Development of photovoltaic thermal systems in hot countries

Mohammad ALOBAID [1], Dominic O'CONNOR [1], Ben HUGES[1]

[1] Energy Engineering Group 2050, The University of Sheffield
The Arts Tower, Level 1, Western Bank, Sheffield, S10 2TN, msalobaid1@sheffield.ac.uk.

Abstract: Alternative renewable sources of energy such as solar energy, wind energy and geothermal energy are required to produce electricity in order to reduce CO2 and greenhouse gas emissions. Research in photovoltaic thermal collector systems (PVT) in hot countries has not yet made substantial progress. The opportunity to utilize the outlet PVT water temperature to be used for cooling systems such as absorption cooling systems, adsorption cooling systems and desiccant cooling systems has not been investigated in hot climatic conditions.

The main objective of this study is to investigate the effect of PVT outlet water temperatures and solar cell temperature on both electrical and thermal efficiency especially in extremely hot climate conditions. The factors that affect the heat transfer rate of PVT collectors such as ambient temperature have also been discussed and the PVT outlet fluid temperature is optimized in order to reach the highest overall efficiency. Computational fluid dynamics (CFD) has been used to develop a PVT system and the results validated by experimental data from the literature. The PVT was examined for different ambient temperatures which varied from 288 K to 325 K and for different inlet temperatures which varied from 294.4 K to 385 K. Thermal efficiency of 81 % has been achieved at 325 K ambient temperature and 294.4 K inlet temperature. Average electrical efficiency is also affected by ambient and inlet temperature and was in the range of 10 % to 15 %. A maximum increase of 11.8 K in the inlet temperature has been achieved and further investigation is required to increase the outlet fluid temperature.

Keywords: Photovoltaic, PVT, CFD, Thermal efficiency, Electrical efficiency

1. INTRODUCTION

Solar energy can be transformed to useful forms such as heat or electricity by using a solar collectors. Photovoltaic thermal collectors or hybrid PV/T systems utilise solar radiation to produce both electricity and thermal energy. These systems have a combination of solar cells with solar thermal collector. Water is the most common fluid that is used to remove heat from the collector but there are many options such as air or Nano fluid. Sheet and tube PVT is the most common configuration where PV cells are fixed with flat plate collector. The main components of PVT are the PV cells to produce electricity, channels or tube for the fluid, absorber plate and thermal insulation to minimize the heat loses as shown in Figure 1.

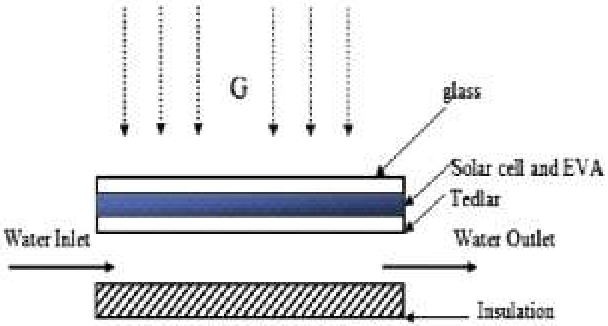

Figure 1 Schematic diagram PVT collector (Bahaidarah, Subhan et al. 2013, Bahaidarah, Rehman et al. 2013).

Photovoltaic thermal collectors (PVT) have been used for several applications such as solar cooling systems in order to produce both electricity and thermal energy. This also can improve electrical efficiency by 23.8 % more than the conventional photovoltaic panel (PV) (Fang, Hu et al. 2010). Thermal and electrical efficiency for PVT in cooling applications were in the range of 0.23 to 0.35 and 0.1 to 0.17 respectively(Calise and Vanoli 2012), (Vokas, Christandonis et al. 2006), (Fang, Hu et al. 2010), (Phongsitong, Jaikla et al. 2006), (Papoutsis, Koronaki et al. 2017), (Koronaki, Papoutsis et al. 2016), (Calise, Dentice d'Accadia et al. 2016). For concentrated photovoltaic systems (CPVT) thermal efficiency was in the range of 0.32 to 0.63 while electrical efficiency in the range of 0.08 to 0.4 (Mittelman, Kribus et al. 2007), (Pean, Gennari et al.), (Buonomano, Calise et al. 2013), (Calise, Cipollina et al. 2014), (Xu and Kleinstreuer 2014), (Calise, d'Accadia et al. 2013), (Garcia-Heller, Paredes et al. 2014).

