Journal of Engineering Technology and Applied Physics

Parametric Study of Photovoltaic Thermal Solar Collector Using An Improved Parallel Flow

Sakhr Mohammed Sultan*, Chih Ping Tso, Ervina Efzan Mohd Noor, Fadhel Mustafa Ibrahim and Saqaff Ahmed Alkaff
Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, 75450, Melaka, Malaysia
*mas2007_eng@yahoo.com
https://doi.org/10.33093/jetap.2020.2.1.4

Abstract – **Photovoltaic Thermal Solar Collector (PVT) is a hybrid technology used to produce electricity and heat simultaneously. Current enhancements in PVT are to increase the electrical and thermal efficiencies. Many PVT factors such as type of absorber, thermal conductivity, type of PV module and operating conditions are important parameters that can control the PVT performance. In this paper, an analytical model, using energy balance equations, is studied for PVT with an improved parallel flow absorber. The performance is calculated for a typical sunny weather in Malaysia. It was found that the maximum electrical and thermal efficiencies are 12.9 % and 62.6 %, respectively. The maximum outlet water temperature is 59°C.**

Keywords—Solar energy, photovoltaic thermal solar collector (PVT), absorber design, efficiency

I. Introduction

Photovoltaic Thermal solar collector (PVT) is a combination between photovoltaic and solar thermal collector technologies. The major features of a PVT are [1-8]:

1. It can be used for heat and electricity production.
2. It is efficient and flexible.
3. It has a large variety of applications.
4. It is realistic and inexpensive.

In the last two decades, research has been conducted in order to improve the overall PVT performance. Jones *et al.* [9] have performed experimental study on the photovoltaic module temperature profile under a non-steady state condition for clear and sunny day. They showed that the temperature of the PV module varied from 27°C to 52°C for ambient temperature of 24.5°C. Chow T. T. [10] conducted a performance analysis of PVT in a transient condition. A thermal metallic bonds collector of tube and sheet type used in his study. Results showed that the PV module temperature was reduced by 2 %. Zondag *et al.* [11] studied the electrical and thermal yield of PVT. They showed that the electrical and thermal efficiencies are 6.7 % and 33 %, respectively. Analytical and experimental study for PVT with a polymer absorber plate [12]. Results showed that the electrical efficiency is mainly depending on the solar cell temperature, ohmic losses and the packing factor. He *et al.* [13] designed a hybrid PVT using aluminum-alloy channel under tropical climate conditions of Hong Kong. Later, Hansen *et al.* [14] performed the market, modeling demonstration and testing of PVT based on IEA framework. Frassie *et al.* [15] performed an energy performance evaluation of water based-PVT. Although, results show that there was a significant decrease of the electrical performance compared with the conventional PV module, there was a total increase of 6 % of electrical energy for unglazed PVT. This is because of the relation between the temperatures of the solar cell and the glass cover. The electrical output of PVT with unglazed cover was 10 % which is 6 % better than a conventional PV module due to the cooling effect. They showed that the PVT with unglazed cover gives better electrical performance if the thermal efficiency is not to be considered. Assoa *et al.* [16] studied a new concept of PVT. The PVT was a combination of preheating of the air and water. An analytical model of a simplified steady-state two-dimensional mathematical model was developed. The experimental study was performed to validate the developed analytical model results. They found that the thermal efficiency can reach up to 80 % for a given specific fluid mass flow rate and collector length. Tiwari *et al.* [17] performed exergy analysis of the PVT under constant mass flow rate and constant collection temperature modes. Results showed that the daily thermal efficiency increases by increasing the mass flow rate of the fluid. Kalogirou *et al.* [18] studied the hybrid PVT for electricity and domestic hot water production. When properly designed, the PVT can take out the heat produced from PV module for air/water heating to minimize the solar cell temperature and thereby, to maintain the electrical efficiency at desirable levels. The results indicates that the output electrical energy

