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Article

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Performance analysis of PV/T modules with and without glass cover and effect of mass flow rate on electricity and hot water generation

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Abstract

Two types of hybrid photovoltaic/thermal (PV/T) modules, with and without glass cover for generating hot water and electricity (combined heat and power, CHP) were tested to investigate power generation performance in terms of generated power (P_e) with module temperature (T_m) and solar radiation level (I_T); and thermal performance in terms of thermal efficiency (η_m) with$(T_{fi} - T_a)/I_T$. A method for calculating the hot water temperature and the generated power was also developed and the results agreed well with the experimental data. With the model, the effect of water mass flow rate on the energy outputs was carried out by exergy analysis. It could be found that low second law efficiency was found with higher mass flow rate at low solar radiation level and high inlet water temperature.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Photovoltaic/thermal module; Combined heat and power; Performance analysis; Exergy; Water flow rate

1. Introduction

Thailand is in the tropical area with high solar radiation level which is around 19–20 MJ/m^2-day. So far there are a lot of projects on solar collector for water heating and the performance improvement [1] including solar cell module for electricity generation [2].

Due to the Government promotion on solar electrification, solar farm and rooftop solar cell module have been installed in many areas of the Country. Recently, solar photovoltaic/thermal (PV/T) module is available in the market. The unit could generate both electrical power and heat rate simultaneously as a combined heat and power (CHP) unit [3,4] so this one is pretty good to be implemented in hospital or factory that needs electricity and hot water at the same time thus the total efficiency is higher than the units those generate only electrical power. Kalogirou and Tripanagnostopoulos [5] and Tarabsheh et al. [6] reported on the use of PV/T and it was found that higher

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Nomenclature

A_m	surface area of module, m^2
C_p	heat capacity of water, J/kg K
D	diameter of riser tube of PV/T module, m
Ex_m	exergy rate generated by PV/T module, W
f	friction factor
$F_R(\tau\alpha)_e$	optical characteristic of PV/T module
$F_R U_L$	thermal loss characteristic of PV/T module, W/m^2 K
I_T	solar radiation incident on PV/T module, W/m^2
L	length of riser tube in PV/T module, m
$\dot{m}$	mass flow rate, kg/s
n	number of riser tubes in PV/T module
ΔP	pressure drop of fluid flow in PV/T module, N/m^2
P_e	electrical power generation, W
T_m	module temperature, K
T_a	ambient temperature, K
T_{fo}	outlet water temperature, K
T_{fi}	inlet water temperature, K
T_s	effective sun surface temperature, K
$(UA)_m$	overall heat transfer coefficient-area between water flowing inside PV/T module and module surface, W/K
$\dot{W}_h$	hydraulic power, W
ρ	water density, kg/m^2
η_m	thermal efficiency of PV/T module
$\eta_{,2nd}$	second law efficiency

electrical power generation could be obtained and with hot water production the total efficiency was better than that of the PV module that generates electricity only [5,6]. Anyhow, when the PV module or the PV/T module exposes to the sun, the operating module temperature is rather high then the generated power decreases significantly [7,8]. For the latter one, the water mass flow rate at various inlet temperatures should give thermal effect on the module performance both power generation and hot water production and this leads to an objective of this study.

In this paper, performance analyses of PV/T modules with and without glass cover for generating electricity and hot water simultaneously were presented. A method to predict the module temperature, the outlet hot water temperature including the generated electrical power was also developed. From the model the exergies due to power generation and hot water production at various water mass flow rates were also investigated

2. Theory

PV/T module could generate electrical power and hot water, simultaneously. The generated electrical power depends on the solar radiation and the modules temperature, $P_e = f(I_T, T_m)$ [2] as

$$P_e = a + b(I_T) + c(I_T^2) + d(T_m) + e(I_T T_m) + f(I_T^2 T_m). \tag{1}$$

In term of hot water production, the thermal performance of the PV/T is similar to that of the solar collector. The heat rate obtained by the module could also be

$$\dot{Q}_m = \left(\dot{m}C_p\right)\left(T_{fo} - T_{fi}\right) = A_m\left[F_R(\tau\alpha)_e I_T - F_R U_L\left(T_{fi} - T_a\right)\right] \tag{2}$$

or

$$\eta_m = \frac{\left(\dot{m}C_p\left(T_{fo} - T_{fi}\right)\right)}{(I_T A_m)} = F_R(\tau\alpha)_e - \frac{F_R U_L\left(T_{fi} - T_a\right)}{I_T}. \tag{3}$$

Table 1. Constant values of PV/T and PV/Tc modules for power generation equation.

	a	b	c	d	e	f
PV/T (without glass cover)	−16.38099	−0.183125	0.0014218	1.426173	0.0103664	-2.21×10^{-5}
PV/Tc (with glass cover)	−377.2	1.5435	−0.000623	5.1081	−0.012849	7.38×10^{-6}

$F_R(\tau\alpha)_e$ and F_RU_L are thermal characteristics of PV/T module those could be found out by testing following standard test for solar collector testing. Note that η_m is the thermal efficiency of the PV/T module for hot water production.

