International Journal of Smart Grid and Clean Energy

Testing alternative Photovoltaic-Thermal (PVT) prototype panels

Stuart Baur [a], Nicole Annis [a], Kelly Homan [b] and Joon-Ho Choi [c]

[a] *Civil, Architectural and Environmental Engineering Department, Missouri University of Science & Technology, Rolla, MO*
[b] *Mechancial and Aerospace Engineering Department, Missouri University of Science & Technology, Rolla, MO*
[c] *School of Architecture, University of Southern California, Los Angeles, CA*

Abstract

The purpose of this research was to develop a modular photovoltaic-thermal panel, which would be easily implemented and maintained. Three different prototype panels were tested simultaneously. The system was fixed at an angle of 37.95 ° to the surface of the earth based on the local area (Rolla, Missouri) latitudinal angle to optimize the solar potential energy. The first two panels (PVT A & B) consisted of a highly conductive thermal sheeting and different sized copper tubing. The third panel (PVT C) consisted of copper tubing with an aluminium fin. Thermal images were used to verify the heat transfer across the panels and compare with the standard photovoltaic panel (PV D). The PVT panels A, B and C had thermal efficiencies of 33.6%, 26.4% and 28.7%, respectively. It is found that the change in diameter of piping while maintaining a constant flow rate of the water as working fluid indicates varying improvements to the thermal yields. It is also found that the types of heat sink materials used effects the overall efficiency of thermal output. Furthermore, the impact of photovoltaic/thermal collector design parameters on the electrical and thermal performances has been analysed and discussed.

Keywords: solar, photovoltaic-thermal panel, PVT, solar water heater, thermal gain

1. Introduction

Solar thermal panels (T) typically use a fluid (usually water), air or a combination of the two to reclaim heat to be used for domestic applications. One of the most com-mon thermal panels is a flat plate collector, which is an enclosed insulated metal box with a dark-color absorber plate. Solar thermal panels are relatively inexpensive to produce and are comprised of common building materials. According to the U.S. Department of Energy [1], “a typical residential solar water-heating system reduces the need for conventional water heating by about two-thirds.”

Solar Photovoltaic-Thermal panels (PVT) use Photovoltaic (PV) cells in combination with a thermal (T) flat plate collector. This combined system has several advantages over the separate photovoltaic and thermal panels. Since more than half of the solar radiation is exhausted by the photovoltaic panel as excess heat, the thermal panel fluid aids in the reclaiming of heat from behind the photovoltaic cells. This is most advantageous since photovoltaic cells decrease in electrical efficiency and overall life expectancy as the temperature rises above the standard operating range for an extended amount of time.

Based on a study on PVT domestic systems that water cooled photovoltaic-thermal panels performed better than those cooled by air [2]. The research concluded that the covered panels in a closed loop system performed considerably better than uncovered panels in open loop systems. Another study concluded that covered photovoltaic-thermal yielded higher thermal efficiencies, but uncovered panels typically yield higher electrical efficiencies [3]. A comparison was made between the efficiency and cost of larger systems versus smaller systems [4]. They found that the typical photo-voltaic panels without heat extraction units

* Manuscript received December 29, 2021; revised June 17, 2022.
Corresponding author. *E-mail address:* baur@mst.edu.
doi: 10.12720/sgce.11.3.118-126

(i.e. thermal panels) produce about 38% more electrical energy, but all excess heat is lost from the panels. The team also concluded that the photovoltaic-thermal units became more viable with larger arrays and areas with higher available solar radiation.

Various photovoltaic-thermal panel configurations in Greece were investigated [5]. The report concluded that the use of an additional layer of glazing helped to increase thermal output and a booster diffuse reflector increased electrical and thermal output. Another study compared different PVT panel configurations with a combination of restricted and unrestricted flows using water and air combined cooling [6]. The primary conclusion was that the PV on-sheet-and-tube design was 2% worse in thermal efficiency compared to the channel-below-transparent-PV, but due to ease in fabrication the sheet-and-tube design was favored over more complex configurations. W. He et al. found that daily thermal efficiencies could reach around 40% when the fluid inlet and air ambient temperature were the same [7].