In the last few years, there has been a growing interest to improve the efficiencies of solar collectors. Recently (Alobaid, Hughes et al. 2017) reviewed the use of solar collectors for cooling system which included experimental and computational projects. The authors highlighted that the thermal collectors efficiency were in the range of 0.06–0.64 and sufficient efficiency for the PVT could be achieved in the range of outlet temperature of 60–80 °C. Generally the performance of the solar collector was highly affected by ambient temperature, inlet temperature, solar radiation and the configuration of the collectors. (Guo, Lin et al. 2017) reviewed the utilization of PVT for desiccant cooling and dehumidification that required a temperature in the range of 50 ºC to 60 ºC. The study concluded that the most important design factors to achieve high outlet PVT temperature were mass flowrate, glazed cover and hydraulic channel geometry.

(Aste, del Pero et al. 2014) classified PVT water collectors into four main types based on heat exchanging method and water flow pattern. These types are sheet and tube, channel free flow and two absorber collector. Figure 2 shows the design and the components of these types.

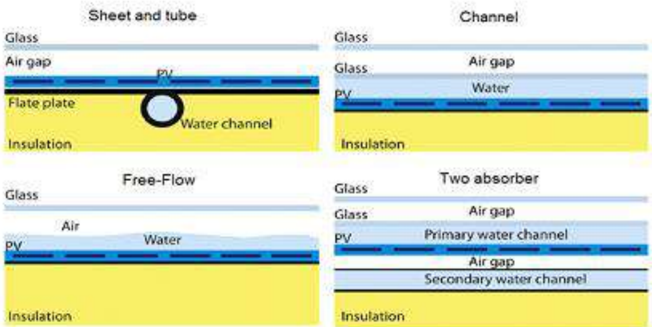

Figure 2 PVT water collectors (four main types in (Aste, del Pero et al. 2014)).

The authors reported that the maximum thermal and electrical efficiency of sheet and tube PVT for flow rate of 0.02 Kg/s-m^2 were 66% and 14% respectively whereas for the PVT box channel were 70% and 15% respectively. The authors also highlighted the main absorber materials that are usually used as a main component in PVT included copper, aluminium, steel or polymer. The main features affecting efficiency were thickness, density, thermal conductivity and heat capacity. Table 1 shows examples for main features of absorber materials.

Table 1: Main features of absorber materials(Aste, del Pero et al. 2014).

Absorber material	Thickness (mm)	Density (kg/m3)	Thermal conductivity (W/m K)	Heat capacity (J/kg K)
Copper	~0.3	8920	380	350
Aluminum	~1	2700	160	900
Steel	~2	7860	50	450
Polymer	~2–3	900–1500	0.2–0.8	1200–1800

(Cristofari, Notton et al. 2009) developed a finite difference model for a PVT system in order to study thermal and electrical efficiency. This model used water as working fluid and pc-Si PV panel to supply hot water and electricity for residential purposes. They reported that yearly average thermal efficiency was about 55% and electrical efficiency of 12.7 %. They also reported the advantages of using copolymer in the PVT which can reduce the cost and weight of the module.

(Dubey and Tay 2014) developed a model of 52 PVT modules that produced 10 KW$_p$ as a nominal electrical capacity. Several assumptions had been made to solve energy equations and calculate the performance of the system. The assumptions included that heat capacity for the materials in the system was neglected compared to the heat capacity of the water. One dimensional heat transfer and steady state method was applied in the study, and no temperature stratification in the storage tank. In the experiment condition, the authors calculated the optimum flowrate for the PVT system to be 0.039 Kg/(s m^2) and the average thermal and electric efficiency were 34% and 12% respectively.

(Yazdanifard, Ebrahimnia-Bajestan et al. 2016) investigated the effect of solar radiation, Reynolds number and the geometry on the performance of flat plat PVT system. Mathematical model has been developed based on several assumptions such as one dimensional heat transfer. Specific heat of the materials and temperature dependence were neglected except for water. The authors highlighted that the glazed PVT system provides higher efficiency compared to unglazed system. They also reported that the length of the collector affects the total efficiency negatively.

(Fortuin, Hermann et al. 2014) reported the important parameters that affected the overall efficiency of thermal photovoltaic modules included characteristics of the cover and absorber of the PVT. These characteristics include transmittance (τ), absorbance (α) and emittance (ϵ). Figure 3 illustrate that the solar energy received by the surface of the PVT module transforms to electricity, thermal energy or wasted energy to the environment.

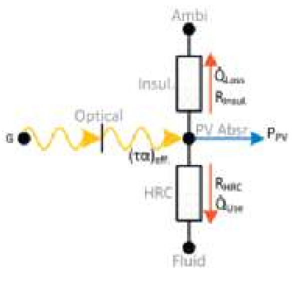

Figure 3 Illustration of thermal analysis model of a PVT collector (Fortuin, Hermann et al. 2014).

