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Determining Outdoor CPV Cell Temperature

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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 shutters 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/m^2) and concentrator standard operating conditions (CSOC, 20°C ambient, 900W/m^2). 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.

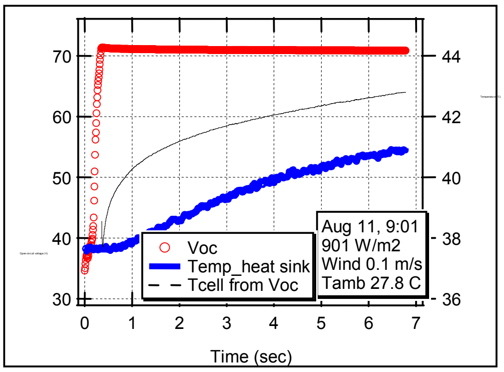

Fig.1 Example Results from Shutter Procedure.
Voc and heat sink temperature are measured while cell temperature is calculated using Eq. (1).

$$T_{cell} = T_{h,0} + (V_{max} - V_{oc(t)})/(N_s \cdot \beta_{Vocr}) \quad (1)$$

N_s = Number of cells in series in module
T_{cell} = Calculated cell temperature
$T_{h,0}$ = Heat sink temperature at shutter initiation
V_{max} = Maximum measured V_{oc} for shutter event
$V_{oc(t)}$ = Measured V_{oc} as a function of time
β_{Vocr} = V_{oc} temperature coefficient, -0.0045 (V/°C/cell)

Eq. (1) assumes the cell temperature is approximately equal to the heat sink temperature when V_{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 1 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].

$$T_{c,Voc,Isc} = [V_{oc} - V_{ocr} + \beta_m \cdot T_r]/[N_s \cdot (n \cdot k/q) \cdot \ln(I_{sc}/I_{scr}) + \beta_m] \quad (2)$$

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

The values for I_{scr}, V_{ocr}, β_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 ($T_{h,sink}$) 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/m^2 and the wind was approximately 4 m/s.

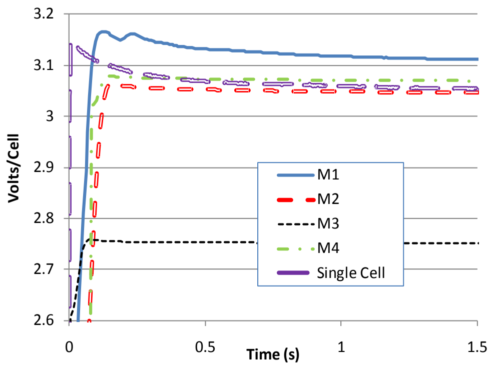

Fig. 2 Voltage Transients During and After Shuttering

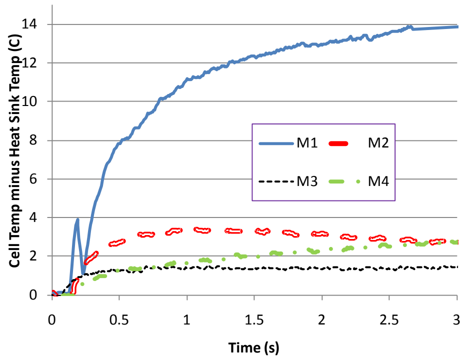

Fig.3 Calculated T_{cell}-$T_{h,sink}$ following the shutter event.

The time to reach the maximum Voc varies from about 0.005 to 0.15 seconds and is assumed to be the shutter time. The shortest shutter time was achieved using the mechanical aperture. The remaining variation in shutter time is due to inconsistency in manually pulling cloth off modules and from the range of module sizes tested. For modules about a meter wide, ~0.1 seconds was the shortest shutter time that was achieved. Summary information associated with Fig.

2 and Fig. 3 is presented in Table 1 along with the number of rows built into the module, the manufacturer-suggested T_{cell}-$T_{h,sink}$ for 1-sun conditions, and T_{cell}-$T_{h,sink}$ calculated using Eq. (2) on long term data taken at NREL for the same modules.