From Eqs. (2) and (3),

$$T_{fo} = T_{fi} + \frac{A_m}{\dot{m}C_p}\left[F_R(\tau\alpha)_e I_T - F_RU_L\left(T_{fi} - T_a\right)\right]. \quad (4)$$

With the values of T_{fi} and T_{fo}, the average module temperature, T_m, could be estimated from

$$T_{fo} = T_{fi} + \left(T_m - T_{fi}\right)\left(1 - e^{\frac{-(UA)_m}{\dot{m}C_p}}\right). \quad (5)$$

$(UA)_m$ is the overall heat transfer efficient and surface area product from the working fluid to the PV/T module surface. This term could be experimentally tested by varying the mass flow rate and measuring the related temperatures.

With given values of the solar radiation and the ambient temperature, by varying T_{fi} and $\dot{m}$, then calculate T_{fo} from Eq. (4) and T_m from equation (5). Therefore, the power generated by the module could be calculated from Eq. (1).

Since the PV/T module generates both electrical power and heat rate for hot water production, the unit performance could be calculated by exergy analysis. The total exergy output of the PV/T module could be shown as

$$Ex_m = P_e + \dot{m}C_p\left[\left(T_{fo} - T_{fi}\right) - T_o \ln\left(\frac{T_{fo}}{T_{fi}}\right)\right]. \quad (6)$$

The indicator to justify the PV/T module performance could be performed by second law efficiency, $\eta_{,2nd}$ as

$$\eta_{,2nd} = \frac{Useful\ exergy}{input\ exergy} = \frac{P_e + \dot{m}C_p\left[\left(T_{fo} - T_{fi}\right) - T_o \ln\left(\frac{T_{fo}}{T_{fi}}\right)\right]}{I_T A_m\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{4}{3}\left(\frac{T_a}{T_s}\right)^4\right] + \dot{W}_h}. \quad (7)$$

Where T_s is the effective sun surface temperature (5,777 K) [9], $\dot{W}_h$ is the minimum hydraulic power to feed the fluid through the PV/T module that could be calculated by

$$\dot{W}_h = \dot{m}\frac{\Delta P}{\rho}. \quad (8)$$

ΔP is the pressure drop of working fluid in PV/T that could be found out by

$$\Delta P = \frac{f\rho L}{2D}\left(\frac{4\frac{\dot{m}}{n}}{\rho\pi D^2}\right)^2. \quad (9)$$

n is the number of flow riser tube in the PV/T module.

3. Tested PV/T modules

Fig. 1 shows a schematic sketch of an experiment setup for testing performance of the PV/T modules. Table 1 shows the tested PV/T module and other instruments description.

Four PV/T modules in series connection, facing south with 18° inclination, supplied power to a 1TR air conditioner. The modules with and without glass cover each was monocrystalline having 180 Wp and 200 Wp, respectively. There was a water stream circulating between the modules and a storage tank. There was a radiator

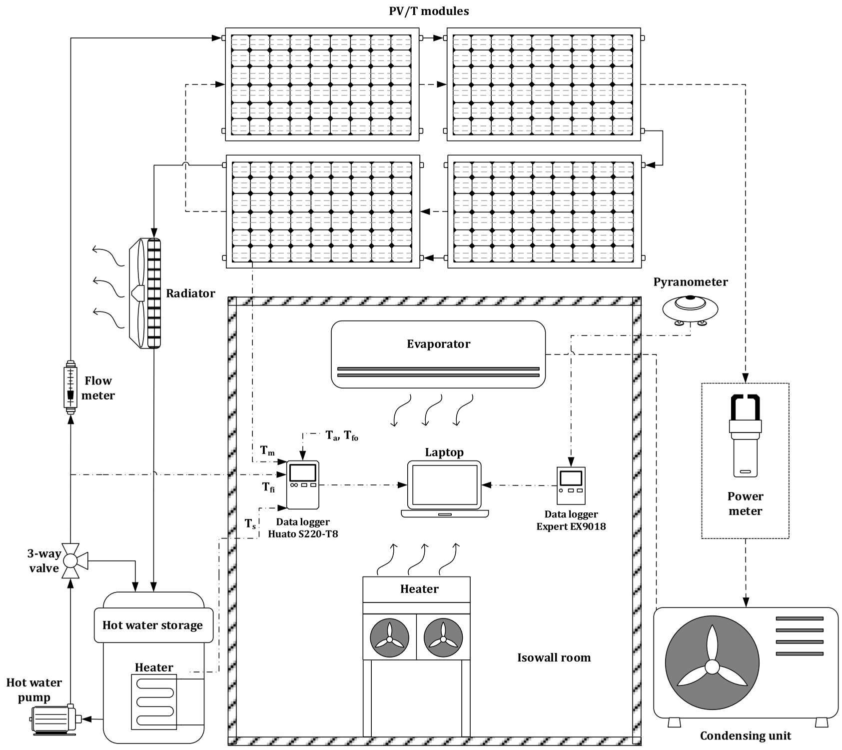


Fig. 1. The experimental set up.

