Preliminary Studies on Design of Photovoltaic Thermal (PVT) Solar Collector for Roofing System Application.

Zariq Imran Abdul Manap¹, Hanani Abd Wahab¹⁺, Ong Pauline¹, Al-Emran Ismail¹, Maznan Ismon¹, Zaleha Mohamad¹
Faculty of Mechanical & Manufacturing Engineering Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, Malaysia.

E-mail: *nani@uthm.edu.my

Abstract. This study was conducted to develop and study the performance of a Photovoltaic Thermal (PVT) system technology, a system which combines the Photovoltaic (PV) system with a solar thermal (T) system that produces electricity and hot water simultaneously. The objective of this study is to develop a working prototype of the PVT system for roofing system application with water as the cooling agent. A polycrystalline PV cells was used as the solar collector while a transparent rubber tube was attached at the backside of the PV panel with water flowing directly from a water tap source. Two designs were examined for the heat absorber design which was categorized as the parallel and spiral flow design. The system was run at an open space to simulate real life application. A working PVT system was developed; however an electrical efficiency drops 0.3% and 1.07% on the parallel and spiral design respectively when compared to the standard PV system.

1. Introduction

Renewable energy has been the talks of the industry for decades. Based on Malaysia Five Fuel strategy policy, it is targeted for renewable energy to be the source of 11% electricity generation that will subsequently amount to 2080MW of installed capacity by the year 2020. Among the sources of renewable energy available, Solar Photovoltaic (PV) has shown the most significant demand among citizens in Malaysia with a total of 97.63% consumer application received by the Sustainable Energy Development Authority (SEDA) in 2015 as compared with biogas, biomass, small hydro, and geothermal [1].

Photovoltaic (PV) systems introduced in Malaysia in the 1980s, since then the PV cell become one of the best alternative for generating power source. PV systems have many benefits for the user such as, lower maintenance costs [2]. Mostly, PV system manufacturer gives 20 – 25 years warranty with no moving parts, no wear, and tear. Using the PV system can reduce the electricity bills since the PV system just needs the energy from the sun, which is a free and unlimited source to produces the electric power. Also, PV system is very versatile; it can be uses for small or big applications [3].

Photovoltaic thermal (PVT) hybrid solar collector is system that converts solar radiation into thermal and electrical energy. These systems combine a solar cell, which converts sunlight into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module. There have been many studies of PVT systems integrated to building systems focusing on numerical methods, control and design optimisation, production materials,
innovative systems and economic analysis [4-12]. Therefore, this study are made to develop and study a hybrid PVT solar collector system in terms of efficiency and application capability by adding a water based cooling system into the panel system.

2. Methodology

2.1. General System Selection
The system selection for the roof PVT module will be a static type module and is suitable for Malaysian standard roofing pattern. The system will be based on an off-grid PVT system. The main components that will be needed for the prototype to work are:

i. Tiled roof
ii. PVT module
iii. Water storage tank
iv. Pumping system
v. Cable and piping

2.2. Type and Size of PV Module
The sizes of the PV module that will be used for the simulation are a 4m² flat plate, unglazed polycrystalline PV cell. This type of cell is used instead of the higher efficient monocrystalline cells due to its lower manageable cost and acceptable working efficiency. Based on the literature review, a polycrystalline cell possesses a working efficiency value of around 12% - 16%. Rekha, Vijayalakshmi, and Natarajan [4] claims that a PV system with a 4m² module area are able to generate as much as 3kWh of electricity per day. This amount will be sufficient as the common current usage of 2 – 4 kWh per day for any normal household of 1-4 persons. The size will also enable the panel to receive 100 liter per day of hot water with temperature of 80°C [4].

2.3. Collector Properties
The material that was chosen to be used as the collector body is diverse. Using a less expensive material such as steel will not influence any significant change in terms of the absorber thermal and electrical performance even though they have a low thermal conductivity [5, 10]. The design of the collector uses the spiral flow absorber design is as shown in a study by Ibrahim as in Figure 1 configuration of PVT collector design. Whereby, the spiral flow design simulates the best thermal and cell efficiency which is 50.12% and 11.98% respectively [6].