(Spertino, D'Angola et al. 2016) investigated a theoretical PVT model by validating the data with outdoor experiment. The authors mentioned that the thickness of the PV layer usually is not provided by manufacturers because it's sensitive information. The configuration of the PVT included polycarbonate front sheet, thermoplastic polyurethane (TPU1), m-si solar cell with anti-reflective coating (ARC) and water channel. The authors used thermal model to calculate temperatures at interfaces by solving energy balance equation at each layer. The authors assumed, one dimensional heat transfer, constant thermal conductivity, contact resistances between layers were neglected, cell thickness was neglected, uniform surface cell temperature, and thermal absorptivity for TPU and PC were neglected. The authors highlighted that the energy gain from the PVT is strongly affected by the flow rate of water and the value of flow rate depends on the location and climate condition.

In this paper, Computational fluid dynamics (CFD) has been used to develop a PVT system and the results validated by experimental data from (Spertino, D'Angola et al. 2016). The aim of this study is to investigate the effect of PVT outlet water temperatures and solar cell temperature on both electrical and thermal efficiency for different range of ambient temperature, solar radiation and inlet water temperature.

2. CFD MODELLING AND METHODOLOGY

Computational fluid dynamics (CFD) has been used to develop a PVT system based on the experimental geometry from the literature (Spertino, D'Angola et al. 2016). The experimental layout, structure of the PVT and the geometry of the PVT in this study are shown in Figure 4. The unglazed photovoltaic thermal module has been developed in Ansys. The module consists multilayer of polycarbonate sheet, thermoplastic polyurethane (TPU1), m-si solar cell with anti-reflective coating (ARC) and water channel. In this study, radiation model was discrete ordinate (DO) with laminar viscous model. Semi-transparent boundary condition has been applied on the top layer of the PVT while the layers which are placed under the PV panel were opaque. Convection boundary condition has been applied on the top and bottom layers. The inlet water flowrate and temperature were 0.0139 kg/s and 294.4 K respectively with regards to the experiments boundary conditions in (Spertino, D'Angola et al. 2016). Table 2 shows materials property for the PVT.

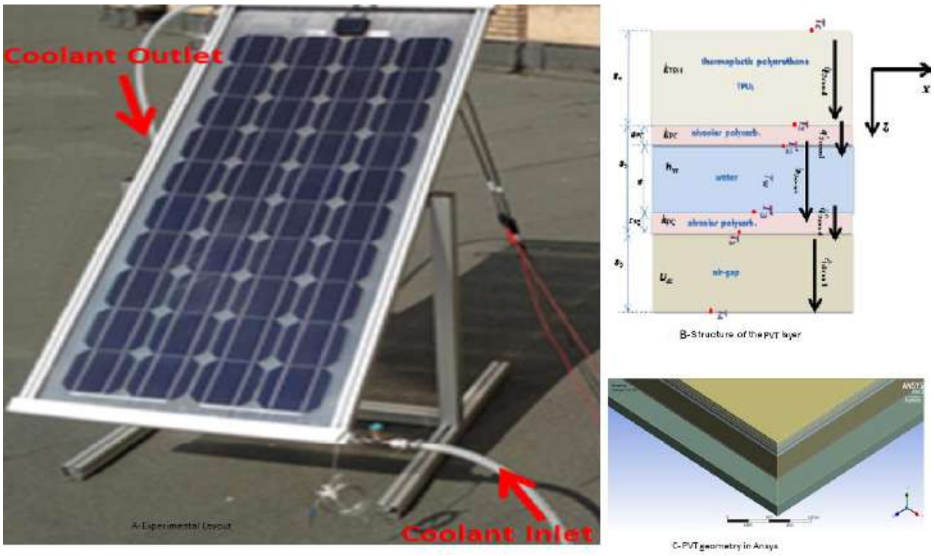

Figure 4 A) Experimental layout(Spertino, D'Angola et al. 2016) B) Structure of the PVT(Spertino, D'Angola et al. 2016) C- Ansys Geometry of the PVT in this study.

Table 2: The values used for the PVT during the simulation.