to reject heat from the water stream before entering the storage tank. In addition, there was an electrical heater to control the water temperature before entering the modules. The solar radiation level on the PV/T modules, the module surface temperature, the inlet and the outlet water temperatures of the modules, the generated electrical power and the water flowrate were recorded.

Experimental study was separated into two parts. For the first one, the PV/T module thermal performance was tested following ASHREA standard under steady-state condition when the inlet water temperatures were 30–50 °C with the water mass flow rates of 2–6 LPM. For the second part, a correlation of the output generated electrical power with the PV/T module temperature and the incident solar radiation was developed. With the information, the second law efficiency on the combined heat rate and the power generation could be evaluated at various operating conditions. Then the appropriate water mass flow rate could be selected at any solar radiation level and water inlet temperature to obtain high second law efficiency.

4. Results and discussion

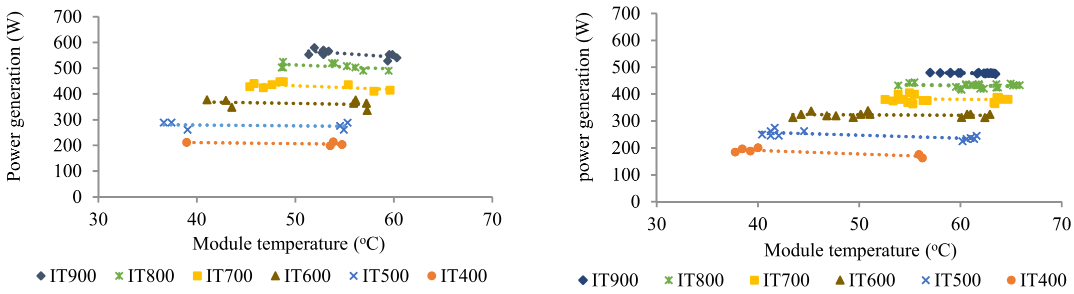
4.1. Power generation

With the measured module temperature of each unit, the solar radiation incident on the PV/T modules and the power generation, the performance on power generation could be presented in Fig. 2.

It could be seen that higher the solar radiation level and lower the module temperature, higher generated electrical power could be calculated. The correlation could be calculated in the form of Eq. (3) and the constant values could be given in Table 1.

4.2. Thermal performance

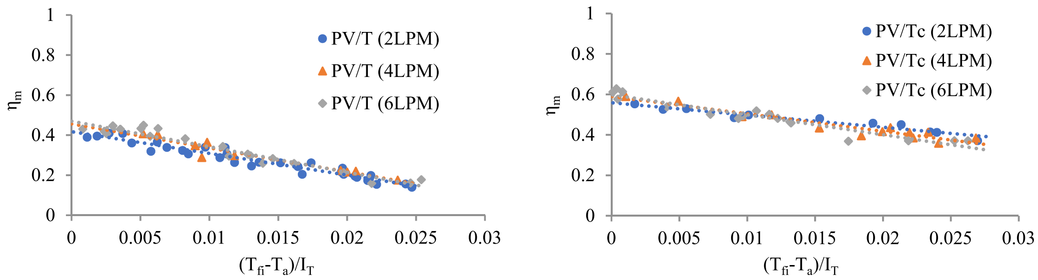
Fig. 3 shows thermal performances of the PV/T module when the units were used to generate hot water.



(a) The PV/T module (without glass cover).

(b) The PV/T module (with glass cover).

Fig. 2. Correlation of electrical power and module temperature of the PV/T module.



(a) The PV/T module (without glass cover).

(b) The PV/Tc module (with glass cover).

Fig. 3. The correlation of thermal efficiency and $(T_{\mathrm{fi}} - T_{\mathrm{a}})/I_{\mathrm{T}}$ of PV/T module with the water flow rate of 2–6 LPM variation.

