Determination of Empirical Coefficients and $\Delta T$ for Sandia Thermal Model Dependence on Backsheet Type

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J. Oh; A. Pavgi; G. Tamizhmani

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Determination of Empirical Coefficients and $\Delta T$ for Sandia Thermal Model: Dependence on Backsheet Type

Jaewon Oh, Ashwini Pavgi, and Govindasamy Tamizhmani
Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL), Mesa, AZ 85212, USA

Abstract — Sandia thermal model has been extensively used by the industry to predict cell temperature of photovoltaic (PV) module using a few empirical coefficients and $\Delta T$ (temperature difference between cell and typical backsheet). We present the empirical coefficients and $\Delta T$ of the PV modules equipped with various types of new polymer backsheets and glass substrate. These backsheet-specific coefficients and $\Delta T$ provide more accurate predicted cell temperature. It was shown that $\Delta T$ can be as high as 4.1°C at 1000 W/m² irradiance depending on the substrate type. It has been demonstrated that the temperature coefficients, using model converted cell temperature from module substrate temperature, can be overestimated when non-thermal equilibrium condition is existing in the PV module.

Index Terms — thermal model, photovoltaic cells, temperature coefficient, silicon.

I. INTRODUCTION

Photovoltaic (PV) module performance is dictated by environmental factors, such as, irradiance and ambient temperature. These two factors affect PV cell temperature, and typical crystalline silicon PV module performance is dependent on the temperature of PV cells due to its intrinsic thermal property. It has been widely known that output power of PV module decreases relatively 0.5% as the cell temperature increases every 1°C. Since the environmental condition affecting PV module temperature and performance is varied by field installation site, it is necessary to develop a thermal model to predict estimated output power in the field. Several thermal models were already developed and are used in the PV industry [1]. The one we want to investigate in this paper is Sandia Thermal Model developed by King et al., at Sandia National Laboratory [2]. In the Sandia model, first, PV module temperature, i.e., substrate temperature, is determined by using plane of array (POA) irradiance, ambient temperature, wind speed, and empirical coefficients. And then, cell temperature is determined by the predicted module temperature with $\Delta T$, which is a temperature difference between cell and substrate. The empirical coefficients and $\Delta T$ are presented with Sandia Thermal Model, however they are only applicable for two types of substrates, which are polymer backsheet and backside glass used in dual glass modules. PV modules. When the Sandia Thermal Model was developed at 2004, there were only few types of polymer backsheet, which were mainly Tedlar (PVF: polyvinyl fluoride) based backsheet. Nowadays, new polymer material backsheets, for example, Kynar (PVDF) based backsheet, are being used by PV module manufacturer. Some of these polymer backsheets show high thermal conductivity leading to lower cell temperature as compared to the conventional Tedlar based backsheet [3]. In addition, $\Delta T$ can be affected by thermal property of backsheet used in PV module. In this paper, we investigate the empirical coefficients and $\Delta T$ of PV modules for the new backsheets and glass substrate.

II. EXPERIMENTAL METHODS

One-cell modules and nine-cell (3 × 3) modules having typical PV module structure (glass-encapsulant-cell-encapsulant-backsheet/glass) were fabricated for this work. The dimensions of one-cell module and nine-cell module are 8 in × 11 in and 20.5 in × 22 in, respectively. Commercial 156 × 156 mm² mono crystalline silicon solar cells were encapsulated by using PV module laminator. 3.2 mm thick low-iron solar glass and ethylene vinyl acetate (EVA) was used for front superstrate and encapsulant, respectively. For dual glass modules, same type of glass used as a front glass was used as a backside glass substrate. A total of three different type of polymer backsheets were used in building the modules. Tedlar based backsheet (TPT: Tedlar-PET-Tedlar) was used for reference modules, and other backsheets for comparison were polyvinylidene fluoride (PVDF)-PET-EVA and polyamide (PA)-aluminum (Al)-PET-PA. To measure the cell temperature, T-type thermocouples with extremely thin wires (36 AWG) were attached to the backside of the solar cell prior to the lamination. Substrate temperature was also measured by T-type thermocouples. In the nine-cell modules, the cell and backsheet temperature data was
collected from three locations; center cell, corner cell, and edge cell. The modules were installed on open-rack, which is south-facing with 45° fixed tilt angle, as shown in Fig. 1. Campbell Scientific CR1000 data logger was used to collect all the temperature data and weather data used in this study for every 30 seconds in a month of October 2017. Temperature coefficients were obtained by taking multiple current-voltage (I-V) curves using outdoor I-V curve tracer with various cell and module temperature.