Material	Density (kg/m3)	Thermal conductivity (W/m K)	Heat capacity (J/kg K)
PV	347	1.2	800
TPU	600	0.2	2500
PC	1190	0.2	1200

Thermal efficiency of PVT collector is the ratio of the collected energy to the energy received by solar collector surface. It is calculated by the following expression (Gunjo, Mahanta et al. 2017) (Chow 2010) (Dubey and Tay 2014):

$$\eta_{th} = C_p\, \dot{m}\, \frac{T_o - T_i}{G\ A_c} \qquad (1)$$

Where: m'. : Mass flowrate of the coolant (kg/s), C_p : Specific heat of the coolant,(kJ/kg-K), A_c: Collector area, (m^2), T_i : Inlet temperature of the coolant, (K), T_o : Outlet temperature of the coolant which is calculated by the CFD model (Fluent) in this study, (K), G: Incidence solar irradiance normal to the surface, (W/m^2).

The method that widely used in the literature to calculate PVT electrical performance is to calculate the maximum current power and voltage especially for experimental projects (Bahaidarah, Subhan et al. 2013). The method proposed here is to calculate electrical performance based on the average temperature of the PV layer which is determined by the CFD model. The following expression is used to calculate electrical efficiency (Dubey and Tay 2014):

$$\eta_{el} = \eta_o[1 - \beta\,(T_{sc} - 25\ ^oC) \qquad (2)$$

β is the photovoltaic temperature coefficient.

3. MODEL VALIDATION

Computational fluid dynamics (CFD) which has been used to develop a PVT system and the results were validated by experimental data from the literature (Spertino, D'Angola et al. 2016). The percentage error in water outlet temperature between the simulation results and the published work was 0.22 %. Figure 5 shows the agreement between them at different location between the inlet and outlet.

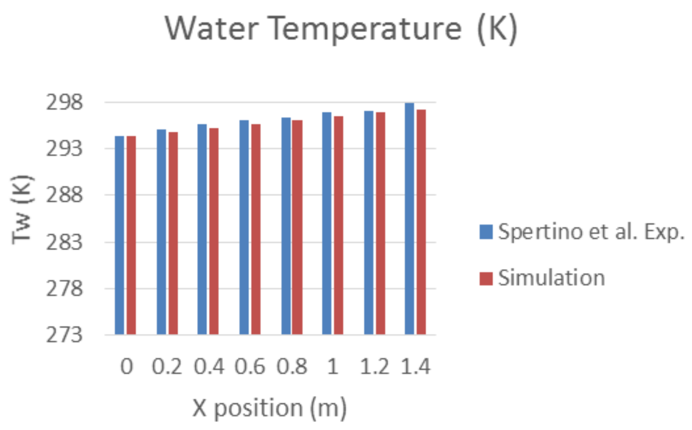

Figure 5 PVT Water temperature at different location between the inlet and outlet

The percentage error in PV temperature between the simulation and the published work was 0.47 % and Figure 6 shows the agreement between them at different location between the inlet and outlet.

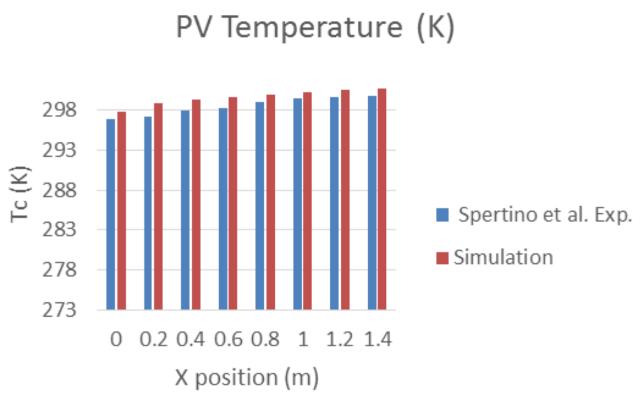

Figure 6 PVT cell temperature at different location between the inlet and outlet

4. RESULTS AND DISCUSSION

The PVT system is simulated in Ansys in order to illustrate temperature distribution in the PV panel and through the water stream which enters the PVT parallel to the x-axis. Temperature distribution has been studied for the PVT model for different ambient and inlet water temperature. For all cases, the minimum PV temperature occurred in the entrance and get hotter due to the increase in the water stream until the outlet. Figure 7 shows temperature contour for the PV panel.

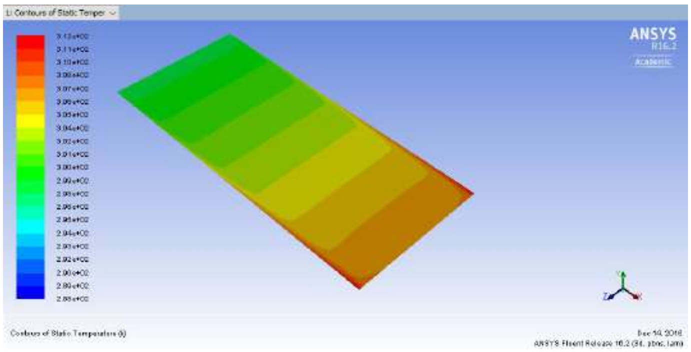

Figure 7 Contours of static temperature of the Photovoltaic Panels (PV).

