



Experimental and model validation of photovoltaic-thermal (PVT) air collector: exergy analysis

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Received 21 February 2021; Accepted 09 June 2021; Published online 31 July 2021

Abstract

Solar energy is a renewable energy that can produce heat via a thermal system and generate electricity via a photovoltaic (PV) module. A photovoltaic-thermal (PVT) collector is a system that has a PV module combined with a thermal collector system. The PVT collector is a popular technology for harvesting solar energy. A PVT collector can generate both electrical and thermal energies simultaneously. The study aims to validate the PV and outlet temperature for various mass flow rates and solar radiation. To develop a predictive model, a steady-state energy analysis of a PVT air collector was performed. An energy balance equation was solved using the matrix inversion method. The theoretical model was developed and validated against the experimental results, which have a similar trend and are consistent with the experimental results. On the other hand, the validated model was used to study the performances of PVT air collectors using exergy analysis for the mass flow rate ranging from 0.007 kg/s to 0.07 kg/s and solar radiation ranging from 385 W/m² to 820 W/m². The result from the mathematical model was found to be consistent with the experimental data with an accuracy of about 95%. The average PVT exergy efficiency was found to be 12.7% and 12.0% for the theoretical and experimental studies, respectively.

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Keywords: mathematical model; thermal efficiency; electrical efficiency; second law efficiency.

1. Introduction

Global crisis on primary energy sources, such as coals and gas, has facilitated the study of renewable energy technologies. Studies have focused on solar energy to address the global crisis on oil and gas prices worldwide. Sustainable energy sources, such as solar energy, are clean energy that contributes a substantial proportion to fulfilling the energy demand by societies. The yielding of solar energy for photovoltaic (PV) systems in energy technology can

be broadly classified into two systems. PV energy system changes solar energy into electrical energy, and thermal energy system converts solar energy into thermal energy. The combination of PV and solar thermal collectors in the system can produce heat and electrical energy from solar energy. The use of a cooling system alongside PV system is validated as PVT system or PV with the cooling system. Given the beneficial dual use of PVT compared with a single PV system, efficient use of solar energy may contribute to the demand for heat and electrical energy to be supplied to industries and societies [1][2].

PVT collector systems using air as heat transfer medium are known as PVT air collector systems. The

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air circulation in the system is air circulating through the path between the back of the PV module surface with the system or path insulation on both sides of the PV module. Air is streamed directly through natural convection or forcefully. The hot air that comes out of this system is useful for drying and heating purposes. This system is widely applied in two designs namely the PV system that is integrated with the solar thermal collector system and PV system that is integrated into the building ventilation system. The energy analysis of the PVT air collector has been carried out by researchers. The efficiency of energy analysis is usually determined regardless of the power loss factor for the system. Therefore, over the past few years, most systems are analyzed and designed by taking into consideration the cost, the economy, the environment, and efficiency [3]. PVT collectors can attain net (electrical plus thermal) efficiencies of 70 % or more, depending on the conditions, with electrical efficiencies of 15 – 20 % and thermal efficiencies of more than 50 %. [4]. PVT technologies offer the ability to reduce the number of materials used, the time it takes to install, and the amount of space needed [5]. PVTs are useful for household applications since they can generate both electricity and thermal energy at the same time. Commercial PVT systems, despite their enormous potential, are still not as popular as stand-alone, individually installed PV and thermal systems [6][7].