According to M. Bakker et al. [8], the market is ready for cost-effective photovoltaic-thermals. Their study (consisting of 25 m^2) concluded that the photovoltaic-thermal system cost and payback period was two-thirds that of separate photovoltaic and thermal systems of the same size. In a study completed by E. Erdil et al. found that the addition of a thermal system to a standard size (10 m^2) photovoltaic array in Cyprus added approximately 2.8 KWh of thermal energy per day [9]. This reduced the electrical output by about 11.5%, but the pay-back period for the modification was less than 2 years.

Fudholi et.al. [10] performances of photovoltaic thermal (PVT) water collectors were determined under 500–800 W/m^2 solar radiation levels, mass flow rates ranging from 0.011 kg/s to 0.041 kg/s were introduced. This absorber produced a PVT efficiency of 68.4%, a PV efficiency of 13.8%, and a thermal efficiency of 54.6%.

There have been other documents published to help the research and development and the market introduction of photovoltaic-thermal technology, such as ‘PVT Roadmap,’ which was released within Europe attempts to set standards for the testing of PVT panels [11]. The reports outline potential problem areas, when certain tests should be performed, annual energy predictions, and measurement of various collector characteristics and efficiency measurements. Other documents designed to help fascinate the acceptance and standardization of photovoltaic-thermal panels, system designs and PVT modeling as a developing technology with far reaching capabilites [12] [13] [14].

A building-integrated solar thermal electrical panel (STEP) system, which was tested and used on the university’s entry to the Solar Decathlon [15]. The basis for the PVT system was a standing seam metal roof with channels for the copper pipes. The metal roof acted as a fin or absorbing plate for the pipes. The photovoltaic portion was comprised of self-adhered amorphous silicon solar cells connected in series. The en-tire system was encapsulated with low-iron glass to trap and amplify the solar irradiation.

A major issue was emphasized after the testing and application of the solar thermal electric panel (STEP) system on the home. The STEP system was complex to con-struct, install and maintain since the entire system was building-integrated. Creating a modular, easy-to-construct PVT panel was the basis for this research. The following PVT panel designs were easy to construct, used readily available materials, and did not damage or modify the manufactured PV panel. In addition to reducing the labor costs, the modular PVT panels also require less material to construct the panels, be-cause the metal frame that held the photovoltaic panel also contained the pipes and insulation for the thermal panel. The PVTs were also a more efficient use of roof space and required less mounting equipment, compared to separate photovoltaic and thermal systems.

An additional concern relates to the collecting and transference of thermal energy from the collector to the liquid. While there are several parameters to consider in terms of pipe diameter, length of piping, flow rate, placement of piping between each other just to name a few this research focused on a few of these variables to better understand and optimize performance of the proposed PVT system.

2. Materials and Methods

A series of three different photovoltaic-thermal (PVT) panels (Fig. 1) were tested alongside a fourth photovoltaic (PV) panel. The standalone PV panel was used to establish a baseline for the three PVT panels.

Each PVT panel contained one modification from the previous panel as to minimize the number of variables when comparing overall performance.

