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Solar Energy 85 (2011) 388–392
SOLAR ENERGY
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Solar cell junction temperature measurement of PV module

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Received 22 July 2010; received in revised form 3 November 2010
Available online 18 December 2010

Communicated by: Associate Editor Manuel Romero-Alvarez

Abstract

The present study develops a simple non-destructive method to measure the solar cell junction temperature of PV module. The PV module was put in the environmental chamber with precise temperature control to keep the solar PV module as well as the cell junction in thermal equilibrium with the chamber. The open-circuit voltage of PV module V_{oc} is then measured using a short pulse of solar irradiation provided by a solar simulator. Repeating the measurements at different environment temperature (40–80 °C) and solar irradiation S (200–1000 W/m^2), the correlation between the open-circuit voltage V_{oc}, the junction temperature T_j, and solar irradiation S is derived.

The fundamental correlation of the PV module is utilized for on-site monitoring of solar cell junction temperature using the measured V_{oc} and S at a short time instant with open circuit. The junction temperature T_j is then determined using the measured S and V_{oc} through the fundamental correlation. The outdoor test results show that the junction temperature measured using the present method, T_{jo}, is more accurate. The maximum error using the average surface temperature T_{ave} as the junction temperature is 4.8 °C underestimation; while the maximum error using the present method is 1.3 °C underestimation.

Keywords: Solar cell junction temperature; Solar cell measurement; Solar PV

1. Introduction

Solar cell junction temperature can seriously affect the power output of solar PV module (King et al., 1997; Nordmann and Clavadetscher, 2003). Hence, an accurate solar cell junction temperature measurement is important in order to correctly assess the temperature effect of a solar PV module.

The solar cell junction temperature depends on the packaging of solar cells and the environmental factors such as ambient temperature and wind speed/direction. There are some methods to measure the solar cell junction temperature. Usually, the junction temperature T_j is taken as the average value of the surface temperatures of the bottom side T_{bot} and the top side T_{top}, i.e.

$$T_j = T_{ave} = (T_{top} + T_{bot})/2 \tag{1}$$

Due to the thermal resistance of the packaging materials and the interior temperature gradient, the junction temperature measured in this way may be inaccurate. Some investigators use numerical method and a simple energy balance to predict the junction temperature (Mattei et al., 2006).

The other method as adopted in IEC904-5 Standard (IEC Standard 904-5, 1993) (IEC method) uses the pre-determined V_{oc1} at known S_1 and T_{j1} to determine the equivalent cell temperature (ECT) from the measured S_2 and V_{oc2} using the average temperature coefficient of V_{oc}, C_T, and the given diode thermal voltage D for a given n_s (number of series connection of PV cells). The measurement is however tedious.

In the present study, we attempt to develop a simple non-destructive method to measure the solar cell junction temperature which can be used in on-site monitoring of solar PV performance.

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doi:10.1016/j.solener.2010.11.006

Nomenclature

A_{oc}	intercept coefficient of V_{oc}, V	T_{jd}	real solar cell junction temperature measured by direct method, °C
C_T	temperature coefficient of V_{oc}, V/°C	T_{jo}	solar cell junction temperature measured by the present method, °C
S	solar radiation intensity incident upon the PV module, W m^{-2}	T_{ave}	the average temperature of top and bottom surfaces of PV module, °C
T_{bot}	surface temperature on the back of solar PV module, °C	V_{oc}	open-circuit voltage of solar PV module, V
T_{top}	surface temperature on the top of solar PV module, °C		
T_j	solar cell junction temperature, °C		

2. Measurement of solar cell junction temperature

It is known that the open-circuit voltage of solar cell V_{oc} decreases with increasing junction temperature T_j. V_{oc} is also affected by solar irradiation S. That is, V_{oc} follows the function of Eq. (1).

$$V_{oc} = f(S, T_j) \tag{2}$$

Measuring V_{oc} and solar irradiation S allows us to determine T_j, if the basic relation, Eq. (2), is pre-determined experimentally.

The relations of V_{oc} *vs.* T_j at various solar irradiations S can be determined in an environmental chamber which keeps the solar PV module in thermal equilibrium within a temperature-controlled chamber. In an on-site application, the solar cell junction temperature can be determined by a suddenly disconnection of the solar PV module for a short period of time in order for measuring the V_{oc}. The junction temperature T_j can then be converted from the measured V_{oc} and solar irradiation S using the pre-determined relation. The measurement is simple, non-destructive and can be very accurate.