Exergy analysis is a measure of consistency in determining the value of the economy as mentioned by many researchers. Through exergy analysis, the real efficiency value can be determined by determining the value of system power loss. Consequently, if the energy efficiency value and the efficiency of the exertion are different, the energy efficiency is higher than the efficiency of the previously mentioned factor. Exergy analysis is a very clever step in the design and process of the industry. This is because optimum energy consumption is an important issue. Information from exogenous value is also very important in operating costs, energy recovery, diversity of fuels, and pollutants. Now, exergy analysis is widely used in solar energy assessment such as solar drying systems, solar collectors, and PVT systems [8]. Jadallah *et al.* [9] designed, fabricate, and modeled for double-pass PVT collectors for drying applications. In the diverse weather conditions, Zoukit *et al.* [10] constructed and forecasted an indirect form of solar dryer that functions in both forced and natural convection modes. Tiwari *et al.* [11] constructed and built a hybrid PVT air collection with a dryer, then assessed the system's thermal model. The dryer chamber performed better for crops in forced convection mode than in natural convection mode [11]. The indirect dryer was shown to be more efficient than an open solar dryer [12]. For drying pear, Hajar *et al.* [13] designed an indirect solar drier method. The higher output temperature reached 57 °C when solar radiation was 900 W/m², and the drying room's thermal efficiency was 11.11 % [13].

The loss of PV module efficiency is one of the most serious issues with a building-integrated photovoltaic (BIPV) system. As the temperature of a PV panel rises by 1 °C from 25 °C, its efficiency drops by roughly 0.4 – 0.5 %. [14]. Theoretical study and experimental validation of energetic performances of PVT air collectors were studied by Touafek *et al.* [15]. The simulation results were compared to those obtained through experimentation from outdoor testing. Their comparison reveals a high level of agreement. In the case of the intake and output fluid temperatures, this agreement is more pronounced. This study will derive the output temperature and the PV temperature from the mathematical model and validate them against an experiment from indoor testing.

The study aims to validate the PV and outlet temperature for a mass flow rate of air ranging between 0.007 kg/s and 0.07 kg/s and solar radiation of 385 W/m² and 820 W/m². The validated data would then be used to analyze the exergy of PVT air collector and compare it with the exergy of the PVT used in the experiment. Exergy analysis identifies the causes, locations, and magnitude of the inefficiencies of the system and provides an accurate measure of how a system approaches the ideal.

II. Materials and Methods

A. Mathematical modeling

The cross-sectional view of the PVT air collector is shown in Figure 1. Various heat transfer coefficients are shown in the Figure 1. The energy balance equation for PVT air collectors is based on the following assumptions: all convection heat transfer coefficients in the channels and flowing air are equal and constant; the usable heat gain to by air is uniform along the length of the collector; and the ohmic losses in the solar cell are insignificant [16]. Figure 1 shows temperatures such as T_p is PV temperature, T_i is inlet temperature, T_b is bottom temperature, T_f is fluid (air) temperature, and T_o is outlet temperature. U_t and U_b are top and bottom loss coefficients. S is solar radiation, α , τ coefficients are absorption and transmission coefficient, respectively. Heat transfer coefficient of radiation from PV to ambient (h_{rpa}), heat transfer coefficient of radiation from PV to bottom (h_{rpb}), and heat transfer coefficient of convection from PV to fluid (h_{cpf}).

The steady-state energy balance equations for PVT air collectors are given as follows:

For PV,

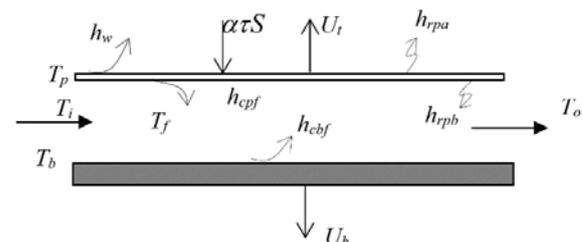


Figure 1. Schematic diagram of heat transfer coefficients in a PVT air collector

$$\tau\alpha S = U_t(T_p - T_a) + h_{cpf}(T_p - T_f) + h_{rpb}(T_p - T_b) + \frac{\mu C}{k} \quad (1)$$