The inlet water in the PVT panel then increased due to the heat transfer from PV panel then leaves the PVT at the maximum temperature. Figure 8 illustrates water stream temperature contour.

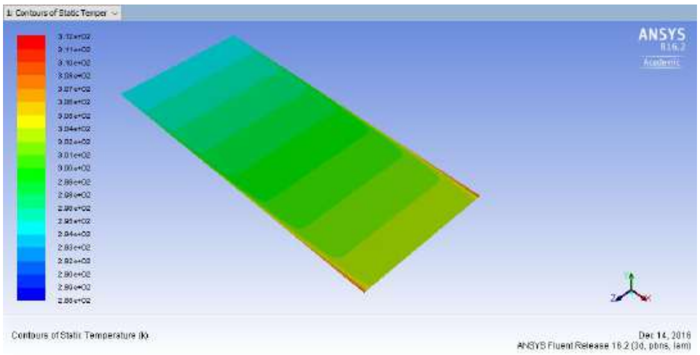

Figure 8 Contours of static temperature inside the water channel for the PVT.

4.1. Effect of inlet water temperature on PVT performance

Different inlet water temperatures were applied in the PVT in order to illustrate the effect on outlet fluid temperature, PV cell temperature and PVT performance. At ambient temperature (Ta) of 318 K, a maximum increase of 10.1 K in the inlet water temperature has been achieved at the minimum inlet temperature (Tin=294.4 K). PVT cell temperature was also influenced by inlet water temperature. There was an increase in both outlet water temperature and average cell temperature due to the increase in inlet water temperature until specified point where both of them have the same value. At this point, the heat transfer from the top panel to the water through the PV panel equal to zero. From the inlet to the end of the PVT, the water temperature got close to the PV cell temperature and then decreased heat transfer from the PV cell to the water. Figure 9 shows PVT outlet water temperature and cell temperature for different inlet water temperature.

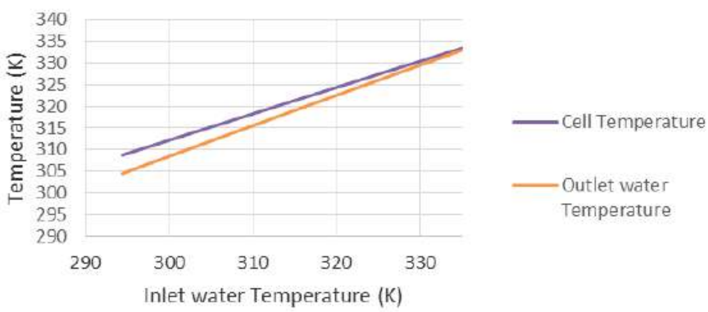

Figure 9 PVT outlet water temperature and average cell temperature for different inlet water temperature.

Thermal efficiency decreased due to the increase in the inlet temperature. For 318 K ambient temperature, maximum thermal efficiency of 69 % was achieved at the minimum inlet temperature where the water inters at 294.4 K. Electrical efficiency decreased from 14.3% to 12.8 % due to the increase in the inlet water temperature of the PVT from 294.4 K to 328.5 K. Figure 10 shows PVT thermal and electrical efficiency for different inlet water temperature. The maximum inlet temperature that applied in this study was 328.5 K where there is no increase to the inlet temperature (T_{in}=T_o).

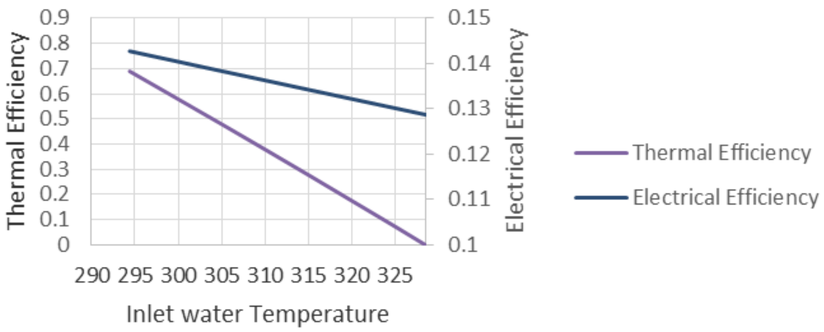

Figure 10 PVT thermal and electrical efficiency for different inlet water temperature at Ta= 318 K.