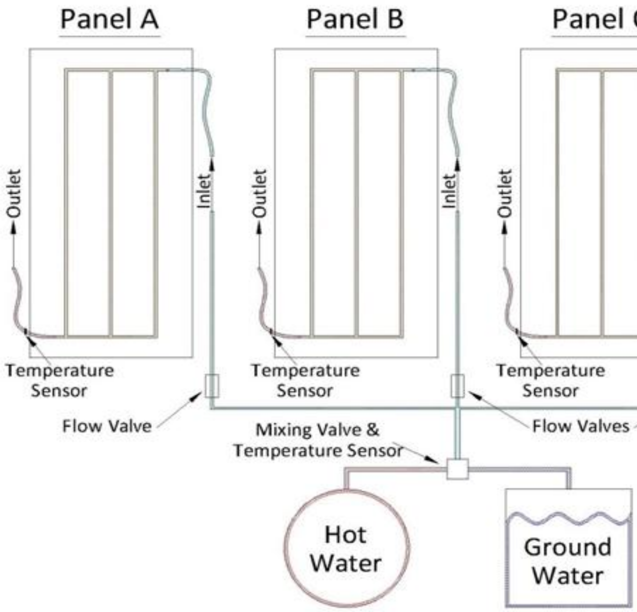


Fig. 1. Thermal system schematic

Panel A (PVT A) was comprised of a BP 4175B, a 175-watt, monocrystalline panel. The thermal section was constructed with three 12.7mm (0.5") copper pipes at 1.26 m (49.5") in length and spaced 22.3 cm (8.75") apart. The longitudinal pipes were connected with two 1.3 cm (0.5") lateral pipes that served as the inlet/outlet for the thermal panel. The more typical fin absorber plate was replaced with a highly conductive thermal sheet. This minimized the variables between the PVT prototypes. The thermal sheeting was a graphite-base laminated sheet was used in place of the more traditional aluminum fin. The sheet came in a roll, which was 45.7 cm (18") wide and had an adhesive backing on one side. One sheet of 3.8 cm (1.5") extruded polystyrene foam board was cut to the size of the photovoltaic frame and grooves were channeled for the thermal panel pipes. Strips of the graphite sheeting were cut to the width of the panel with several extra inches, so the sheeting could be wrapped around the cop-per pipes. Each graphite sheet was tightly fit into the three grooves across the panel, and then kept in place with the adhesive backing. The pipe assembly was tapped into place. Extra strips of the graphite sheeting were cut and attached to the top of the copper pipes, which were not in contact with the foam. These small strips provided a bridge as to minimize any gaps across the back of the photovoltaic panel and created a consistent flow of heat. The completed thermal panel was placed into the back aluminum frame of the photovoltaic panel with the copper pipes and thermal sheet facing the back of the photovoltaic panel. Strips of wood were bolted to the pre-existing holes within the BP 4175B frame. The strips forced the thermal panel into contact with the back of the photovoltaic panel and required no modification to the PV panel itself.

Panel B (PVT B) used the same BP 4175B photovoltaic and was constructed to use the same thermal configuration as PVT A, except for the pipe diameter was 19.1 mm (0.75"). PVT B used the graphite sheeting with three 19.1 mm (0.75") pipes at 1.26 m (49.5") in length and spaced 22.23 cm (8.75") apart. The longitudinal pipes were connected with two 19.1 mm (0.75") lateral pipes that served as the inlet/outlet for the thermal panel. The graphite sheet and 3.8 cm (1.5") extruded polystyrene foam board was cut and placed in the same configuration as PVT A.

Panel C (PVT C) was comprised of the same BP 4175B photovoltaic panel as PVT A and B, and the thermal section used the same pipe size and layout as PVT B. The three 19.1 mm (0.75") copper pipes continuing 1.3 m (49.5") up the length of the back of the photovoltaic panel. The pipes were spaced 22.3

cm (8.75”) apart from each other. Two copper pipes connected the longitudinal pipes laterally on either end. The lateral pipes also served as the inlet/outlet for the thermal panel. PVT C used a more traditional tube-fin configuration for the thermal panel. The absorber plate was made from an extruded aluminum fin with a snap in rounded portion for the pipes and a flat portion to connect to the back side of the panel. The flat portion conducted heat to-ward the copper pipes. The fins were attached only on the three longitudinal pipes, but each pipe had one continuous fin that continued the entire length of the pipe. The pipes and fins were adhered to the back of the photovoltaic panel using a thin layer of silicone caulk. The whole assembly was enclosed with a sheet of 19.1 mm (0.75”) thick extruded polystyrene foam board.