For the airflow channel,

$$mC(T_o - T_i) = h_{cpf}(T_g - T_f) + h_{cbf}(T_b - T_f) \quad (2)$$

For the backplate,

$$h_{rpb}(T_p - T_b) = h_{cbf}(T_b - T_f) + U_b(T_b - T_a) \quad (3)$$

where

$$U_b = \frac{k_t}{l_t} \quad (4)$$

$$U_t = \left(\frac{1}{h_w + h_{rpa}} \right)^{-1} \quad (5)$$

$$h_{rpb} = \frac{\sigma(T_p + T_b)(T_p^2 + T_b^2)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1 \right)} \quad (6)$$

$$h_{rpa} = \varepsilon_p \sigma (T_p^2 + T_{sky}^2) (T_p - T_{sky}) \quad (7)$$

$$T_{sky} = 0.0522T_a^{1.5} \quad (8)$$

Where ε_p , σ , T_a , T_{sky} , T_b and T_p are the emissivity of PV, Stefan– Boltzmann constant, ambient temperature, sky temperature, backplate temperature, and PV temperature, respectively.

The convective heat transfer coefficients [16] are given as in equations (9) to (15).

$$h = \frac{k}{D_h} Nu \quad (9)$$

in which

$$D_h = \frac{4Wd}{2(W+d)} \quad (10)$$

where W , d , and D_h are the width, depth, and equivalence diameter of the channel, respectively; k is the air thermal conductivity, and; Nu is the Nusselt number [16].

Nusselt numbers are given as follows [16]:

For $Re < 2300$ (laminar flow region),

$$Nu = 5.4 + \frac{0.00190 \left[Re Pr \left(\frac{D_h}{L} \right) \right]^{1.71}}{1 + 0.00563 \left[Re Pr \left(\frac{D_h}{L} \right) \right]^{1.17}} \quad (11)$$

For $2300 < Re < 6000$ (transition flow region),

$$Nu = 0.116 \left(Re^{2/3} - 125 \right) Pr^{1/3} \left[1 + \left(\frac{D_h}{L} \right)^{2/3} \right] \left(\frac{\mu}{\mu_w} \right)^{0.14} \quad (12)$$

For $Re > 6000$ (turbulent flow region),

$$Nu = 0.018 Re^{0.8} Pr^{0.4} \quad (13)$$

where Re and Pr stand for Reynolds and Prandtl numbers, given as [16]

$$Re = \frac{mD_h}{A_{ch}\mu} \quad (14)$$

$$Pr = \frac{\mu C}{k} \quad (15)$$

For a short collector of less than 10 m, the theoretical model assumes that the mean air temperature is equal to the arithmetic mean [16], where

$$T_f = \frac{(T_i + T_o)}{2} \quad (16)$$

The physical properties of air are density, specific heat, thermal conductivity, and viscosity as published. The major design parameters are given as $W = 0.53$ m, $L = 1.2$ m, $T_a = T_i = 27$ °C, $\varepsilon_p = 0.7$, $\tau = 0.92$, $\varepsilon_b = 0.9$, $\alpha = 0.9$, and $V = 1$ m/s [16].

For simplicity, equations (1) to (3) can be presented in a 3×3 matrix form:

$$[A][T] = [B] \quad (17)$$

$$\begin{bmatrix} Z_1 & -h_{cpf} & -h_{rpb} \\ h_{cpf} & Z_3 & h_{cbf} \\ h_{rpb} & h_{cbf} & Z_5 \end{bmatrix} \begin{bmatrix} T_p \\ T_f \\ T_b \end{bmatrix} = \begin{bmatrix} Z_2 \\ Z_4 \\ Z_6 \end{bmatrix} \quad (18)$$

where

$$Z_1 = U_t + h_{cpf} + h_{rpb} \quad (19)$$

$$Z_2 = \alpha\tau S + U_t T_a - \eta_p S \quad (20)$$

$$Z_3 = -(h_{cpf} + h_{cbf} + 2mC) \quad (21)$$

$$Z_4 = -2mCT_i \quad (22)$$

$$Z_5 = -(h_{cbf} + h_{rpb} + U_b) \quad (23)$$

$$Z_6 = -U_b T_a \quad (24)$$

The temperature vector can be calculated using the matrix inversion form, as shown in equation (17)

$$[T] = [A]^{-1} [B] \quad (25)$$

The first and second laws of thermodynamics are used to conduct exergy analysis, which includes taking into account total exergy intake, exergy outflow, and exergy destructed from the system. The general exergy balance is expressed as [16][17]: if the effects related to kinetic and potential energy changes are ignored:

$$\sum Ex_i - \sum Ex_o = \sum Ex_d \quad (26)$$

or

$$\sum Ex_i - \sum (Ex_{th} + Ex_{pv}) = \sum Ex_d \quad (27)$$

in which

$$Ex_i = ANS \left[1 - \frac{4}{3} \left(\frac{T_a}{T_s} + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right) \right] \quad (28)$$

$$Ex_{th} = mC(T_o - T_i) \left(1 - \frac{T_a + 273}{T_o + 273} \right) \quad (29)$$

$$Ex_{pV} = \eta_p AS . \quad (30)$$

PVT air collectors' electrical efficiency can be computed as

$$\eta_p = \eta_0 \left[1 - 0.0045 (T_p - 25) \right] \quad (31)$$

The overall performance of the system is evaluated using the total efficiencies, known as overall efficiency or PVT efficiency (η_{PVT}) and can be expressed as

$$Ex_{PVT} = Ex_{th} + Ex_{pV} \quad (32)$$

where Ex_{th} is the thermal exergy, Ex_{pV} is the PV exergy, Ex_{PVT} is the PVT exergy, Ex_o is the output exergy, Ex_i is the input exergy (radiation exergy), Ex_d is the exergy destroyed, A is the PV area, N is the PV number, S is the solar radiation, T_s is the solar temperature ($T_s = 5777K$), T_a is the ambient temperature, T_o , T_i , and T_p are the outlet, inlet, and PV temperatures, respectively.

The PVT exergy efficiency is expressed as

$$\eta_{ex,PVT} = \frac{Ex_o}{Ex_i} \quad (33)$$

B. Experimental study

This PV has been tested by the manufacturer in the industry under the radiation intensity of 1000 W/m^2 and room temperature of $25 \text{ }^\circ\text{C}$ to achieve a maximum power of 80 W . The PVT air collector was evaluated using a specially constructed solar simulator in the laboratory, as shown in [Figure 2](#) and [Figure 3](#).

The solar simulator was made using 23 halogen bulbs, each rated at 500 W , as seen in [Figures 2](#) and [3](#). The solar simulator's brightness and solar radiation were controlled using regulators. The tests were carried out with five different mass flow rates (0.007 kg/s to 0.07 kg/s) and solar radiations of 385 W/m^2 and 820 W/m^2 . The air velocity reading



Figure 2. Photograph of PVT air collector under solar simulator

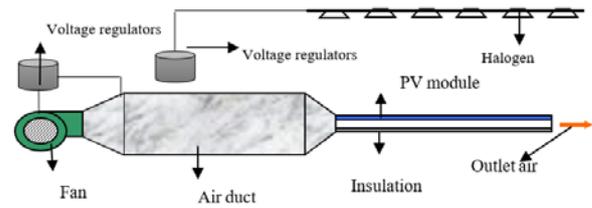


Figure 3. Schematic of PVT air collector under solar simulator

range was 0.2 to 40 m/s , with an accuracy of 1% of the reading 1 digit and a precision of 0.01 m/s . It was decided to utilize an Eppley pyranometer since it is simple to operate and does not require the usage of a sun tracking equipment. This pyranometer was intended to be able to detect 90% or more of all solar radiation data on the world. The constants for the Eppley pyranometer used in this study were $11.99 \times 10^{-6} \text{ V/Wm}^{-2}$. The thermocouples temperature range for J-type is $0 \text{ }^\circ\text{C} - 760 \text{ }^\circ\text{C}$ which was suitable with the multimeter used. Materials used in the experiment were shown in [Table 1](#). Data were recorded to calculate electrical and thermal efficiencies.

