:10	41.06	41.13	42.69	-0.07	-1.63
17:11	41.06	41.13	43.25	-0.07	-2.19
17:12	40.94	40.94	42.81	0	-1.87

17:13	40.81	40.75	42.44	0.06	-1.63
17:14	40.81	40.75	42.88	0.06	-2.07
17:15	40.63	40.56	42.63	0.07	-2
17:16	40.5	40.38	42.06	0.12	-1.56
17:17	40.44	40.38	42.19	0.06	-1.75
17:18	40.44	40.38	42.38	0.06	-1.94
17:19	40.44	40.38	42.31	0.06	-1.87
17:20	40.31	40.19	42.19	0.12	-1.88
17:21	40.38	40.25	42.44	0.13	-2.06
17:22	40.13	39.94	41.94	0.19	-1.81
17:23	39.63	39.5	41.5	0.13	-1.87
17:24	39.13	39	40.88	0.13	-1.75
17:25	38.88	38.81	40.94	0.07	-2.06
17:26	38.5	38.5	40.25	0	-1.75
17:27	38.44	38.5	40.63	-0.06	-2.19
17:28	38.38	38.44	40.69	-0.06	-2.31
17:29	38.44	38.5	40.69	-0.06	-2.25
17:30	38.63	38.69	40.75	-0.06	-2.12
17:31	38.81	38.81	40.81	0	-2
17:32	38.75	38.81	40.75	-0.06	-2
17:33	38.69	38.69	40.44	0	-1.75
17:34	38.56	38.56	39.94	0	-1.38
17:35	38.56	38.5	40.13	0.06	-1.57
17:36	38.63	38.56	40.38	0.07	-1.75
17:37	38.81	38.75	40.56	0.06	-1.75
17:38	38.81	38.69	40.44	0.12	-1.63
17:39	38.69	38.63	40.31	0.06	-1.62
17:40	38.5	38.38	39.63	0.12	-1.13
17:41	38.44	38.25	39.63	0.19	-1.19
17:42	38.31	38.25	39.81	0.06	-1.5
17:43	38.31	38.19	39.88	0.12	-1.57
17:44	38.19	38.06	39.5	0.13	-1.31
17:45	38.13	38.06	39.63	0.07	-1.5
17:47	38.13	38.06	39.63	0.07	-1.5
17:48	37.94	38	39.5	-0.06	-1.56
17:49	37.69	37.88	39.38	-0.19	-1.69
17:50	37.5	37.81	39.44	-0.31	-1.94
17:51	37.44	37.69	39.5	-0.25	-2.06
17:52	37.38	37.56	39.56	-0.18	-2.18
17:53	37.31	37.44	39.31	-0.13	-2
17:54	37.19	37.25	38.94	-0.06	-1.75
17:55	36.94	37	38.5	-0.06	-1.56
17:56	36.81	36.88	38.5	-0.07	-1.69
17:57	36.75	36.81	38.25	-0.06	-1.5
17:58	36.63	36.69	38.13	-0.06	-1.5
17:59	36.5	36.56	38	-0.06	-1.5
18:00	36.38	36.5	37.88	-0.12	-1.5

APPENDIX II: POWER OUTPUT DATA

May 18, 2021

				Improvement(%)	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**
11:30	3.47	3.89	3.74	12.10	7.78
12:00	1.64	1.71	1.75	4.27	6.71
12:30	3.18	3.31	3.4	4.09	6.92
13:00	2.89	3.03	3.14	4.84	8.65
14:00	2.645	2.67	2.77	0.95	4.73
14:50	2.37	2.6	2.54	9.70	7.17
15:30	2.18	2.25	2.26	3.21	3.67
16:00	1.74	1.75	1.61	0.57	-7.47

May 19, 2021

				Improvement(%)	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**
10:00	3.13	3.27	3.32	4.47	6.07
10:30	2.93	3.37	3.2	15.02	9.22
11:00	2.91	3.32	3.32	14.09	14.09
11:30	3.25	3.24	3.45	-0.31	6.15
12:00	3.29	3.55	3.65	7.90	10.94
12:30	3.28	3.42	3.57	4.27	8.84
13:00	3.22	3.42	3.5	6.21	8.70
13:30	3.1	3.24	3.4	4.52	9.68
14:00	2.95	3.14	3.2	6.44	8.47
14:30	2.82	2.98	2.98	5.67	5.67
15:00	2.35	2.55	2.64	8.51	12.34
15:30	2.2	2.34	2.32	6.36	5.45
16:00	1.78	1.87	1.77	5.06	-0.56
16:30	1.45	1.46	1.35	0.69	-6.90
17:00	1.25	1.32	1.21	5.60	-3.20