4.2. Effect of outlet water temperature on PVT performance

Thermal and electrical efficiency are also influenced by outlet water temperature of the PVT. Due to the increase in outlet temperature from 304.5 K to 328.5 K, thermal efficiency decreased from 69% to zero, and Electrical efficiency decreased from 14.3% to 12.8 % as in Figure 11.

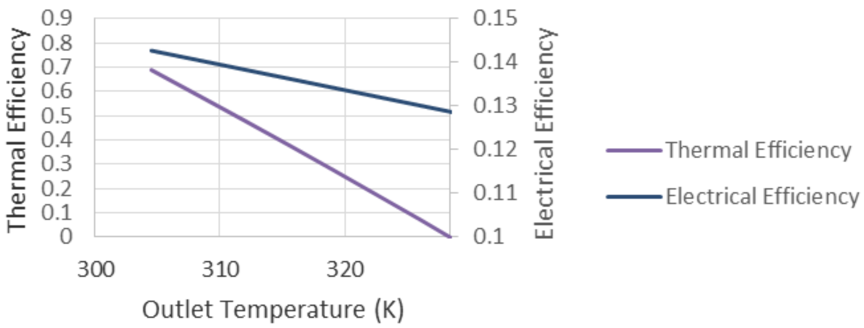

Figure 11 PVT thermal and electrical efficiency for different outlet water temperature at Ta= 318 K.

4.3. Effect of PV cell temperature on PVT performance

Figure represents thermal and electrical efficiency for different average PV temperature of the PVT. Due to the increase in the average PV temperature from 308.8 K to 329.5 K, thermal efficiency decreased from 69% to zero, and electrical efficiency decreased from 14.3% to 12.8 %.

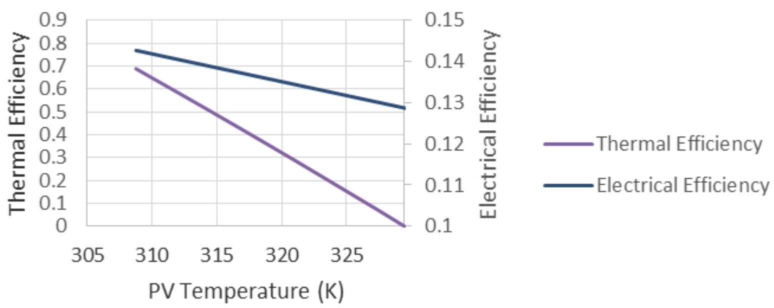

Figure 12 PVT thermal and electrical efficiency for different outlet water temperature at Ta= 318 K.

4.4. PVT performance for different ambient temperature

In the study, five different ambient temperatures have been examined by varying the inlet water temperature. The performance of the PVT was highly affected by the ambient temperature. There was an increase in average cell temperature due to the increase in the ambient temperature for the all cases. Figure 13, shows that there was an average increase of 0.3 K in the PV temperature for each ambient degree increased.

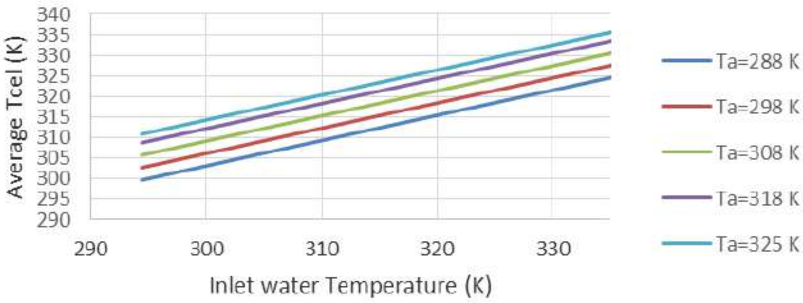

Figure 13 PVT average cell temperature Vs inlet water temperature for different ambient temperature.

Figure 14 represent the outlet water temperature versus inlet water temperature for different ambient temperature. It shows that there was an increase of 0.24 K in the outlet water temperature for each ambient degree increased.

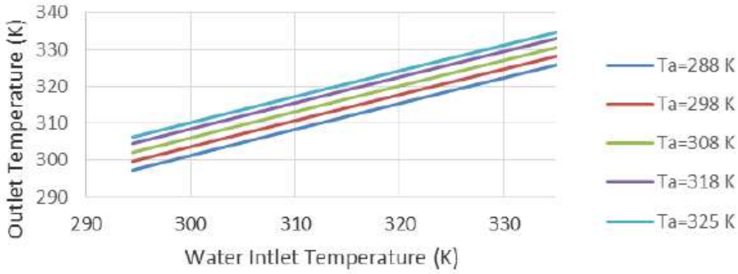

Figure 14 PVT outlet water temperature Vs inlet water temperature for different ambient temperature.