III. Results and Discussions

The efficiencies of PVT air collectors were obtained. The temperature distribution of PVT air

Table 1.
Material used in the experiment

No.	Material	Number	Function
1	SHARP NE-80E2EA Polycrystalline 80 W PV panel	1	Generate electricity
2	500 W halogen lamp	23	Supply of light and thermal radiation
3	350 W (Yuhchang) fan	1	Cooling the PV
4	Air heater (500 W halogen lamp)	2	Heating the inlet air
5	2000 VA voltage regulator	6	Changing power halogen lights
6	2000 VA voltage regulator		Changing wind velocity of the fan
7	500 VA voltage regulator	1	Changing the heating power of the air
8	Insulation		Prevent air out
9	Pyranometer	1	To observe solar radiation
10	J-type thermocouples		Detect heat to a certain point
11	Switches (such as switch fan)		Connection to 10 thermocouples
12	Air duct	1	Connect solar collector with fan
13	DTA 4000 anemometer		Detecting the velocity of the wind
14	52 K/J thermometer multimeter	2	Pointing temperature readings from thermocouples
15	$72-7740$ multimeter (connect to the pyranometer)	1	To detect the radiation intensity

collectors was determined using the mathematical model's. The result shows that by lowering the temperatures T_p , T_f , and T_b simultaneously, the mass flow rate increases, as shown in Figure 4 and Figure 5. Since can be seen in Figures 4 and 5, raising the mass flow rate simultaneously decreased the temperatures (T_p and T_o) of the PVT collector for both solar radiations, as more and more air volume is available to remove heat from the channel walls, lowering PV temperature. Because the air velocity in the channel is increased, the outlet air temperature decreases as the air flow rate rises [18]. This is because air has less time inside the channel to reach higher outlet temperatures.

For the PVT which received solar radiation of 820 W/m^2 , output air temperature and PV temperature presents higher values (Figure 5) than the PVT which received solar radiation of 385 W/m^2 (Figure 4). The reason for this observation is due to more irradiance intercepted by the PVT collector hence more heat energy is transferred to the PV. This leads the PV to attain a higher temperature and allows more heat energy to be transferred to the airflow in the channel increasing the output temperature [19].

Table 2 shows the results of PV and the outlet temperature of the PVT air collector. The average errors in the calculation of the outlet and PV temperature were 6.3% and 5.1% for $S = 385 \text{ W/m}^2$, and 3.8% and 5.7% for $S = 820 \text{ W/m}^2$, respectively. The mathematical model made reasonable forecasts for outlet and PV temperatures, with average errors of 5.0% and 5.4%, respectively. The mathematical model's outputs are 95% and 94.6% accurate, respectively, when compared to experimental data for outlet and PV temperatures.

Figure 6 and Figure 7 show the exergy analysis of PVT air collectors. PVT exergy efficiency is in a similar trend and rises very slowly for both experimental and theoretical studies, which produced PVT exergy efficiencies of 11.5% to 12.9%. For solar radiation of 385 W/m^2 in the theoretical study, the PVT air collector produced a PVT exergy of 28.6 W to 29.3 W with electrical exergy of 26.8 W to 28 W and thermal exergy of 1.2 W to 1.9 W. For solar radiation of 385 W/m^2 in the experimental study, the PVT air collector produced a PVT exergy of 27.8 W to

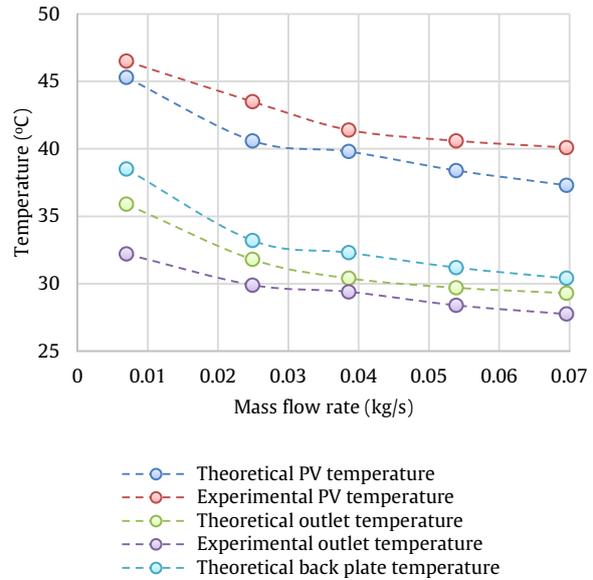


Figure 4. Mathematical model and experimental result of PVT air collectors for solar radiation of 385 W/m^2

