Design and Thermal Performance Test of a Solar Photovoltaic/Thermal (PV/T) Collector

Jiang Fan, Toh Peng Seng, Goh Leag Hua, Leung Kin On, and Kelvin Loh

***Abstract*—Photovoltaic/Thermal (PV/T) collector is a hybrid device that combines photovoltaic (PV) cells and solar thermal panel together so as to convert solar energy into electricity and thermal energy simultaneously in an effective way. PV/T technology is suitable for a highly urbanized country like Singapore because it harvests more solar energy per unit surface area than a combination of separate PV modules and solar thermal panels. Although we have conducted the research on performance of three different types of PV/T systems developed locally and obtained the experimental results through one-year site testing, it is essential to develop improved PV/T collector with higher conversion efficiency that can be verified by accurate PV/T testing system. This paper addresses the design of a new mc-Si based glazed PV/T collector and the setup of PV/T thermal testing system in accordance with EN 12975 for site testing of the new collector. The test results on a commercial solar water heater and the improved PV/T collector are presented to illustrate the operations of the testing system under tropical weather condition and performance of the improved PV/T collector.**

***Index Terms*—Solar photovoltaic, solar thermal, photovoltaic/thermal (PVT), EN12975.**

I. Introduction

Solar Energy can be deployed and converted directly to two types of useful secondary energy, i.e. electrical energy and thermal energy. Solar energy can be converted to electricity by the use of photovoltaic (PV) cells/modules, and to thermal energy by solar thermal panel. A Photovoltaic/Thermal (PV/T) collector is a hybrid device that combines PV cells with solar thermal panel to converts solar energy into both electricity and heat simultaneously. The advantages of a PV/T collector over either PV module or solar heater include a higher energy yield per unit area and reduction of cost of balance of system (BOS). There exist two common PVT collectors in applications, i.e. glazed collector with a glass cover and unglazed collector without glass cover. The main advantage of a glazed PVT collector over an unglazed PVT collector is higher conversion efficiency that is of paramount to Singapore where land is very limited. To investigate the feasibility of applications of PV/T technology in the country, Singapore Polytechnic and Grenzone Pte Ltd were funded in 2010 to prototype PV/T collectors and set up the PV/T systems to explore their feasibility for the tropic climate.

Three types of PV/T systems have been developed and tested at the solar test-bed of Singapore Polytechnic as shown in the Fig. 1, which include (1). 1.536 kW_p unglazed, forced circulation a-Si PV/T system, (2). 1.8kW_p glazed, forced circulation mc-Si PV/T system and (3). 1.2kW_p grid-tied forced-circulation CIGS PV/T system. Each PV/T system has the same configuration as depicted in Fig. 2 for experimental study on their operational performance. Based on the analyses on experimental data of the PV/T systems, it has turned out that the PV/T systems with three prototypes of PV/T collectors presented different system average conversion efficiencies, ranging from 34.87% for unglazed CIGS PV/T system, 40.05% for unglazed a-Si PV/T system to 41.08% for glazed mc-Si PV/T system [1]-[4]. The results proved the feasibility of PV/T system in the tropical region but improved PV/T collector with high conversion efficiency is needed to enable potential commercialization.

This paper will address the design of a new mc-Si PV/T collector. In order to specify the conversion efficiency of the PV/T collector over a wide range of operating temperature and solar irradiance, the accurate and reliable testing system complying with EN12975 needs to be established. The paper will introduce the design of the PV/T testing system and also present the experimental results of our mc-Si PV/T collector obtained by use of the testing system.

