Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Simulation Study of Computational Fluid Dynamics on Photovoltaic Thermal Water Collector with Different Designs of Absorber Tube

Open Access

Mohd Afzanizam Mohd Rosli[1,2], Yap Joon Ping[1,*], Suhaimi Misha[1,2], Mohd Zaid Akop[1,2], Kamaruzzaman Sopian[3], Sohif Mat[3], Ali Najah Al-Shamani[4], Muhammad Asraf Saruni[1]

[1] Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2] Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3] Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[4] Al-Furat Al-Awsat Technical University, 31003 Kufa, Iraq

ARTICLE INFO

Article history:
Received 31 May 2018
Received in revised form 24 August 2018
Accepted 2 November 2018
Available online 2 December 2018

Keywords:
Photovoltaic thermal collector, CFD Ansys Fluent, temperature outlet, efficiency

ABSTRACT

The purpose of this research is to investigate and comparing the thermal efficiency, electrical efficiency and total efficiency of photovoltaic thermal collector (PVT) with different design of absorber tube. ANSYS Fluent software was used to carry out computational fluid dynamics (CFD) simulation. In this study, water was selected as the heat transfer fluid. The geometric model was drawn in CATIA V5R20 and imported into ANSYS software to generate mesh model. In setup, the flow, radiation model and material properties were constructed. In radiation mode, surface to surface (S2S) model was used. Comparison between author simulation results and previous experiment results shows good agreement. The root mean square error was only 1.29°C. Meanwhile, the root mean square error between previous research simulation and previous experimental results was 2.08°C. The influences of mass flow rate on performance of PVT was determined. In range between 0.0005kg/s and 0.005kg/s, serpentine, u-flow and spiral design of PVT achieved their highest thermal efficiency at 0.005kg/s, which are 22.62%, 21.02% and 22.96% respectively. In term of electrical efficiency, u-flow design managed to achieve 11.78%, which is highest electrical efficiency among the 3 designs at 0.005kg/s. Both of serpentine and spiral design had same electrical efficiency at 0.005kg/s which is 11.67%. In range between 0.0005kg/s and 0.005kg/s, all three design of PVT achieved their highest total efficiency at 0.005kg/s. At 0.005kg/s, spiral showed highest total efficiency, 34.63%, followed by serpentine design, 34.29%, then u-flow design, 32.8%.

[*] *Corresponding author.*
E-mail address: joon_ping@hotmail.com (Yap Joon Ping)

1. Introduction

Photovoltaic Thermal (PVT) system is the combination of photovoltaic system and solar thermal system. PVT system is capable of converting solar radiation into electrical energy and thermal energy simultaneously for the application of solar drying, water heating for domestic hot water, pool heating, food processing for industry, air or space heating for domestic, etc. [14]. However, at high temperature, the performance of photovoltaic panels will be reduced while at low temperature, the solar collector will underperform.

Conventional photovoltaic (PV) panel only require photon from light to generate electrical energy, however the heat from solar radiation tends to increase the PV panel and reduce its electrical efficiency [10]. Photons of longer wavelength do not generate electron-hole pairs but only dissipate their energy as heat in the PV cell. PVT system able to extract the heat from PV panel by using heat transfer fluid such as water and air. This cools down the PV panel to provide a better efficiency. The heat gain by heat transfer fluid can be used for space heating and water heating.

The first designed and operated combined Photovoltaic/Thermal model in accordance with ASHRAE criteria was implemented at Texas University. The study indicated that combined Photovoltaic/Thermal model generates more energy per unit area than the single PV and solar thermal model. It was also more cost-effective in comparison to traditional photovoltaic cell and solar thermal collectors [1].

Fudholi *et al.*, [5] had conducted an experiment to compare the performance of photovoltaic thermal collector with different design of absorber pipe. The experiment shows that the photovoltaic thermal collector with spiral flow has better efficiency compared to web flow and direct flow. It followed by direct flow. Web flow has the lowest efficiency among these three designs of absorber.

Glazed photovoltaic thermal collector model is selected for CFD simulation. The average thermal efficiencies of the glazed and unglazed PVT collectors were about 38% and 24% respectively [10]. On the other hand, the electrical efficiencies of glazed and unglazed PVT collectors were about 10.3% and 11.8% [11].

A simulation of water based photovoltaic thermal (PVT) was performed based on the different geometry of water channel of absorber. Round tubes and square tubes are selected for the shape of cross-sectional of channel. In the study, the square tubes with 65mm gap achieve the highest thermal efficiency, 49% among the 4 designs of tubes under solar irradiance in between 300 to 1000 W/m^2 [12].

A photovoltaic thermal collector (PVT) which utilize single-crystalline silicon cells designed for natural circulation was constructed. In outdoor experiment, the results showed the PVT had higher than 52% in characteristics daily total efficiency and can achieve up to 65% in the characteristic daily primary-energy saving [7].

