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The effect of Joule heating to thermal performance of hybrid PVT collector during electricity generation

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ABSTRACT

The aim of this paper is to discuss the performance of a hybrid photovoltaic and thermal (PVT) collector by focusing on the utilization of Joule heating as additional heat for improving thermal efficiency, when both thermal and electrical energies are generated (PVT-mode), by comparing with when only the thermal energy is generated (T-mode). During the maximum power point and the peak irradiation, the temperature differential in PV material was increased due to the rise in current flow. The Joule heating or internal heating also increased proportional to the square of electric current. The conducted heat also increases through the PV surface to the thermal absorber in the PVT collector. For that reason, the experiment was performed using higher irradiation with a bigger PVT collector at four different inlet water temperatures, i.e., 12, 15, 20, and 25 °C. The water flow rate was 6.7×10^{-5} m^3/s (≈ 4 L/minute). The irradiation data was collected for an hour from 12:00 to 13:00 to keep a steady-state thermal performance and also to minimize the hysteresis effect. In the present PVT collector's system and configuration, the result showed that even a moderate wind speed below 1 m/s results in a non-negligible loss of the thermal efficiency. The thermal efficiency of PVT collector in PVT-mode is higher than T-mode at the lower range of first order thermal efficiency gradient, when the inlet water temperature is close to the ambient air temperature, or when the total irradiation is high. The behavior of the thermal efficiency of PVT-mode also seems to be appreciably influenced by other factors, such as the internal heating during the operation. During the higher irradiation periods, the Joule heating effect has the potential to improve the thermal efficiency of PVT-mode up to 13%. The internal heating in PV cell apparently affects both the effective absorption and heat loss coefficient. The practical relevance of Joule heating in a real-life PVT system is for low temperature applications, such as swimming pool heating, low temperature source heat pumps, and floor heating.

1. Introduction

Sophisticated utilization of solar energy is the main area of concern these days. Using a hybrid Photovoltaic and thermal (PVT) collector, the abundant solar energy available can be converted simultaneously into electricity and heat. A PVT collector system consists of a Photovoltaic (PV) cell placed at the top and a thermal collector at the bottom. The estimated total efficiency of the PVT collector is about 60–80%. So far, electricity conversion rate of silicon PV cells on the market is around 20% at most [1] and the thermal efficiency of the flat-plate thermal collector is 40–60%. That is, most of the solar energy is converted into heat. Therefore, the utilization of the heat is the key subject.

Research on PVT collectors has been carried out intensively since the publication of the first PVT model in 1978 [2]. Based on reviews [3–9], until now the PVT collector has been studied from various aspects, including system design, performance analysis, simulation models, field or indoor experimental validation, economic and cost-effective analysis, and so on. Although many studies of PVT have been widely spread in the public, however, the thermal performance behavior of PVT collectors still seems unclear, especially when electrical energies generated (PV-on or PVT-mode), or without electrical energies generated (PV-off or T-mode). One of the reasons is the lack of scientific publications that focus on these issues.

Sandness and Rekstad [10] studied a PVT collector using modified polyphenylenoxid (PPO) or black plastic solar heat as absorber and a wall to wall channel filled with ceramic granulates. The water was the heat carrier and was circulated at a single flow rate. Within

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the first order thermal efficiency gradient, with the ratio between temperature difference of inlet water and ambient air with irradiance $(T_i - T_a)/I$ ranging from 0.0 to 0,016 m^2. C/W, the thermal efficiency of PVT-mode is 10% lower than T-mode.

Zondag et al. [10] have built four numerical models to simulate the thermal yield of a combined PVT collector: a 3D dynamic model and three (3D, 2D, and 1D) steady-state models [11]. They have also evaluated the yield of nine different designs of PVT collectors from simple types to the more complicated ones [12]. Both studies showed the similar thermal performance graph that T-mode is higher than PVT-mode.

Coventry [13] has developed and tested a photovoltaic/thermal (PVT) collector at the Australian National University (ANU), called combined heat and power solar (CHAPS) collectors, with a geometric concentration ratio of 37. It consists of glass-on-metal mirrors that focus light onto high-efficiency monocrystalline silicon solar cells for generating electricity. Water, with anti-freeze and anti-corrosion additives, flows through a conduit at the back cells to remove most of the remaining energy as heat. The result from load-on (PVT-mode) and load-off (T-mode) tests showed that the thermal efficiency of T-mode is higher than PVT-mode.

Ito et al. [14] studied the performance of three type air collectors; Type I consisted of two amorphous silicon PV modules connected in series under a glass cover, Type II used ten amorphous silicon PV modules connected in series in the space between a glass cover and absorber plate at 1° tilted angle, and Type III was a flat plate collector without any PV modules. They noted that the difference of thermal efficiency for PVT-mode and T-mode is small. The thermal efficiency of Type I collector was higher than that of Type II collector for $(T_i - T_a)/I$ larger than 0,035 m^2. C/W. The total efficiency of Type I collector in PVT-mode is a little larger than the total efficiency in T-mode. The thermal efficiency of Type II collector was highest for the zero reduced temperature was less than 0,035 m^2. C/W, or in other words when the inlet water temperature was close to the ambient air temperature, or when the irradiation is high.