II. Design of a mc-Si PV/T Collector

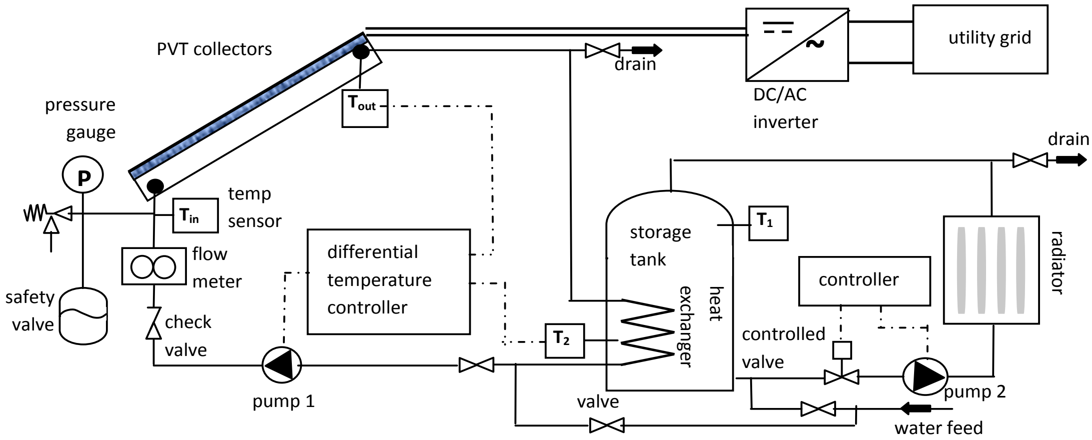
Two types of PV/T collector are considered for the domestic hot water supply in the tropical region, i.e. 1). glazed PV/T collector and 2). unglazed PV/T collector. Their basic structures are illustrated in Fig. 2. As can be seen from the figure, an unglazed collector has simpler structure without a glass plate on top of the PV cells. The simplicity in design with less parts, an unglazed collector is less expensive than a glazed collector. As this type of PV/T collector usually applies thin-film PV cells to convert solar energy to electricity, it has relatively lower PV conversion efficiency compared with its glazed counterpart. In addition, an unglazed collector has higher heat losses from its front surface than a glazed collector through convection and radiation. In contrast, a glazed collector is made from silicon type of PV cells and good heat conductor tubing on a metal plate both of which are covered by a low iron tempered glass with anti-reflection surface. Therefore a glazed collector can operate more efficiently because it absorbs more sunlight and has lower thermal losses than an unglazed collector. The structure of glazed PV/T was applied in our design in order to achieve high conversion efficiency in tropical applications.

Manuscript received June 25, 2015; revised October 12, 2015. This work was supported by the Ministry of Education, Singapore and Singapore Polytechnic.

Jiang Fan, Goh Leag Hua, Leung Kin On, and Kelvin Loh are with the School of Electrical & Electronic Engineering, Singapore Polytechnic, Singapore (e-mail: jiangfan@sp.edu.sg, gohleaghua@sp.edu.sg, leungko@sp.edu.sg, kelvin_loh@sp.edu.sg).

Toh Peng Seng is with Grenzone Pte Ltd., Singapore (e-mail: tohpengseng@grenzone.com).

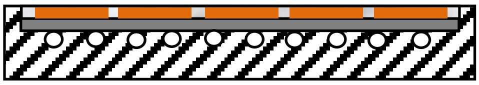
doi: 10.18178/jocet.2016.4.6.327



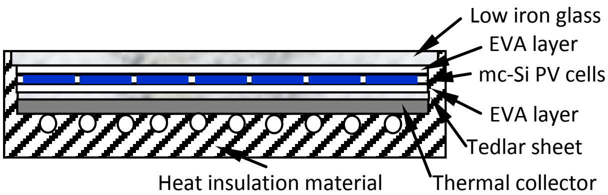
(a). The common configuration of PV/T systems.

(b). Photo of PV/T test-bed.

Fig. 1. Research on the solar PV/T systems in tropical area.



(a). An unglazed PV/T collector.



(b). A glazed PV/T collector.

Fig. 2. Structures of flat type liquid PV/T collector.

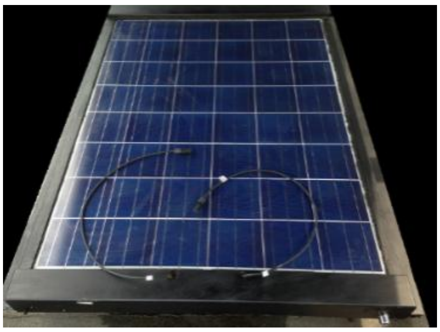


Fig. 3. Structures of flat type liquid PV/T collector.