The electrical efficiency of photovoltaic cells is strongly affected by operating temperature and irradiance or light intensity. The electrical efficiency decreases linearly with operating temperature and irradiance [2,15]. An experimental study has been conducted to determine the effect of light intensity on performance of photovoltaic cell [8]. The study shows that the performance of photovoltaic cell is decreases with illumination intensity. However, the rate of decrease is lower at higher illumination intensity.

The objective of current research is to investigate the outlet temperature of heat transfer fluid and photovoltaic cell temperature with different mass flow rate in Kuala Lumpur, Malaysia. Heat transfer fluid used in this research is water. The simulation was performed in steady state condition.

2. Methodology
2.1 Geometry Modelling

In this research, CATIA V5R20 was used to draw the PVT model. Three different absorber tubes were designed, which are serpentine, u-flow and spiral. The arrangement from the top of the PVT is top glass cover, upper EVA encapsulant layer, photovoltaic panel, lower EVA encapsulate layer, tedlar, thermal paste, absorber tube and water. Figure 1 shows the arrangement of PVT. The dimensions of the layers of PVT is shown in Table 1. Figure 2 - 4 shows isometric view of serpentine, u-flow and spiral absorber tube. Figure 5 shows cross-section of the absorbers. The length of absorber of 3 design are same, which are 1.8m.

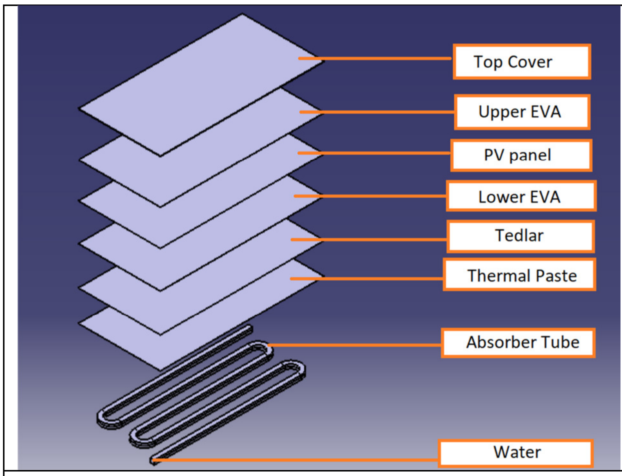


Fig. 1. Arrangement of PVT Water

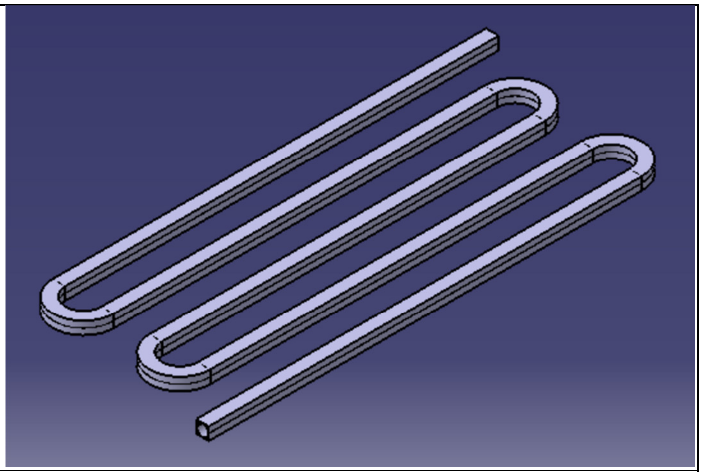


Fig. 2. Serpentine Absorber in CATIA Part Design

Table 1
Dimensions of PVT Parts

PVT Components	Dimensions $(L\ x\ W\ x\ t)\ (m^3)$
Top cover	1.0 x 0.5 x 0.003
Encapsulant of PV	1.0 x 0.5 x 0.0008
PV panel	1.0 x 0.5 x 0.0001
Backsheet	1.0 x 0.5 x 0.00005
Thermal Paste	1.0 x 0.5 x 0.0003

