Determining Outdoor CPV Cell Temperature

Preprint

Matthew Muller, Chris Deline, Bill Marion, Sarah Kurtz, and Nick Bosco

Presented at the 7th International Conference on Concentrating Photovoltaic Systems (CPV-7)
Las Vegas, Nevada
April 4-6, 2011
NOTICE

The submitted manuscript has been offered by an employee of the Alliance for Sustainable Energy, LLC (Alliance), a contractor of the US Government under Contract No. DE-AC36-08GO28308. Accordingly, the US Government and Alliance retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.
Determining Outdoor CPV Cell Temperature

Matthew Muller, Chris Deline, Bill Marion, Sarah Kurtz, Nick Bosco
National Renewable Energy Laboratory (NREL), Golden, CO, 80401 USA (303)384-6164

Abstract. An accurate method is needed for determining cell temperature when measuring CPV modules outdoors. It has been suggested that cell temperature can be calculated through a procedure that shuts sunlight to the cells while measuring the transients in open-circuit voltage (Voc) and heat sink temperature. This paper documents application of this shutter procedure to multiple CPV modules at NREL. The challenges and limitations are presented along with an alternate approach to measuring CPV cell operating temperature.

Keywords: CPV, Cell, Temperature, Power, Ratings, IEC.
PACS: 85.30, 88.05, 88.40

INTRODUCTION

The CPV community has been working to standardize a procedure for rating module power. The IEC TC82 WG7 recently agreed to define power ratings at concentrator standard test conditions (CSTC, 25°C cell, 1000W/m²) and concentrator standard operating conditions (CSOC, 20°C ambient, 900W/m²). Translation between CSOC and CSTC requires knowledge of the cell temperature for both conditions [1]. With CPV modules the heat sink temperature can be measured, but the difference between the heat sink and the cell temperatures can easily be 10-30°C and is dependent on heat sink design, thermal attachment, measurement location, irradiance, wind speed and other factors.

A procedure has been suggested that requires shuttering the module aperture while measuring meteorological conditions, module voltage and heat sink temperature. The data from this procedure, combined with the cell temperature coefficient of voltage, provide a means to determine the temperature difference between the cell and the measurement location on the heat sink. An assumption that this temperature difference is proportional to direct normal irradiance (DNI) allows a translation to cell temperature at CSOC.

This study applies the above shuttering procedure to multiple module designs that are on-sun at NREL. The challenges and limitations of the shutter procedure are discussed along with a cautionary note for indoor flash testing of CPV modules. Finally an alternate method is considered for calculating outdoor CPV cell temperature.

METHODS

The principle of shuttering a PV/CPV module while measuring voltage transients has been discussed for many years though there exists no formal procedure. A very basic approach is used in this study for both the shuttering and accompanied measurements. A piece of heavy black cloth is placed over the face of the module and then manually snapped off the module to complete the shutter event. For comparison, a fast (~5 ms) mechanical aperture is similarly employed to shutter directly in front of a CPV cell under 1000x concentration. During shuttering, Keithley multimeters are used to measure module open-circuit voltage (Voc) and heat sink temperature using a fast response platinum resistance temperature detector (RTD). The module is covered for a significant period of time before all shuttering events in an attempt to equilibrate the cell and heat sink temperature within 1 degree Celsius.

Figure 1 provides an example of what is measured and what is calculated when using the shutter procedure.
\[ T_{\text{cell}} = T_{h,0} + \left( \frac{V_{\text{max}} - V_{\text{oct}(t)}}{(N_c \beta_{\text{Vocr}})} \right) \]

\[ N_c = \text{Number of cells in series in module} \]
\[ T_{\text{cell}} = \text{Calculated cell temperature} \]
\[ T_{h,0} = \text{Heat sink temperature at shutter initiation} \]
\[ V_{\text{max}} = \text{Maximum measured } V_{\text{oct}} \text{ for shutter event} \]
\[ V_{\text{oct}(t)} = \text{Measured } V_{\text{oct}} \text{ as a function of time} \]
\[ \beta_{\text{Vocr}} = \frac{V_{\text{oct}} \text{ temperature coefficient}, -0.0045 (V/°C/cell)}{\text{cell}} \]

Eq. (1) assumes the cell temperature is approximately equal to the heat sink temperature when \( V_{\text{max}} \) is reached. Even if the light is shuttered instantaneously, the increase in \( V \) may be delayed if the photocarrier lifetime in the germanium junction is long or by capacitive effects.

**ALTERNATIVE METHODS FOR DETERMINING CELL TEMPERATURE**

Two primary alternative methods are currently in use for quantifying operating cell temperature for CPV modules.

1) The manufacturers may characterize the thermal resistance between the cell and a thermocouple on the heat sink by a range of methods that involve access to the inside of the module.