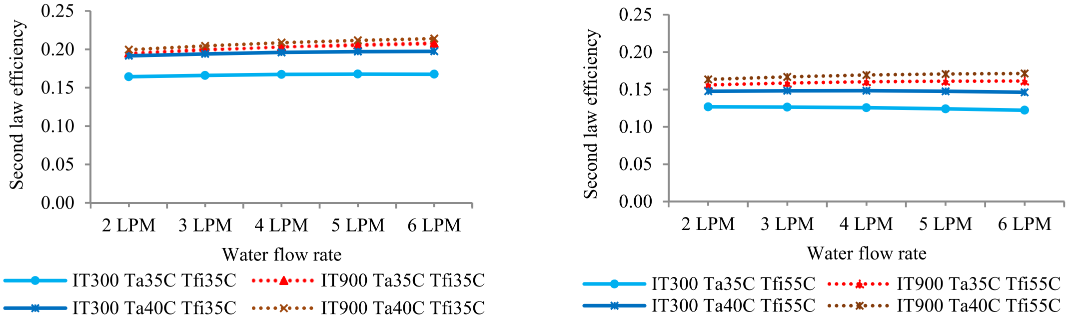
Table 2. $F_R(\tau\alpha)_e$ of and $F_R U_L$ of PV/T module with water flow rate variation.

Type of PV/T module		Water flowrate (LPM)		
		2	4	6
Without glass cover (PV/T)	$F_R(\tau\alpha)_e$	0.417	0.456	0.469
	$F_R U_L$	10.840	11.976	12.760
	UA	33.01	40.89	48.26
With glass cover (PV/Tc)	$F_R(\tau\alpha)_e$	0.558	0.589	0.598
	$F_R U_L$	6.062	8.623	9.876
	UA	28.79	30.41	32.82

The relation between the thermal efficiency V.S. $(T_{\mathrm{fi}} - T_{\mathrm{a}})/I_{\mathrm{T}}$ of the PV/T units was also in a linear form of which the slope was $F_R U_L$ and the intercept on the η_m axis was $F_R(\tau\alpha)_e$. It could be noted that the values of $F_R U_L$ and $F_R(\tau\alpha)_e$ were reduced with lower the mass flow rate as shown in Table 2. The UA could also be evaluated and it could be seen that the value increased slightly with the increase of mass flow rate.

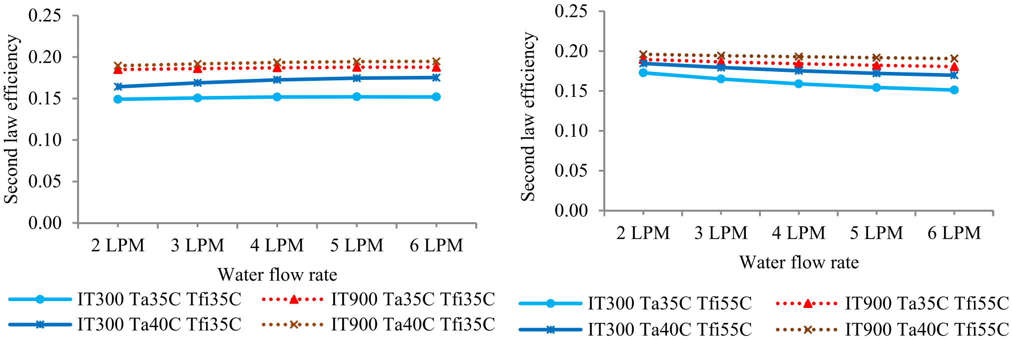
4.3. Exergy analysis

Overall performances of PV/T modules could be considered from the second law efficiency. At low solar radiation level (300 W/m^2), the second law efficiency tended to be lower with higher mass flow rate due to higher heat loss over the solar radiation heat absorbed and the result was significantly observed when the inlet temperature was high (55 °C). At high solar radiation level (900 W/m^2), the efficiency was higher with the increase of mass flow rate. Higher exergy losses at high inlet water temperature were found significantly for the unit with glass cover. All the results were shown in Figs. 4–5. Therefore, low water flow rate was recommended at low solar radiation level and high inlet water temperature to get high second law efficiency.



(a) The second law efficiency at T_{fi} = 35°C. (b) The second law efficiency at T_{fi} = 55°C.

Fig. 4. The exergy analysis of PV/T module (without glass cover) with high and low solar radiation and ambient temperature variation at inlet water temperature of 35 and 55 °C.



(a) The second law efficiency at T_{fi} = 35°C. (b) The second law efficiency at T_{fi} = 55°C.

Fig. 5. The exergy analysis of PV/Tc module (with glass cover) with high and low solar radiation and ambient temperature variation at inlet water temperature of 35 and 55 °C.

5. Conclusions

5.1 Thermal characteristics of PV/T modules with and without glass cover were tested. It was found that the $F_R U_L$ and $F_R\,(\tau\alpha)_e$, were reduced with lower the mass flow rate. In addition, a model for evaluating the generated electrical power of with and without glass cover were developed.

5.2 The second law efficiency on combined generated heat rate and power was an indicator to find out the suitable mas flow rate. At low solar radiation level and high inlet water temperature, low water mass flow rate is recommended especially for the PV/T with glass cover.

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