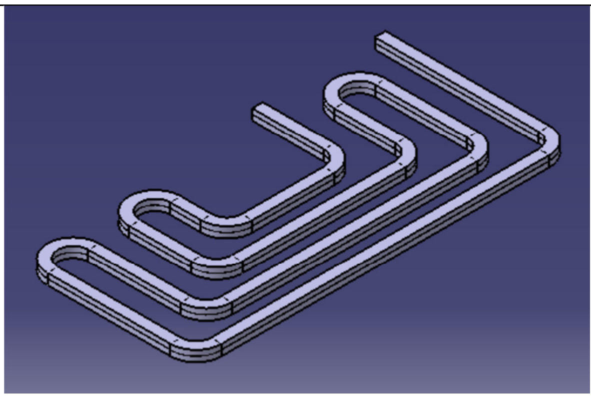


Fig. 3. U-flow Absorber in CATIA Part Design

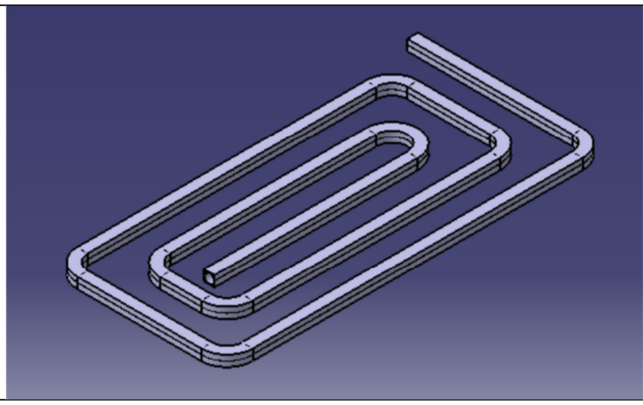


Fig. 4. Spiral Absorber in CATIA Part Design

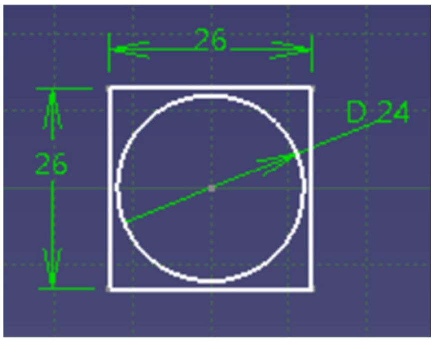


Fig. 5. Cross-section of the absorber

2.2 Meshing

Meshing can be defined as a process to divide a geometry into number of elements and nodes. Therefore, when load is applied on the geometry, the load can be distributed uniformly on the geometry. The more the elements and nodes, which mean the smaller the elements, the more accurate the results but more time consuming. However, too few of elements will lead to inaccurate results [9]. In the simulation in this study, "Fine" is chose for the relevance center and "High" is selected for smoothing in Sizing section. The meshing elements are mainly made up of tetrahedral and hexahedral elements. The nodes of the mesh obtained were about 170k – 190k whereas elements of the mesh were about 270k – 300k.

2.3 Pre-processing

The double precision option is activated to obtain the more accurate results. The energy equation is enabled to allow the calculation of heat transfer. Laminar flow model is used for the simulations. For the radiation model, surface-to-surface (S2S) model is applied. S2S radiation model assumes the surfaces are gray and diffuse surfaces. Hence, the model is not involved in absorption, emission, and scattering of radiation, only "surface to surface" radiation is participated [4]. In the simulation of this study, the direction of solar irradiance irradiated perpendicularly to the surface of the glass cover. Water is selected as the heat transfer fluid. The mass flow rate of inlet flow is varied from 0.0005kg/s to 0.005kg/s. Table 2 shows the material properties of layers of PVT.

Table 2
Material Properties of Layers of PVT [13]

Components of PVT	Material	Density (kg/m^3)	Specific Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)
Top cover	Glass	2450	500	2
Encapsulant of PV	EVA (Ethylene-vinyl-acetate	950	2090	0.311
PV panel	Silicon	2329	700	148
Backsheet	Tedlar/PVF (Polyvinyl fluoride)	1200	1250	0.15
Thermal Paste	Conductor	2600	700	1.9
Absorber	Aluminum	2700	900	160
Heat transfer fluid	Water	998.2	4182	0.6

Mass flow inlet boundary condition was selected for inlet boundary. Velocity is computed for the inlet boundary zone and the velocity is used to calculate the relevant solution variables fluxes into the domain. The computed velocity is adjusted therefore the correct mass flow rate is maintained. The formula below is used in inlet boundary condition, where ρ is density, v_n is normal velocity, ṁ is mass flow rate and A is area of inlet.

$$\rho v_n = \frac{\dot{m}}{A} \tag{1}$$

The static temperature at the inlet is computed from the total enthalpy, which is determined from the total temperature that has been set as a boundary condition. The total enthalpy is given by

$$h_0(T_0) = \mathrm{h(T)} + \frac{1}{2}v^2 \tag{2}$$

Fluent solves the energy equation by using the following equation.

$$\frac{\partial}{\partial \mathrm{t}}(\rho E) + \nabla \cdot \left(\vec{v}(\rho E + p)\right) = \nabla \cdot (k_{eff}\nabla \mathrm{T} - \sum_j h_j \vec{J_j} + (\overline{\overline{\tau_{eff}}} \cdot \vec{v})) + S_h \tag{3}$$

where k_{eff} is the effective conductivity and $\vec{J_j}$ is the diffusion flux of species j. The first three terms of right-hand side represent energy transfer due to conduction, species diffusion and viscous dissipation respectively. S_h represents the heat of chemical reaction and any volumetric heat sources that defined in earlier.

2.4 Post-processing

Contour diagrams of temperature can be plotted after the numerical calculation is completed. From the contour diagrams, temperature of every spot on the selected surface can be reviewed. Besides that, average temperature on the surface of outlet and PV panel is also required to obtain for the calculation of thermal efficiency and electrical efficiency.

