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Research Article

Experimental Study of the Performance of Two Different Types of Photovoltaic Thermal (PVT) Modules under Singapore Climatic Conditions*

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Abstract In this paper, experimental studies on the performance of two different photovoltaic thermal (PVT) modules, under the tropical climatic conditions of Singapore, are evaluated. For this evaluation, two different types (type A and type B) of commercially available PVT modules have been installed and tested at the National University of Singapore (NUS), Singapore. The type A PVT module comprises mono-crystalline Si solar cells integrated with a tube-and-sheet type thermal collector, while the type B PVT module comprises multi-crystalline Si solar cells integrated with a parallel-plate type thermal collector. The experiments have been performed at different flow rates (0.03 kg/s and 0.06 kg/s) under typical climatic conditions. Validation of the thermal performance of the modules via theoretical analyses is also presented. It has been found that the average thermal efficiency and PV efficiency for the type A PVT module are 40.7% and 11.8%, respectively, and those for the type B PVT module are 39.4% and 11.5%, respectively.

Keywords photovoltaic thermal collectors; thermal efficiency; PV efficiency; solar energy

1 Introduction

Many theoretical and experimental studies of photovoltaic thermal (PVT) modules have been reported. Jones and Underwood [5] have studied the temperature profile of a photovoltaic module in a non-steady-state condition with respect to time. They conducted experiments for cloudy as well as clear day conditions. They observed that the PV module temperature varied in the range of 27 °C–52 °C for an ambient air temperature of 24.5 °C. The electrical performance of a PV module depends mainly on ohmic losses and the temperature of the module. The PV efficiency can be increased by withdrawing the thermal energy dissipated in the PV module [1,12]. Chow [1] carried out an analysis of a PVT water collector with single glazing in a transient condition. He observed that the module temperature was reduced and the PV efficiency increased by 2% (relative) at a mass flow rate of 0.01 kg/s for a 10 kW/m^{2}K plate-to-bond heat transfer coefficient. A similar study was also carried out by Zondag et al. [11] who reported PV and thermal efficiencies of 6.7% and 33%, respectively. Tripanagnostopoulos et al. [9] presented test results on thermosyphon-type PVT water-heating systems and mentioned that the glazed PVT systems improved the thermal efficiency by up to about 30% but reduced the PV efficiency by about 16% as compared to unglazed systems. Sandnes and Rekstad [6] observed the behavior of a PVT module which was constructed by pasting mono-crystalline silicon solar cells onto a black plastic solar heat absorber (unglazed PVT system). Zakharchenko et al. [10] have also studied an unglazed hybrid PVT system with suitable thermal contact between the PV panel and the thermal collector. They have proved that the areas of the PV panel and the thermal collector in a PVT module need not be equal for higher overall efficiency. He et al. [4] developed and tested an aluminium-alloy channel-type PVT water collector at the City University of Hong Kong under sub-tropical climatic conditions.

To date, very few studies have been carried out on PVT systems operating in the tropics for production of both electricity and hot water. This paper describes the experimental analysis of PVT modules under the tropical climatic conditions of Singapore using two different designs of PVT modules.

2 Experimental setup

Two PVT modules of type A (tube-and-sheet) and type B (parallel-plate) were installed and tested on the roof of a