Chow et al. [15] developed a prototype thermosyphon PVT collector made of aluminum alloy flat box. Their experiment was done from 08:00–16:00 to compare the performances of closed-circuit (PVT-mode) and open circuit (T-mode) at 20° and 38° tilted angle. The result showed that, for the same operation mode, 38° gave higher thermal efficiency than 20° tilted angle. They also mentioned that the thermal efficiency for a PVT-mode was higher than that for T-mode by around 4%–5% at $(T_i - T_a)/I \approx 0$, or at the inlet air and the ambient air temperature is equal. The gaps gradually narrowed down at higher values of reduced temperature.

Bernardo et al. [16] have done the testing and performance simulation of an innovative tracking hybrid solar system developed by a company. The performance of Solar8 PVT collector was compared with the conventional PV panels and the thermal collectors on the market working side-by-side. A graph shows that when an electric load is connected to the circuit, power can be extracted. This means that part of the incoming irradiation is transformed into electricity by the PV cells instead of being absorbed by the thermal receiver. Hence, the thermal output decreases as much as the electrical output is extracted.

Ghoneim et al. [17] constructed the hybrid system by pasting a PV laminates containing multicrystalline silicon cells (Shell PowerMax Plus 50) into the absorber plate of a conventional glass covered sheet and fin tube collector. A thin layer of silicon adhesive was used to paste the PV laminates into the absorber plate. The combined system was then integrated into the test rig installed on the roof of the main building at the College of Technological Studies, Kuwait. The collector test facility consists of a solar collector, storage tank of 100 L capacity, cross flow heat exchanger, constant temperature circulator and a circulator pump to overcome the pressure resistance of the system. The result indicated that extracting electrical energy from the PV panels reduces the solar energy absorbed by the combined collector, and consequently reduces the thermal efficiency of the combined collector by approximately 12%.

Dupeyrat et al. [18] investigated the thermal and electrical performances of several single glazed flat plate PVT based on water circulation using a simple 2D thermal model, then tested the improve design of a prototype single glazed flat plate PVT collector focusing on the heat transfer between PV cells and fluid, and also on the optical properties of materials. A high thermal efficiency was reached at $(T_i - T_a)/I \approx 0$ and the electrical efficiency is lower comparing to the standard PV panel using the same technology. The result also showed that the thermal efficiency during open-circuit (T-mode) is higher than closed circuit (PVT-mode) at the maximum power point (MPP). Using the same prototype and method testing, they reported the same result in Ref. [19] for the uncovered and covered PVT collector.

Table 1
Summary studies of PVT-mode and T-mode.

Items	Sandnes et al. [10]	Zondag et al. [11] [12]	Coventry [13]	Ito et al. [14]	Chow et al. [15]	Bernardo et al. [16]	Ghoneim et al. [17]	Dupeyrat et al. [18] [19]
PVT type	FPC	FPC	CFPC	FPC	FPC	PCFPC	FPC	FPC
PV type	Mono-C	Multi-C	Mono-C	Amorphouss	Mono-C	–	Multi-C	Mono-C
PV area	0,32 m^2	0,94 m^2	–	0,42 m^2	1,11 m^2	3,50 m^2	0,83 m^2	0,63 m^2
Absorber	Polymer	Chopper	Aluminium	Steel	Polymer	–	Chopper	Metal
Absorber area	0,48 m^2	1,12 m^2	–	0,58 m^2	1,76 m^2	4,60 m^2	2,0 m^2	0,44 m^2
Cons/Config.	C-L-PV-A-T-I	C-G-PV-A-T-I	C-L-PV-A-T-I	C-G-PV-A-T-I	C-G-PV-A-T-I	C-L-PV-A-T-I	C-G-PV-A-T-I	CU-L-PV-A-T-I
System	Active	Active	Active	Active	Thermosyphonn	Active	Active	Active
Test site	Simulation	Simulation	Outdoor	Outdoor	Outdoor	Outdoor/Sim.	Outdoor	Indoor
Obs. Period	11AM - 5PM	8AM - 6PM	–	10AM - 15PM	8AM - 4PM	8AM - 5PM	8AM - 5PM	Simulation
Working fluid	Water	Water	Water	Air	Water	Water	Water	Water
Flow rate	–	0,020 kg/s	0,038–0,043 kg/s kg/s42.5 ml/s	0,014 kg/s	Natural	–	20,8–33,3 kg/s	0,045 –0,072 kg/s
In. water temp	10-12 °C	20-60 °C	20-80 °C	20-60 °C	7,5/31,8 °C	25 °C	30-80 °C	10 ± 3.5 °C
Amb. temp.	8-9 °C.	20 °C.	14,8–27,5 °C.	20-60 °C	11,2/32,1 °C.	–	30-40 °C	30-33 °C.
Wind Speed	–	1 m/s	0,21 m/s	3 m/s	–	–	–	3 m/s
Irradiation	749 w/m^2	800 w/m^2	829-928 w/m^2 w/m^2	800 w/m^2	446/771 w/m^2	>900 w/m^2	650-1000 w/m^2 w/m^2	960 w/m^2
Thermal.eff.	PVT < T*	PVT < T*	PVT < T*	PVT > T**	PVT > T**	PVT < T*	PVT < T*	PVT < T*

Construction/Configuration: C (glass cover) or U (uncovered), L (laminated), G (gap), PV (pv), A (adhesive), T (thermal absorber), I (back insulation).
Thermal eff.: *For all range of first order thermal efficiency gradient considered, **For the higher first order thermal efficiency gradient considered.