3. Experimental setup

Fig. 1 shows the experimental apparatus setup to determine Eq. (2) of a PV module. We used a solar simulator (Burger PSS30) to provide artificial light incident upon the PV module. The open-circuit voltage of the PV module is measured at the time when the solar simulator flashes the light in a short period of time, 10 ms. This flash time is too short to cause temperature rise of solar cell during measurement. The environmental chamber is designed with an electric heater connected to a PID (proportional–integral–derivative) controller to control the heating power so as to control the chamber at a fixed temperature.

The design of the environmental chamber is as shown in Fig. 2 which was made of aluminum. The chamber is thermally insulated and uses a glass cover to allow solar light to pass through only. The PV module is fixed inside the chamber. Inside the chamber a fan was used for air circulation to create a uniform temperature over the PV module.

Table 1 shows the characteristic of the solar PV module used in this experiment. The data of Table 1 are taken separately from the standard test results of *I–V* curve of the solar PV module. During the heating process, the temperature uniformity inside the chamber will affect the temperature uniformity of the PV module and may lead to experimental errors. The first test is to measure the temperature distribution of the PV module surfaces as well as the solar cell. Twenty-seven T-type thermocouples were mounted evenly on the top and bottom surfaces of PV module and inserted between the glasses and the solar cell,

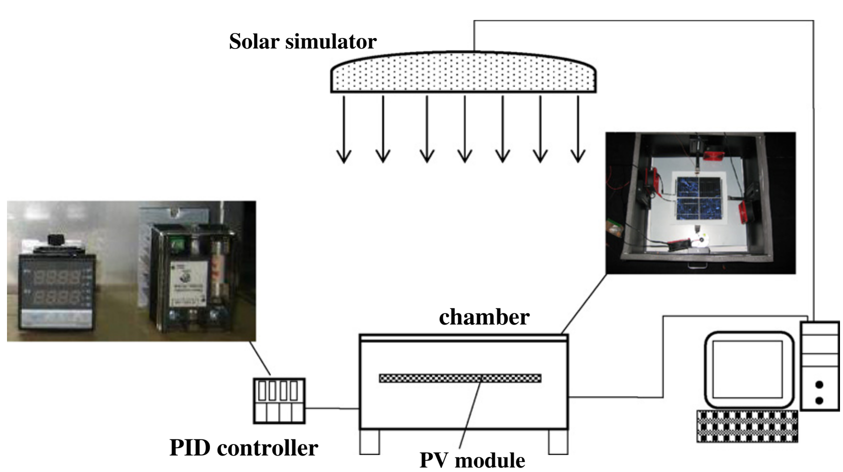

Fig. 1. Experimental apparatus.

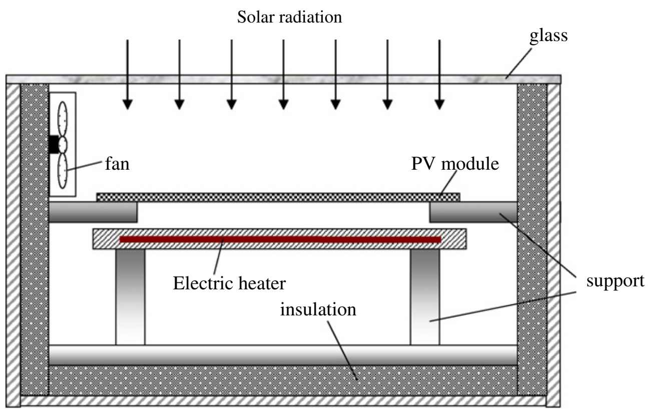

Fig. 2. Environmental chamber design.

Table 1
Single-crystalline solar PV module characteristics.