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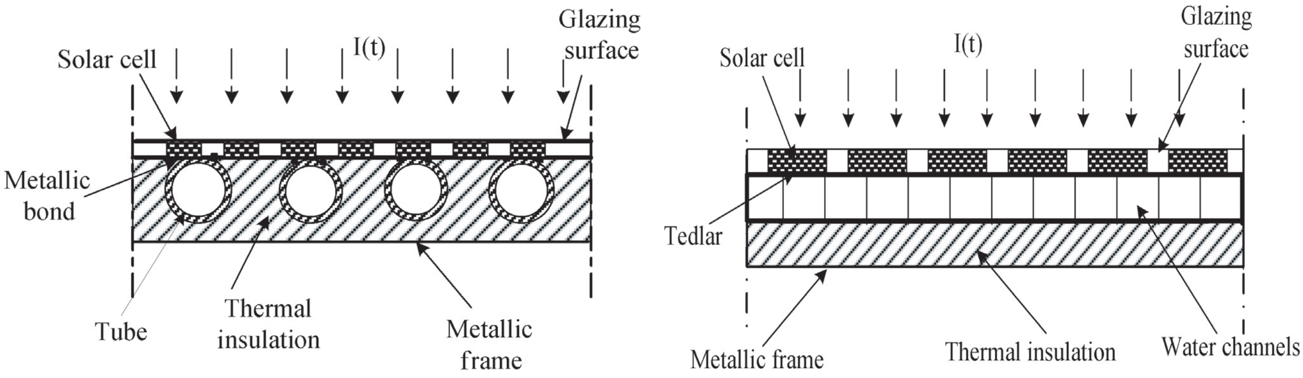


(a) (b)

Figure 1: (a) Cross-sectional view of type A PVT module. (b) Cross-sectional view of type B PVT module.

building at NUS. The cross-sectional views of the flow channels for both PVT types are shown in Figure 1. The thermal part of type A is made of copper, whereas that of type B is made of aluminium. The type A PV module is encapsulated with mono-crystalline Si solar cells, whereas type B is encapsulated with multi-crystalline Si solar cells. In both types, the PV panel is simply mechanically clamped to the thermal collector without any bonding adhesive. The power ratings of type A and type B PV modules are 190 Wp and 200 Wp, respectively.

The PVT modules were mounted over stainless steel frames as shown in Figure 2. Singapore is at latitude 1.37° north; however, the modules are tilted at 10° to the horizontal plane in order to minimize the accumulation of dirt on the surface of the module. Both modules are individually connected to a single storage tank of a 200-liter capacity along with a flow meter and a valve to regulate the flow rate in the thermal collector. Water is circulated between collectors and storage tank using a pump. The circulation of water under the PV panels helps to reduce the temperature of the PV cells and hence increase the PV efficiency. To measure the inlet, outlet, tank water temperature, and temperature across the different layers in the PVT modules, calibrated T-type (copper-constantan) thermocouples have been attached using thermal glue. Solar radiation is measured using a precision pyranometer, and voltage is measured using an MPP tracker and DC shunt. All the thermocouple voltage points are connected to a data logger system (Agilent model 34970A). The data are measured at 10-minute intervals on typical days. However, as the percentage variation is small, average values of the parameters are presented on an hourly basis.

3 Thermal modeling

In order to write the energy balance equation for each component of a PVT solar water heating system, the following assumptions are made:

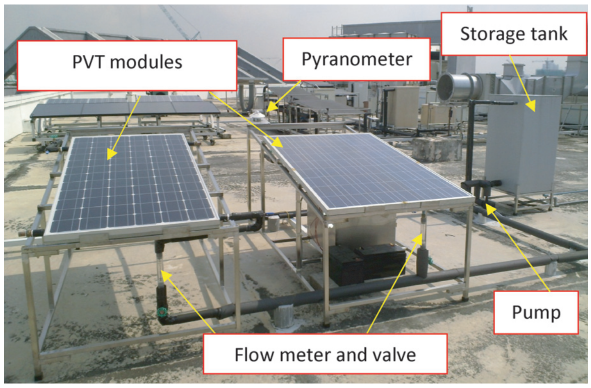


Figure 2: Photograph of PVT modules and the outdoor test rig.

(i) the heat capacity of the PVT module is neglected in comparison with the heat capacity of water in the storage tank;
(ii) there is no temperature stratification of the water in the storage tank due to the forced circulation mode of operation and a relatively small tank;
(iii) one-dimensional heat transfer analysis is adequate for the present study;
(iv) the system is in quasi-steady state.

Following Tiwari et al. [7] and Dubey and Tiwari [2], the energy balance equations for all the components of the integrated PVT module are written as follows.