2.5 Mathematics Calculation

Electrical efficiency, η_{el} is expressed as

$$\eta_{el} = \eta_{ref}\,[1 - \beta_{ref}\left(T_c - T_{ref}\right)] \tag{4}$$

where η_r represents reference efficiency of PV panel, β_{ref} represents temperature coefficient, T_c represents PV cell temperature and T_{ref} is reference temperature [3]. For $T_{ref} = 25°\mathrm{C}$, the η_{ref} and β_{ref} of silicon-based PV panel are about 0.12 and 0.0045°C^{-1} respectively [16]. By using this formula, the PV temperature obtained from simulation can used to calculate the electrical efficiency since η_{ref}, β_{ref} and T_{ref} are constant. Thermal efficiency is expressed as

$$\eta_{th} = \frac{Useful\ energy\ gain}{Total\ solar\ irradiace\ received} \tag{5}$$

$$\eta_{th} = \frac{mc_p(T_o - T_i)}{IA} \tag{6}$$

where m is mass flow rate, c_p is specific heat capacity of heat transfer fluid, T_o is outlet temperature, T_i is inlet temperature, *I* represents solar irradiance intensity and A is area of collector [17]. Total efficiency, η_T is sum of the thermal efficiency and electrical efficiency [6].

$$\eta_{Total} = \eta_{el} + \eta_{th} \quad (7)$$

3. Validation

Validation was conducted by referring to the previous research [15]. The coordinates of location used in simulation was set at India. There were two comparisons in this validation, first was compared to previous research simulation results, second was compared to experimental results. The material properties of parts of PVT is shown in Table 3. The direction and intensity of solar radiation were determined by inserting the coordinates and date into the solar calculator. The location and date were Madhya Pradesh in India and in April.

Table 3
Material Properties of PVT in Validation

Components of PVT	Material	Density (kg/m^3)	Specific Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)
Top cover	Glass	2450	500	2
Encapsulant of PV	EVA (Ethylene-vinyl-acetate	950	2090	0.311
PV panel	Silicon	2330	677	130
Back sheet	Tedlar/PVF (Polyvinyl fluoride)	1200	1250	0.15

From Figure 6, it shows the experimental and simulation results from 8a.m. to 5p.m. on a specific day of April. The difference of the outlet temperature between author simulation results and previous research simulation results varied from 0% to 9.33%. The highest percentage difference was 9.33% and root mean square error is only 2.52°C. The root mean square error between previous research simulation and previous experimental results is 2.08°C. The difference of the outlet temperature between author simulation results and previous research experimental results varied from 0.22% to 6.89%. The highest percentage error was 6.89% and root mean square error is 1.29°C, which is lower than root mean square error between previous research simulation and previous experimental results. Hence, this method is validated and assumed as applicable to case in this study.

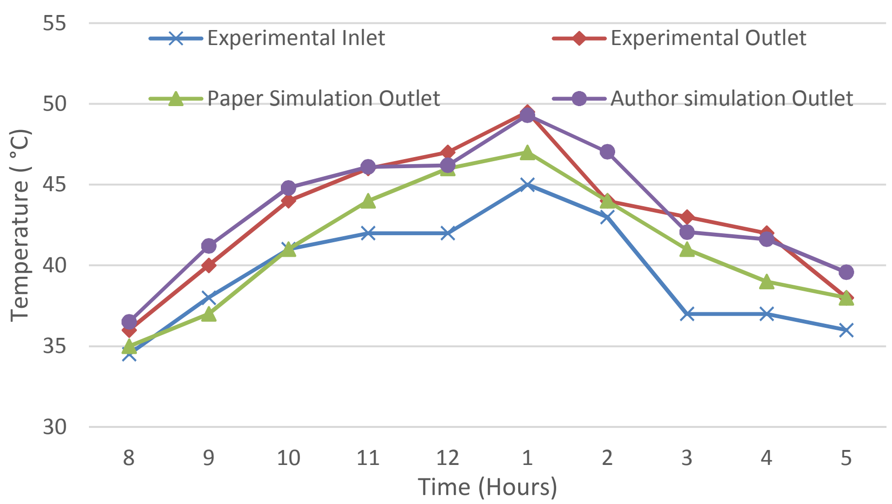


Fig. 6. Changes in Outlet Temperature with Time

4. Results and Discussion

4.1 Influence of Mass Flow Rate on Thermal Efficiency

Mass flow rate and temperature difference are the variables to determine the thermal efficiency. Figure 7 is illustrated the changes in temperature difference and thermal efficiency with mass flow rate from 0.0005 kg/s to 0.005 kg/s under $1000W/m^2$ solar irradiance.

Based on Figure 7, under $1000W/m^2$ solar irradiance, the highest temperature differences between inlet and outlet is achieved at 0.0005 kg/s. At 0.0005 kg/s, spiral absorber obtained 47.20°C temperature difference and followed by u-flow absorber and serpentine absorber which had 46.51°C and 45.74°C temperature difference respectively. Spiral absorber had the highest thermal efficiency, 19.74% at 0.0005 kg/s. U-flow absorber and serpentine absorber have 19.45% and 19.13% respectively.