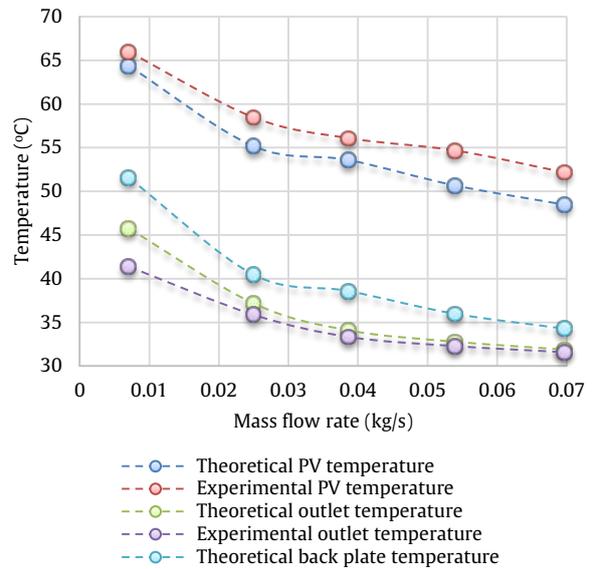


Figure 5. Mathematical model and experimental result of PVT air collectors for solar radiation of 820 W/m^2

Table 2. Comparison of theoretical and experimental studies for outlet and PV temperatures of PVT air collectors

m (kg/s)	S (W/m^2)	Outlet temperature ($^{\circ}\text{C}$)			PV temperature ($^{\circ}\text{C}$)		
		Theoretical	Experimental	% error	Theoretical	Experimental	% error
0.00696	385	35.9	32.2	11.5	45.3	46.5	2.6
	820	45.8	41.4	10.6	64.4	66.0	2.5
0.02492	385	31.8	29.9	6.4	40.6	43.5	6.7
	820	37.2	35.9	3.6	55.2	58.5	6.0
0.03861	385	30.4	29.4	3.4	39.8	41.4	3.9
	820	34.1	33.4	2.2	53.6	56.1	4.7
0.05387	385	29.7	28.4	4.6	38.4	40.6	5.4
	820	32.8	32.3	1.5	50.7	54.7	7.9
0.06958	385	29.3	27.8	5.6	37.3	40.1	7.0
	820	31.9	31.6	0.9	48.5	52.2	7.6
Average				5.0			5.4

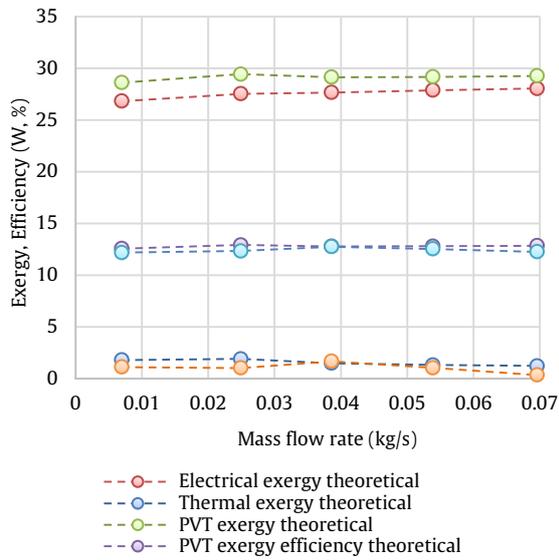


Figure 6. Variations of exergies and exergy efficiency with mass flow rate for 385 W/m²