May 21, 2021

				Improvement(%)	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**
10:00	2.91	3.34	3.4	14.78	16.84
10:30	3.1	3.3	3.55	6.45	14.52
11:00	3.33	3.36	3.48	0.90	4.50
11:30	3.35	3.3	3.65	-1.49	8.96
12:00	3.21	3.26	3.45	1.56	7.48
12:30	3.34	3.3	3.51	-1.20	5.09
13:00	3.32	3.25	3.46	-2.11	4.22
14:00	2.74	2.75	3	0.36	9.49
14:30	2.74	2.77	2.92	1.09	6.57
15:00	1.34	1.57	1.56	17.16	16.42
15:30	1.91	1.8	2.04	-5.76	6.81
16:00	1.7	1.58	1.78	-7.06	4.71

May 22, 2021

	Panels			Improvement(%)	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**
10:30	2.82	3.12	3.33	10.64	18.09
11:00	2.74	3.02	3.37	10.22	22.99
11:30	2.94	3.2	3.38	8.84	14.97
12:00	2.73	3.22	3.42	17.95	25.27
12:30	2.88	3.14	3.2	9.03	11.11
13:00	2.7	2.97	3.07	10.00	13.70
13:30	2.64	2.95	3.16	11.74	19.70
14:00	2.56	2.83	2.99	10.55	16.80
14:30	2.4	2.57	2.64	7.08	10.00
15:00	2.09	2.44	2.07	16.75	-0.96
15:30	1.4	1.35	1.54	-3.57	10.00
	Average			9.93	14.70

May 31, 2021

				Improvement(%)	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**
11:00	3.02	3.04	3.4	0.66	12.58
11:30	3.03	3.1	3.4	2.31	12.21
12:00	2.86	3.02	3.24	5.59	13.29
12:30	3.1	3.17	3.29	2.26	6.13

June 1, 2021

				Improvement(%)	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**
10:00	3.1	3.07	3.39	-0.97	9.35
10:30	3.02	3.06	3.35	1.32	10.93
11:00	3.18	3.25	3.47	2.20	9.12
11:30	3.1	3.28	3.5	5.81	12.90
12:00	3.24	3.33	3.44	2.78	6.17
12:30	3.2	3.25	3.39	1.56	5.94
13:00	3.06	3.12	3.22	1.96	5.23
13:30	2.91	3.12	3.16	7.22	8.59
14:00	2.72	2.8	2.99	2.94	9.93
14:30	2.63	2.74	2.9	4.18	10.27
15:00	2.1	2.36	2.42	12.38	15.24
15:30	1.52	1.65	1.69	8.55	11.18
16:00	1.16	1.18	1.26	1.72	8.62

Note : All values are in Watts (W).

APPENDIX III: ELECTRICAL EFFICIENCY DATA

May 18, 2021

				Improvement(%)		Difference	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**	**Tubes**	**Container**
11:30	13.6	15.25	14.67	12.13	7.87	1.65	1.07
12:00	6.43	6.7	6.85	4.20	6.53	0.27	0.42
12:30	12.5	12.98	13.34	3.84	6.72	0.48	0.84
13:00	11.34	11.88	12.32	4.76	8.64	0.54	0.98
14:00	10.4	10.5	10.88	0.96	4.62	0.10	0.48
14:30	9.3	10.16	10	9.25	7.53	0.86	0.70
15:30	8.56	8.8	8.87	2.80	3.62	0.24	0.31
16:00	6.84	6.88	6.3	0.58	-7.89	0.04	-0.54

May 19, 2021

				Improvement(%)		Difference	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**	**Tubes**	**Container**
10:00	12.26	12.82	13.02	4.57	6.20	0.56	0.76
10:30	11.5	13.2	12.6	14.78	9.57	1.70	1.10
11:00	11.4	13.02	13.05	14.21	14.47	1.62	1.65
11:30	12.74	12.7	13.5	-0.31	5.97	-0.04	0.76
12:00	12.88	13.9	14.3	7.92	11.02	1.02	1.42
12:30	12.88	13.4	13.99	4.04	8.62	0.52	1.11
13:00	12.6	13.4	13.72	6.35	8.89	0.80	1.12
13:30	12.1	12.7	13.34	4.96	10.25	0.60	1.24
14:00	11.6	12.31	12.52	6.12	7.93	0.71	0.92
14:30	11.05	11.7	11.7	5.88	5.88	0.65	0.65
15:00	9.2	10	10.4	8.70	13.04	0.80	1.20
15:30	8.6	9.2	9.1	6.98	5.81	0.60	0.50
16:00	7	7.35	6.94	5.00	-0.86	0.35	-0.06
16:30	5.7	5.7	5.3	0.00	-7.02	0.00	-0.40
17:00	4.88	5.18	4.74	6.15	-2.87	0.30	-0.14