Published by MMU PRESS. URL: https://journals.mmupress.com/index.php/jetap/index

of using polycrystalline solar cells is higher than that of the amorphous one. Touafek *et al.* [19] performed an experimental study on a new PVT. A new design approach, with aiming to maximize the electric and thermal outputs with lowest cost as compared with the commercial PVT was proposed. The simulation results were validated by experimental measurements and showed that the thermal efficiency of the new PVT has a significant improvement compared with the conventional one. Tiwari *et al.* [20] carried out performance evaluation of unglazed and glazed hybrid air-based PVT with and without tedlar. The analytical model was based on the composite climatic conditions of New Delhi, India. They concluded that the glazed hybrid PVT without tedlar gave the best performance. Bergene *et al.* [21] performed model calculations on a flat-plate solar heat collector. They showed that this model can be used to predict the amount of heat that can be extracted from the system. They used the tube and sheet with fin configuration. They concluded that the predictable performance is 60–80%. By using sheet and tube concept, an experiment was conducted to evaluate the performance of hybrid PVT [22]. They used 440 watt PV module connected to black paint coated copper pipe as a tube covered by thick copper sheet. They concluded that the PVT was not suitable to the Saudi Arabia climate conditions due to the high ambient temperature during summer.

Huang *et al.* [23] carried out performance study to understand and evaluate the PVT. They compared PVT with the conventional solar water heater. The polycrystalline PV module has been added to the thermal collector. They concluded that the solar collector made from corrugated polycarbonate panel can generate good thermal output. Tonui *et al.* [24] studied air-cooled PVT with low cost performance improvements. A theoretical model showed good agreement with experimental measurements. The validated model was used to study the effect of various factors such as the channel depth, mass flow rate and channel length on electrical and thermal efficiency. Aste *et al.* [25] designed and carried out performance evaluation of a hybrid air-based PVT. The designed PVT is a combination of a PV module integrated in common sloped roofs, replacing the external covering and insulation layers. The upper layer of the PVT was covered by glass type PV module. The simulation model can numerically predict the electrical and thermal performance of a PVT. Fadhel *et al.* [26] performed theoretical study of a new PVT configuration. They used the spiral flow absorber design. Results showed that the maximum thermal and electrical efficiencies are 64.4 % and 12.13 %, respectively.

The objective of this paper is to present a detailed parametric study of the PVT with the improved parallel flow design under typical sunny weather in Malaysia. The performance in terms of outlet water temperature, electrical and thermal efficiencies is evaluated using energy balance.

II. THE PVT DESCRIPTION

Figure 1 shows the schematic diagram of the PVT. The PVT consists of five layers. These layers are glass, air gap, PV panel, absorber and insulating material layer. A mono-crystalline PV module with an effective area of 1.267 m^2 is integrated with the improved parallel flow as shown in Fig. 2. The pattern of water flow in the absorber is depicted in Fig. 2. The absorber is made of copper material with circular tubes. The size of each tube is 12.7 mm in length and 1mm in width. The spacing between adjacent tubes of the absorber is playing an important role in controlling the PVT performance. As a result, a large amount of heat can be absorbed, hence better thermal and electrical efficiencies can be obtained. The absorber has narrow spacing between tubes that is 0.02 m. Moreover, it has an area of 1.267 m^2. The absorber has one inlet and one outlet channel where water can flow in and out. To study the flow of water phenomenon in the absorber, the total area has been divided into three small and equal areas which are A_1, A_2 and A_3. The inlet water, T_{fi}, flows in the first area A_1. As a result, T_{fo1} will be the outlet water from A_1. T_{fo1} will be the inlet water for the second area A_2. The outlet water from A_2 is T_{fo2}. The final outlet water of the overall PVT is T_{fo3}. In this case, the radiation from the sun is transferred through PV module, and finally absorbed by the collector. Therefore, the thermal energy from PV module is transmitted to absorber by convection. The water flowing in tubes gets heated.

Table I. Mono-crystalline Si PV specifications.

Parameters	Values
Solar cell size	0.125 m × 0.125 m
I_{sc}	5.91 A
V_{sc}	43.2 V
I_{max}	5.28 A
V_{max}	36 V
PV area	1.267 m^2
Number of cells	72
Power	190 W

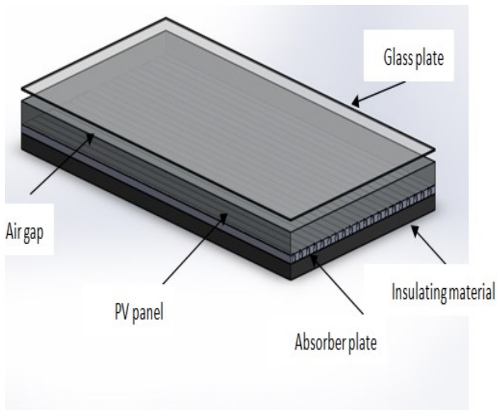

Fig. 1. Layers associated with PVT.