Efficiency (%)	14.50–14.74
Maximum-power output (W)	2.29
Maximum-power current (A)	4.6
Short circuit current I_{sc} (A)	4.377
Maximum-power voltage (V)	0.497
Open-circuit voltage V_{oc} (V)	0.598

for a specially-made PV module. Three thermocouples were installed in each location (total nine locations): top surface, cell surface (between the glasses), and bottom surface. The surface temperature non-uniformity of the PV module is less than 1 °C. This experiment can also determine the temperature response of solar PV module for reaching a steady state between measurements at different operating conditions. The PV temperature uniformity test uses a specially-made PV module with thermocouples inserted onto the solar cell surface as well as outside surfaces to check the design of the environmental chamber. After this temperature uniformity test, a real PV module is then put into this chamber for regular experiment.

The chamber temperature is first set at 40 °C with increment 10 °C for successive experiments. The PID controller regulates the chamber temperature as well as the PV module surface temperature. The test results indicate that the top surface temperature response of the PV module to the new setting of the chamber temperature is about 20 min to reach a steady state and the surface temperature uniformity of PV module is satisfactory, within ±1 °C.

It is found that the cell temperature takes about 30 min to obtain thermal equilibrium in each temperature setting of the chamber. The test results indicate that any change of the operating condition during test requires at least 30 min to reach a thermal equilibrium.

4. Results and discussion

4.1. Determination of fundamental correlation of PV module

After the PV module in thermal equilibrium with the chamber, which takes about 30 min for each temperature setting, the open-circuit voltage of the PV module V_{oc} is measured when the solar simulator is turned on in a short period of time, 10 ms. This time period is too short to cause a significant temperature rise of solar cell during measurement. V_{oc} was measured repeatedly every 10 °C increment from 40 °C to 80 °C for different S. The experimental result of Fig. 3 shows that at fixed S, V_{oc} decreases linearly with increasing T_j which satisfies the relation of Eq. (2):

$$V_{oc} = A_{oc} - C_T T_j \tag{3}$$

where A_{oc} is the intercept coefficient of V_{oc} at $T_j = 0$ °C and C_T is the temperature coefficient of V_{oc}. A relation between A_{oc} and S, Eq. (4), can be derived from the determined

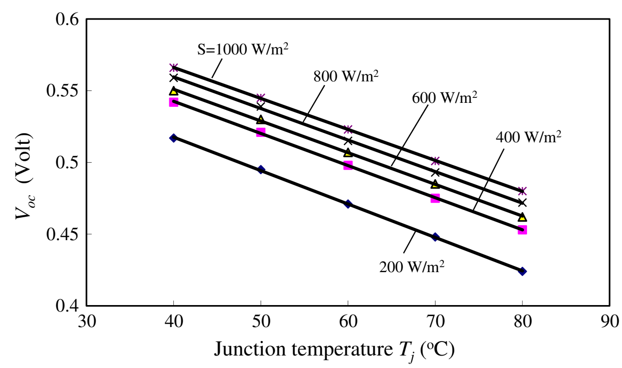

Fig. 3. Variation of V_{oc} with T_j.

Table 2
Experimental determination of the relation of V_{oc}.

Irradiation (W/m²)	Linear relation	Intercept coefficient A_{oc} (V)	Temperature coefficient C_T (V/°C)
1000	$V_{oc} = -0.002160T_j + 0.6526$ $R^2 = 0.9999$	0.6526	0.002160
800	$V_{oc} = -0.002200T_j + 0.6476$ $R^2 = 0.9993$	0.6476	0.002200
600	$V_{oc} = -0.002210T_j + 0.6394$ $R^2 = 0.9994$	0.6394	0.002210
400	$V_{oc} = -0.002240T_j + 0.6322$ $R^2 = 0.9998$	0.6322	0.002240
200	$V_{oc} = -0.002330T_j + 0.6108$ $R^2 = 0.9998$	0.6108	0.002330

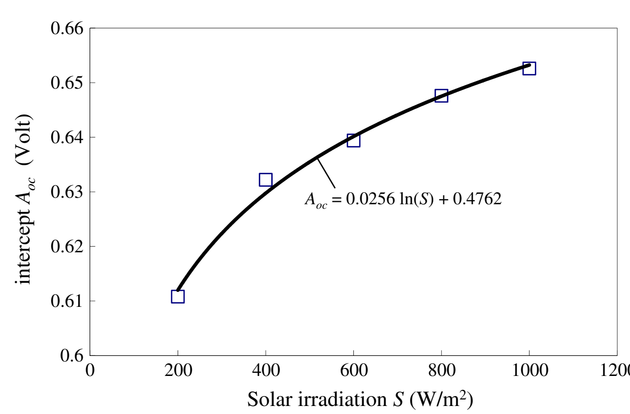

Fig. 4. Variation of A_{oc} with S.