As the mass flow rate increased, the temperature difference decreased but thermal efficiencies were still increased. This proved that the effect of mass flow rate is override the effect of temperature difference. The highest thermal efficiencies of each of three designs were achieved at 0.005kg/s. At 0.005kg/s, spiral absorber had highest thermal efficiency, 22.96% and followed by serpentine absorber and u-flow absorber with 22.62% and 21.02%.

Figure 7 shows the higher the mass flow rate, the higher outlet temperature. Since water mass flow rate is directly proportional to water velocity, at low mass flow rate, velocity of water is low, therefore water has longer time to absorb the heat from PV panel. This resulting in high outlet temperature when the mass flow rate is low. At high mass flow rate, the water velocity is high, hence the time for water to accumulate heat is short, this cause the outlet temperature is low.

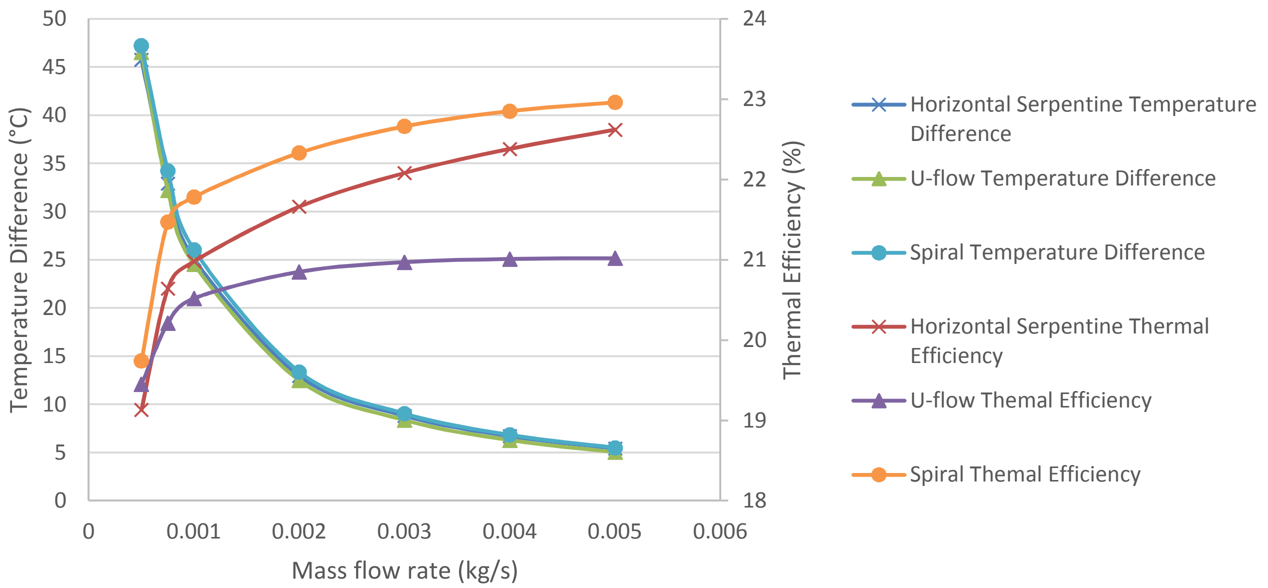
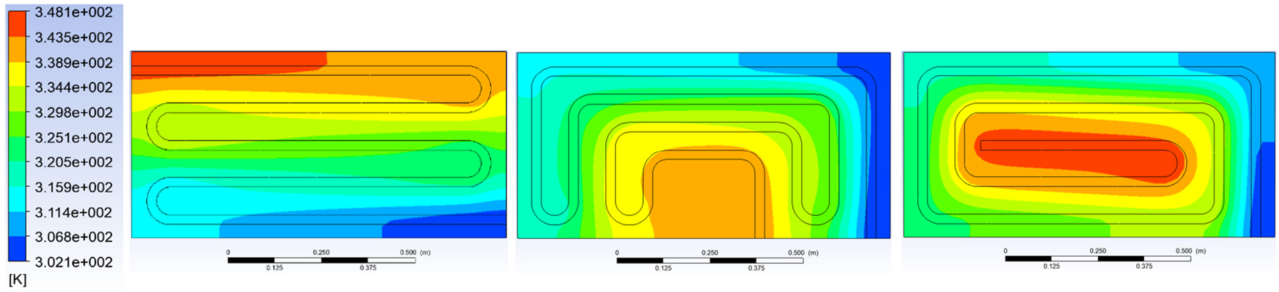


Fig. 7. Changes in Temperature Difference and Thermal Efficiency with Various Mass Flow Rate under $1000W/m^2$ Solar Irradiance

In range between 0.0005kg/s and 0.001kg/s, the thermal efficiencies are increase dramatically while the trends between 0.003kg/s to 0.005kg/s are almost flat. The reason of this phenomenon happened is time is too short for heat transfer between PV panel and water in the case of 0.003kg/s and above, cause the outlet temperatures are almost same as the inlet temperature, this means that the temperature difference between inlet and outlet is approaching to 0°C.