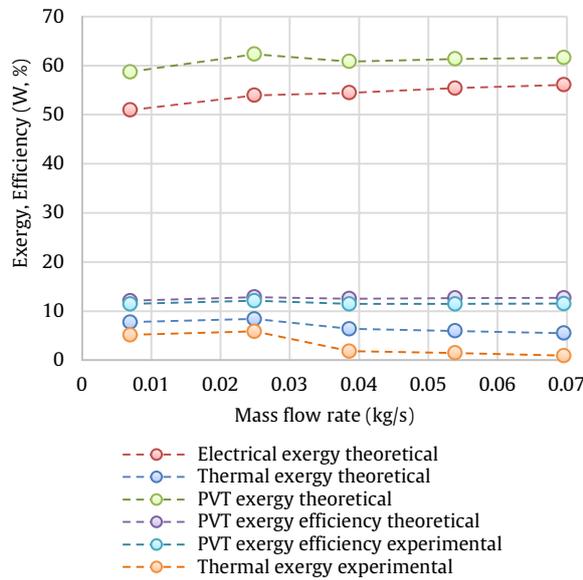


Figure 7. Variations of exergies and exergy efficiency with mass flow rate for 820 W/m²

29.1 W with electrical exergy of 26.6 W to 27.6 W and thermal exergy of 0.3 W to 1.7 W. Referring to Figure 7, for solar radiation of 820 W/m², the PVT air

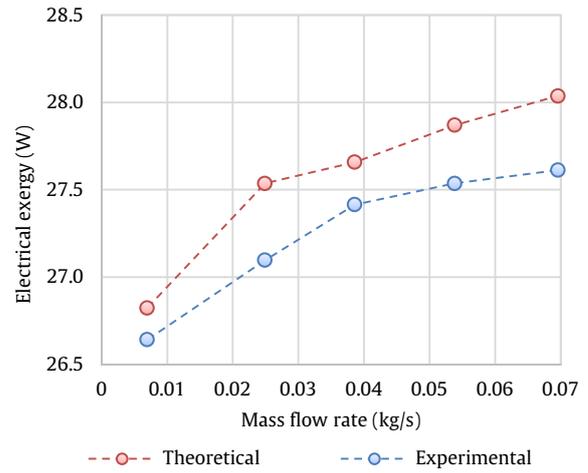


Figure 8. Electrical exergy versus mass flow rate for 385 W/m²

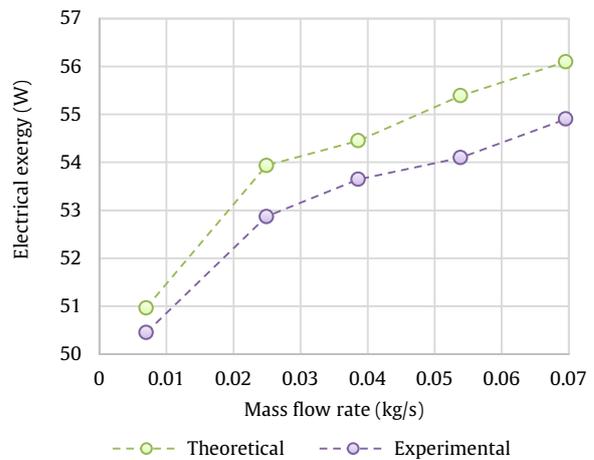


Figure 9. Electrical exergy versus mass flow rate for 820 W/m² collector produced a PVT exergy of 58.7 W to 62.3 W with a thermal exergy of 5.5 – 8.4 W and an electrical exergy of 51 – 56.1 W for the theoretical study, and a PVT exergy of 55.5 – 58.7 W with thermal exergy of 0.9 – 5.9 W and electrical exergy of 50.4 – 53.7 W for the experimental study. Table 3 shows the errors for exergy efficiencies of PVT air collectors.