TABLE 1. Summary Data for Modules and Single Cell

	Shutter Time (s)	V/Cell Decline Rate Maximum Measured (V/(s*cell))	T_{cell}-$T_{h,sink}$ Shutter Method (°C)	T_{cell}-$T_{h,sink}$ 1-sun Suggested Value (°C)	T_{cell}-$T_{h,sink}$ 1-sun Voc,Isc Method (°C)
Single Cell	0.005	-.60	16	N/A	N/A
M1 1 row	0.13	-0.46	19	18	33-43
M2 4 rows	0.15	-0.14	2	27	15-22
M3 >10 rows	0.083	-0.09	<1	15	5-12
M4 >10 rows	0.14	-0.05	4	24	4-14

ANALYSIS

In Table 1, for M2-M4 T_{cell}-$T_{h,sink}$ 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.

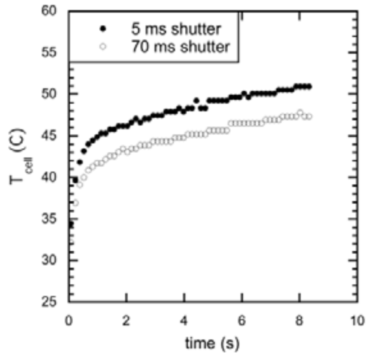

Fig. 4 Calculated T_{cell} for two shutter times

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.

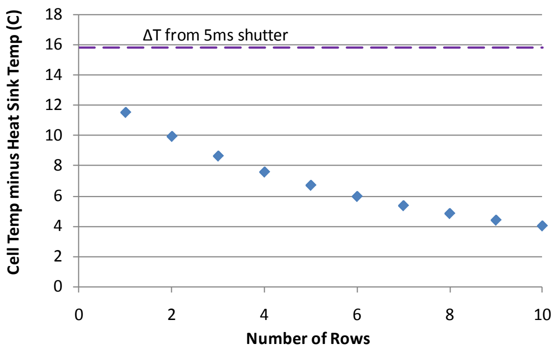

Fig. 5 Modeling the effect of a finite shutter speed on the calculation of T_{cell}-$T_{heat,sink}$ for a module with 1-10 rows

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 $T_{c,Voc,Isc}$-$T_{heat,sink}$ 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 β_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, β_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_{ocr} is taken from the indoor I-V data, β_m=0.0045* N_s, and n=3. In parameter set 2, V_{ocr} has been increased by 1.4%, β_m is varied with irradiance as documented by Kinsey, et al [5], and n=3.9. For both parameter sets, $T_{c,Voc,Isc}$ -$T_{heat,sink}$ is approximately linear with Isc 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).

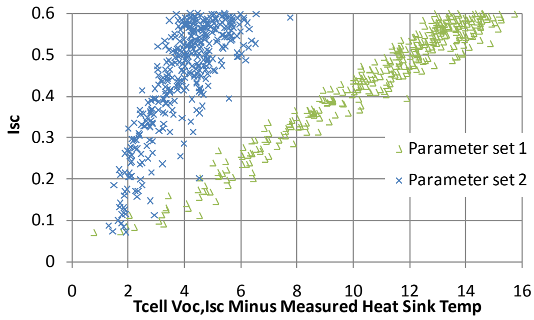

Fig. 4 $T_{c,Voc,Isc}$- $T_{heat,sink}$ against I_{sc} for M4

While it is ideal to have all parameters clearly specified for Eq. (2), β_m and n are most critical as they establish the slope of the linear relationship. I_{scr} 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 β_m and n are known it is possible to adjust V_{ocr} to reflect zero temperature difference for zero irradiance, minimizing potential errors associated with deviation of the V_{ocr} from the nameplate V_{ocr}.

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 β_m and n. Adjustment of the V_{ocr} to reflect zero temperature difference for zero irradiance can minimize potential errors associated with deviation of the V_{ocr} from the nameplate V_{ocr}.

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