There was one photovoltaic panel tested, Panel D (PV D). It was the same type of BP 4175B, which was a 175-watt, monocrystalline panel with a starting efficiency of 14.7%. The panel was tested alongside the photovoltaic-thermal panels to obtain a baseline for the electrical output and thermal gradation across the panel. Panel D was setup with nothing attached to the backside of it to allow for unobstructed air flow behind the panel.

The experimentation portion of this research was completed at the university in Rolla, Missouri. The data was collected on seven days in late August and early September.

The goal of the setup was to test different photovoltaic-thermal panels and determine the most efficient panel. The testing procedure included setting up the mounting systems, positioning the photovoltaic-thermal panels, connecting the wires and pipes, calibrating the sensors, setting the water flow and collecting the testing data. Testing was done over the course of several days to obtain more reliable data. After the testing was complete, the data was complied, analyzed, and graphed for comparison.

2.1. Description and setup

The panels were were positioned on the ground facing south and tilted at 38 degrees up from the ground. The tilt angle was chosen to optimize the system for year-round in Rolla, Missouri (37.95-degree latitude). A pyranometer was placed between the panels on the frame to record the available irradiance on the panels.

The setup consisted of same make and model panels for each of the three-prototype panels (PVT A, B and C) as well as the one photovoltaic panel (PV D). All four panels were tested alongside one another to decrease the number of weather-based variables. The simultaneous testing also allowed for inlet temperatures to be consistent for all of the panels, enabling a direct comparison between the photovoltaic-thermal panels as shown in Figure 2.

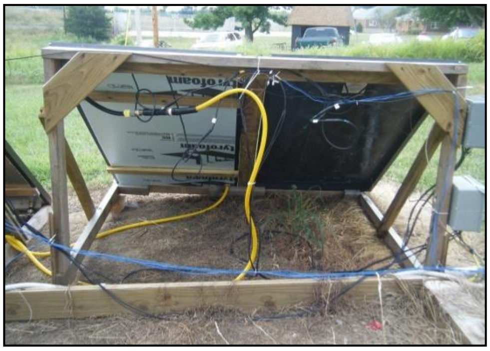
The electrical system consisted of the same four photovoltaic panels connected to a series of shunts and 100 watt lights. The lights were connected directly to the photovoltaic panels, so the data logger was able to record the actual voltage and current output via the shunt. The lights were rated for one hundred watts (100W) and twelve volts (12V) each. The links were used as a load to complete the circuit. Two lights were connected together in series for each panel being tested. The coupled lights, two groups in total, were connected in parallel for both the photovoltaic (PV) and the photovoltaic-thermal (PVT) systems. A schematic of the electrical system, which was used for both the PVT and PV panels, can be found in Figure 3.

The equations for thermal efficiency (Equation 1) and electrical efficiency (Equation 2) are shown below. The x-axis is the difference in inlet and ambient temperatures, divided it by the available solar radiation (Equation 3). A line of best fit was plotted from the data points, and the line equation(s) was generated. Figure 6 graphically shows the thermal efficiency summaries for each photovoltaic-thermal panel.

A.) Front of PVT A (right) and PVT B (left)

B.) Front of PVT C (right) and PV D (left)

C.) PVT A (left) and PVT B (right)



D.) PVT C (left) and PV D (right)

Fig. 2. Front and back of PVT and PV panel

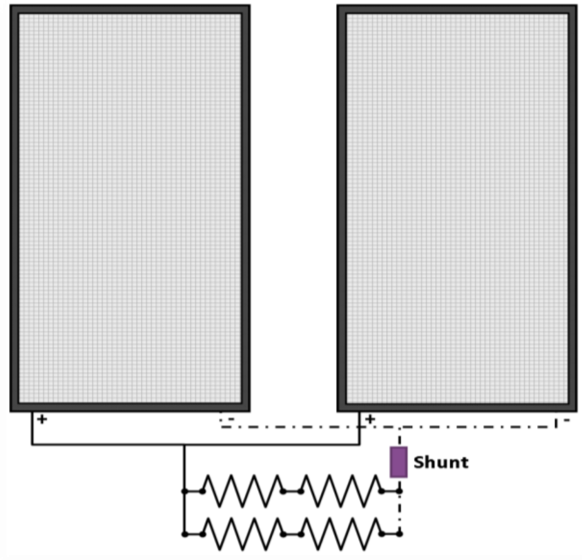


Fig. 3. Electrical system schematic

$$n_{thermal} = \frac{[\dot{m} \cdot C_p \cdot (T_{out} - T_{in})]}{A \cdot G} \tag{1}$$