May 21, 2021

				Improvement(%)		Difference	
Time	Normal	Tubes	Container	Tubes	Container	Tubes	Container
10:00	11.44	13.13	13.34	14.77	16.61	1.69	1.90
10:30	12.14	12.93	13.92	6.51	14.66	0.79	1.78
11:00	13.05	13.2	13.64	1.15	4.52	0.15	0.59
11:30	13.15	12.94	14.3	-1.60	8.75	-0.21	1.15
12:00	12.6	12.78	13.53	1.43	7.38	0.18	0.93
12:30	13.1	12.95	13.77	-1.15	5.11	-0.15	0.67
13:00	13	12.78	13.55	-1.69	4.23	-0.22	0.55
14:00	10.76	10.78	11.8	0.19	9.67	0.02	1.04
14:30	10.75	10.86	11.46	1.02	6.60	0.11	0.71
15:00	5.26	6.14	6.11	16.73	16.16	0.88	0.85
15:30	7.5	7.04	8	-6.13	6.67	-0.46	0.50
16:00	6.66	6.2	6.99	-6.91	4.95	-0.46	0.33

May 22, 2021

				Improvement(%)		Difference	
Time	Normal	Tubes	Container	Tubes	Container	Tubes	Container
10:30	11.08	12.25	12.98	10.56	17.15	1.17	1.90
11:00	10.75	11.84	13.2	10.14	22.79	1.09	2.45
11:30	11.5	12.6	13.25	9.57	15.22	1.10	1.75
12:00	10.72	12.64	13.4	17.91	25.00	1.92	2.68
12:30	11.3	12.32	12.6	9.03	11.50	1.02	1.30
13:00	10.5	11.67	12.02	11.14	14.48	1.17	1.52
13:30	10.33	11.55	12.4	11.81	20.04	1.22	2.07
14:00	9.96	11.1	11.74	11.45	17.87	1.14	1.78
14:30	9.16	10.08	10.34	10.04	12.88	0.92	1.18
15:00	8.2	9.6	8.1	17.07	-1.22	1.40	-0.10
15:30	5.5	5.3	6.06	-3.64	10.18	-0.20	0.56

May 31, 2021

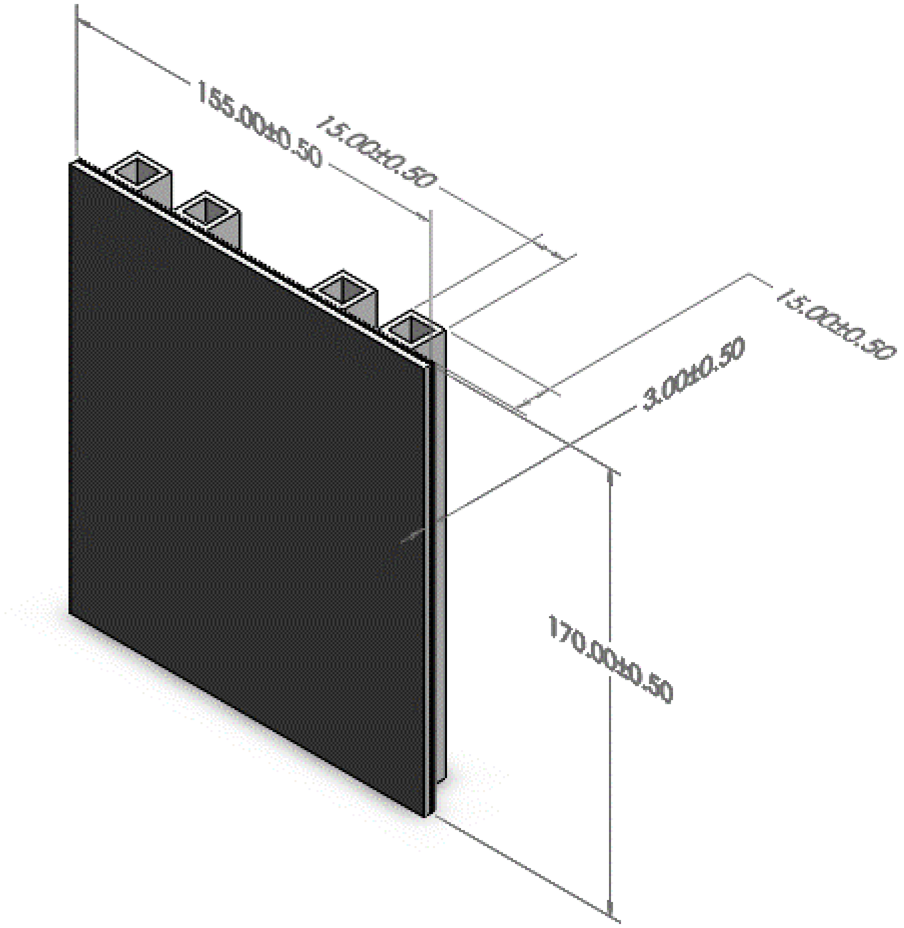
				Improvement(%)		Difference	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**	**Tubes**	**Container**
11:00	11.85	11.94	13.3	0.76	12.24	0.09	1.45
11:30	11.88	12.2	13.34	2.69	12.29	0.32	1.46
12:00	11.23	11.82	12.7	5.25	13.09	0.59	1.47
12:30	12.16	12.43	12.9	2.22	6.09	0.27	0.74