parameters of Table 2. Fig. 4 shows the correlation between A_{oc} and S.

$$A_{oc}(S) = 0.0256\ \ln\ S + 0.4762 \tag{4}$$

Fig. 5 shows the correlation between C_T and S. A relation of C_T with S, Eq (5), can be derived from the determined parameters of Table 2.

$$C_T = -0.000188\ \ln(S) + 0.003525 \tag{5}$$

Combining Eqs. (3)–(5), we can obtain the functional relation of Eq. (6).

$$V_{oc}(S, Tj) = (0.0256\ \ln\ S + 0.4762) - (-0.000188\ \ln\ S + 0.003525)T_j \tag{6}$$

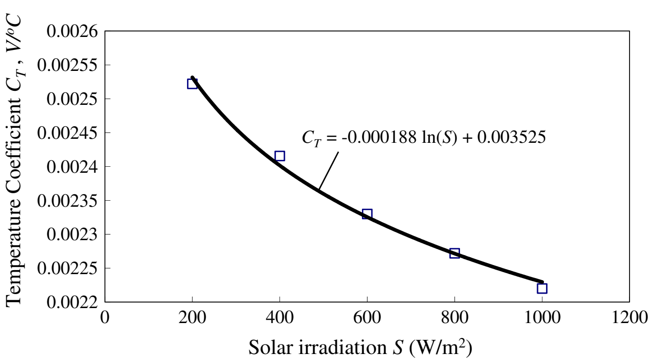

Fig. 5. Variation of C_T with S .

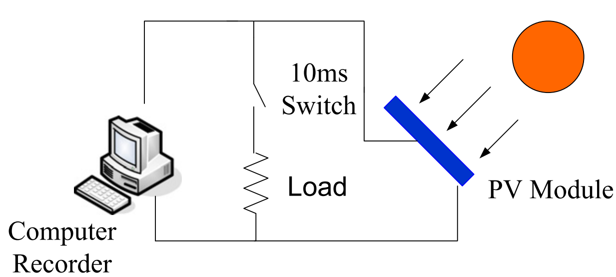

Fig. 6. Electronic circuit for measuring V_{oc}.

Eq. (6) is the fundamental correlation of V_{oc}, T_j, and S which can be utilized in the determination of solar cell junction temperature in the field operation of PV module.

4.2. On-site measurement of solar cell junction temperature

Eq. (6) is the fundamental correlation of a PV module which can be utilized in on-site solar cell junction temperature monitoring if V_{oc} and S are measured in a short time instant at open circuit. The same PV module used in the present study was installed outdoor and run with a constant load (resistor) to simulate the performance of a solar PV power generation. In order to determine the PV junction temperature T_j, a circuit was designed to disconnect the load (open-circuit of PV module) for a very short period of time, 10 ms in the present study, for measuring V_{oc}. The measuring circuit is shown in Fig. 6. Instantaneous junction temperature is then calculated from Eq. (6) using the measured solar irradiation S and V_{oc}, which is denoted T_{jo}. For monitoring purpose, T_{jo} was measured every 3 min. The energy loss due to the disconnection of power generation circuit during T_j measurement is only 10 ms/180 s = 0.05%, which is negligible.

To verify the accuracy of the above measured results T_{jo}, a thin T-type thermocouple was installed into the PV junction during the module packaging in order to directly measure the junction temperature T_{jd} and compare with T_{jo}.

Table 3
Measurement errors of different methods.

	Real junction temperature T_{jd} (°C)	$T_{ave\_}$ (°C)	Error (°C)
Max error	65.9	61.1	−4.8
Min error	60.3	59.8	−0.5
	Real junction temperature T_{jd} (°C)	Present method T_{jo} (°C)	Error (°C)
Max error	57.9	56.6	−1.3
Min error	62.7	62.7	−0.03

