Case Studies in Thermal Engineering 18 (2020) 100595

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: http://www.elsevier.com/locate/csite

Theoretical study and indoor experimental validation of performance of the new photovoltaic thermal solar collector (PVT) based water system

Amira Lateef Abdullah [a,c,*], S. Misha [a,b], N. Tamaldin [a,b], M.A.M. Rosli [a,b], F. A. Sachit [a,c]

[a] Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
[b] Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
[c] Ministry of Electricity, Baghdad, Iraq

ARTICLE INFO

Keywords:
Thermal
Electrical and total efficiency
PVT water collector
Cell temperatures
New absorber design

ABSTRACT

Hybrid Photovoltaic Thermal (PVT) systems are an solar technology that the enables simultaneous the conversion of solar energy into electrical and thermal energy. One of the major problems of photovoltaic plates PV is high temperature due to excessive solar radiation and high ambient temperature leads to reduced efficiency in solar panels. The hybrid photovoltaic thermal (PVT) systems are one of the most common methods for cooling photoelectric panels and improve performance. The heat from the PV panel is transferred through working fluids such as water. The extracted heat is used in low temperature applications, including household hot water. A new dual oscillating absorber copper pipe flow that was designed based on the water-based PVT system, was developed and studied. This paper discusses experimental data utilizing in the MATLAB program with indoor experimental studies of the water-based PVT system and compare the results of the new design dual oscillating absorber of the PVT water system with a normal PV panel without a cooling system. The simulation results were validated with experimental results. The simulation and experimental results were found to be in good agreement. The performances of the water-based PVT system that includes the electrical, thermal and total efficiency was measured in the solar radiation range from 500 to 1000 W/m2 and different mass flow rate from 2 to 6 LPM. The results show that the maximum electrical efficiency is 11.5% at 500 W/m^2 and 6 LPM, the maximum thermal efficiency is 58.64% at 1000 W/m^2 and 5 LPM, and the total efficiency is 66.87% at 1000 W/m^2 and 5 LPM. The results show that increasing the mass flow rate and solar radiation leads to an increase in the thermal and total efficiency, but after the optimal value, the thermal and total efficiency decreases. The increasing mass flow rate lead to reduces the cell temperature and increases the electrical efficiency.

1. Introduction

The rapid increase in global energy demand is due to an increase in population and industrial activity [1]. Electricity in Malaysia

* Corresponding author. Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia.

E-mail address: amiraaljboury@gmail.com (A.L. Abdullah).

https://doi.org/10.1016/j.csite.2020.100595
Received 8 November 2019; Received in revised form 23 January 2020; Accepted 29 January 2020
Available online 30 January 2020

Nomenclature

PVTs	Photovoltaic thermal collector
T	Temperature (°C)
G	Solar irradiation (W/m^2)
η_{el}	Electrical efficiency (%)
F_R	Heat removal factor
U_L	Overall heat loss coefficient (W/m^{2}K)
$\dot{m}$	Mass flow rate (LPM)
P.F	Packing factor
PV	Photovoltaic panel
η_{PVT}	Total efficiency (%)
η_{th}	Thermal efficiency (%)
C_p	Heat capacity of flowing medium (J/kg.°C)
F'	Fin efficiency factor
Ac	Collector area (m^2)
h_{fi}	Heat-transfer coefficient of the fluid (W/m^2 k)
W	Tube spacing (m)
C_b	Conductance of the bond between the fin and tube
D	Diameter of collector (m)
I_{abs}	Absorber thickness (m)
K_{abs}	Absorber thermal conductivity(W/m.°C)
I_{pv}	Photovoltaic panel thickness (m)
K_{pv}	Photovoltaic panel conductivity (W/m.°C)
T_c	Cell temperature (°C)
Q_u	Actual useful heat gain (W)
A_m	Panel area (m^2)
η_{el}	Electrical efficiency (%)
U_t	Top loss coefficient (W/$m^{2\circ}C$)
$U_{tc,\ a}$	Overall heat transfer coefficient
MAPE	Mean absolute percentage error (%)
Pmax	Electrical power (W)
σ	Represent stefan-boltzman constant (W/$m^2 .\ k^4$)
α	Absorbance
θ	Collector tilts
τ	Transmittance
ε	Emittance

Subscripts

w	Wind speed
t	Tube
r	Reference
pm	- Mean plate
P	Plate
o	Outlet
i	Inlet
c	Cell
a	Ambient
Exp	Experimental
The	Theoretical mathematical model

continues to be produced using fossil fuels such as coal, oil and gas. However, fossil fuels cannot be replenished and are also a source of pollution, carbon dioxide emissions and global warming. Industrialization and sustained economic growth require more electrical energy. Climate change, protected homes and other pollutants, and environmental impact from traditional non-renewable energy resources should be mitigated and this can be done by promoting the use of renewable energy resources such as photovoltaic solar panels [2,3]. Today, fossil fuels emit large amounts of polluting gases to meet energy requirements and cause serious damage to the ecosystem. The major problem that threatens the survival of humans is global warming [4,5].

Solar thermal collectors are the device generates heat and electrical by utilizes the solar radiation ultraviolet and infrared to produce thermal energy [6]. This liquid may be used to heat water through a heat photovoltaic thermal (PVT) system. The PVT system is used to supply hot water for residential applications. The PVT systems can also be used by coupling the systems with a turbines to produce electricity. The liquid used in the thermal collector can be air, water or any other liquid. Many configurations and designs of solar collectors are used by Refs. [7,8].