![Figure 1. Configuration of absorbers design [6].](image)

2.4. Water Flow Rate
Water flow rate plays a significant role in determining the output temperature of the heated water. If the water flow is too fast, the amount of heat absorption will be lower thus increasing the surface
temperature of the PV panel. This means that an optimum rise in water flowrate will affect the rate of heat removal on the collector. The optimum water flow rate that will be used in the simulation will be 20liter/hr. The use of optimum flow rate of 20liter/hr for a PVT system on residential building will increase the PV cells efficiency [7].

2.5. *Malaysia Solar Roofing System Application*

The majority of buildings in Malaysia for example in Batu Pahat, Johor, has a minimum inclined angle of 30°. In the aspect of solar installation, the correct angle of installation will provide better sunlight exposure to the PV panel thus creating a more optimum energy production.

2.6. *Malaysia Meteorological Condition*

The performance of a solar system depends greatly on the meteorological state in a given area. One of the influential factors lies on the strategic geographical location of the nation. Malaysia is located specifically along the South China Sea with coordinates in between of 10 and 70 to the north latitude and 100 to 120 on the south longitude. Whereby, Malaysia is capable of receiving sunlight exposure up to 4 to 8 hours a day [8].

2.7. Prototype Modelling and Design

The software that will be used to visualize the design is the SolidWorks. The components used in the design stage are standard commercialized components. This means that there is no major analysis required to be done on them other than determining the suitable tone-down-ratio counterpart to be used on the smaller scaled prototype.

2.8. *Component Decomposition Analysis*

The decomposition of the components involved in the desired prototype design is as shown in Figure 2. As suggested in the general system selection, the main components of the PVT system consists of the PV module and the thermal absorber, the water tank, and water pump.

2.9. *Function Decomposition Analysis*

Figure 3 shows the function of each of the components involved in the PVT system based on the components decomposition chart.

2.10. *Function Structure*

The function structures explain the functions of the PVT system in the form of a flow chart. Figure 4 shows the overall function of the PVT system where in general, the system received sunlight as an input and produces current and heat as the output.

![Component decomposition chart for the PVT system](image-url)

*Figure 2. Component decomposition chart for the PVT system*
Figure 3. Function decomposition chart for the PVT system

Figure 4. Overall function of the PVT system

Figure 5 illustrate in a more detailed perspective of what is happening inside the system that would generate the output as described in Figure 4. The function flow is shown step by step so that a clear understanding regarding the system function can be obtained. This part is essential in order to have a clean view on what to be expected when designing the prototype so that each and every component are placed and used in their best possible position so that the desired end result will be achieved more efficiently.

Figure 5. Flow chart of function structure for the PVT system
3. Result and discussion

3.1. SolidWorks Design
Figure 6 shows the prototype design made on the SolidWorks software which was used as the reference for product fabrication.

(a) The prototype main frame
(b) The main frame with a 35°C angle
(c) The main frame with roof tile
(d) The design for spiral water tube heat absorber
(e) The design for parallel water tube heat absorber

Figure 6. PVT Prototype design using Solidworks

3.2. Fabricated Prototype
Figure 7 shows the experimental setup for PVT system with parallel and spiral absorber design.
3.3. Expected Experiment Results

Based on the literature review made at the early stage of this study, it is expected that:

i. The PV panel experience voltage production drop as its surface temperature rise

ii. The PV panel current production is dependant towards the level of solar radiation it receives from the sun which is determined through the weather condition.

iii. The amount of maximum power generated by the panel to be at 10-12 p.m. as the solar radiation peaks at that time.

iv. The amount of power production decreases after 12 p.m. as solar radiation level decreases.

When the system is changed from PV to PVT, it is expected that:

i. The range of voltage production increase compared to the standalone PV system

ii. The panel power generation will increase significantly

iii. The panel surface temperature will be relatively lower than the PV setup.

iv. There is a significant increase in water temperature after it circulated through the PV panel

v. The overall efficiency of the panel in PVT system increases compared to the PV system.
3.4. Experiment Results and Discussion

3.4.1. Photovoltaic Setup. The photovoltaic setup is the setup in which only the PV panel are placed on the roof frame without the water tube circulation system. This data collected on this setup were made as the benchmark performance that needed to be overcome by the later system designs.

The setup parameters are as follow:

i. Setup : Photovoltaic system
ii. Place : Taman Wira Neighbourhood, Parit Raja
iii. Placement time : 10.00 a.m. to 3.00 p.m.