2) The Voc of the on-sun module, corrected for irradiance, is used to calculate the temperature [2-3]. Method 2 can provide accurate measurements, but is not easily verified on a closed module. With Method 2, the Voc can be corrected for variable irradiance using the measured irradiance as defined in IEC 60904-5 [2] or the module’s own Isc as described by King as the “Voc,Isc Method” [3] and as in Eq. (2) [4].

\[ T_{c,\text{Voc,Isc}} = \frac{[V_{\text{oct}} - V_{\text{oct}}(T_c)]}{[N_c; (n \cdot k/q) \cdot \ln(I_{\text{sc}}/I_{\text{isc}})] + \beta_{m}} \]

Where:
\( I_{\text{sc}} = \text{Measured short-circuit current, (A)} \)
\( V_{\text{oct}} = \text{Measured open-circuit voltage, (V)} \)
\( T_c,\text{Voc,Isc} = \text{Average module cell temperature (K)} \)
\( T_r = 298.15 \text{ Kelvin Reference temperature} \)
\( I_{\text{isc}} = \text{Isc of module at reference conditions (A)} \)
\( V_{\text{oct}} = \text{Voc of module at reference conditions (V)} \)
\( \beta_m = \text{Module Voc temperature coefficient (V/°C) at measured irradiance} \)
\( n = \text{Empirically determined dimensionless cell ‘diode factor’; for triple junction CPV cell, this will be ~}3 \)
\( k = \text{Boltzmann’s constant, 1.38066E-23 (J/K)} \)
\( q = \text{Elementary charge, 1.60218E-19 (coulomb)} \)

The values for \( I_{\text{isc}}, V_{\text{oct}}, \beta_m \), and \( n \) can be estimated using cell measurements in conjunction with the number of cells wired in series and the number of parallel strings within the module.

**RESULTS**

The shutter procedures described above were applied to four modules of different designs and to a single cell behind a CPV lens. Initial voltage transients for all modules and the single cell are presented in Fig. 2. For comparative purposes, the module Voc was divided by the number of cells wired in series. The differences between measured heat sink temperatures (\( T_{h,\text{sink}} \)) and calculated cell temperatures, based on the voltage transients in Fig. 2, are plotted in Fig. 3. All four modules were measured on the same day when the DNI was between 950-1000 W/m² and the wind was approximately 4 m/s.
2 and Fig. 3 is presented in Table 1 along with the number of rows built into the module, the manufacturer-suggested $T_{\text{cell}}-T_{\text{heat,sink}}$ for 1-sun conditions, and $T_{\text{cell}}-T_{\text{heat,sink}}$ calculated using Eq. (2) on long term data taken at NREL for the same modules.

**TABLE 1.** Summary Data for Modules and Single Cell

<table>
<thead>
<tr>
<th></th>
<th>Shutter Time (s)</th>
<th>V/Cell Decline Rate Maximum Measured (V/(s*cell))</th>
<th>$T_{\text{cell}}-T_{\text{heat,sink}}$ Suggested Method (°C)</th>
<th>$T_{\text{cell}}-T_{\text{heat,sink}}$ 1-sun Suggested Value (°C)</th>
<th>$T_{\text{cell}}-T_{\text{heat,sink}}$ Voc,Isc Method (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Cell</td>
<td>0.005</td>
<td>-0.60</td>
<td>16</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>M1 1 row</td>
<td>0.13</td>
<td>-0.46</td>
<td>19</td>
<td>18</td>
<td>33-43</td>
</tr>
<tr>
<td>M2 4 rows</td>
<td>0.15</td>
<td>-0.14</td>
<td>2</td>
<td>27</td>
<td>15-22</td>
</tr>
<tr>
<td>M3 &gt;10 rows</td>
<td>0.083</td>
<td>-0.09</td>
<td>&lt;1</td>
<td>15</td>
<td>5-12</td>
</tr>
<tr>
<td>M4 &gt;10 rows</td>
<td>0.14</td>
<td>-0.05</td>
<td>4</td>
<td>24</td>
<td>4-14</td>
</tr>
</tbody>
</table>

**ANALYSIS**

In Table 1, for M2-M4 $T_{\text{cell}}-T_{\text{heat,sink}}$ is significantly lower using the shutter method as compared to manufacturer suggestions or using Voc, Isc, and reference conditions at 25°C. Temperatures suggested by the manufacturers have not been verified but the shutter-method results for M2 and M3 appear to be too low to be credible.

The maximum measured voltage decline rates show that the cell temperature is increasing much faster in the single cell and M1 as compared to the other modules. It is expected that the rate of decline in Voc is related to cell design and design for thermal management but the specifics of these designs are unknown. Interestingly, with the given data set, as the number of rows in the module increases the maximum voltage decline rate decreases. If the number of rows in a module impacts the measured voltage decline rate this will introduce systematic error to the shutter procedure, causing an underestimation of the temperature difference. To this end, a simple model was constructed to simulate the effect of a finite shuttering speed on the maximum measureable cell temperature. Voltage measurements of the single cell shuttered with the mechanical aperture (5 ms) and by hand (70 ms) were first converted to cell temperature using the Eq. (1), see Fig. 4. The temperature rise of the cell was then fit with a double exponential function for each shuttering event. Each fit yields two time constants and temperature off-sets, the faster of which is taken as the temperature increase of the cell over the heatsink. The voltage response according to this exponential fit is then summed for a number of rows, which are simulated to start heating according to the shuttering speed of 70 ms.