The PVT system allows the use of full energy from the sun enables to convert it into heat and electricity at the same time. Much of the solar energy captured in photoelectric plates raises the temperature of its cells, leading to a deterioration in the efficiency of the unit, can be removed heat from PV panels with use the PVT system with water. The extracted heat from PV panel may be used as low temperature applications [9–11]. The general classification of PVT systems are based on the working fluid such as PVT water and PVT air type [12,13] and PVT (water and air) type [14].

PVT systems can be used for a wide variety of applications, including: PV in buildings, electricity generation in a photovoltaic power plant, PV satellites, desalination process for supplying drinkable water in coastal regions and PV in agriculture, … etc [15–19].

Using water as a coolant in a PVT system will increase both the thermal efficiency and electrical efficiency because Water has a higher thermal capacity than air. It also has better optical properties in near infrared radiation. The high specific heat value of water can absorb about four times as much heat as air [20]. Two PVT water collectors were fabricated by A. Ibrahim et al. [21], the first designed collector has a single-pass rectangular tunnel and the second collector was a spiral flow absorber. The results show that the spiral flow design is the best design with the highest thermal and electrical efficiency. Three PVT water collectors were designed and compared in terms of thermal performance before being fabricated into prototypes by Sopian et al. [22], the first designed collector has a direct and the second collector was a parallel, and the third collector was asplit flow. The results show that the split flow design of water-based PVT system provides better performance because the cold water comes from both sides. Therefore the uniform heat distribution of absorber will improve the water-based PVT system both thermal and electrical efficiency by split flow design. In this study, a new dual oscillating absorber in water-based PVT system was designed and developed. The theoretical simulation was performed using MATLAB and an indoor experiment conducted under a solar simulator. The simulation results were validated with the experimental results.

2. Experimental setup

The PVT water collector was tested in the laboratory in the Green Vehicle Technology laboratory Faculty of Mechanical Engineering (FKM), Universiti Teknikal Malaysia Melaka (UTEM). The experimental indoor setup of the water-based PVT system and the equipment used in experiment as shown in Fig. 1(A) and (B) respectively. Accurate measurements can be obtained with indoor tests in the laboratory because the solar radiation can be controlled. There were two photovoltaic modules used in this study, one photovoltaic panel was mounted on the new design of tube absorber as water-based PVT system while the other was a conventional PV module. Both types of photovoltaic were from the same modules, thus the specification was the same. The absorber was installed at the bottom of the

Fig. 1. The experimental indoor setup of water-based PVT system.

water-based PVT system with an aluminium frame to install the absorber and an insulator. For higher accuracy, the recording process was conducted automatically every minute. The data acquisition system is considered the brain of the measurement system. It can control the sensors to record and store the data from the sensors that are connected to it. The measurements for the water-based PVT system and normal PV panels were taken using various sensors. These measurements were done before, during and after the run of the system. Various parameters must be determined to derive the thermal and electrical efficiency such as wind speed, ambient temperature, solar irradiance, temperatures of the various parts of the system, the mass flow of the fluid, etc. These data were collected and stored on a personal computer. The equipment in the experiment used which include K-type thermocouples, pyranometer and anemometer, data logger, flow meter F-400, storage tank, thermal imaging camera, three voltage regulators and the halogen lamps which are widely used in solar beam experiments (SBE) for solar simulation applications because of their extremely stable and smooth spectral output. The halogen lamps were arranged in (4×3) metrics for uniform distribution of irradiance. The water-based PVT system and PV panel were tested under a solar simulator which has 12 tungsten halogen lamps. The maximum electrical power used by each lamp was 400 W at 240 V and 11 A. The measurement of voltage, current and power max by Live tester, has been conducted simultaneously with other devices. Shatat et al. [23] used 30 halogen lamps of 400W each in this Experiment. The solar simulator with variable depth solar collector was investigated experimentally by Razak et al. [24].

2.1. PVT system design

The system design consisted of the PV panel, absorber plate and new absorber tube made of copper at the bottom. The PV panel is coated and bonded with high temperature silicone adhesive and sealant with copper plate. The copper water tubes were attached to the bottom of the copper plate absorber by copper welding. The dimensions of the copper plate are 1.18 m long, 0.54 m wide and 0.003 m thick below the PV panel. The thermal insulation was fixed at the bottom and the edges of the PVT absorber tube to reduce the heat loss from the bottom and edges. The hybrid PVT water collector was made by placing a polystyrene board at the bottom and edges of the standard PV module. The absorber collector assists in ensuring a uniform temperature within the system and reducing the temperature of the solar PV panel. The normal PV panel is monocrystalline silicone, a semi-flexible type which is composed of 36 monocrystalline cells connected in series/parallel. This PV generator can produce power of 100 W and consists of five layers (transparent PET, Ethylene Vinyl Acetate (EVA) film, Silicon solar cell, EVA and TPT). The new absorber water collector dual oscillating is in the shape of a tube and made up of one outlet and inlet as shown in Fig. 2. The water flows in and out via the outlet and inlet tube arrangements. The cold water flow to both directions left and right and the hot water come out side by two pipes of both directions left and right, they meet with one pipe to exit. Hot and cold temperature position is alternating. Distribution will be more uniform. Therefor the uniform heat distribution of absorber will improve the PVT both thermal and electrical efficiency and also covers the entire PV panel. The low to medium-temperature water penetrates the coil and comes out of the absorber collector as hot water, which may be used or stored for later use. In this work, solar energy may be completely used. The water passing through the absorber tube is heated by touching the