3.4.2. Photovoltaic Thermal with Parallel Water Tube Design. The photovoltaic thermal with parallel water tube design setup is the improved design in which the PV panel are equipped with a cooling system in a form of water tube. The tube will serve as a heat transfer mechanism which drains the heat from the PV panel into the water inside the tube. As the water circulates, the heat will be transferred away from the panel and hot water will be additionally obtained. The setup parameters and results obtained are as follow:

i. Setup : Photovoltaic-Thermal system with parallel water tube system
ii. Place : Research Centre for Soft Soil (RECESS) UTHM
iii. Placement time : 10.00 a.m. to 3.00 p.m.
iv. Water flowrate : 0.0156 L/s

3.4.3. Photovoltaic Thermal with Spiral Water Tube Design. The photovoltaic thermal with spiral water tube design is the setup that works under the same principle as the previous PVT-spiral tube design. The difference in this system lies on the design of the water tube. Instead of lining the tube parallel, this design sets the tube position in a spiralling manner. The idea of the design is to increase the contact surface area between the tube and the panel, providing a more even and higher potential of heat removal. The setup parameters and results obtained are as follow:

i. Setup : Photovoltaic-Thermal system with parallel water tube system
ii. Place : Taman Wira Neighbourhood, Parit Raja
iii. Placement time : 9.50 a.m. to 3.00 p.m.
iv. Water flowrate : 0.0046 L/s

3.5. Observations

During the experimentation period, it is observed that the PV panel produced the highest and lowest amount of power output at 12 p.m. and 3 p.m. respectively. The weather is seen to be a bit cloudy at 11 p.m. and gradually getting cloudier on 1 p.m. onwards. A good and clear weather condition is observed at 10 p.m. and 12 p.m. while a slight breeze is felt throughout the day. The PV temperature is observed to be hotter than the roof temperature at all time of the day. The upper area of the roof showed a higher temperature range as compared to the lower portion but slowly gained thermal equilibrium as the days goes on.

The PVT panel with parallel design produced the highest and lowest amount of power output at 11 p.m. and 3 p.m. respectively. Contrary to the weather condition for the previous experiment, the weather showed a good sunny condition all day with exception on 12 p.m. which is the only time on the day that is cloudy. The day is also observed to be slightly windy. The PV temperature is also observed to be hotter than the roof temperature at all time of the day. The upper area of the roof showed a higher temperature range as compared to the lower portion but slowly gained even heat.
distribution at 3 p.m. the PV panel however, is observed to be much hotter as compared to the previous experiment without the water system.

The PVT spiral design panel on the other hand, produced the highest and lowest amount of power output at 1 p.m. and 11 p.m. respectively. This experiment ran under a very good sunny day for all hour. An occasional slight wind was observed at 10 p.m., 11 p.m., and 3 p.m. The PV temperature is also observed to be hotter than the roof temperature at all time of the day. The upper area of the roof showed a higher temperature range as compared to the lower portion but slowly gained even heat distribution at 3 p.m. The PV panel is again, observed to be much hotter as compared to the previous experiment without the water system. It is in fact hotter than the parallel water tube system.

3.6. Data Representation

3.6.1. Ambient Temperature versus Time. Figure 8 shows the relation of ambient temperature versus time for each experiment.

Figure 8. Ambient temperature versus time
3.6.2. Roof Temperature versus Time. Figure 9 shows the relation of roof temperature versus time for each experiment.

![Graph of roof temperature versus time for different setups](image1)

(a) PV setup  
(b) PVT parallel setup  
(c) PVT spiral setup

**Figure 9.** Graph of roof temperature versus time

3.6.3. Panel Temperature versus Time. Figure 10 shows the relation of ambient temperature versus time for each experiment.

![Graph of panel temperature versus time for different setups](image2)

(a) PV setup  
(b) PVT parallel setup
3.6.4. Voltage versus Time. Figure 11 shows the relation of ambient temperature versus time for each experiment.

(c) PVT spiral setup

Figure 10. Panel temperature versus time

Figure 11. Voltage versus time
3.6.5. Current versus Time. Figure 12 shows the relation of ambient temperature versus time for each experiment.

![Figure 12. Current versus time](image)

3.6.6. Power versus Time. Figure 13 shows the relation of ambient temperature versus time for each experiment.

![Figure 13. Power versus time](image)
3.6.7. Water Temperature versus Time. Figure 14 shows the relation of ambient temperature versus time for each experiment.