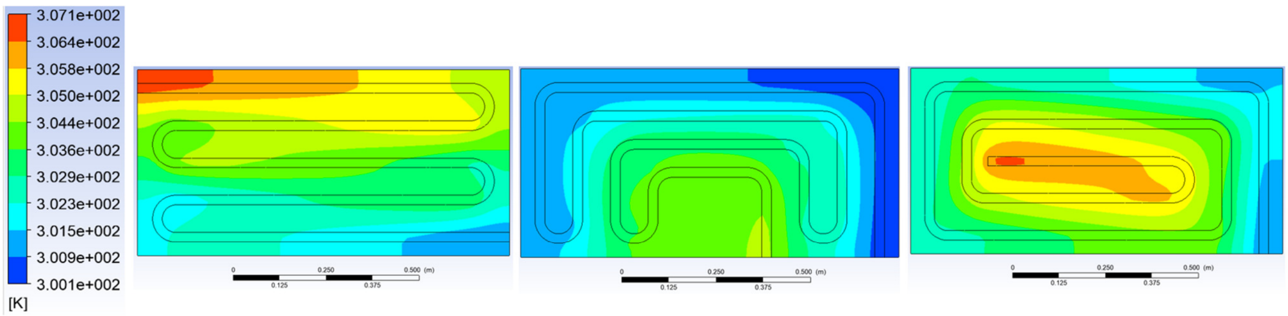
4.2 Influence of Mass Flow rate On Photovoltaic Panel Efficiency

Figure 8 and Figure 9 show the temperature distribution contour of PV at 0.0005kg/s and 0.005kg/s respectively. Red colour represents high temperature while blue represents low temperature. In Figure 8(c), spiral design shows large area of red colour at the middle of PV, serpentine design shows a smaller area of red colour at top left corner, while u-flow design did not show red colour in the temperature contour. In Figure 9(b), u-flow design shows larger area of blue colour compared to the other two design. From these 2 temperature distribution contours, clearly show that the u-flow design has the lowest temperature.



(a) (b) (c)

Fig. 8. Temperature Distribution of PV at case of 0.0005kg/s



(a) (b) (c)

Fig. 9. Temperature Distribution of PV at case of 0.005kg/s

Figure 10 shows the changes in PV temperature with various mass flow rate. The PV temperature is directly proportional to electrical efficiency. PV temperature is the only variable to determine electrical efficiency. PV panel has a characteristic which is it will perform at low efficiency in high temperature and vice versa. Figures 10 also illustrate a decrease in PV temperature as result of the increased in mass flow rate.

Based on Figure 10, the higher the mass flow rate, the lower the PV temperature, hence the electrical efficiency was higher. This is due to at higher mass flow rate, higher the volume of water involved in the heat transfer between PV panel and water, therefore resulting in better cooling effect to PV panel.

The trend of increase rate of electrical efficiency was similar to the trend of thermal efficiency. From 0kg/s to 0.001kg/s, the trends of PV temperature are decline steeply while trends of electrical efficiency increase sharply. At high mass flow rate (0.003kg/s to 0.005kg/s), PV temperature and electrical efficiency did not show significant changes. The reason is at high mass flow rate, the temperature of PV panel is near and approaching to temperature of inlet water. After the PV temperature is same as water inlet temperature, the trend will be totally flat.