(1) For the solar cells of the PV module:

$$\begin{aligned}\tau_g\alpha_{sc}\beta_{sc}I(t)W\,dx &= \left[U_{tc,a}\left(T_{sc}-T_a\right)+U_T\left(T_{sc}-T_{bs}\right)\right]W\,dx \\ &\quad +\eta_{sc}\beta_{sc}I(t)W\,dx.\end{aligned} \tag{1}$$

(2) For the back surface of the Tedlar sheet:

$$\begin{aligned}\tau_g\alpha_T\left(1-\beta_{sc}\right)I(t)W\,dx+U_T\left(T_{sc}-T_{bs}\right)W\,dx \\ = h_T\left(T_{bs}-T_f\right)W\,dx.\end{aligned} \tag{2}$$

Table 1: Design parameters of photovoltaic thermal (PVT) systems.

Parameters	Type A	Type B	Parameters	Type A	Type B
A_c	1.267 m^2	1.47 m^2	U_b	0.84 W/m^2 K	0.84 W/m^2 K
C_f	4,190 J/kg K	4,190 J/kg K	U_L	5.81 W/m^2 K	6.51 W/m^2 K
F'	0.956	1	U_T	150 W/m^2 K	150 W/m^{2}K
F_R	0.948	0.96	U_{tT}	6.81 W/m^2 K	6.81 W/m^{2}K
h_T	45 W/m^2 K	130 W/m^2 K	$U_{tc,a}$	7.14 W/m^2 K	7.14 W/m^2 K
h_{p1}	0.954	0.954	$(UA)_{tk}$	0.8 W/K	0.8 W/K
h_{p2}	0.854	0.956	V	1.0 m/s	1.0 m/s
K	204 W/m K	204 W/m K	W	0.125 m	—
K_g	1.0 W/m K	1.0 W/m K	δ	0.002 m	—
K_{ins}	0.042 W/m K	0.042 W/m K	α_{sc}	0.90	0.90
K_T	0.033 W/m K	0.033 W/m K	α_T	0.50	0.50
L_g	0.003 m	0.003 m	β_{sc}	0.80	0.80
L_{ins}	0.035 m	0.035 m	β_o	0.0045	0.0045
L_T	0.00022 m	0.00022 m	η_o	0.15	0.15
M_w	200 kg	200 kg	τ_g	0.96	0.96

(3) For water flowing below the PV module: the energy balance for water flowing through the absorber tube (Figure 1(a)) is given by

$$F' h_T \left(T_{bs} - T_f\right) W\,dx = \dot{m}_f C_f \frac{dT_f}{dx} dx + U_b \left(T_f - T_a\right) W\,dx. \tag{3}$$

By rearranging and integrating both sides of (3) and using boundary conditions, namely, $T_f|_{x=0} = T_{fi1}$ and $T_f|_{x=L} = T_{fo}$, the expression for the outlet fluid temperature can be written as

$$T_{fo} = \left[\frac{h_{p2}(\alpha\tau)_{m,\mathit{eff}} I(t)}{U_L} + T_a\right]\left[1 - \exp\left(-\frac{F' A_c U_L}{\dot{m}_f C_f}\right)\right] + T_{fi} \exp\left(-\frac{F' A_c U_L}{\dot{m}_f C_f}\right). \tag{4}$$

(4) The rate of collection of thermal energy: the expression for the rate of thermal energy collected from the collector is derived as

$$\dot{Q}_{u,c} = A_c F_R \left[h_{p2}(\alpha\tau)_{m,\mathit{eff}} I(t) - U_L \left(T_{fi} - T_a\right)\right]. \tag{5}$$

(5) Instantaneous collector thermal efficiency: an expression for the instantaneous thermal efficiency of a flat plate collector is given as [3,8]

$$\eta_i = F_R \left[(\alpha\tau)_{\mathit{eff}} - U_L \frac{T_{fi} - T_a}{I(t)}\right]. \tag{6}$$

Details of the parameters used in the above equations are given in Table 1.