Fig. 3 shows the new mc-Si glazed PV/T collector, PV/T CS200, developed jointly by Grenzone Pte Ltd and Singapore Polytechnic. The PV/T collector consists of a glass cover, ethyl-vinyl-acetate (EVA) layer, 48 mc-Si PV cells, EVA encapsulation layer, tedlar sheet, thermal collector and heat insulation material. The technical parameters of PV/T collector are listed in Table I in which the PV/T efficiency was estimated to be higher than 48% before the PV/T collector was tested.

TABLE I: TECHNICAL DATA OF PV/T COLLECTOR — CS200

Electrical specification(under **STC***)	
P_{max}(W)	200
V_{max}(V)	24.5
I_{max}(A)	8.2
V_{oc}(V)	29.8
I_{sc}(A)	8.9
Solar cells	48 multicrystalline
certifications	IEC61215, 61730
Thermal specification	
Volume of water(litre)	7.5
Collector area(m2)	1.5
Predicted efficiency (%)	> 48%
Heating medium	water
Length(m)	1.4
Width(m)	1.1
Thickness(m)	0.04
Weight(kg) with/without water	43/35
Water temperature(℃)	> 45

* *STC*: standard testing conditions

III. THE PV/T COLLECTOR TESTING SYSTEM

In order to foster solar energy to produce electricity and hot water, reliable PV/T collector must be offered to a PV/T system. It is well known that the performance of a PV/T collector depends on the PV efficiency, 'η_{PV}', and the solar thermal efficiency, 'η_{Th}' as given below,

$$\eta_{PVT} = \eta_{PV} + \eta_{Th} = \frac{E_{PV}}{E_{sun} \times A} + \frac{mC_p \Delta T_{PVT}}{3600 \times E_{sun} \times A} \tag{1}$$

where 'E_{pv}(kWh)' is the electrical energy yield of PV cells, 'E_{sun}(Wh/m^2)' is the irradiation, 'A(m^2)' is the area of PV/T surface area, 'm(kg)' is the fluid mass that equals product of mass rate and time period, 'C_p(J/kg·K)' is the fluid specific heat and 'ΔT_{PVT}(℃)' is the water temperature difference between the outlet and the inlet of PV/T collector.

The thermal performance of PV/T collector plays an important role in operation and needs to be tested properly to work out the thermal efficiency curve in a wide range of operating temperature. For this purpose, the standard EN 12975 has been developed to certify both quality and performance test of a solar heater [5]-[8]. According to the standard, a solar thermal collector must be subjected to standard tests for evaluation of their efficiency curve. The PV/T testing system complying with EN12975 was designed and set up in Singapore Polytechnic to perform the site test on PV/T collector under the tropical weather conditions as depicted in Fig. 4 and Fig. 5. In the system design, the important measurement and control parameters that must be taken in design considerations are included in below.

Because the weather conditions outdoor vary during the testing period and are difficult to estimate accurately and control, the following testing requirements for the PV/T Testing System need to be met in order to comply with EN 12975:

1) The range of inlet water temperature of the solar collector: setting value ± 1 ℃) throughout single test period (>15 minutes).
2) The control range of system flow rate: setting value ±1% throughout single test period (> 15minutes) and ranging from 0 to 5 liter/min.
3) A set point of inlet water temperature: ranging from 30 ℃ to 60 ℃ with a setting step of 5 ℃ or 10 ℃. A new temperature setting point after completion of one test should be stabilized and achieved within short time (15~30 minutes) after completion of one test.

The data logging system is able to capture all the important parameters which are useful for evaluation of PV/T collector under testing.

Fig. 4. PV/T testing system setup.