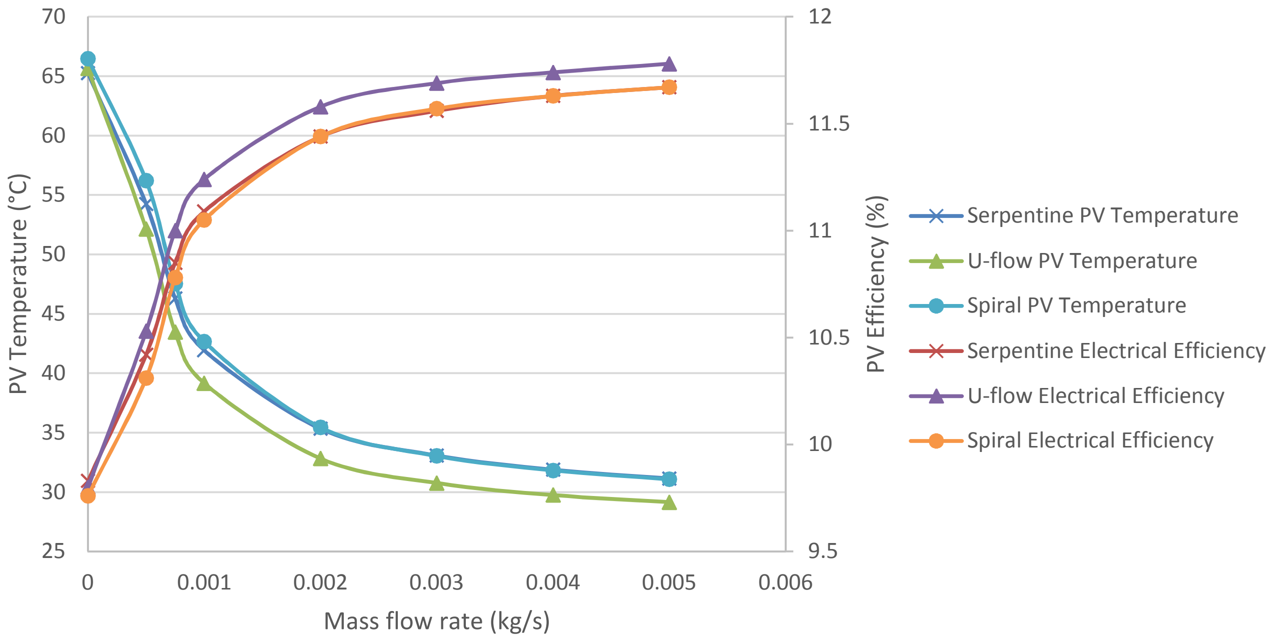


Fig. 10. Changes in PV Temperature and Electrical Efficiency with Various Mass Flow Rate under $1000W/m^2$ Solar Irradiance

At 0.005kg/s mass flow rate, three of the design achieved their own highest electrical efficiency, serpentine and spiral absorber obtained 11.67% of electrical efficiency while u-flow achieved the highest electrical efficiency among the three design, 11.78%. The increasing of mass flow rate increased the cooling effect to the PV panels, therefore as the mass flow rate increase, the PV temperature decrease.

4.4 Overall Performance of PVT

The total efficiency of PVT represents the performance of PVT. Total efficiency is the sum of the thermal efficiency and electrical efficiency. Figure 11 shows the total efficiency of three different design.

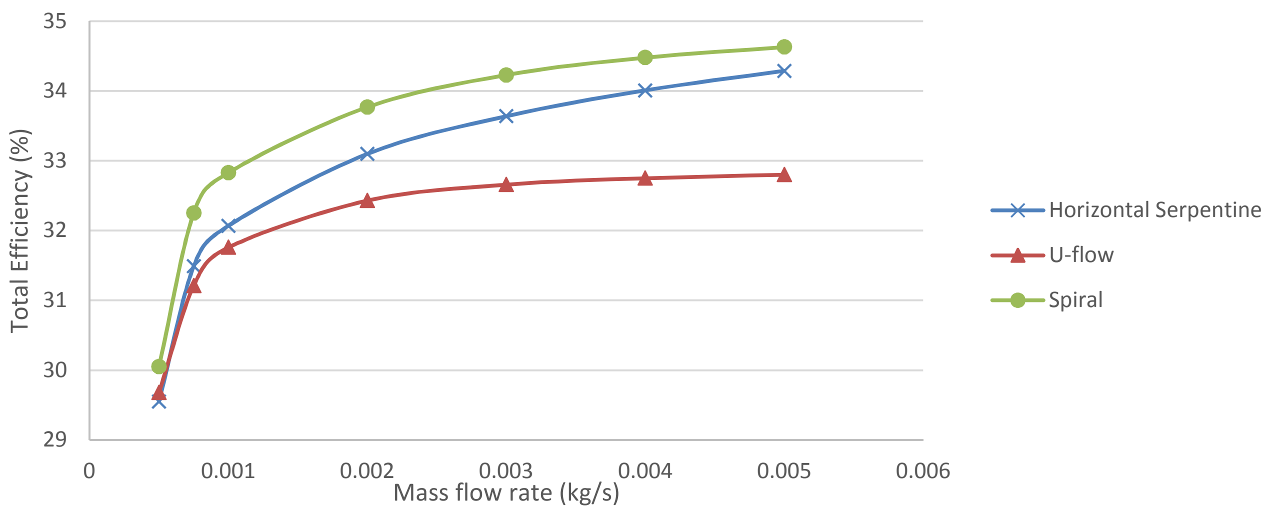


Fig. 11. Evolution of Total Efficiency under $1000W/m^2$ Solar Irradiance Intensity

The spiral absorber PVT had the highest total efficiency among the three different design of absorber, from 30.05% to 34.63%. It followed by serpentine absorber PVT, from 29.55% to 34.29%. The PVT which has lowest total efficiency is PVT with u-flow design of absorber, from 29.68% to 32.8%.

5. Conclusions

This study focuses on investigating and comparing the thermal efficiency, electrical efficiency and total efficiency of PVTs with different design of absorber. Results were obtained from simulation under steady state condition.

For thermal efficiency, the higher the mass flow rate, the higher the thermal efficiency, even though the temperature difference between water inlet and outlet is lower. After reaching a certain level of thermal efficiency, influence of mass flow rate on water outlet temperature and thermal efficiency will become insignificant.