III. RESULTS AND DISCUSSIONS

A. Sandia Thermal Model Coefficients

In Sandia thermal model, module operating temperature is determined by following equation [2].

\[
T_m = E \times (e^{a+b \times WS}) + T_{amb}
\]

(1)

where:
- \(T_m\): module temperature (backsheet temperature) (°C)
- \(E\): plane of array irradiance (W/m²)
- \(WS\): wind speed (m/s)
- \(T_{amb}\): ambient temperature (°C)
- \(a\): empirically-determined coefficient establishing the upper limit for module temperature at low wind speeds and high solar irradiance
- \(b\): empirically-determined coefficient establishing the rate at which module temperature drops as wind speed increases

The empirical coefficients \(a\) and \(b\) were obtained by a linear regression fit to the data, which are \(\ln[(T_m - T_{amb})/E]\) vs. wind speed as shown in Fig. 2. A month of October 2017 at Mesa, Arizona data was used to obtain the coefficients, and only clear sunny days were selected to avoid temperature transient effect due to intermittent cloud cover. Table I shows the obtained empirical coefficients.

![Fig. 2. Plotted empirical data to determine the coefficients (a, b). \(T_m\) was measured from center cell of nine-cell module.](image)

![Fig. 3. \(\Delta T\) with respect to irradiance for Glass/Polymer (TPT) nine-cell modules. (a) at 0 m/s wind speed, (b) at 1 m/s wind speed.](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Module Type</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-cell module</td>
<td>Glass/Polymer (PVDF-PET-EVA)</td>
<td>-3.60</td>
<td>-0.1101</td>
</tr>
<tr>
<td></td>
<td>Glass/Polymer (PA-Al-PET-PA)</td>
<td>-3.58</td>
<td>-0.1080</td>
</tr>
<tr>
<td></td>
<td>Glass/Polymer (TPT)</td>
<td>-3.52</td>
<td>-0.1154</td>
</tr>
<tr>
<td></td>
<td>Glass/Glass</td>
<td>-3.53</td>
<td>-0.1037</td>
</tr>
<tr>
<td>9-cell module (center cell)</td>
<td>Glass/Polymer (PVDF-PET-EVA)</td>
<td>-3.38</td>
<td>-0.1033</td>
</tr>
<tr>
<td></td>
<td>Glass/Polymer (PA-Al-PET-PA)</td>
<td>-3.29</td>
<td>-0.1125</td>
</tr>
<tr>
<td></td>
<td>Glass/Polymer (TPT)</td>
<td>-3.34</td>
<td>-0.1225</td>
</tr>
</tbody>
</table>

-1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0
△T (°C)

0 200 400 600 800 1000 1200
Tc - Tm (°C)

\(y = 0.0044x - 0.332\)  \(R^2 = 0.9434\)
\(y = 0.0024x - 0.0495\)  \(R^2 = 0.8705\)
\(y = 0.0029x - 0.0938\)  \(R^2 = 0.9398\)

Overall, the coefficient ‘a’ of all the one-cell modules obtained at ASU-PRL is practically similar to Sandia thermal model coefficient, which is -3.56. However, there is a slight difference among glass/polymer backsheet modules depending on the backsheet type. It is clear that the coefficient ‘a’ can be varied if different polymer material backsheet or layer structure...
is used. Interestingly, there is no coefficient ‘a’ difference between the glass/polymer module and the glass/glass module while King et al. [2], reported −3.47 as a coefficient ‘a’ for glass/glass module.

For the coefficient ‘b’, all the values obtained from the modules used in this study are higher (smaller) than Sandia reported values, which are −0.0750 and −0.0594 for glass/polymer module and glass/glass module, respectively. This change means that a temperature of the polymer backsheets used in PV modules these days are more affected by wind speed. Therefore, it is suggested to obtain backsheet-specific empirical coefficients (a, b) to predict more accurate module temperature when using Sandia thermal model.