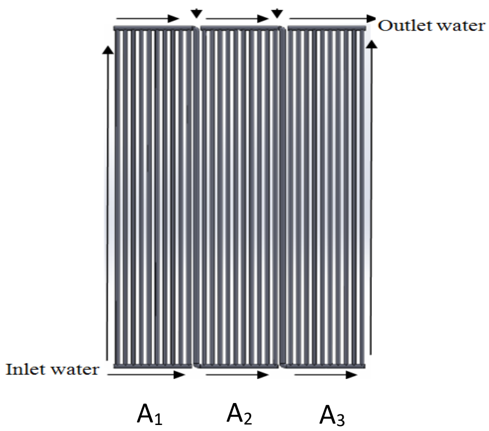

Fig. 2. The improved parallel flow.

Table II. Design parameters of PVT.

Parameters	Values
A_c	1.267 m²
C_p	4190 J/kg K
F_R	0.960
h_T	500 W/m² K
h_{p1}	0.8772
h_{p2}	0.9841
k	0.039 W/m K
k_g	1.0 W/m K
k_{ins}	0.035 W/m K
k_T	0.033 W/m K
L	1.105 m
L_g	0.003 m
L_{ins}	0.05 m
L_T	0.0005 m
M_w	45 kg
U_b	0.62 W/m² K
U_L	9.24 W/m² K
U_T	66 W/m² K
$U_{t,ca}$	8.1028 W/m² K
V	1 m/s
W	808 mm
α_c	0.85
β_c	0.90
η_c	0.12
α_t	0.50
τ_g	0.95

III. THE THERMAL MODEL

Some assumptions are considered:

1. Solar cells, insulation and tedler heat capacities were ignored.
2. One dimensional heat conduction was taken into consideration.
3. Transmissivity of EVA is 100 %.
4. The system is in quasi-steady-state.

The energy balance equations for different components of PVT are as the following:

A. For Solar Cells of PV Module:

The energy balance equation for solar cell temperature (T_{cell}) can be written as,

$$T\_cell = \frac{\tau_g[\alpha_c\beta_c + \alpha_T(1-\beta_c)]I(t) - \beta_c\eta_c I(t) + U_{tc,a}T_a + U_T T_{bs}}{U_{tc,a} + U_T}. \quad (1)$$

B. For the Surface of the Tedlar:

The temperature of the collector plate (T_{bs}) is

$$T_{bs} = \frac{h_{p1}(\tau\alpha)_{eff}I(t) + U_{tT}T_a + h_T T_f}{U_{tT} + h_T}, \quad (2)$$

where

$$(\tau\alpha)_{eff} = \tau_g(\beta_c\alpha_c + \alpha_t(1-\beta_c) - \eta_c\beta_c). \quad (3)$$

C. For the Water Flowing Below the Tedlar:

There are three stages to calculate the outlet water temperature of the collector. The first stage is when the inlet water passes under the area A_1, so the numerical calculation of the outlet water temperature at the end of this area will be as the following:

$$T_{fo1} = \left[\frac{h_{p2}(\tau\alpha)_{eff}I(t)}{U_L} - T_a\right] \times \left[1 - \exp\left(-\frac{A_1 U_L F'}{mC_p}\right)\right] + T_{fi}\exp\left(-\frac{A_1 U_L F'}{mC_p}\right). \quad (4)$$

Then, the outlet water from area A_1 will be inlet water for area A_2. Hence, the expression of the outlet water temperature from area A_2 is governed by the equation as below:

$$T_{fo2} = \left[\frac{h_{p2}(\tau\alpha)_{eff}I(t)}{U_L} - T_a\right] \times \left[1 - \exp\left(-\frac{A_2 U_L F'}{mC_p}\right)\right] + T_{fo1}\exp\left(-\frac{A_2 U_L F'}{mC_p}\right). \quad (5)$$