3.7. Data Calculation

3.7.1. General power efficiency. The general power efficiency represents the average power generated by the panel through recorded data. It can be calculated by using the formula below:

\[
\text{Efficiency}_{\text{avg}} = \frac{P_{\text{avg}}}{P_{\text{max}}} \times 100
\]  

Where:

- \( P_{\text{avg}} \): Average power produced under throughout the experiment time
- \( P_{\text{max}} \): Maximum potential power produced by the panel

3.7.2. Electrical efficiency. Electrical efficiency describes the amount of electrical output generated by the system based on the panel temperature. It can be calculated by using the equation below:

\[
\eta_e = \eta_r [1 - \beta (T_c - T_r)]
\]  

Where:

- \( \eta_e \): Electrical efficiency
- \( \eta_r \): PV module efficiency (16.5%)
\( \beta = \) Temperature coefficients (0.0045°C)
\( T_c = \) Solar cell temperature
\( T_r = \) Ambient temperature

3.7.3. Accumulated heat. The level of heat accumulated on the water system can be calculated by using the equation below:

\[
Q_a = \dot{m} C_p (T_a - T_i)
\]  

Where:
\( \dot{m} \) = Mass flow rate of water used
\( C_p \) = Heat capacity of collector coolant
\( T_a \) = Collector temperature
\( T_i \) = Input fluid temperature

3.8. Direct Water-Cooling Method
The result of the previous three experiments showed that both PVT systems failed to demonstrate that water can be used as a working fluid to decrease the PV panel temperature. This experiment was made in order to justify and prove that water can be used as a working fluid to decrease the PV panel temperature since the theory were failed to be proven during the previous setup due to various factors such as the tube materials among others. Figure 15 shows the assembled prototype. The experimental setup is as follows:

i. Setup : Photovoltaic-Thermal system with direct water flow above the panel surfaces
ii. Place : Taman Wira neighbourhood, Parit Raja
iii. Placement time : 10.00 a.m. to 12.30 p.m.
iv. Water flowrate : not measured

Figure 15. PVT direct water-cooling setup

3.8.1. Observations and Analysis
The direct water-cooling method recorded a significant cooling effect towards the solar panel. In just one hour of operation, the panel temperature was able to be reduced up to 17.8°C. The PV panel also recorded an increase in voltage production which almost peaks to the maximum. The water heating factor however, can only be seen at the early stage of the experiment.
4. Conclusion
A small scaled prototype of PVT solar with water cooling system were successfully designed and fabricated. The prototype was tested and is able to run as it is intended to. The prototype succeeded in generating electricity and hot water at the same time. Thus, the main objective of this study was successfully achieved. The prototype was also able to demonstrate and prove certain solar panel theories such as the inversely proportional relationship between the solar panel temperature and its voltage production capacity, the dependency of the current production towards the solar radiation which is greatly affected by the weather condition, variables that affect the current and voltage generation will affect the power production, the theory that hot water can be produced and used from the cooling system, and the capability of water to cool down a solar panel and increase it voltage generation. The final theory however, was proven by an additional experiment which is not originally included as one of the prototype designs.

Both prototypes however, failed to demonstrate an increase its performance when compared with the standalone PV panel. By generalizing the result, both PVT design which consists of the spiral and parallel water tube recorded a decrease in electrical efficiency by 0.3% and 1.07% respectively when compared to the PV system. Hot water was able to be produced. There is however, a slight increase in the general power generating efficiency showing that the voltage production was slightly stabilized when the PVT system is used. Reasons for the results obtained are deduced through observation and analytical approach which suggest the study has various flaws regarding material selection, possible data handling procedure, and some uncontrollable factors that affected the data collection.

To conclude, the prototype made for this study was able to run as it is intended to. It was able to produce slightly more stable electricity and produce slightly hot water for additional usage. The performance of the prototype however, does not perfectly demonstrate a more efficient performance when compared with the commercialized PV panel due to several flaws existed during the experimentation period. It can be said that the main objective of this study is achieved in terms of proving the working theories behind the PVT system. The study however, failed to demonstrate the PVT theories through a single working prototype. Therefore, as for further study, it is requires improvement in terms of material selection, experimentation handling and data harvesting methodology.

5. References

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