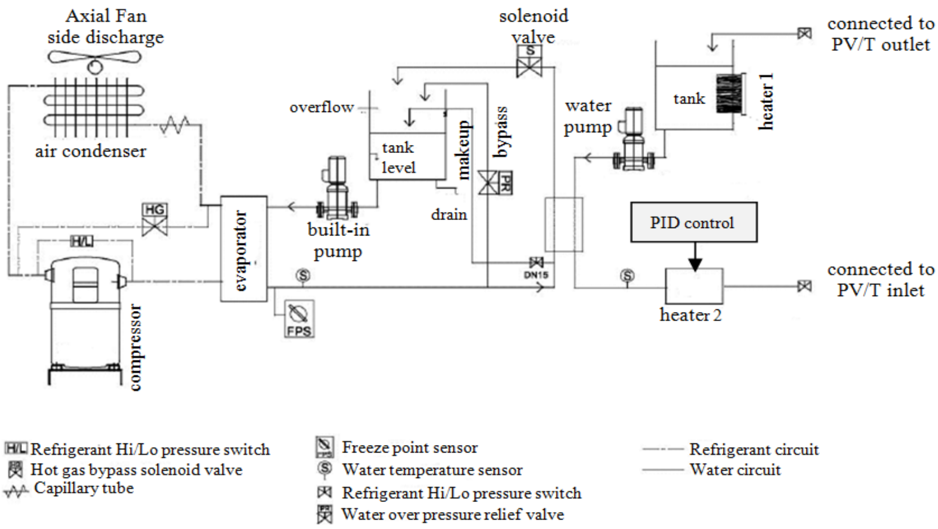


Fig. 5. Configuration of PV/T testing system.

IV. Experimental Data and Performance Analyses

According to the standard, the thermal efficiency of the PV/T collector, 'η_{Th}', can be defined by

$$\eta_{Th} = \eta_0 - a_1\left(T^*\right) - a_2 G\left(T^*\right)^2 \qquad (2)$$

where

$$T^* = \frac{t_m - t_a}{G}$$

$$t_m = \frac{t_{\text{out}} + t_{\text{in}}}{2}$$

η_0, a_1 and a_2 are constants, t_m is the mean temperature of the PV/T thermal panel, t_{in} and t_{out} are inlet and outlet water temperature of PV/T collector respectively, and G is solar irradiance that equals 800 W/m^2.

When the testing system was completed by mid of April 2015, a commercial solar water heater (Titan Series solar heater, Solar Edwards, Australia [9]) was used to undergo site tests so as to verify the functionality of the testing system before our PV/T collector was tested. The efficiency curve of solar water heater given by the manufacturer is shown below

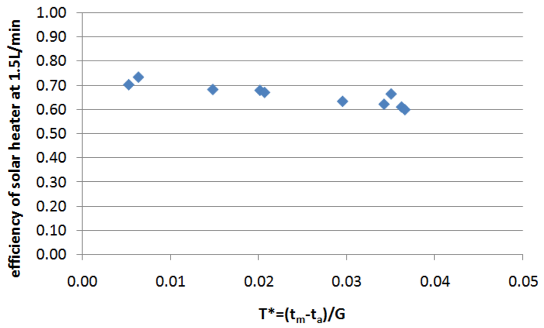
$$\eta_{Th} = 0.77 - 3.78\left(T^*\right) - 6.4\left(T^*\right)^2$$

Fig. 6 presents two sets of testing results of the commercial solar heater using the testing system, one at flow rate of 1.5L/min and another at flow rate of 2.5L/min. To work out the efficiency curves from the experimental data, Microsoft "Excel Solver" was implemented to perform nonlinear regression of testing data. Through the nonlinear regression, efficiency equations for the two sets of data obtained are given as follows.