$$n_{electrical} = \frac{(I \cdot V)_{MPP}}{(A \cdot G)} \tag{2}$$

$$X_{axis} = \frac{(T_{in} - T_a)}{(G)} \tag{3}$$

3. Results

Data points were collected from all temperature, electrical and pyranometer sensors every fifteen (15) seconds during each testing day. Data was gathered approximately three hours before and three hours after solar noon for six days in August and one day in September. The weather was sunny with average temperature of 28.5 C (83.3 °F). Once the data was combined with the weather information, a third-order of two standard deviations statistical analysis was performed on the thermal and electrical efficiencies calculated from the testing data. This removed any data outliers. After the statistical analysis, graphs were generated from the data. Thermal efficiency and electrical efficiency curves were generated for each photovoltaic-thermal panel for both setups.

The overall ambient temperatures ranged from 37.9 ℃ to 17.4 ℃ with an average temperature of 28.9 ℃. The overall ambient irradiance on the panels ranged from 1,060.35 W/m^2 to 23.5 W/m^2 with an average irradiance level of 637.4 W/m^2. The overall wind speeds ranged from 5.08 m/s to negligible with an average wind speed of 1.68 m/s.

The electrical portion of the photovoltaic-thermal system consisted of the electrical wiring, batteries, lights, shunts and the photovoltaic panel. Solar cells, even highly efficient mono-crystalline cells, vary slightly from cell to cell. As a result, photovoltaic panels themselves vary slightly in efficiency and electrical output from one panel to the next. Since the experimental setup used the same make and model panel for each of the three-prototype photovoltaic-thermal panels, the variation in electrical output was minimal to definitively conclude the cause.

Consider the fact, when the sun's energy enters a photovoltaic cells a low proportion of the energy is converted into electricity. A large proportion of the sun's energy is converted to heat. Photovoltaic-thermal panels, however, reclaims a portion of the excess heat by transferring the energy into a liquid in this case water. The condition water may be used directly for domestic purposes with little to no supplemental heat. The results comparing the electrical and thermal efficiency output for both the photovoltaic and photovoltaic-thermal panels is shown below.

Figure 4 illustrates the difference in actual electrical output (shown as dash-dot lines) and thermal gain in terms of power (shown as dashed lines) for 1.9 lpm (0.5 gpm) flow. For the conversion between thermal gain and electrical power the specific heat of water (4186 J/kg ·℃) was used along with the assumption that the conversion was ideal. This assumption made the total system output rather conservative since most electrical hot water heaters are as high as 90% efficient. Panels A, B and C at 1.9 lpm (0.5 gpm) demonstrated thermal gain. The average thermal efficiencies for PVT A, B and C were as such: 33.6%, 26.4% and 28.7%, respectively. A summary of the panel properties and efficiencies at standard conditions can be found in Table 1.

Table 1. Panel A-D properties and results summary

Properties	PVT A	PVT B	PVT C	PV D
Panel Type	PVT	PVT	PVT	PV
Inlet/Outlet Size	1/2" Φ	3/4" Φ	3/4" Φ	-
Conducting Material	Graphite Sheeting	Graphite Sheeting	Aluminium Fins	-
Thermal Efficiency	33.6%	26.4%	28.7%	-