June 1, 2021

				Improvement(%)		Difference	
Time	**Normal**	**Tubes**	**Container**	**Tubes**	**Container**	**Tubes**	**Container**
10:00	12.16	12.05	13.31	-0.90	9.46	-0.11	1.15
10:30	11.82	12	13.14	1.52	11.17	0.18	1.32
11:00	12.5	12.75	13.67	2.00	9.36	0.25	1.17
11:30	12.12	12.88	13.7	6.27	13.04	0.76	1.58
12:00	12.7	13.07	13.5	2.91	6.30	0.37	0.80
12:30	12.55	12.75	13.3	1.59	5.98	0.20	0.75
13:00	12	12.23	12.63	1.92	5.25	0.23	0.63
13:30	11.4	12.24	12.4	7.37	8.77	0.84	1.00
14:00	10.67	11	11.7	3.09	9.65	0.33	1.03
14:30	10.3	10.75	11.4	4.37	10.68	0.45	1.10
15:00	8.2	9.42	9.47	14.88	15.49	1.22	1.27
15:30	5.96	6.5	6.6	9.06	10.74	0.54	0.64
16:00	4.57	4.64	4.93	1.53	7.88	0.07	0.36

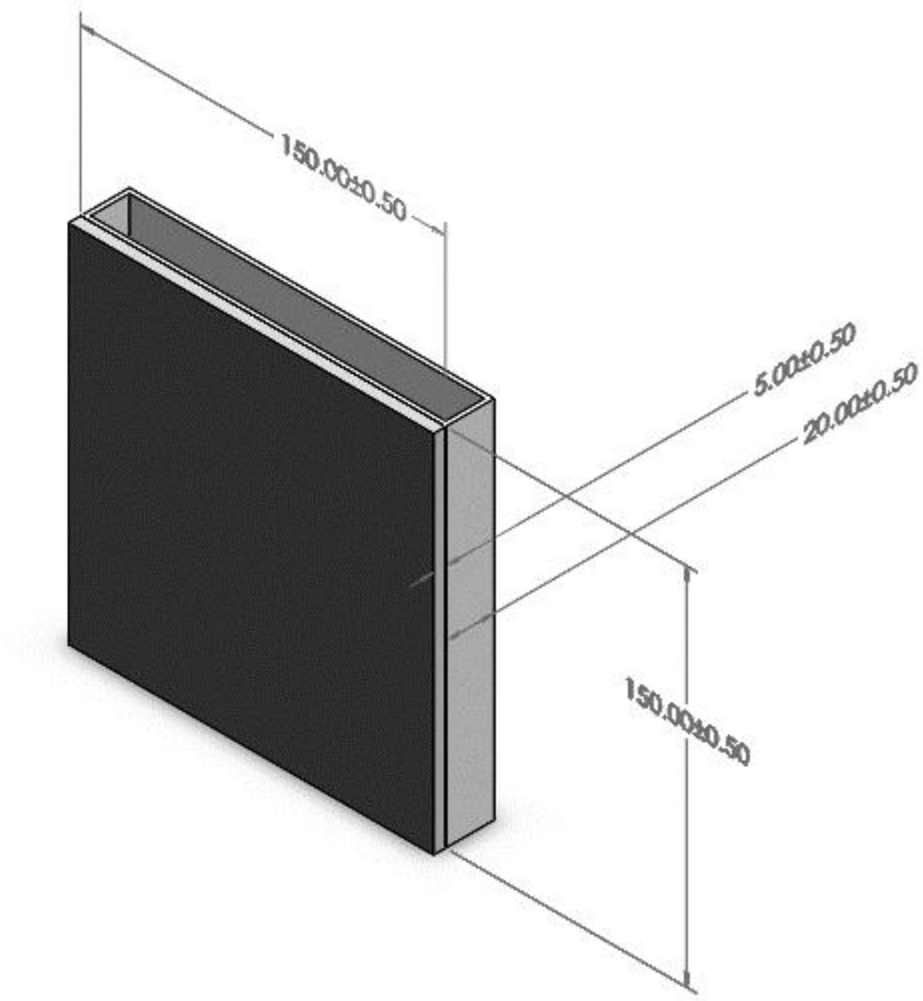
APPENDIX IV: DETAILED DESIGN VIEWS WITH DIMENSIONS

PCM Tubular Design



Note : All units are in mm.

PCM Containment Design



Note : All units are in mm.