Finally, T_{fo2} will act as the inlet water for area A_3, so the calculation for the outlet water temperature for the overall collector (T_{fo3}) is giving by

$$T_{fo3} = \left[\frac{h_{p2}(\tau\alpha)_{eff}I(t)}{U_L} - T_a\right] \times \left[1 - \exp\left(-\frac{A_3 U_L F'}{mC_p}\right)\right] + T_{fo2}\exp\left(-\frac{A_3 U_L F'}{mC_p}\right). \quad (6)$$

Substituting Eq. 5 into Eq. 6, we will get,

$$\begin{aligned} T_{fo3} = &\left[\frac{h_{p2}(\tau\alpha)_{eff}I(t)}{U_L} - T_a\right] \times \left[1 - \exp\left(-\frac{A_3 U_L F'}{mC_p}\right)\right] \\ &+ \left[\left[\frac{h_{p2}(\tau\alpha)_{eff}I(t)}{U_L} - T_a\right] \times \left[1 - \exp\left(-\frac{A_2 U_L F'}{mC_p}\right)\right]\right. \\ &+ \left(\left[\frac{h_{p2}(\tau\alpha)_{eff}I(t)}{U_L} - T_a\right] \times \left[1 - \exp\left(-\frac{A_1 U_L F'}{mC_p}\right)\right]\right. \\ &\left.\left. + T_{fi}\exp\left(-\frac{A_1 U_L F'}{mC_p}\right)\right)\exp\left(-\frac{A_2 U_L F'}{mC_p}\right)\right]\exp\left(-\frac{A_3 U_L F'}{mC_p}\right). \end{aligned} \quad (7)$$

D. The Thermal Energy Rate of the Collector:

The useful energy gain, Q_u, expression is defined as

$$Q_u = A_c F_R\left[h_{p2}(\tau\alpha)_{eff}I(t) - U_L(T_{fi} - T_a)\right]. \quad (8)$$

E. The Collector Instantaneous Thermal Efficiency:

Flat plate collector's instantaneous thermal efficiency is giving by,

$$\eta_{thrm} = F_R\left[(\tau\alpha)_{eff} - U_L\frac{(T_{fi} - T_a)}{I(t)}\right]. \quad (9)$$

In addition to above equations, calculation for the flow rate factor (F_R) of the collector is governed by the following relations:

The fin efficiency factor of the collector (F) is defined as

$$F = \frac{\tanh m\frac{W-D}{2}}{m\frac{W-D}{2}}. \quad (10)$$

The flat plate collector efficiency (F') is

$$F' = \frac{1}{WU_L\left[\frac{1}{\pi Dh_T} + \frac{1}{C_b} + \frac{1}{D + (W - D)F}\right]}. \quad (11)$$

Now, the flow rate factor (F_R) is

$$F_R = \frac{mC_p}{A_c U_L F'} \times \left[1 - \exp\left(-\frac{U_L A_c F'}{mC_p}\right)\right]. \quad (12)$$

IV. THE ELECTRICAL MODEL

The photovoltaic performance of the PVT depends on the cell temperature, T_{cell}, that proposed by Florschuetz [27],

$$\eta_{Electrical} = \eta_{ref}[1 - 0.0045(T_{cell} - T_{ref})]. \quad (13)$$

V. RESULTS AND DISCUSSION

The hourly ambient temperature and solar radiation intensity for typical sunny day in Malaysia and the design parameters of the PVT are shown in Table I and Table III, respectively. The typical inputs from Table I and Table III are used to evaluate the performance of the PVT such as, electrical and thermal efficiencies as well as the outlet water temperature. The hourly variation of outlet water temperature with different PVT length has been studied as shown in Fig. 3. In Fig. 3, the outlet water temperature can be increased as the length of the PVT is increased, due to the fact that the area of the PVT exposed by sunlight is increased.

Table III. The hourly ambient temperature and solar radiation for typical sunny day in Malaysia [28].