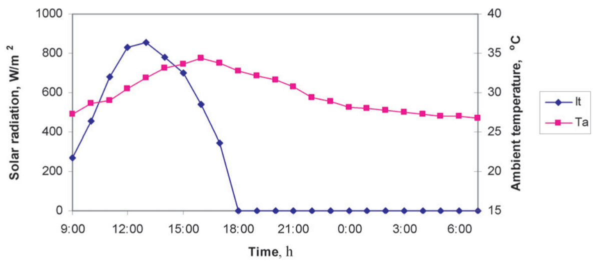
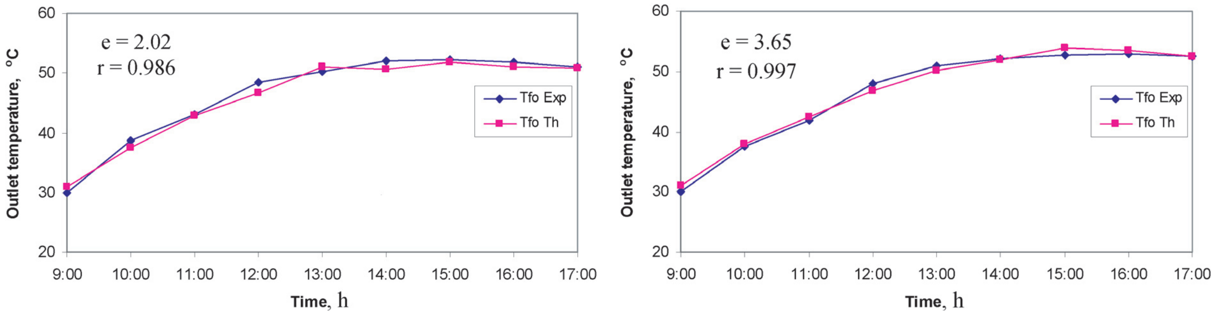


Figure 3: Hourly variation of solar radiation and ambient temperature on the test day.

4 Results and discussion

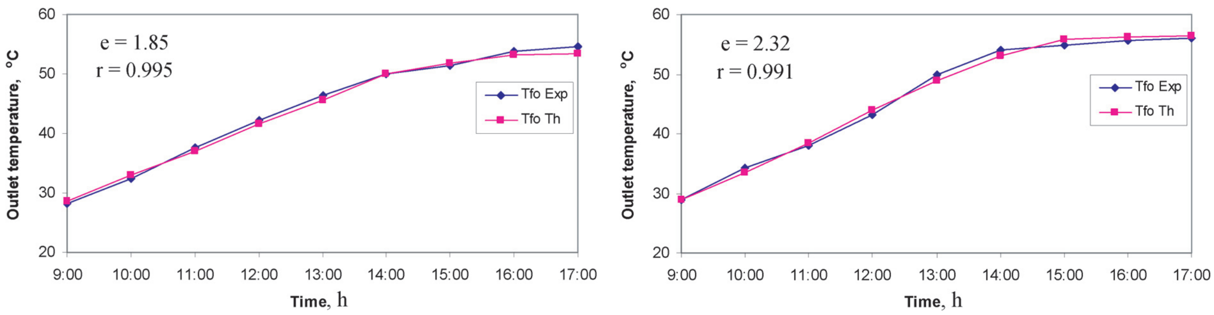
The hourly variation of solar intensity and ambient temperature for the particular test day 29/07/2010 is shown in Figure 3. Equation (4) was used to calculate the outlet water temperature of type A and type B PVT modules for a given system configuration and climatic parameters. The flow rate was varied from 0.03 kg/s to 0.06 kg/s. The hourly variations of theoretical and experimental results are shown in Figures 4 and 5. The maximum collector outlet water temperatures at flow rates of 0.03 kg/s and 0.06 kg/s are 55.3 °C and 52.1 °C, respectively, for type A, and 56.0 °C and 53.4 °C, respectively, for type B. The variation in outlet water temperature also depends upon the intensity of the solar radiation on the day. The correlation coefficient (r) and root mean square percent deviation (e) were also evaluated and shown in the same figures. It is observed that there is good agreement between theoretical and experimental values.