The summed voltage response is then divided by the number of rows considered and converted to temperature with Eq. (1). The modeled shutter procedure results for a module with 1-10 rows are presented in Fig. 5 along with the temperature offset calculated with the fast 5 ms mechanical aperture. The results suggest a 25 % error due to the shuttering speed on only 1 row of cells, while increasing the number of rows further increases the error to over 70 % with a 10 row module.

The data shown in the rightmost column of Table 1 are presented as a range because accurate module or cell data, as required by Eq. (2), were not readily available. Consider $T_{c,Voc,Isc}-T_{\text{heat,sink}}$ for M4, which is plotted against Isc in Fig. 6 for a clear-sky monthly data set. M4 was shipped to NREL with indoor I-V data but no information on $\beta_m$ and n. For this reason, two different parameter sets have been applied in Eq. (2) as shown in Fig. 6. Data from Kinsey et al [5] indicate, for triple junction Spectrolab cells, $\beta_m$ can range from 4-6 mV/°C per cell at varying concentration levels and that n ranges from 3-4 depending on cell properties. Taking this data into
account, for parameter set 1, $V_{oc}$ is taken from the indoor I-V data, $\beta_m=0.0045* N_s$, and $n=3$. In parameter set 2, $V_{oc}$ has been increased by 1.4%, $\beta_m$ is varied with irradiance as documented by Kinsey, et al [5], and $n=3.9$. For both parameter sets, $T_{c,Voc,Isc -Theat,sink}$ is approximately linear with $I_{sc}$ and extrapolates to zero when $I_{sc}$ is near zero. Although both calculations present plausible results, they range from 4-14°C at the maximum $I_{sc}$, demonstrating a potential error of 10°C associated with Eq. (2).

Fig. 4 $T_{c,Voc,Isc -Theat,sink}$ against $I_{sc}$ for M4

While it is ideal to have all parameters clearly specified for Eq. (2), $\beta_m$ and $n$ are most critical as they establish the slope of the linear relationship. $I_{sc}$ from indoor flash testing or estimates from on-sun testing are adequate as a 10% error results in only a 1°C change in the calculated cell temperature. If $\beta_m$ and $n$ are known it is possible to adjust $V_{oc}$ to reflect zero temperature difference for zero irradiance, minimizing potential errors associated with deviation of the $V_{oc}$ from the nameplate $V_{oc}$.

IMPLICATIONS FOR FLASH TESTING

The voltage transients presented in Table 1 and in Fig. 2 show that rapid cell heating introduces significant error to the shutter procedure. This raises questions about the possibility of significant heating while flash testing modules indoors. The voltage of the single cell presented in Fig. 2. rises from 2.15 to 3.15 volts in 5ms and then declines to 3.12 volts after 60 ms. This indicates that the cell temperature has risen ~6.5°C in just 60 ms. It should be noted that this particular cell was under ~1000X geometric concentration and was packaged by a CPV manufacturer. Although the voltage transient can vary from manufacturer to manufacturer, such rapid heating suggests that flash tests need to be conducted in less than 20-30 ms and that I-V sweeps should be run in both directions to confirm that heating is insignificant during the sweeps.

CONCLUSIONS

Shuttering CPV modules has been investigated as a method for calculating on-sun cell temperature. The shuttering procedure can be useful for small modules or when a fast shutter is available, but this study suggests that heating of the initially exposed cells during the shuttering process may underestimate the cell temperature by as much as 5-10°C. Temperatures calculated using the shuttering procedure are up to 25°C lower than temperatures measured by the module manufacturers, implying that the error can be even greater in some cases.

Single-cell data show that in just 60 ms it is possible for cell temperature to rise ~ 6.5°C. This rapid heating suggests that indoor flash tests need to be completed in 20-30 ms in order to avoid significant rise in cell temperature. It is suggested that I-V sweeps be performed in both directions to validate that cell temperature is maintained during the I-V sweeps.

Alternative methods for calculating on-sun cell temperature are discussed. Specifically, with correction for irradiance variations, the Voc is only an accurate indicator of cell temperature if accurate data is available for $\beta_m$ and $n$. Adjustment of the $V_{oc}$ to reflect zero temperature difference for zero irradiance can minimize potential errors associated with deviation of the $V_{oc}$ from the nameplate $V_{oc}$.

ACKNOWLEDGMENTS

This work was completed under contract # DE-AC36-08GO28308. The authors would like to acknowledge Keith Emery’s help in acquiring data using a mechanically controlled aperture.

REFERENCES

2. IEC 60904-5, “Photovoltaic Devices – Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method.”