Time (h)	Ambient Temperature (°C)	Intensity (W/m^2)
8	23.9	36.11
9	25.8	313.85
10	27.9	561.11
11	29.3	707.56
12	30.4	913.85
13	31.9	891.67
14	31.9	611.11
15	31.1	350
16	30.2	186.11
17	27.1	177.78
18	27.6	50

The effect of different mass flow rate values on the outlet water temperature, thermal and cell efficiencies has been illustrated in Fig. 4 and Fig. 5. Result indicates that there is a significant effect of mass flow rate on the hourly outlet water temperature (Fig. 4). As the mass flow rate decreases, the outlet water temperature increases. From Fig. 4, it is shown that the maximum outlet water temperatures are 69, 59, 55 and 50°C at mass flow rates of 0.01, 0.015, 0.018 and 0.02 kg/s, respectively. From Figure 5, we can say that the thermal and cell efficiencies are increasing very slowly once the mass flow rate approaches an optimum value. After the optimum value, any increase of the mass flow rate will have negligible and insignificant rise of the PVT efficiencies. It can be concluded that optimized PVT mass flow rate should be identified.

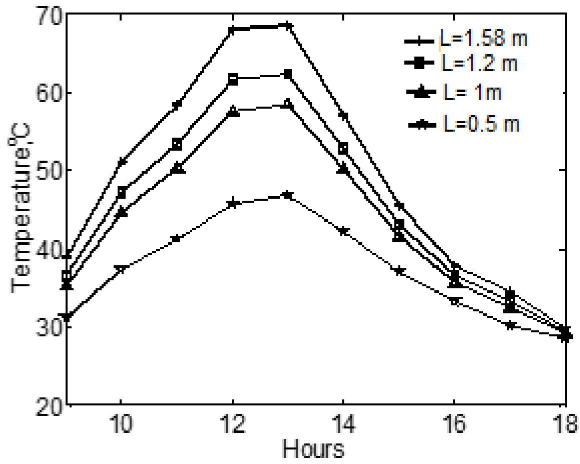

Fig. 3. Hourly variation of outlet water temperature with different PVT length at $mf = 0.01$ kg/s.

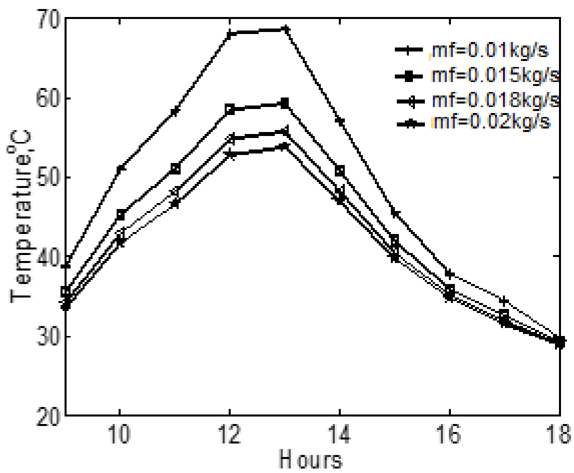

Fig. 4. The hourly variation of outlet water temperature with different mass flow rate values at $L = 1.58$ m.

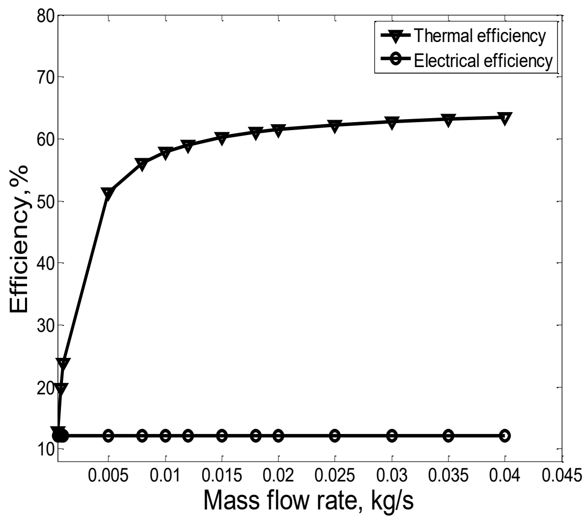

Fig. 5. Efficiencies versus mass flow rate.

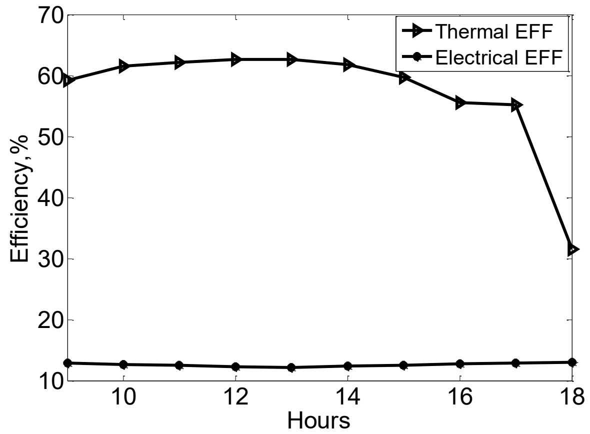

Fig. 6. Hourly variation of thermal and electrical efficiencies.