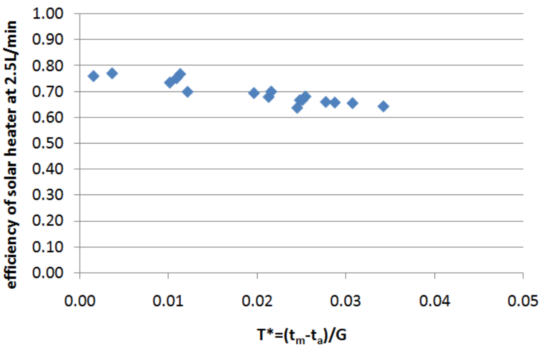
$$\eta_{Th}(at\ 1.5L/\min) = 0.733 - 2.601\left(T^*\right) - 13.6\left(T^*\right)^2$$

$$\eta_{Th}(at\ 2.5L/\min) = 0.782 - 4.766\left(T^*\right) + 14.4\left(T^*\right)^2$$

For the ease of comparison, the manufacturer's efficiency curve and two testing efficiency curves are displayed together in Fig. 7. It is noticeable that the testing efficiency curves in the figure closely fit the manufacturer's curve. It proved that the PV/T testing system can be employed to test and evaluate the thermal efficiency of PV/T collector.



(a). The measured efficiency at flow rate of 1.5L/min.



(b). The measured efficiency at flow rate of 2.5L/min.

Fig. 6. Testing results of commercial solar water heater.

The site experiments on PV/T collector were performed and the PV/T efficiency equation was obtained and shown below.

$$\eta_{Th}(at\ 4L/\min) = 0.685 - 10.530\left(T^*\right) - 78.4\left(T^*\right)^2$$

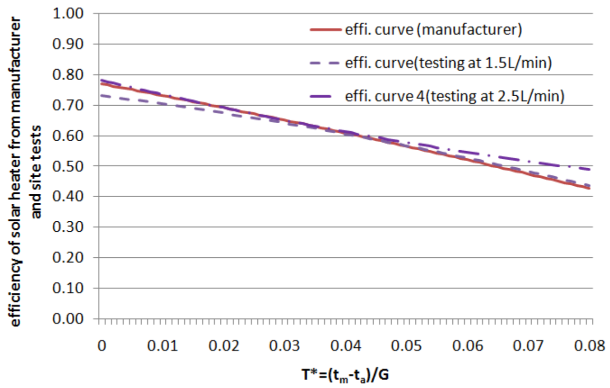


Fig. 7. Comparison of testing efficiency curves of solar heater with manufacturer's efficiency curve.

The PV/T efficiency curve displayed in Fig. 8 indicates apparently that the thermal efficiency of PV/T collector declines faster than a solar heater as both a_1 and a_2 in the equation are bigger than the solar heater. To achieve 40% of thermal conversion efficiency, T^* of PV/T collector should be less than 0.0235 K m^2/W. More site tests on the PV/T collector are still ongoing for thorough study on PV/T thermal performance.

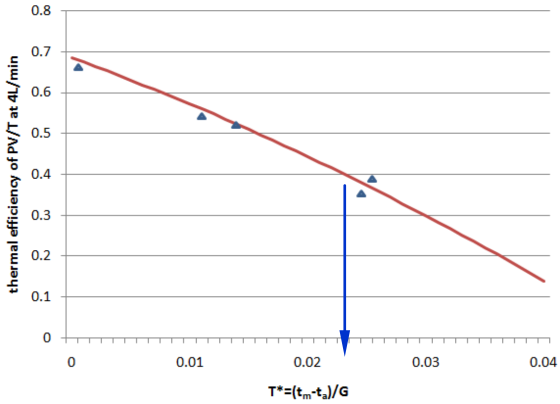


Fig. 8. The thermal efficiency curve of PV/T collector.

V. Conclusion

This paper presented the design and thermal performance test of a new mc-Si glazed PV/T collector. The PV/T thermal testing system was designed based on standard EN12975. To investigate the operation of testing system, a commercial solar water heater was selected to go through the site tests at two different flow rates and the testing results were compared with the manufacturer's data. The comparison reveals that the testing results fit the manufacturer's data closely. Finally, the paper presented the measurement results of our mc-Si glazed PV/T collector that help to understand the performance of PV/T collector under different operating conditions (T^*) as well as the performance difference between solar water heater and PV/T collector.

Acknowledgment

The authors would like to express their thanks to Ministry of Education (MOE), Singapore for the project funding and Singapore Polytechnic and Grenzone Pte Ltd and for their support to the project.