B. Temperature Difference between Cell and Backsheet

It has been known that ΔT is typically 2 to 3 °C at 1000W/m² for glass/polymer and glass/glass PV modules at open rack condition [2]. Fig. 3 shows measured ΔT values at 3 different cell locations in the TPT nine-cell module with respect to POA irradiance at zero and 1 m/s wind speed. It was observed that overall ΔT was center>edge>corner, and it was as high as 5.5-5.8 °C at center cell. It is attributed to a number of surrounded cells blocking heat dissipation. The number of surrounded cell is 8, 5, 3 for center cell, edge cell, and corner cell, respectively. Thus, a decrease of center cell temperature by convection/wind speed is small although backsheet temperature is decreased. Table II shows ΔT at 1000W/m² for all the samples used in this study based on linear regression fit. Generally, one-cell module ΔT is higher than nine-cell modules. At higher wind speed, ΔT is a bit increased due to decreased backsheet temperature by wind. ΔT of the center cell can be varied as high as 1.5 °C among the ‘polymer backsheet’ modules, and the highest ΔT (4.1°C at 1000 W/m²) was observed from the center cell of the TPT 9-cell module.

The obtained coefficients (a, b) and ΔT with eq. (1) are used to predict cell temperature (Tc) as shown in the equation below [2].

\[ T_c = T_m + \frac{E}{E_0} \times \Delta T \]  

where:

- \( T_c \): cell temperature (°C)
- \( E \): measured POA irradiance (W/m²)
- \( E_0 \): reference irradiance (1000 W/m²)
- ΔT: temperature difference between cell and backsheet at 1000 W/m² (°C)

Using individually obtained coefficients (Table I) and ΔT (Table II) lead to more accurate predicted Tc with higher R², however, Sandia thermal model default coefficients and ΔT still show reasonable prediction, as shown in Fig. 4.

Temperature coefficients of commercial PV modules are determined by measuring backsheet temperature, which can be converted to a cell temperature by adding 2-3°C. Since our nine-cell modules have thermocouple attached to the cell, we were able to determine the temperature coefficients based on measured cell temperature. Four different backsheet material were used for these nine-cell modules. They are TPT (Module A), PVDF-PET-EVA (Module B), PA-Al-PET-PA (Module C), and PVDF-PET-EVA (Module D).

### TABLE II

<table>
<thead>
<tr>
<th>Sample</th>
<th>Module type</th>
<th>ΔT at 0 m/s WS</th>
<th>ΔT at 1 m/s WS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-cell module</td>
<td>Glass/Polymer (PVDF-PET-EVA)</td>
<td>2.6</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Glass/Polymer (PA-Al-PET-PA)</td>
<td>2.6</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Glass/Polymer (TPT)</td>
<td>2.7</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>Glass/Polymer (PA-Al-PET-PA)</td>
<td>2.9</td>
<td>3.7</td>
</tr>
</tbody>
</table>

### TABLE III

<table>
<thead>
<tr>
<th>Module</th>
<th>Temperature COEFFICIENTS IS SHOWN AT LAST COLUMN.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module A</td>
<td>Tm+2.5°C</td>
</tr>
<tr>
<td>Module B</td>
<td>Tm+2.5°C</td>
</tr>
<tr>
<td>Module C</td>
<td>Tm+2.5°C</td>
</tr>
<tr>
<td>Module D</td>
<td>Tm+2.5°C</td>
</tr>
</tbody>
</table>

Fig. 4. Sandia thermal model coefficients and ΔT validation between Sandia provided values and individually obtained values.
C), and proprietary backsheet (Module D). As shown in Table III, maximum power ($P_{\text{max}}$) temperature coefficient using the measured cell temperature as high as 8.7% larger than the one using converted cell temperature ($T_{\text{m}+2.5^\circ\text{C}}$ in this case) depending on the type of backsheets. This is attributed to non-thermal equilibrium of PV module while the PV module outdoor is heated by sun for temperature coefficient measurement. It is noted that initially $\Delta T$ was small and then the $\Delta T$ is getting larger with respect to time exposed to sun, as shown in Fig. 5. Due to this thermal equilibrium issue, $P_{\text{max}}$ could be overestimated when $T_{\text{m}+2.5^\circ\text{C}}$ was used rather than $T_c$ as shown in last column of Table III. Therefore, an effect of PV thermal equilibrium should be considered in determining accurate temperature coefficients.

**IV. SUMMARY**

Empirical coefficients and $\Delta T$ were determined for Sandia thermal model using one-cell modules and nine-cell modules having various new polymer backsheets and glass substrate. It was shown that the backsheet-specific coefficients and $\Delta T$ obtained in this work provides more accurate predicted cell temperature as compared to the generic Sandia coefficients and $\Delta T$. It has been demonstrated that the temperature coefficients, using model converted cell temperature from module substrate temperature, can be overestimated when non-thermal equilibrium condition is existing in the PV module.
ACKNOWLEDGEMENT

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