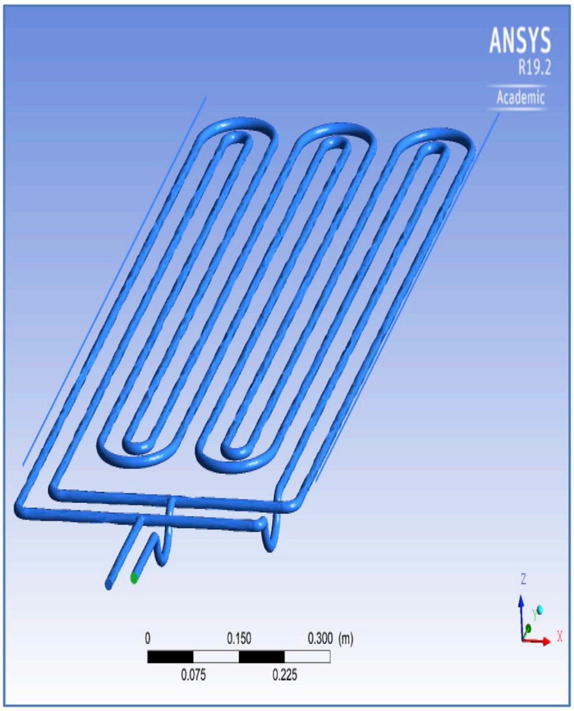

Fig. 2. A new design of the PVT (dual oscillating absorber).

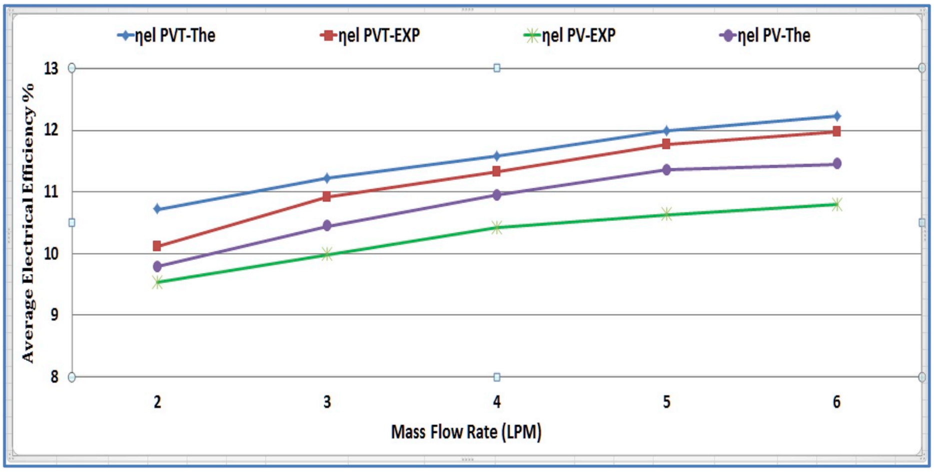

Fig. 3. The experimental and theoretical results of the electrical efficiency with different the mass flow rate.

bottom of the PV module. The cold water that enters the round tube is heated continuously by the hot panel. Typically, the hot-water storage tank in water-based PVT system is situated in close proximity to the ground level, whereas the solar module is located above the roof. The heat loss could be prevented by ensuring a proper insulation of the pipes. Only the collector unit absorbs the heat, and water is heated using the heat absorbed by the collector.

2.2. Indoor experimental method

The water-based PVT system and PV panel were tested in laboratory with used the solar simulator and voltage regulator was used to control the amount of irradiance which use three unites in the indoor setup. The mass flow rate of cooling fluid varied, by use flow meter F-400 is a device that measure flow rate of the fluid and the range of flow rate is between 2 and 20 L per minute (LPM). The precise control of the flow rate is done by the flow control knob on the flow meter. The experimental setup of indoor testing are included: study the effect of the change mass flow rate with a constant value solar radiation and the effect of a change in solar radiation with a constant mass flow rate as shown in Table 1.

1 Studying effect of the mass flow rate by:
   - The fixed values of the solar radiation are from 500 to 1000 W/m^2 and the changes in the mass flow rate are from 2 to 6 LPM.
2 Studying effect of the solar radiation by:
   - The fixed values of the mass flow rate are from 2 to 6 LPM and the changes in the solar radiation from 500 to 1000 W/m^2.

During the test, the water inlet and outlet are controlled and reconnected to the storage tank to form a closed loop system. The used a digital data logger to collect and stored data every minute. The model used is the DAS-TC16 system. The data recorded by a USB memory device were then extracted or downloaded to spreadsheets and files ready for transfer to data analysis tools using the web interface, and these data were thereafter used to determine the electrical and thermal efficiency of the water-based PVT system.

3. Energy balance analysis of the PVT water collector

The analysis and simulation of both systems are presented using experimental data utilizing in the MATLAB program and compared the results of the new design dual oscillating absorber of the PVT water system with a normal PV panel without a cooling system. The value variation includes thermal, electrical and overall efficiency, temperature of the PV module and temperature of outlet water, with solar radiation rate from 500 to 1000 W/m^2 and the range of the mass flow rate from 2 to 6 LPM. The evaluation of the water-based PVT system performance is based on electrical and thermal efficiency, whereas the analysis is based on design parameters and basic

Table 1
Summarizes of the change of the mass flow rate and the solar radiation.