References

[1] F. Jiang, T. P. Seng, and G. L. Hua, "Development of solar a-Si PV/thermal(PVT) system for tropical region," in *Proc. ISES Solar World Congress*, Aug. 28–Sept. 2, 2011, Kassel, Germany.

[2] T. P. Seng, J. Fan, and G. L. Hua, "Solar photovoltaic/thermal (PVT) test-bed," in *Proc. 2012 International Congress on Informatics, Environment, Energy and Applications*, March 17-18, 2012, Singapore.

[3] J. Fan, T. P. Seng, and G. L. Hua, "Development of an unglazed solar photovoltaic/thermal (PV/T) collector," in *Proc. International Conference on Clean Energy*, Sept. 2012, Quebec, Canada.

[4] J. Fan, T. P. Seng, L. K. On, and G. L. Hua, "Experimental study on glazed mc-Si solar photovoltaic/thermal (PVT) system," in *Proc. the 6th International Conference on Applied Energy*, May 30-June 2, 2014, Taipei, Taiwan.

[5] M. G. Kratzenberg, H. G. Beyer, S. Colle, and A. A. Gonçalves, "Test facility for quasi dynamic collector tests for the characterization of thermal solar collectors in accordance with the international norms," in *Proc. METROLOGIA*, September 1-5, 2003, Pernambuco, Brazil.

[6] M. Emery and B. A. Rogers, "On a solar collector thermal performance test method for use in variable conditions," *Solar Energy*, vol. 33, no. 2, pp.117-123, 1984.

[7] S. Fischer and H. Müller-Steinhagen, "Collector efficiency testing - reduction of test duration by using a 2-node collector model," in *Proc. ISES World Congress*, 2007, pp. 731–734.

[8] P. Horta, M. J. Carvalho, and S. Fischer, "Solar thermal collector yield — experimental validation of calculations based on steady-state and quasi-dynamic test methodologies," in *Proc. Eurosun*, 2008, pp. 1-8.

[9] Solar water heater manufacturer. [Online]. Available: http://www.edwards.com.au

Jiang Fan was born in China in 1957 and received the B.Sc. degree from the Electrical Engineering Department of Fuzhou University, China, the M.Sc. degree in Electrical Power Research Institute (EPRI) of China and the Ph.D. degree in The Robert Gordon University, UK.

Recently he is a senior lecturer in the School of Electrical and Electronic Engineering, Singapore Polytechnic. He is the course manager of diploma in clean energy and has been the manager of Technology Centre of Energy Conservation from 8 years. His main areas include smart grid, renewable energy (solar and wind energy), electrical power system operation and control, high voltage engineering. He has published eighty-three journal and conference papers in his research areas.

Toh Peng Seng was born in Singapore in 1961, received training in engineering and practices engineering, and appropriate technological solutions. He graduates from Nanyang Technology University and National University of Singapore, received his PhD degree from Imperial College.

Peng Seng is a director of Grenzone, a company focusing on renewable energy, green building solution and affordable housing in the ASEAN region.

Goh Leag Hua was born in Singapore in 1966 and received her bachelor of engineering degree in electrical & electronic from Nanyang Technological University of Singapore in 2001.

She joined SP in 2009 and is currently a research engineer in the EEE of Singapore Polytechnic. Prior to joining SP, she worked in Grenzone Pte Ltd as a R&D/product engineer. Goh's research area is in the renewable energy.

Leung Kin On was born in Hong Kong in 1954 and achieved his BSc (Hons) degree in Southampton University, the MEd degree in Sheffield University and M.Sc. (Dist.) degree in Essex University. He has joined Singapore Polytechnic for 23 years and is currently a senior lecturer in the School of Electrical & Electronic Engineering. Prior joining SP he had worked in process and automation industries for about 10 years.

Kelvin Loh was born in Singapore on March 11, 1989. He received a B.Eng. (Hons) degree in mechanical design engineering, from University of Glasgow (Singapore Institute of Technology), Singapore, in 2013.

He joined the School of Electrical and Electronic Engineering in Singapore Polytechnic, Singapore, in 2014, as a research engineer.