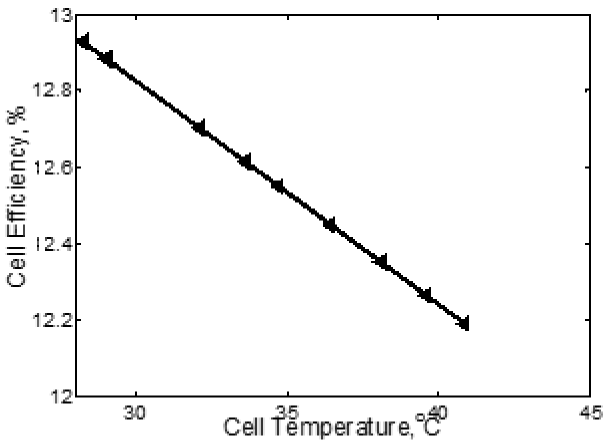

Fig. 7. Cell efficiency as a function of solar cell temperature.

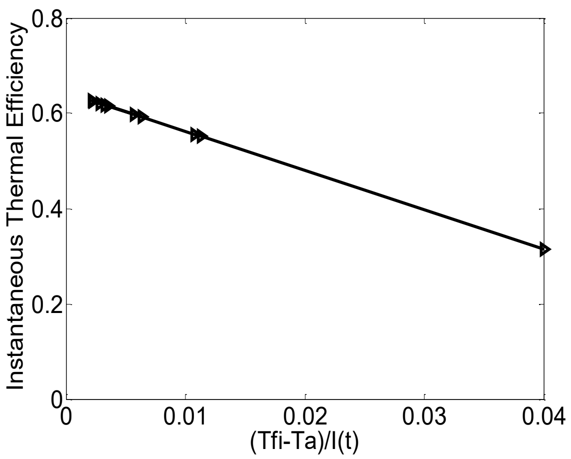

Fig. 8. Variation of thermal efficiency as a function of the ratio $(T_{fi} - T_a)/I(t)$.

Effects of different solar radiation and ambient temperature (Table III) on the thermal and electrical efficiencies of the PVT are shown in Fig. 6. The thermal efficiency increases as solar radiation intensity and ambient temperature increase. There is also influence of solar radiation and ambient temperature on the electrical efficiency. The electrical production of the PVT is decreased as the solar radiation and ambient temperature increase due to excessive heating on the solar cell. At 10 AM (solar radiation and ambient temperature of 561.11 W/m^2 and 27.9 °C), the electrical efficiency is 12.8 %. At 1 PM (solar radiation and ambient temperature of 891.67 W/m^2 and 31.9 °C), the electrical efficiency is 12 %.

Figure 7 shows the cell efficiency as a function of solar cell temperature. It is noticed that the cell efficiency is inversely proportional to the increasing of the solar cell temperature. Figure 8 indicates the variations of the instantaneous thermal efficiency of the collector as a function of the ratio (Tfi - Ta)/I(t). We can say that the thermal efficiency of PVT reaches 62.6 %.

VI. Conclusion

Simulation work is conducted to study the performance of PVT using an improved parallel flow design. An analytical model based on the basic energy balanced equations has been performed. PVT performance evaluation as a function of the design parameters for typical sunny weather in Malaysia has been predicted. Results show that the maximum thermal and electrical efficiencies are 62.6 % and 12.9 %, respectively. The outlet water temperature has been studied under different mass flow rate values and PVT lengths. The maximum outlet water temperature is 59 °C.