Mass Flow Rate (LPM)	Solar Radiation G (W/m^2)					
2	500	600	700	800	900	1000
3	500	600	700	800	900	1000
4	500	600	700	800	900	1000
5	500	600	700	800	900	1000
6	500	600	700	800	900	1000

energy balance equations. The basic energy balance equations discussed by Ref. [25] was used in the present study. The purpose of energy balance is to find the relationship between PV solar energy and cooling fluid output temperature. To simplify the mathematical models of the normal PV panel generator and the PVT water system. The thermal energy balance is based on the following assumptions:

- It is assumed that the thermal-physical properties of each layer are constant.
- Wind speed surrounding the systems is uniform.
- Under force mode operation, the water flow is uniform
- Heat losses occur from the top, no heat loss from the back and the edge (the device is well insulated) during the same environmental conditions.
- It was assumed that there is partial shading or no dust on the PVT system.
- The system is in an almost-constant state.
- The physical-thermal properties of the photovoltaic panels, water and absorber tubes are independent of temperature.

The photovoltaic thermal collector characteristics are presented in Table 2.

The total efficiency (η_{PVT}) of the PVT system are used to evaluate the overall system performance as follows [16,26].

$$\eta_{PVT} = \eta_{th} + \eta_{el} \tag{1}$$

The thermal efficiency of the PVT system (η_{th}) is the ratio of the useful collected heat (Q_u) to the overall incident solar radiation (G), as follows [27,28]:

$$\eta_{thermal} = \frac{\int Q_u \, dt}{A_m \int G \, dt} \tag{2}$$

The useful heat collected and absorbed by the PVT system collector is the average mass flow rate *($\dot{m}$), (Cp)* is heat capacity of flowing medium and *(To - Ti)* is temperature difference at the collector inlet and outlet. The useful heat collected can be expressed as follows by Refs. [29–31].

$$Q_u = \dot{m}\, C_p (To - Ti) \tag{3}$$

In addition, the useful heat gain of the PVT system collector is the difference between the absorber solar radiation and thermal heat losses, can be written as follows [25,30]:

Table 2
Characteristics of the water–based PVT system.

Parameter	Value	Unit
α_c	0.85	–
τ_{PET}	0.88	–
β_c	0.83	–
τ_c	0.95	–
ε_p	0.95	–
α_p	0.8	–
τ_{PET}	0.88	–
σ	$5.67*10^{-8}$	$W/m^2.\,k^4$
W	0.042	m
D	0.0127	m
D_i	0.01198	m
h_{fi}	333	W/m .k
k_{abc}	401	W/m. k
I_{abc}	0.001	m
k_{pv}	130	W/m. k
η_c	15.5	%
T_a	299.15	$^\circ K$
T_{ref}	298.15	$^\circ K$
h_{pf}	100	$W/m^2.K$
C_p	4190	$J/kg.^\circ C$
G	(500–1000)	W/m^2
A_c	0.489	m^2
A_m	0.6372	m^2
Ti	299.15	°K

$$Q_u = A_c F_R \left[G\,(\tau\alpha)_{pv} - U_L (T_i - T_a) \right] \tag{4}$$

U_L is the overall collector heat loss, *(Ta)* is the ambient temperature, *(A)* is the collector area, *(Ti)* is the inlet temperature, (G) is the solar radiation, $(\tau\alpha)_{pv}$ is the PV thermal efficiency. (F_R) is the heat removal efficiency factor and was expressed as follows [25,28,32].

$$F_R = \frac{\dot{m} C_P}{A_C\, U_L} \left[1 - exp\left(-\frac{A c U_L F^{'}}{\dot{m} C_P} \right) \right] \tag{5}$$

Where $F^{'}$ is the collector efficiency factor, this factor is expressed as follows:

$$F^{'} = \frac{{}^{1}/U_L}{W\left[\frac{1}{U_L \quad [D+(W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi h_{fi} D_i} \right]} \tag{6}$$

(h_{fi}) is the heat-transfer coefficient of the fluid, W is the tube spacing, C_b is the conductance of the bond between the fin and circular tubes, D is the diameter and Fin efficiency factor F given is expressed as follows [33].

$$F = \frac{\tanh \mathrm{M}(\mathrm{W} - \mathrm{D})/2}{\mathrm{M}(\mathrm{W} - \mathrm{D})/2} \tag{7}$$

Coefficient *(M)* in Eq. (4.10)is the thermal conductivity of the absorber and the PV cell, can expressed as follows [34].

$$\mathrm{M} = \sqrt{\frac{U_L}{k_{abs}\, l_{abs} + k_{pv}\, l_{pv}}} \tag{8}$$

Where l_{abs} is the absorber thickness, k_{abs} is the absorber thermal conductivity, l_{pv} is the PV panel thickness and k_{pv} is the PV thermal conductivity [25,30] U_L the overall loss coefficient is expressed as follows:

$$U_L = U_t + U_b + U_e \tag{9}$$

U_b *is* Loss coefficient of the bottom, U_t is top loss coefficients and U_e is the edge loss coefficient. The top loss coefficient (U_t) is calculated as follows:

$$U_t = \frac{1}{\frac{N}{\frac{c}{T_{Pm}\left(\frac{T_{Pm}-T_a}{N+f}\right)^{e}} + \frac{1}{h_w}}} + \frac{\sigma(T_{Pm} + T_a).\left(T_{pm}^2 + T_a^2\right)}{\frac{1}{\varepsilon_p + 0.00591.N.h_w.} + \frac{2.N+f+0.133\varepsilon_p}{\varepsilon_{PET}} - N} \tag{10}$$