**Power due to actual output plus thermal gain in terms of power*

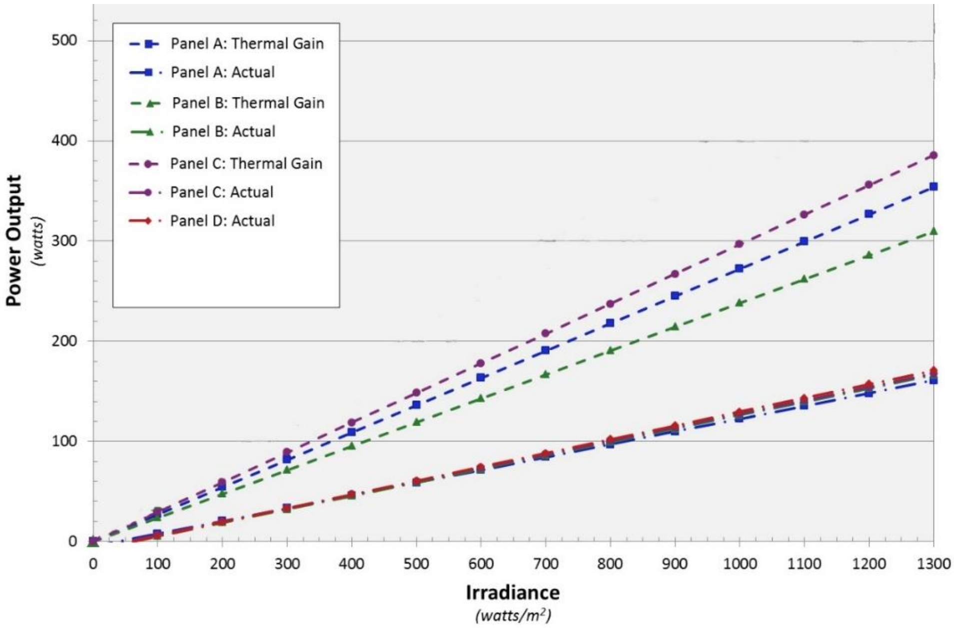


Fig. 4. Comparing thermal gain with actual power output

4. Discussion

The electrical portion of the experiment showed no difference in the rate of electrical outputs for the PVT and PV panels during the two data sets. At lower irradiance levels (around 600 W/m^2 and below) there was minimal difference in the electrical outputs between the stand-alone PV panels or the hybrid PVT panels. Above approximately 600 W/m^2, there was a slight advantage given to the PV systems in terms of amperage output. Above approximately 600 W/m^2, there was a slight advantage given to the PVT systems in terms of voltage output. However, the PV system ultimately had a higher power output (wattage) at high irradiance levels.

The thermal portion of the photovoltaic-thermal system included all water pipes, tanks, pumps, valves and the copper manifold, which was enclosed behind the photovoltaic panel. The delay in the heat transfer from the solar irradiance or changes in the inlet temperatures is an inherent challenge when testing photovoltaic-thermal panels. The lag time associated with the heat transfer from the photovoltaic panel through the absorbing plate and into the fluid or inversely from the fluid to the photo-voltaic panel has been observed in prior studies. As a result, the open-loop system was selected to maximize the thermal gain potential for each panel style and minimize the thermal massing effect.

Using an open-loop system allowed for consistent inlet temperatures over the duration of testing thus providing a consistent statistical comparison between the various thermal gains between setups and fewer outliers.

The main water supply used during testing was the local groundwater, which had an average temperature of approximately 12.8-15.6 ℃ (55-60 ℉). To obtain data for various inlet temperatures, a hot water heater was used in conjunction with the groundwater. The two sources were connected to a mixing value, which allowed the desired inlet temperature to be set and changed when needed. The flow was controlled individually with separate mechanical flow meters on each water line. The flow meters were carefully monitored during the experiment since they worked of pressure in the water lines to stay consistent.

Photovoltaic panels typically have very consistent temperatures across the panel as depicted in the in the thermal images in Fig. 5 and 6 with PV D. The surplus solar energy is radiated into the atmosphere as thermal energy from the back of the panel. Because panels A, B and C are encased with insulation on the back side of the panel, the capture thermal energy is transferred to the pipes. This thermal transference to the fluid in the pipes would potentially provide conditioned water to be used in domestic hot water supply.