Regarding to electrical efficiency, the higher the mass flow rate, the better cooling effect to PV panel, hence the electrical efficiency was higher. The PV temperature will approach to water inlet temperature as mass flow rate increase. The nearer to the water inlet temperature, the lower the increasing rate of electrical efficiency.

The comparison of performance of PVT with different design of absorber tube exhibited that the spiral absorber had the highest of total efficiency at all of the mass flow rate conditions. Serpentine absorber had the second highest total efficiency and followed by u-flow design. However, in term of electrical efficiency, the u-flow design has the best performance among these 3 designs.

Acknowledgement
This project is supported by Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka (UTeM).

References
[1] Abdullah, Ahmed L., S. Misha, N. Tamaldin, M. A. M. Rosli, and F. A. Sachit. "Photovoltaic thermal /solar (PVT) collector (PVT) system based on fluid absorber design: A review." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 44, no. 1 (2018): 85-98.
[2] Daghigh, Ronak, Adnan Ibrahim, Goh Li Jin, Mohd Hafidz Ruslan, and Kamaruzzaman Sopian. "Predicting the performance of amorphous and crystalline silicon based photovoltaic solar thermal collectors." *Energy Conversion and Management* 52, no. 3 (2011): 1741-1747.
[3] Dubey, Swapnil, Jatin Narotam Sarvaiya, and Bharath Seshadri. "Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world–a review." *Energy Procedia* 33 (2013): 311-321.
[4] Duggal, Rohit, and Ravindra Jilte. "Numerical Investigation on Trapezoidal Cavity Receiver Used In LFR with Water Flow in Absorber Tubes." In *IOP Conference Series: Materials Science and Engineering*, vol. 187, no. 1, p. 012026. IOP Publishing, 2017.
[5] Fudholi, Ahmad, Kamaruzzaman Sopian, Mohammad H. Yazdi, Mohd Hafidz Ruslan, Adnan Ibrahim, and Hussein A. Kazem. "Performance analysis of photovoltaic thermal (PVT) water collectors." *Energy conversion and management* 78 (2014): 641-651.
[6] Ibrahim, Adnan, Mohd Yusof Othman, Mohd Hafidz Ruslan, M. Alghoul, M. Yahya, Azami Zaharim, and Kamaruzzaman Sopian. "Performance of photovoltaic thermal collector (PVT) with different absorbers design." *WSEAS Transactions on Environment and Development* 5, no. 3 (2009): 321-330.
[7] Ji, Jie, Jian-Ping Lu, Tin-Tai Chow, Wei He, and Gang Pei. "A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation." *Applied Energy* 84, no. 2 (2007): 222-237.
[8] Khan, Firoz, S. N. Singh, and M. Husain. "Effect of illumination intensity on cell parameters of a silicon solar cell." *Solar Energy Materials and Solar Cells* 94, no. 9 (2010): 1473-1476.

[9] Khelifa, A., K. Touafek, H. Ben Moussa, and I. Tabet. "Modeling and detailed study of hybrid photovoltaic thermal (PV/T) solar collector." *Solar Energy* 135 (2016): 169-176.

[10] Khelifa, A., K. Touafek, H. Ben Moussa, I. Tabet, and H. Haloui. "Analysis of a hybrid solar collector photovoltaic thermal (PVT)." *Energy Procedia* 74 (2015): 835-843.

[11] Kim, Jin-Hee, and Jun-Tae Kim. "Comparison of electrical and thermal performances of glazed and unglazed PVT collectors." *International Journal of Photoenergy* 2012 (2012).

[12] Rosli, M. A. M., S. Mat, H. Ruslan, K. Sopian, and Hang Tuah Jaya. "Parametric study on water based photovoltaic thermal collector." In *7th international conference on renewable energy sources (RES'13),* pp. 135-140. 2013.

[13] Nahar, Afroza, M. Hasanuzzaman, and N. A. Rahim. "A Three-Dimensional Comprehensive Numerical Investigation of Different Operating Parameters on the Performance of a Photovoltaic Thermal System With Pancake Collector." *Journal of Solar Energy Engineering* 139, no. 3 (2017): 031009.

[14] Rosli, M. A. M., S. Mat, K. Sopian, E. Salleh, and M. K. A. Sharif. "Experimental development to determine time constant for polymer collector." (2006).

[15] Senthil Kumar, R., N. Puja Priyadharshini, and Elumalai Natarajan. "Experimental and computational fluid dynamics (CFD) study of glazed three dimensional PV/T Solar panel with air cooling." In *Applied Mechanics and Materials*, vol. 787, pp. 102-106. Trans Tech Publications, 2015.

[16] Skoplaki, Elisa, and John A. Palyvos. "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations." *Solar energy* 83, no. 5 (2009): 614-624.

[17] Struckmann, Fabio. "Analysis of a flat-plate solar collector." *Heat and Mass Transport, Project Report, 2008MVK160*(2008).