The expression for cell temperature is calculated as follows [35,36].

$$T_c = \frac{(\alpha\tau)_{1,\, eff} G + U_{tc,\, a} T_a + h_{c,\, p} T_p}{U_{tc,\, a} + h_{c,\, p}} \tag{11}$$

For blackened absorber plate temperature is calculated as follows [37].

$$T_p = \frac{(\alpha\tau)_{2,\, eff} G + PF_1 (\alpha\tau)_{1,\, eff} I(t) + U_{L2} T_a + h_{pf} T_f F^{'}}{U_{L2} + h_{pf} F^{'}} \tag{12}$$

The electrical efficiency (η_{el}) of a PV module, can expressed as follows [37–39]:

$$\eta_{el} = \eta_c \left[1 - 0.0045 \left(T_c - T_{ref} \right) \right] \tag{13}$$

The thermal efficiency of the collector is expressed as follows [28,30].

$$\eta_{th} = F_R \left[(\tau\alpha)_{pv} - U_L \left(\frac{T_i - T_a}{G} \right) \right] \tag{14}$$

4. Results and observations

The performance of the water-based PVT system is determined by electrical and thermal properties. The proposed water cooling technology significantly reduces the PV panel temperature and increases the output power of the water-based PVT system. The water-based PVT systerm analysis consists of three parts: electrical, thermal and total efficiency.

4.1. Experimental validation

In this present work, the average cell temperatures *(Tc)* for the PV panel and the water-based PVT system with changes in the mass flow rate values from 2 to 6 LPM for the theoretical and the indoor experimental were compared. The results show that increasing the mass flow rate reduces the cell temperature and the PV panel and the water-based PVT system reached the maximum cell temperature values of 64.63 °C and 63.22 °C in theoretical and indoor experiments, respectively. The results show that lowering the PV panel cell temperature improves the electrical efficiency of the PVT water collector. The higher the mass flow rate, the lower the PV panel temperature, which improves electrical efficiency. Table 3 shows a comparison of cell temperatures in the PV panel and the water-based PVT system in the theoretical work and indoor experiment. There is an obvious good agreement in results between the experimental and theoretical models.

The average electrical efficiency *(Ƞel)* values for the PV panel and water-based PVT system with changes in the mass flow rate values from 2 to 6 LPM for the theoretical model and the indoor experiment were compared, as shown in Fig. 3. It can be seen that the PVT electrical efficiency increased with the increase in mass flow rate due to the water cooling capacity, thermal absorber and heat transfer from the PV surface to the thermal absorber. Therefore, increasing the mass flow rate leads to an increase in the electrical efficiency. The results show that the PV panel reached the maximum electrical efficiency of 11.45% and 10.79% in the theoretical model (*Ƞel PV-The*) and the indoor experiment *(Ƞel PV-EXP*), respectively. Meanwhile the PVT water collector reached a maximum electrical efficiency of 12.23% and 11.97% in the theoretical model (*Ƞel PVT-The*) and experimental (*Ƞel PVT-EXP*), respectively.

The average thermal efficiency *(Ƞth)* values of the water-based PVT system with changes in the mass flow rate values from 2 to 6 LPM for the theoretical model and the indoor experiment were compared. For this study, the thermal efficiency of the water-based PVT system increased with an increase in the mass flow rate because at a lower mass flow rate, the working fluid will take more time to absorb heat from the PV panel in comparison to a higher mass flow rate. Therefore, increasing the mass flow rate leads to an increased thermal efficiency up to the optimal value of the mass flow rate at 5 LPM. The values from the results show that the water-based PVT system reached the maximum thermal efficiency values in the theoretical model and the indoor experiment at 63.39% and 58.43%, respectively, with the mass flow rate at 5 LPM. This obviously shows a good agreement in results between the experimental and theoretical models.

4.2. Effect of the mass flow rate and solar irradiance on the thermal performance of the water-based PVT system

The thermal performance of the water-based PVT system using water as the base fluid was evaluated where outlet water temperatures were collected against the mass flow rate for five days. For this study, the outlet temperature of the water drops as the inlet water velocity increases. At very low speeds, it can be seen that the outlet temperature level is very high because at very low speeds the rate of heat removal from the PV panel is high. When the speed is high, the rate of heat removal from the PV panel is low. The results show that increasing the mass flow rate decreases the outlet water temperature at all solar radiation values. Increased solar radiation will also lead to an increased outlet water temperature. The maximum average the outlet water temperature decreased from 44.22 °C to 32.11 °C.

The average thermal efficiency against mass flow rates from 2 to 6 LPM at solar irradiance from 500 to 1000 W/m^2 as shows in Fig. 4. The results show that the increasing mass flow rate and solar radiation lead to an increase in thermal efficiency with the increase in the mass flow rate up to the optimal value of the mass flow rate at 5 LPM. This is because at a lower mass flow rate, the working fluid will take more time in absorbing heat from a PV panel compared to when the speed is high, the rate of heat removal by the tubes from PV panel is low. At a low mass flow rate the outlet temperature increases, but thermal efficiency will drop due to the low mass flow rate. The maximum average thermal efficiency values of the PVT system increased from 41.65% to 58.64% at a solar irradiance of 1000 W/m^2 with increased mass flow rate from 2 to 5 LPM. The experimental thermal efficiency will reach its 'optimum point' at a mass flow rate of 5 LPM.