Nomenclature

A	area, (m^2)
C_b	bond conductance, (W/m K)
C_P	specific heat, (J/kg K)
D	collector diameter, (m)
F′	flat plate collector efficiency factor
F_R	flow rate factor, (dimensionless)
h	heat transfer coefficient, (W/m^2)
h_T	heat transfer coefficient back surface of tedlar to fluid, (W/m^2 K)
hp_1	penalty factor due to the glass cover of PV module, (dimensionless)
hp_2	penalty factor due to the absorber below PV module, (dimensionless)
I	current, (A)
I(t)	incident solar intensity, (W/m^2)
k	thermal conductivity, (W/m K)
L	length, (m)
m	mass flow rate, (kg/s)
M_w	mass of water, (kg)
Q_u	rate of useful energy transfer, (W)
T	temperature, (°C)
$U_{tc,a}$	an overall heat transfer coefficient from solar cell to ambient through glass cover, (W/m^2 K)
U_b	an overall bottom heat transfer coefficient of collector, (W/m^{2}K)
U_{tT}	an overall heat transfer coefficient from solar cell to back surface of tedlar, (W/m^2 K)
U_T	an overall heat transfer coefficient from glass to tedlar through solar cell,(W/m^2 K)
U_L	an overall heat transfer coefficient
V	voltage, (V)
W	collector width, (m)

Subscripts

a	ambient
bs	back surface of tedlar
c	collector
cell	solar cell
eff	effective
f	fluid
fi	inlet fluid

f_o outlet fluid
ins insulation
g glass
m module
max maximum
oc open circuit
ref reference
sc short circuit
T tedler
w water

Greek letters
α absorptivity
$(\alpha\tau)_{eff}$ product of effective absorptivity and transmissivity
βc packing factor of solar cell
η_{thrm} instantaneous thermal efficiency
η_c efficiency at standard test conditions
τ transmissivity