Figure 15 represent the thermal efficiency versus inlet water temperature for different ambient temperature. It shows that there was an increase of 1.65 % in thermal efficiency for each ambient degree increased.

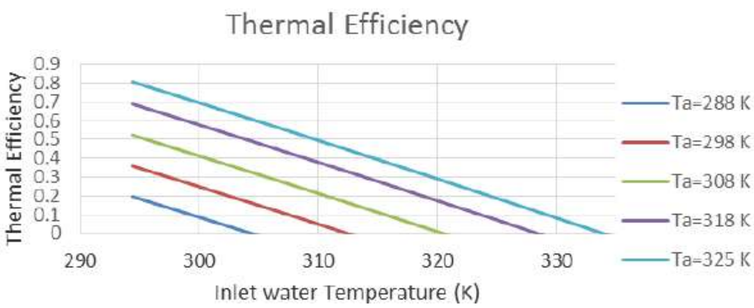

Figure 15 PVT thermal efficiency Vs inlet water temperature for different ambient temperature.

On contrast, there was a decrease in electrical efficiency due to the increase inlet temperature. Figure 16 shows that a decrease of 0.02 % in electrical efficiency was reported for each ambient degree increased.

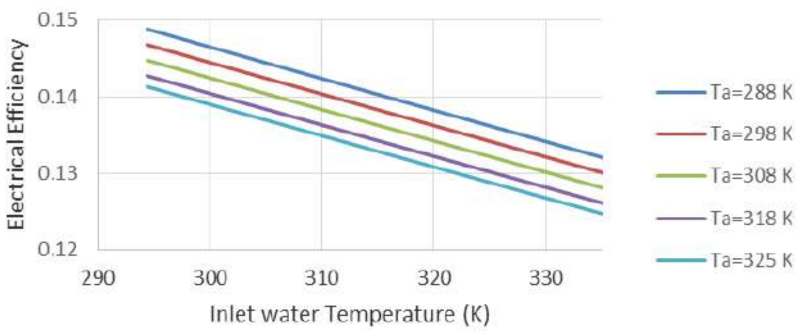

Figure 16 PVT average efficiency Vs inlet water temperature for different ambient temperature.

5. CONCLUSION

Sufficient efficiency for the PVT was achieved in the range of outlet temperature of 304.5 K to 328.5 K. Despite the fact that there has been an improvement of the electrical efficiency due to reduce the PV temperature by the coolant in the PVT system, there is an opportunity to utilize the outlet water from PVT for cooling purposes. Electrical and thermal efficiency are largely affected by ambient temperature and global solar radiation.

CFD was used in this study to develop a PVT system and the results was validated by experimental data from the literature with less than 0.5 % error in both water outlet temperature and PV temperature. This system was used to investigate the effect of PVT outlet water temperatures and solar cell temperature on both electrical and thermal efficiency for different ambient temperature. Maximum thermal efficiency of 81 % was achieved at 325 K ambient temperature and 294.4 K inlet temperature and maximum increase of 11.82 K in the inlet temperature was achieved. Average electrical efficiency was in the range of 10 % to 15 %. Further developments of the present research are under study in order to increase the outlet fluid temperature and enhancing the PVT performance. More investigation is also required in order to increase the heat transfer rate and optimize the length of collector.

6. REFERENCES

ALOBAID, M., B. Hughes, J. K. Calautit, D. O'Connor and A. Heyes (2017). "A review of solar driven absorption cooling with photovoltaic thermal systems." Renewable and Sustainable Energy Reviews **76**: 728-742.

ASTE, N., C. del Pero and F. Leonforte (2014). "Water flat plate PV–thermal collectors: A review." Solar Energy **102**: 98-115.

BAHAIDARAH, H., A. Subhan, P. Gandhidasan and S. Rehman (2013). "Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions." Energy **59**: 445-453.

BUONOMANO, A., F. Calise and A. Palombo (2013). "Solar heating and cooling systems by CPVT and ET solar collectors: a novel transient simulation model." Applied Energy **103**: 588-606.

CALISE, F., A. Cipollina, M. D. d'Accadia and A. Piacentino (2014). "A novel renewable polygeneration system for a small Mediterranean volcanic island for the combined production of energy and water: Dynamic simulation and economic assessment." Applied Energy **135**: 675-693.