4.3. Effect the mass flow rate and solar irradiance on the electrical performance of the water-based PVT system

Solar radiation is another most effective environmental parameter that controls the performance of PV modules. The performance of PV and PVT cell temperatures will be affected by solar radiation and mass flow rate. In this experiment, the average cell temperature with mass flow rates from 2 to 6 LPM at solar irradiance form 500–1000 W/m^2 were studied. However, the temperature of the water-based PVT system cell is reduced because the more water passes through the tubes lead to the removal of more heat from the PV panel and thermal absorber from the PV panel by the water, resulting in a reduction in cell temperature and increasing electrical efficiency. It can be seen that the cell temperature of the water-based PVT system for all mass flow rates has been always below the temperature of the PV panel. The results show that increasing the mass flow rate reduces the cell temperature during solar radiation and increased

Table 3
Comparison of cell temperatures of the PV panel and water-based PVT system.

Mass Flow Rate (LPM)	Cell temperature of the water-based PVT system (°C)		Cell temperature of the PV panel (°C)		Average Error *(MAPE)* (%)	
	Theoretical *(Tc PVT-The)*	Experimental *(Tc PVT-Exp)*	Theoretical *(Tc PV-The)*	Experimental *(Tc PV-Exp)*	PVT	PV
2	58.73	57.32	63.62	62.11	2.45	2.43
3	57.75	56.18	64.63	63.22	2.50	2.23
4	52.46	51.32	59.86	58.22	2.50	2.81
5	51.42	50.32	60.34	59.23	2.18	1.87
6	48.93	47.21	57.04	56.23	3.64	1.44

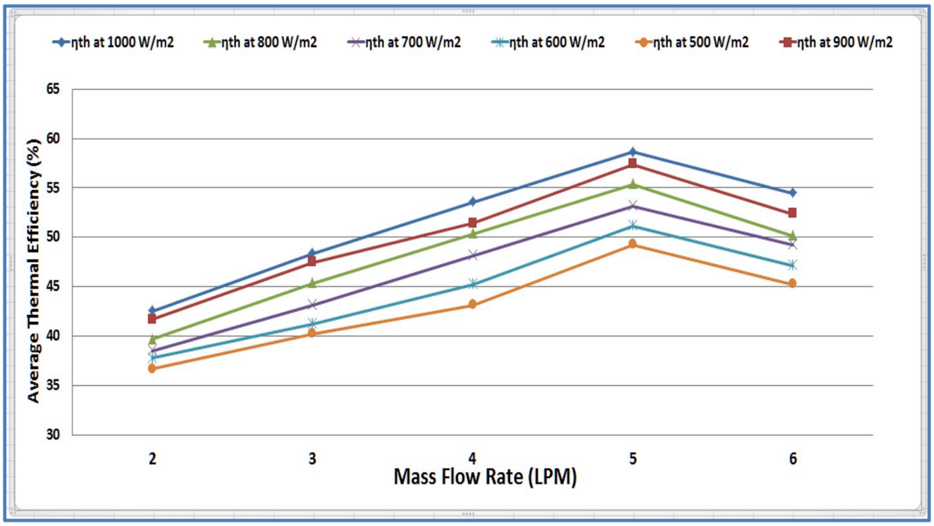

Fig. 4. Average thermal efficiency with different mass flow rate at different solar irradiance.

solar radiation lead to increased cell temperature. The maximum average cell temperature of the PVT system decreased from 61.65 °C to 56.42 °C at a solar irradiance of 1000 W/m^2 with an increase in the mass flow rate from 2 to 6 LPM.

The average electrical efficiency against mass flow rates 2, 3, 4, 5 and 6 LPM at solar irradiance from 500 to 1000 W/m^2 as shown in Fig. 5. The results show that the electrical efficiency increases because increasing the mass flow rate at all solar radiation values due to the cooling water system and heat transfer from the solar cell PV surface into the water passing through the new absorber collector. However, increasing the mass flow rate leads to an increase in the heat transfer coefficient between the tube's walls and the working fluid, resulting in a reduced PV panel temperature and increasing the electrical efficiency. However, increased solar radiation leads to reduced electrical efficiency because the photovoltaic (PV) unit temperature increases along with solar radiation leading to low electrical efficiency.

The average electrical efficiency of the water-based PVT system increase from 6.69% to 8.78% at a solar irradiance of 1000 W/m^2 with an increase in the mass flow rate from 2 to 6 LPM, respectively. The infrared camera was used to show the temperature distribution of the water-based PVT system and PV panel. The system was installed to collect the necessary data of both systems simultaneously. Fig. 6(A) and (B) shows the temperature distribution of the water-based PVT system and PV panel at mass flow rate 3 and 4 LPM respectively. The temperature of the water-based PVT system is much lower than conventional PV panel due to the cooling process at the bottom of the PV panel.