Similarly, (6) was used to calculate the instantaneous collector thermal efficiency at different flow rates. Theoretical and experimental variations of instantaneous collector thermal efficiency versus (T_{fi}-T_a)/It are shown in Figures 6 and 7. Only periods where climatic parameters such as solar radiation intensity and ambient temperature are constant



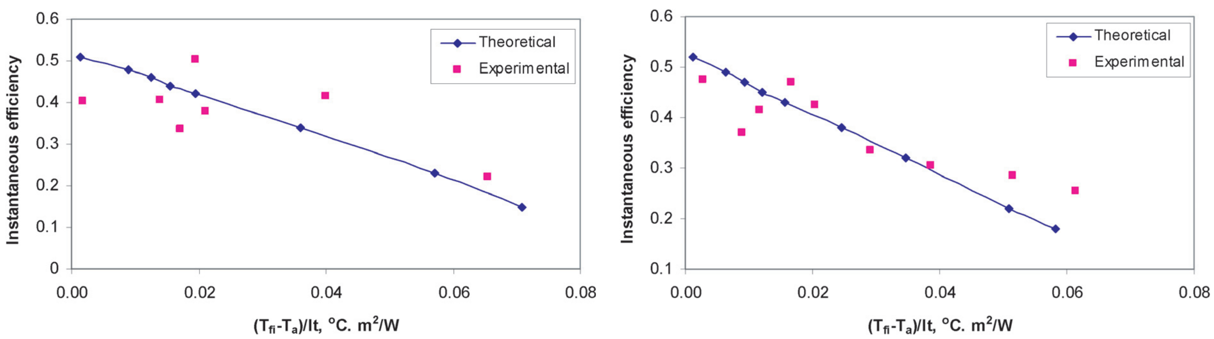
(a) (b)

Figure 4: (a) Hourly variation of calculated and measured outlet water temperature for type A PVT module at circulation flow rate of 0.03 kg/s. (b) Hourly variation of calculated and measured outlet water temperature for type B PVT module at circulation flow rate of 0.03 kg/s.



(a) (b)

Figure 5: (a) Hourly variation of calculated and measured outlet water temperature for type A PVT module at a circulation flow rate of 0.06 kg/s. (b) Hourly variation of calculated and measured outlet water temperature for type B PVT module at a circulation flow rate of 0.06 kg/s.

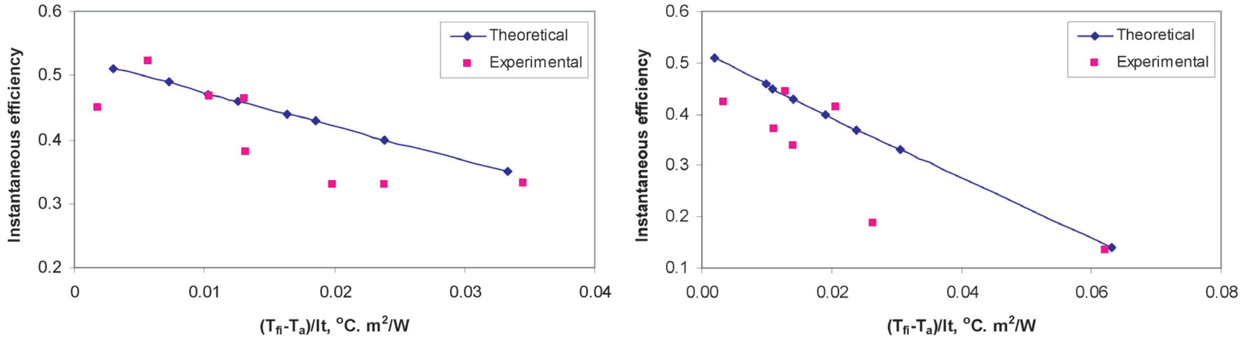


(a) (b)

Figure 6: (a) Variation of instantaneous thermal efficiency of type A PVT module at a circulation flow rate of 0.03 kg/s. (b) Variation of instantaneous thermal efficiency of type B PVT module at a circulation flow rate of 0.03 kg/s.