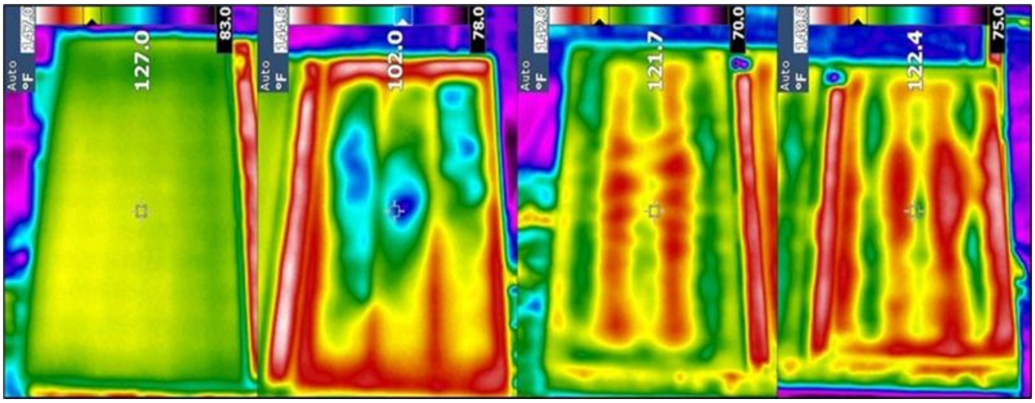


Fig. 5. Thermal images of the front of panels D, C, B and A

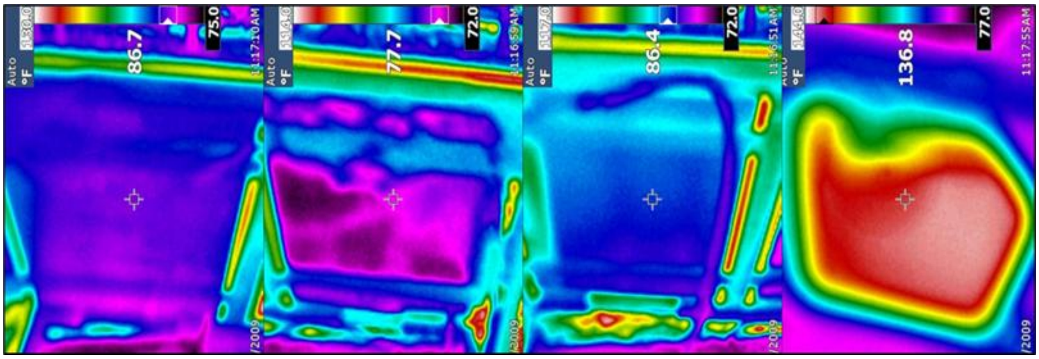


Fig. 6. Thermal images of the back of panels A, B, C and D

5. Conclusion

Three different prototype photovoltaic-thermal panels using water as the cooling fluid were tested simultaneously. The Panel A and B consisted of a highly conductive thermal sheeting and different sized copper pipes 12.7mm and 19.1mm, respectively (0.5” and 0.75”, respectively). The Panel C consisted of 19.1mm (0.75”) copper pipes with an aluminum fin. Thermal images were used to verify the heat transfer across the panels and compare the amount of heat radiating off the back of the photovoltaic-thermal panels versus the standard photovoltaic panel.

The photovoltaic-thermal panels A, B and C had thermal efficiencies of 33.6%, 26.4% and 28.7%, respectively. A comparison of the PVT panels between the thermal images indicated relatively uniform thermal distribution along the runs of the piping using graphite sheets for both panels A and B as compared to the uneven distribution of thermal distribution with the aluminum fins in Panel C. The results also showed that while the flow rate remain constant for each of the three PVT systems Panel A used three rows of copper pipes the diameter 12.7mm (0.5”) running length wise at 1.26 m (49.5”) and spaced 22.3 cm (8.75”) apart yielded the highest efficiency at 33.6%.