The PVT efficiency (η_{PVT}), known as the total efficiency, is used to evaluate the overall system performance and can be represented by a combination of efficiency expressions, which consists of electrical and thermal efficiency. Therefore, the sum of both efficiencies is known as the total efficiency. Increasing the mass flow rate until an optimum value leads to an increase in the thermal and overall efficiency. However, if the optimum value is exceeded, the thermal efficiency is reduced and the electrical efficiency can be further improved until a constant value is obtained. The average total efficiency against mass flow rates from 2 to 6 LPM at solar irradiance from 500 to 1000 W/m^2 as shown in Fig. 7. The results show that increasing the mass flow rate and solar radiation leads to an increase

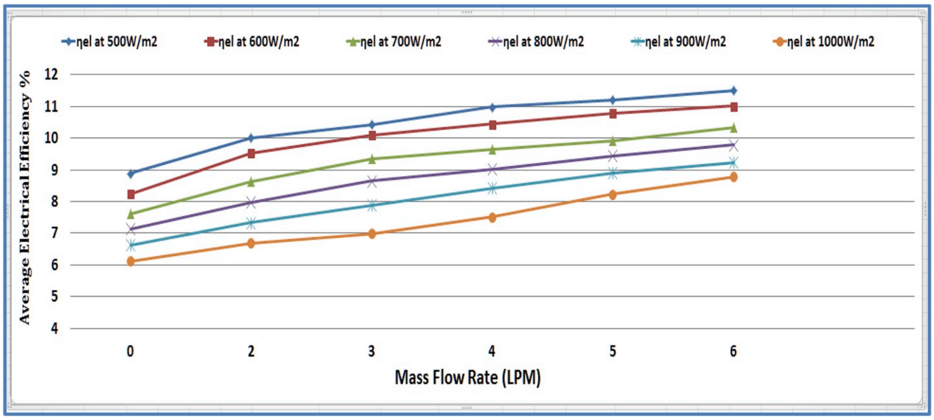

Fig. 5. Average electrical efficiency for different mass flow rates at different solar radiances.

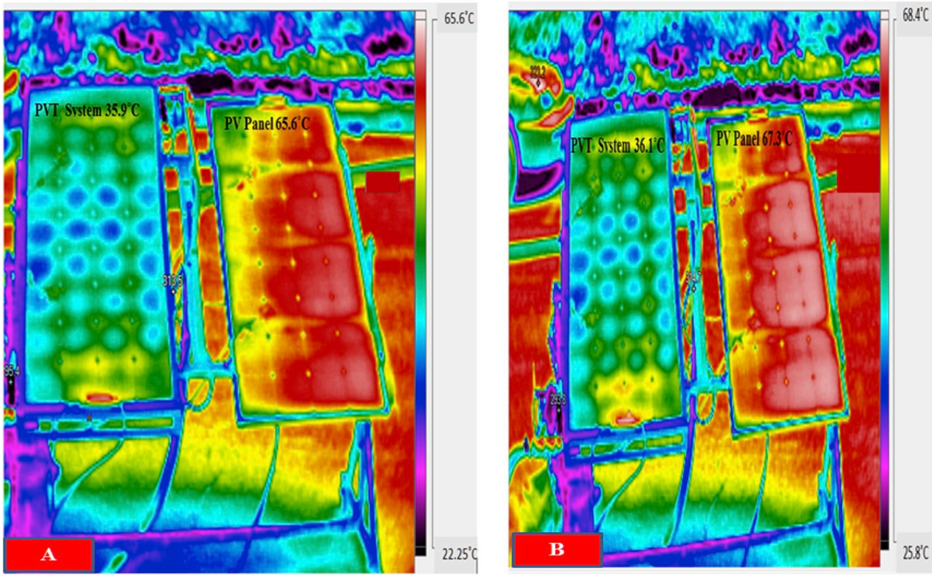

Fig. 6. (A) and (B) temperature distribution of a PV panel and water-based PVT system.

in the total efficiency. The maximum average total efficiency increases from 49.22% to 66.87% at a solar irradiance of 1000 W/m^2 with an increase in the mass flow rate from 2 to 5 LPM.

4.4. Performance of new absorber design compared to other designs

This section shows the comparison element of this research. This offers a layer of validation for the results and illustrates the outcome of this system in comparison to other proposed systems. In addition, this comparison gives an impression of the performance of the proposed PVT collector with respect to research conducted in other countries. Table 4 is a comparison of the thermal, electrical and total efficiencies of the PVT system. There are different affected parameters related to the thermal system type, the technologies used, weather parameters, cooling methods, location and system configuration. The overall comparison is particularly difficult because the circumstances of each study are different. However, the water-based PVT system has a higher efficiency due to a lower cell temperature compared with other systems.

5. Conclusions

Photovoltaic thermal collector (PVT) are renewable energy device which are a combination of solar PV components and solar thermal components. They produce electricity and thermal energy simultaneously. The experimental and theoretical analysis of a water-based PVT system using a new dual oscillating absorber design was studied. The analysis and simulation of the two systems are presented using theoretical data by utilizing the MATLAB program and comparative results of the new design (dual oscillating absorber) of the water-based PVT system with a normal PV panel without a cooling system. Indoor testing was carried out in the laboratory in the Green Vehicle Technology laboratory, Makmal of Fakulti Kejuruteraan Mekanikal of the Universiti Teknikal Malaysia Melaka (UTeM). Finally the numerical simulations and validation were carried out. The finding can be summarized as according to this study:

1 Validation of the model of the experimental data by utilizing the MATLAB program with experimental tests conducted. The results show that:
  - The PV panel reached the maximum cell temperature values in the theoretical model and the indoor experiment at 64.63 °C and 63.22 °C, respectively. The water-based PVT system reached the maximum cell temperature values in the theoretical model and the indoor experiment at 58.73 °C and 57.32 °C, respectively.
  - The PV panel reached the maximum electrical efficiency of 11.45% and 10.79% in the theoretical model and the indoor experiment while the water-based PVT system reached the maximum electrical efficiency of 12.23% and 11.97% in the theoretical model and the indoor experiment, respectively.
  - The water-based PVT system reached the maximum thermal efficiency of 63.39% and 58.43% in the theoretical model and indoor experiment, respectively, with the mass flow rate at 5 LPM.
  - The numerical simulation results of this study are in good agreement with the experimental measurements.