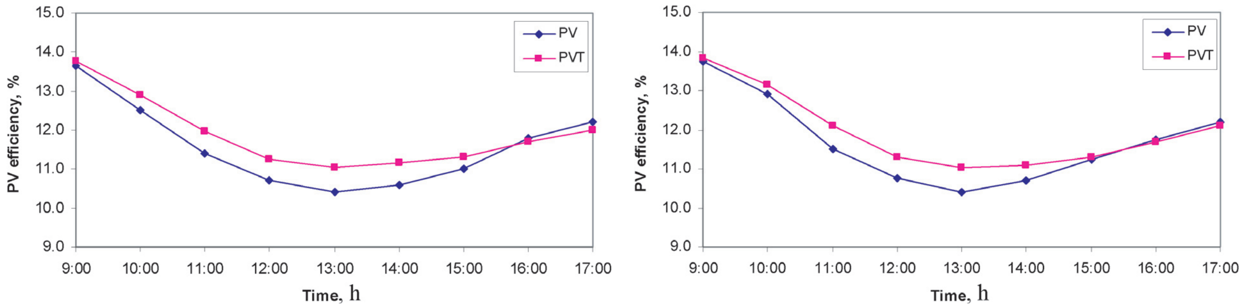
for more than 10 minutes were used for calculating the instantaneous efficiency. This is to ensure that steady-state conditions apply. The gain and loss factors obtained for the type A PVT module are 0.65 and 5.82, respectively, and those obtained for the type B PVT module are 0.71 and 7.24, respectively.

Based on the temperature and efficiency values, the temperature coefficients for type A and type B PVT modules were found to be $0.0051\,K^{-1}$ and $0.0063\,K^{-1}$, respectively. The PV efficiency of the PV panel without the thermal collector was also measured in order to be able to compare it with the situation where it was integrated with



(a) (b)

Figure 7: (a) Variation of instantaneous thermal efficiency for type A PVT module at a circulation flow rate of 0.06 kg/s. (b) Variation of instantaneous thermal efficiency for type B PVT module at a circulation flow rate of 0.06 kg/s.



(a) (b)

Figure 8: (a) Hourly variation of PV efficiency with and without the thermal collector for type A PVT module. (b) Hourly variation of PV efficiency with and without thermal collector for type B PVT module.

the thermal collector. The PV panels were disintegrated from the thermal collector and tested separately to measure their PV efficiencies. It was found that this efficiency was 0.4% (absolute) lower than the average PV efficiency of PVT modules (Figure 8). This demonstrates that the cooling of solar cells with water in a PVT module can indeed improve their PV efficiency.

5 Conclusions

In this paper, two different types of PVT modules were tested and validated with theoretical results. The average thermal efficiency and PV efficiency for type A PVT modules were found to be 40.7% and 11.8%, respectively, while those for type B PVT modules were 39.4% and 11.5%, respectively. The average PV efficiency of PVT modules is about 0.4% (absolute) higher than their corresponding normal PV modules due to the benefit of cooling from the circulating water.

Nomenclature

A Area [m^2]

C Specific heat [J.kg K]

F' Flat plate collector efficiency factor

F_R Flow rate factor [dimensionless]

h_T Heat transfer coefficient back surface of Tedlar to fluid [W.m^2 K]

h_{p1} Penalty factor due to the glass cover of PV module [dimensionless]

h_{p2} Penalty factor due to the absorber below PV module [dimensionless]

$I(t)$ Incident solar intensity [W.m^2]

M_w Mass of water [kg]

$U_{tc,a}$ 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_T An overall heat transfer coefficient from solar cell to back surface of Tedlar [W.m^2 K]

U_L An overall heat transfer coefficient [W.m^2 K]

dx Elementary width

a Ambient

bs Back surface of Tedlar

c Collector

eff Effective

fi Inlet fluid

fo Outgoing fluid
g Glass
m Module
sc Solar cell
tk Water tank
α Absorptivity
β_0 Temperature coefficient
β_{sc} Packing factor of solar cell
η_i Instantaneous thermal efficiency
η_o Efficiency at standard test conditions
τ Transmitivity

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