The variations of PV exergies with mass flow rate are shown in Figure 8 and Figure 9. The PV exergy of PVT air collectors increases with increasing air mass flow rate. A comparison of exergy efficiencies of PVT

Table 3. Error for exergy efficiencies of PVT air collectors based on Figures 6 and 7

m (kg/s)	S (W/m ²)	PVT exergy efficiency (%)			PV exergy efficiency (%)		
		Theoretical	Experimental	% error	Theoretical	Experimental	% error
0.00696	385	12.56	12.18	3.0	10.96	10.88	0.7
	820	12.10	11.46	5.2	9.77	9.67	1.0
0.02492	385	12.91	12.33	4.5	11.25	11.07	1.6
	820	12.84	12.11	5.7	10.34	10.14	2.0
0.03861	385	12.79	12.76	0.2	11.30	11.20	0.9
	820	12.53	11.44	8.7	10.44	10.29	1.5
0.05387	385	12.80	12.53	2.1	11.38	11.25	1.2
	820	12.64	11.46	9.3	10.62	10.37	2.3
0.06958	385	12.84	12.26	4.5	11.45	11.28	1.5
	820	12.69	11.51	9.3	10.76	10.53	2.1
Average				5.3			1.5

Table 4.
Comparison of the exergy efficiencies of PVT air collectors

Results	PVT exergy efficiency (%)		Reference
	Theoretical	Experimental	
Theo.: $\eta_{PV}=10\%$, $\eta_{th}=17.2\%$	10.75	11.5	[20]
Theo.: $\eta_{PV}=14-15\%$	12-15	10.6	[21]
N.A.	13.5	6.4	[22]
Theo.: $\eta_{PV}=9.77-11.45\%$	12.10-12.91	11.44-12.84	Present study
Exp.: $\eta_{PV}=9.67-11.28\%$			

air collectors is presented in Table 4. Figures 8 and 9 show the results for electrical exergy or exergy of PV, Ex_{PV} obtained from the mathematical model (theoretical) and experimental results. Figure 8 shows the variation of electrical exergy for PVT air collectors at a solar intensity of 385 W/m^2 . Figure 9 shows the variation of electrical exergy for PVT air collectors at a solar intensity of 820 W/m^2 . For solar radiation of 385 W/m^2 , the PVT air collector produced electrical exergy of 26.8 W to 28 W in the theoretical study and 26.6 W to 27.6 W in the experimental study. For the case of solar radiation of 820 W/m^2 , the PVT air collector produced electrical exergy of 51 W to 56.1 W in the theoretical study and 50.4 W to 53.7 W in the experimental study.

From Figures 8 and 9, the results indicate that by increasing the mass flow rate there is a clear increase in the electrical exergy (Ex_{PV}) of the PVT collector for both the solar radiations. The likely reason for this observation is due to the decline in the PV temperature when mass flow air of the air increased. This decrease in the PV temperature increased the PV efficiency, mainly because a lower cell temperature increases the voltage significantly (even though it decreases current by a very small amount). For this reason, since the PV efficiency increases, the total useful electrical gain also increased.

The results also show that the total electrical exergy (Ex_{PV}) of the PVT collector for the PVT which received solar radiation of 820 W/m^2 presents higher values (Figure 9) than the PVT which received solar radiation of 385 W/m^2 (Figure 8). The greater number of photons associated with higher solar irradiation creates more electron-hole pairs and thus more current in the PV cell, which is the most likely explanation for this result. The PV packing factor, or the percentage of absorber area occupied by PV cells, has a big impact on electrical production. The electrical output per unit collector area increases as the packing factor rises.

IV. Conclusion

Exergy analysis was used to analyze the performance of PVT air collectors in both theoretical and experimental study. The mathematical model matches the experimental data with an accuracy of around 95%. The average PVT exergy efficiency in the theoretical and experimental studies is 12.7% and 12.0%, respectively. For the theoretical and experimental study, the average PVT exergy is 45.1 W and 42.3 W, respectively, with PV exergies of 40.9 W and 40.2 W and thermal exergies of 4.2 W and 2.1 W.

Acknowledgement

The authors would like to thank the Ministry of Higher Education Malaysia for funding (FRGS/1/2014/ST02/UKM/03/1), as well as the Solar Energy Research Institute (SERI), UKM for providing laboratory facilities and technical support.

Declarations

Author contribution

All authors contributed equally as the main contributor to this study.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare no known conflict of financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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