As noted in Figs. 5 and 6, the thermal images of the panel fronts and backs show the cool fluid within the thermal panels helps reduce the temperature of the photovoltaic panel. The temperature gradient was the result of the fin efficiency, or the absorbing plate’s ability to conduct heat towards the fluid.

Conflict of Interest

"The authors declare no conflict of interest".

Author Contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Baur and Annis; methodology, Annis; validation, Homan, Choi and Baur; formal analysis, Annis; investigation, Annis; resources, Annis; data curation, Annis; writing—original draft preparation, Annis; writing—review and editing, Baur; visualization, Annis; supervision, Baur; project administration, Baur; funding acquisition, Baur.

Acknowledgements

The authors would like to acknowledge the gifts-in-kind from Watts Radiant, Michael and Dan Chiles. They were instrumental in providing the series of supplies and equipment in developing the PV-T. Additionally acknowledgement to Mr. Joel Lamson for his creative input and assistance in developing the latest PVT system known as STEP here at Missouri University of Science and Technology.

References

[1] U.S. Department of Energy: Energy Efficiency & Renewable Energy. Solar Water Heating. 20 July 2006. [Online]. Available: http://www1.eere.energy.gov/solar/m/sh_basics_water.html. [Accessed 16 June 2010].

[2] Zondag H and Helden W. PV-thermal domestic systems. In: *Proc. of 3rd World Conference on Photovoltaic Energy*, Osaka, Japan, 2003.

[3] Mohamed H, M'barek F, Monssif N, Adil Ch. Performance of a photovoltaic-thermal solar col-lector using two types of working fluids at different fluid channels geometry. *Renewable Energy*, 2020; 162: 1723-1734.

[4] Kalogirou S. and Tripanagnostopoulos Y. Hybrid PV/T solar systems for domestic hot water and electricity production. *Energy Conversion and Management*, 2006; 47: 3368-3382.

[5] Tripanagnostopoulos Y, Nousia T, Souliotis M and Yianoulis P. Hybrid photovoltaic/thermal solar systems. *Solar Energy*, 2002; 72(3): 217-234.

[6] Zondag H, Vries D, Helden W, Zolingen R, and Steenhoven A. The yield of different combined PV-thermal Col-lector designs. *Solar Energy*, 2003; 74: 253-269.

[7] He W, Chow T, Ji J, Lu J, Pei G, Chan L. Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water. *Applied Energy*, 2006; 83: 199-210.

[8] Bakker M, Jong M, Strootman K. PVT Panels: Fully renewable and competitive. In: *Proc. of ISES Solar World Congress 2003*, Goteborg, Sweden, 2003.

[9] Erdil E, Ilkan M, Egelioglu F. An experimental study on energy generation with a photovoltaic thermal hybrid system. *Energy*, 2008; 33: 1241-1245.

[10] Fudholi A, K. S. Performance analysis of photovoltaic thermal (PVT) water collectors. *Energy Conversion and Management*, 2014; 78: 641-651.

[11] Collins M and Zondag H. Recommended standard for the characterization and monitoring of PV/thermal systems. *Solar Heating & Cooling Programme*, 2008.

[12] Kazem HA. Evaluation and analysis of water-based photovoltaic/thermal (PV/T) system. *Case Studies in Thermal Engineering*, 2019; 13.

[13] Ibrahim A, Fudholi A, Sopian K, Othman MY, Ruslan MH. Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. *Energy Conversion and Management*, 2014; 77: 527-534.

[14] Joshi S, Dohble A. Photovoltaic-Thermal systems (PVT): Technology review and future trends. *Renewable and Sustainable Energy Reviews*, 2018; 92: 848-882.

[15] Baur S, Lamson J. Thermal energy performance of a solar thermal electric panel. *Journal of Energy Engineering*, September 2012; 138(3).