REFERENCES

[1] A. Hasan and K. Sumathy, "Photovoltaic Thermal Module Concepts and Their Performance Analysis: A Review," *Renewable and Sustainable Energy Reviews*, pp.1845–1859, 2010.
[2] S. M. Sultan, C. P. Tso and E. Efzan, "Comments on "Performance Evaluation of Photovoltaic Thermal Solar Air Collector for Composite Climate of India," *Solar Energy Materials and Solar Cells*, vol. 198, pp. 63-64, 2019.
[3] S. M. Sultan, C. P. Tso and E. Efzan, "A Proposed Temperature-Dependent Photovoltaic Efficiency Difference Factor for Evaluating Photovoltaic Module Cooling Techniques in Natural or Forced Fluid Circulation Mode," *Arab J. Sci. Eng.*, vol. 44, 8123, https://doi.org/10.1007/s13369-019-03932-5, 2019.
[4] S. M. Sultan and E. Efzan, "Review on Recent Photovoltaic/Thermal (PVT) Technology Advances and Applications," *Solar Energy*, vol. 173, pp. 939–954, 2018.
[5] S. M. Sultan, C. P. Tso and E. Efzan, "A Thermal Performance Study for Different Glazed Water based Photovoltaic Thermal Collectors," *In AIP Conference Proceedings*, pp. 020307, 2018.
[6] S. M. Sultan, C. P. Tso and E. Efzan, "The Effect of Mass Flow Rate and Solar Radiation on the Photovoltaic Efficiency of A Glazed Water based PVT," *In AIP Conference Proceedings*, pp. 020309, 2018.
[7] S. M. Sultan, I. Fadhel and S. Alkaff, "Performance Analysis of the Photovoltaic/Thermal Solar Collector for Different Malaysian Climatic Conditions," *J. Appl. Mech. Mater.*, vol. 467, pp. 522-527, 2014.
[8] S. M. Sultan, C. P. Tso and E. Efzan, "A New Production Cost Effectiveness Factor for Assessing Photovoltaic Module Cooling Techniques," *Int. J Energy Res*, pp. 1–10. https://doi.org/10.1002/er.4889, 2019.
[9] A. D. Jones and C. P. Underwood, "A Thermal Model for Photovoltaic Systems," *Solar Energy*, vol. 70, no. 4, pp. 349–359, 2001.
[10] T. T. Chow, "Performance Analysis of Photovoltaic–thermal Collector by Explicit Dynamic Model," *Solar Energy*, vol. 75, pp.143–152, 2003.
[11] H. A. Zondag, D. Vries, V. Helden, V. Zolingen and V. Steenhoven, "The Thermal and Electrical Yield of A PV–thermal Collector," *Solar Energy*, vol. 72, no. 2, pp. 113–128, 2002.
[12] B. Sandnes and J. Rekstad, "A Photovoltaic/thermal (PVT) Collector with A Polymer Absorber Plate: Experimental Study and Analytic Model," *Solar Energy*, vol. 72, no. 1, 63–73, 2002.
[13] W . He, T. T. Chow, J. Ji, J. P. Lu, G. Pei and L. Chan, "Hybrid Photovoltaic and Thermal Solar Collector Designed for Natural Circulation of Water," *Applied Energy*, vol. 83, no. 3, pp. 199–210, 2006.
[14] J. Hansen, H. Sorensen, J. Bystrom, M. Collins and B. Karlsson, " Market, Modelling, Testing and Demonstration in the Framework of IEA SHC Task 35 on PVThermal Solar Systems," *Proc. 22nd European Photovoltaic Solar Energy Conference and Exhibition,* pp. DE2–5. Milan, Italy, 2007.
[15] G. Fraisse, C. Menezo and K. Johannes, "Energy Performance of Water Hybrid PVT Collectors Applied to Combisystems of Direct Solar Floor Type," *Solar Energy*, vol. 81, pp.1426–1438, 2007.
[16] Y. B. Assoa, C. Menezo, G. Fraisse, R. Yezou and J. Brau, "Study of A New Concept of Photovoltaic–thermal Hybrid Collector," *Solar Energy*, vol. 81, pp. 1132–1143, 2007.
[17] A. Tiwari, S. Dubey, G. Sandhu, M. Sodha and S. Anwar, "Exergy Analysis of Integrated Photovoltaic Thermal Solar Water Heater under Constant Flow Rate and Constant Collection Temperature Modes," *Applied Energy*, vol. 86, pp. 2592–2597, 2009.
[18] S. A. Kalogirou and Y. Tripanagnostopoulos, "Hybrid PVT Solar Systems for Domestic Hot Water and Electricity Production," *Energy Conversion and Management*, vol. 47, pp. 3368–3382, 2006.
[19] K. Touafek, M. Haddadi and A. Malek, "Experimental Study on A New Hybrid Photovoltaic Thermal Collector," *Applied Solar Energy*, vol. 45, no. 3, pp. 181–186, 2009.
[20] A. Tiwari and S. M. Sodha, "Parametric Study of Various Configurations of Hybrid PV/Thermal Air Collector: Experimental Validation of Theoretical Model," *Solar Energy Materials and Solar Cells*, vol. 91, pp. 17–28, 2007.
[21] T. Bergene and O. M. Lovvik, "Model Calculations on A Flat-Plate Solar Heat Collector with Integrated Solar Cells,' *Solar Energy*, vol. 55, pp. 453–462, 1995.
[22] A. Harbi, N. N. Eugenio and S. Zahrani, "Photovoltaic-thermal Solar Energy Experiment in Saudi Arabia," *Renewable Energy*, vol. 15, pp. 483–486, 1998.
[23] B. J. Huang, T. H. Lin, W. C. Hung and F. S. Sun, 'Performance Evaluation of Solar Photovoltaic/Thermal Systems,' *Solar Energy*, vol. 70, pp. 443–448, 2001.
[24] J. K. Tonui and Y. Tripanagnostopoulos, "Air-cooled PVT Solar Collectors with Low Cost Performance Improvements," *Solar Energy*, vol. 81, pp. 498–511, 2007.
[25] N. Aste, G. Chiesa and F. Verri, "Design, Development And Performance Monitoring of A Photovoltaic–thermal (PVT) Air Collector," *Renewable Energy*, vol. 33, pp. 914–927, 2008.
[26] S.M. Sultan, C. P. Tso and E. Efzan, "A Case Study on Effect of Inclination Angle on Performance of Photovoltaic Solar Thermal Collector in Forced Fluid Mode," *Renewable Energy Research and Applications*, vol. 1, pp. 187-196, 2020.
[27] L. W. Florschuet, "Extension of The Hottel-Whillier Model to The Analysis of Combined Photo-voltaic/thermal Flat Plate Collectors," *Sol Energy*, vol. 22, pp. 361-366, 1979.
[28] S. M. Sultan, I. Fadhel and S. Alkaff, "Theoretical Study of New Configuration of Photovoltaic/Thermal Solar Collector (PV/T) Design," *Advanced Materials Research*, vol. 772, pp. 681-687, 2013.