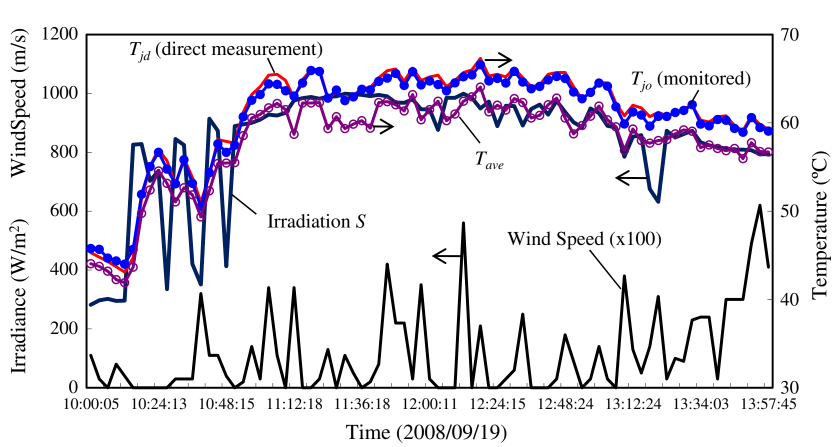

Fig. 7. Outdoor test result of PV module.

Fig. 7 shows the outdoor test results of the same PV module used in the experimental determination of the fundamental correlation. The solar cell junction temperature T_j was determined using the present method and the average of the surface temperatures at the bottom side T_{bot} and the top side T_{top}, Eq. (1). It is seen that the junction temperature determined using the present method, T_{jo}, is more accurate. Table 3 shows the maximum and minimum measurement errors between T_{jo} and T_{ave}. It is found that the maximum error using the conventional T_{ave} as the junction temperature is 4.8 °C underestimation; while the maximum error using the present method is 1.3 °C underestimation.

5. Conclusions

The present study develops a simple non-destructive method to measure the solar cell junction temperature of PV module. Indoor experiment using a simple environmental chamber and a solar simulator is required in order to determine the fundamental correlation of a PV module, i.e. V_{oc}, T_j and S. The PV module has to be put in the environmental chamber with precise temperature control to keep the solar PV module as well as the cell junction in thermal equilibrium with the chamber.

The junction temperature of the PV module in the chamber is not directly measured. But it is assumed to coincide with the chamber temperature itself, within ±1 °C (accuracy of the temperature controller), if thermal equilibrium has been reached. Many tests have shown that it will take about 30 min for the PV module to reach thermal equilibrium with the chamber. The measurement of the chamber temperature T, S and V_{oc} are done after having imposed the conditions that guarantee a good thermal equilibrium for the test PV module.

The open-circuit voltage of PV module V_{oc} is then measured using a short pulse of solar irradiation provided by a solar simulator. Repeating the measurements at different environment temperature (40–80 °C) and solar irradiation S (200–1000 W/m^2), the fundamental correlation between the open-circuit voltage V_{oc}, the junction temperature T_j, and solar irradiation S is derived.

The fundamental correlation of the PV module can be utilized for on-site monitoring of solar cell junction temperature if V_{oc} and S are measured simultaneously at a short time instant with open circuit. In order to measure V_{oc}, we designed a circuit to disconnect the load (open-circuit of PV module) for a very short period of time, 10 ms, for measuring V_{oc}. The junction temperature T_j is then determined using the measured S and V_{oc} through the fundamental correlation.

The outdoor test results of the same PV module used in the experimental determination of the fundamental correlation show that the junction temperature measured using the present method, T_{jo}, is more accurate. The maximum error using the average surface temperature T_{ave} as the junction temperature is 4.8 °C underestimation; while the maximum error using the present method is 1.3 °C underestimation.

The present method of measuring the junction temperature of PV module on-site can be accurate if the PV module used in the experimental determination of the fundamental correlation of the PV module is the same or is similar enough to the PV module used on-site. However, it is highly recommended that the sampling of PV modules used in field installation for the experimental determination of the fundamental correlation is a necessary step in order to obtain an accurate result in measuring the junction temperature on-site. The design of the new environmental chamber to fit the different sizes of PV modules as shown in Fig. 2 is not difficult. The method of the experimental determination of the fundamental correlation of the PV module is exactly the same as described previously (Fig. 1).

Acknowledgements

This publication is based in part on work supported by Photovoltaic Technology Center, ITRI, Taiwan, and Award No. KUK-C1-014-12, made by King Abdullah University of Science and Technology (KAUST), Saudi Arabia.

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