2 Evaluated the performance of the PVT system using water as the base fluid Indoor experimental has been tested at the Park in Green Vehicle Technology laboratory. The results show that:

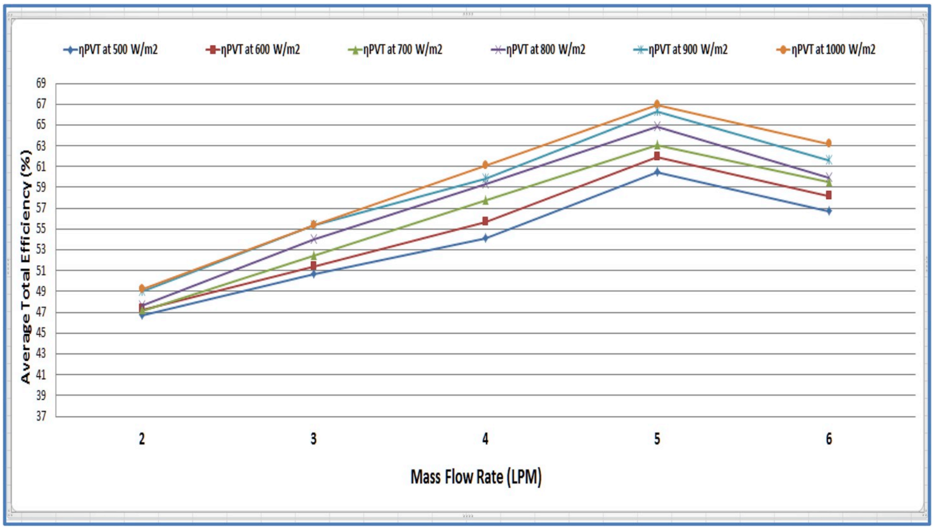

Fig. 7. Average total efficiency against different mass flow rate at different solar irradiance.

Table 4
Current study with new design comparing with other absorber collector designs.

PVT System	Performance of the PVT System		
	Electrical efficiency %	Thermal efficiency %	Total efficiency%
PVT water (tube-and-sheet) [40]	11.5	39.4	50.9
PVT air (duct) [41]	17.18	10.01	45
PVT Water (flow channels) [42]	9.5	50	59.5
PVT water (tube-and-sheet) [43]	11	51	62
Glazed PVT water (tube-and-sheet) [44]	10.3	48.4	58.7
Unglazed PVT water (tube-and-sheet) [44]	11.5	35.8	47.6
PVT Water system [45]	10.90	51.25	62.15
Present study	11.5 at 500 W/m^2 and 6 LPM	58.64 at 1000 W/m^2 and 5 LPM	66.87 at 1000 W/m^2 and 5 LPM

- The maximum average outlet water temperature decreased from 44.22 °C to 32.11 °C at a solar irradiance of 1000 W/m^2 with increase mass flow rate from 2 to 6 respectively.
- The experimental maximum thermal efficiency will reach its 'optimum point' at a mass flow rate 5LPM.The maximum average thermal efficiency increased of the PVT system from 41.65% to 58.64% at a solar irradiance of 1000 W/m^2 with increase mass flow rate from 2 to 5 respectively.
- The maximum average cell temperature of water-based PVT system decreased from 61.65 °C to 56.42 °C at a solar irradiance of 1000 W/m^2 with increase mass flow rate from 2 to 6 respectively.
- The average electrical efficiency of the water-based PVT system increase from 6.69% to 8.78% at a solar irradiance of 1000 W/m^2 with increase mass flow rate from 2 to 6 respectively.
- The maximum average total efficiency increasing from 49.22% to 66.87% at a solar irradiance of 1000 W/m^2 with increase mass flow rate from 2 to 5 respectively. The experimental total efficiency will reach its 'optimum point' at mass flow rate 5LPM.
- The numerical model of PVT with new absorber flow channel has been validated by experimental investigation where the results were found to be in good agreement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Amira Lateef Abdullah: Methodology, Software, Investigation. **S. Misha:** Data curation, Validation. **N. Tamaldin:** Visualization, Writing - review & editing. **M.A.M. Rosli:** Conceptualization. **F.A. Sachit:** Writing - original draft.

Acknowledgement

This work was funded by Universiti Teknikal Malaysia Melaka (Grant No. FRGS/1/2018/TK07/UTEM/02/4). The authors would like to thank the Fakulti Kejuruteraan Mekanikal of the Universiti Teknikal Malaysia Melaka, Centre for Advanced Research on Energy in Universiti Teknikal Malaysia Melaka and Ministry of Electricity in Iraq for supporting this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2020.100595.

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