CALISE, F., M. D. d'Accadia, A. Palombo and L. Vanoli (2013). "Dynamic simulation of a novel high-temperature solar trigeneration system based on concentrating photovoltaic/thermal collectors." Energy **61**: 72-86.

CALISE, F., M. Dentice d'Accadia, R. D. Figaj and L. Vanoli (2016). "A novel solar-assisted heat pump driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic optimization." Energy **95**: 346-366.

CALISE, F. and L. Vanoli (2012). "Parabolic trough photovoltaic/thermal collectors: design and simulation model." Energies **5**(10): 4186-4208.

CHOW, T. T. (2010). "A review on photovoltaic/thermal hybrid solar technology." Applied Energy **87**(2): 365-379.

CRISTOFARI, C., G. Notton and J. L. Canaletti (2009). "Thermal behavior of a copolymer PV/Th solar system in low flow rate conditions." Solar Energy **83**(8): 1123-1138.

DUBEY, S. and A. A. Tay (2014). "The theoretical modelling and optimization of a 10 KWP photovoltaic thermal system for a student hostel in Singapore." International Journal of Green Energy **11**(3): 225-239.

FANG, G., H. Hu and X. Liu (2010). "Experimental investigation on the photovoltaic–thermal solar heat pump air-conditioning system on water-heating mode." Experimental Thermal and Fluid Science **34**(6): 736-743.

FORTUIN, S., M. Hermann, G. Stryi-Hipp, P. Nitz and W. Platzer (2014). "Hybrid PV-thermal Collector Development: Concepts, Experiences, Results and Research Needs." Energy Procedia **48**: 37-47.

GARCIA-HELLER, V., S. Paredes, C. L. Ong, P. Ruch and B. Michel (2014). "Exergoeconomic analysis of high concentration photovoltaic thermal co-generation system for space cooling." Renewable and Sustainable Energy Reviews **34**: 8-19.

GUNJO, D. G., P. Mahanta and P. S. Robi (2017). "CFD and experimental investigation of flat plate solar water heating system under steady state condition." Renewable Energy **106**: 24-36.

GUO, J., S. Lin, J. I. Bilbao, S. D. White and A. B. Sproul (2017). "A review of photovoltaic thermal (PV/T) heat utilisation with low temperature desiccant cooling and dehumidification." Renewable and Sustainable Energy Reviews **67**: 1-14.

KORONAKI, I. P., E. G. Papoutsis and V. D. Papaefthimiou (2016). "Thermodynamic modeling and exergy analysis of a solar adsorption cooling system with cooling tower in Mediterranean conditions." Applied Thermal Engineering **99**: 1027-1038.

MITTELMAN, G., A. Kribus and A. Dayan (2007). "Solar cooling with concentrating photovoltaic/thermal (CPVT) systems." Energy Conversion and Management **48**(9): 2481-2490.

PAPOUTSIS, E. G., I. P. Koronaki and V. D. Papaefthimiou (2017). "Numerical simulation and parametric study of different types of solar cooling systems under Mediterranean climatic conditions." Energy and Buildings **138**: 601-611.

PEAN, T. Q., L. Gennari, B. W. Olesen and O. B. Kazanci Nighttime radiative cooling potential of unglazed and PV/T solar collectors: parametric and experimental analyses. 8th Mediterranean Congress of Heating, Ventilation and Air-Conditioning.

PHONGSITONG, J., S. Jaikla, T. Nualboonrueng and P. Sichanutgrist (2006). A-Si Photovoltaic/Thermal Solar Air-Conditioning System in Thailand. Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on, IEEE.

SPERTINO, F., A. D’Angola, D. Enescu, P. Di Leo, G. V. Fracastoro and R. Zaffina (2016). "Thermal–electrical model for energy estimation of a water cooled photovoltaic module." Solar Energy **133**: 119-140.

VOKAS, G., N. Christandonis and F. Skittides (2006). "Hybrid photovoltaic–thermal systems for domestic heating and cooling—a theoretical approach." Solar Energy **80**(5): 607-615.

XU, Z. and C. Kleinstreuer (2014). "Concentration photovoltaic–thermal energy co-generation system using nanofluids for cooling and heating." Energy Conversion and Management **87**: 504-512.

YAZDANIFARD, F., E. Ebrahimnia-Bajestan and M. Ameri (2016). "Investigating the performance of a water-based photovoltaic/thermal (PV/T) collector in laminar and turbulent flow regime." Renewable Energy **99**: 295-306.