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PREDICTING THE BACK SURFACE TEMPERATURE OF PHOTOVOLTAIC MODULES IN HOT AND HUMID CLIMATES

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ABSTRACT

In this study, the temperature of the back surface of a photovoltaic (PV) module was calculated based on thermal energy balance. A 1D analysis was also conducted. Each layer was modeled in consideration of the effect of heat transfer modes, such as conduction, radiation, and convection. The temperature value of each layer is important for estimating of the efficiency the module or other PV applications. The PV thermal (PVT) is an innovative design that utilizes PV, and back surface temperature is applicable in the detailed analysis of each PVT collector layer. A few assumptions were made to simplify the analysis. Experimental and thermal modeling results are satisfactory, and irradiance does not fluctuate suddenly. The correlation coefficient (r) and the percent deviation in root mean square (e) are 0.931 and 12.1%, respectively. When irradiance fluctuates suddenly, r and e are 0.345 and 58.5%, respectively.

Keywords : *Photovoltaic, thermal modelling, back surface, hot and humid climate*

1.0 INTRODUCTION

The utilization of the sun's rays by solar energy collectors has progressed rapidly. The most popular applications are in solar collectors and photovoltaics (PVs). PV systems produce electricity, whereas solar collector systems generate useful heat. The type of useful heat can be classified in the form of either air or water depending on the type of working fluid and on application. For example, air and water are used in space and water heating, respectively. An innovative design that maximizes the use of the sun's rays involves combining both systems into a single unit known as the PV thermal (PVT). This device produces electricity and useful heat simultaneously [1].

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The basic principle of this system is that the excess heat from the PV is utilized by the collector to generate useful heat. As a result, the accumulated heat under the PV can be reduced and can enhance PV performance. The effect of this condition may differ depending on the type of PV material employed. By contrast, the thermal efficiency of the PVT system is lower than that of a conventional solar collector because the PV material is not designed specifically to absorb heat as a normal absorber does.

One main advantage of such devices is that the output per unit area is higher than that of a conventional arrangement [2]. The PVT device is also suitable for use in small roofing areas and has an aesthetically pleasing design [3]. It consists of glass on the top layer, which is embedded with a PV absorber collector. It is covered by an insulator on the bottom layer. An aluminum mounting frame holds each component in a casing box [4]. The type of PVT device can be classified based on the working fluid used, that is, either liquid or air [5]. The absorber material is normally metal [6]. This collector absorbs excess heat from the top layer and transfers it in the form of either water or air to become useful heat [7]. Meanwhile, the insulator minimizes heat loss by preventing the escape of heat to the surroundings [8].

Variations in the heat transfer mode of each PVT layer changes the temperature on each surface. The temperature data for each layer are crucial in predicting the performance of the PVT device based on the thermal modeling approach. The determination of the temperature of each layer improves estimation with less assumptions. As a result, error or inaccuracy is limited in thermal modeling analysis [9].

In the current study, the back surface temperature of the PV module is validated through experiments and thermal modeling. Two environments are considered: that with and that without sudden irradiance fluctuation. The purpose of the validation process is to verify the method of thermal modeling from the top to the bottom layers (tedlar) before proceeding to the next layer of the absorber collector in thermal analysis. This information can be used in further analysis when the collector and the insulator are combined to estimate the overall PVT performance.

2.0 METHODS

PV modules that are connected by five parallel and two series array configurations are considered for the present study. The specifications are listed in Table 1. The PVs are frameless and are mounted on the roof without an insulator.

Table 1: Parameter of photovoltaic

No	Components / Parameter	Specifications
1.	PV module	120 Watt
2.	PV module type	Polycrystalline
3.	Width of PV module, b	0.662 m
4.	Thickness of glass, L_G	0.003 m
5.	Thickness of tedlar, L_T	0.0001 m
6.	Thermal conductivity of tedlar, K_T	0.36 W/m.K
7.	Thermal conductivity of glass, K_G	0.98 W/m.K
8.	Cell efficiency, η	0.14
9.	Packing factor, β_C	0.9
10.	Absorptivity of cell, α_C	0.8
11.	Absorptivity of tedlar, α_T	0.8
12.	Transmittivity of glass, τ_G	0.85
13.	Tilt angle of photovoltaic on roof	37° facing South- West

A 1.2 kWp PV system is installed on the roof, as shown in Figure. 1. The PV design is depicted in Figure 2, and its heat transfer mode is illustrated in Figure 3.

Figure 1: The PV installation on the roof

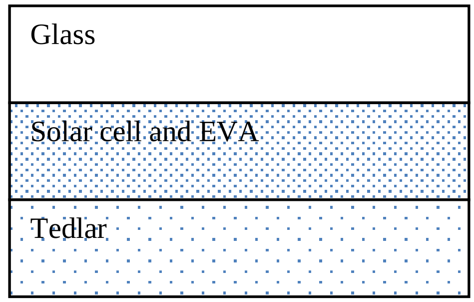


Figure 2: Cross section of the PV

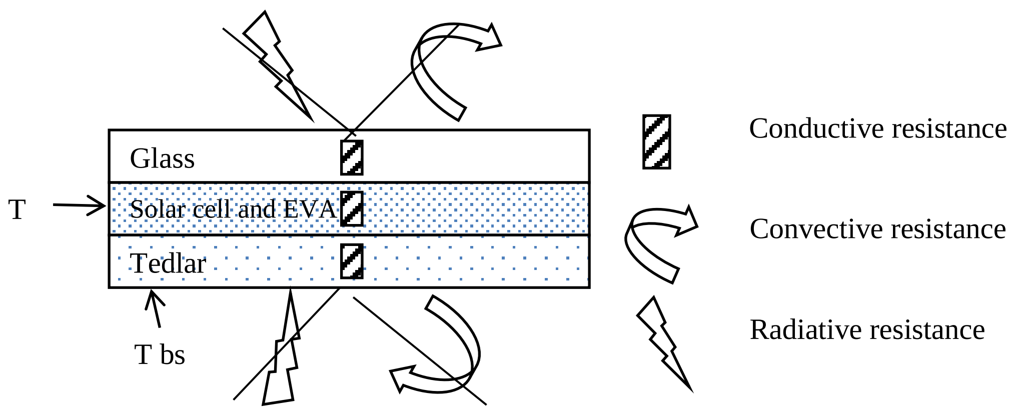
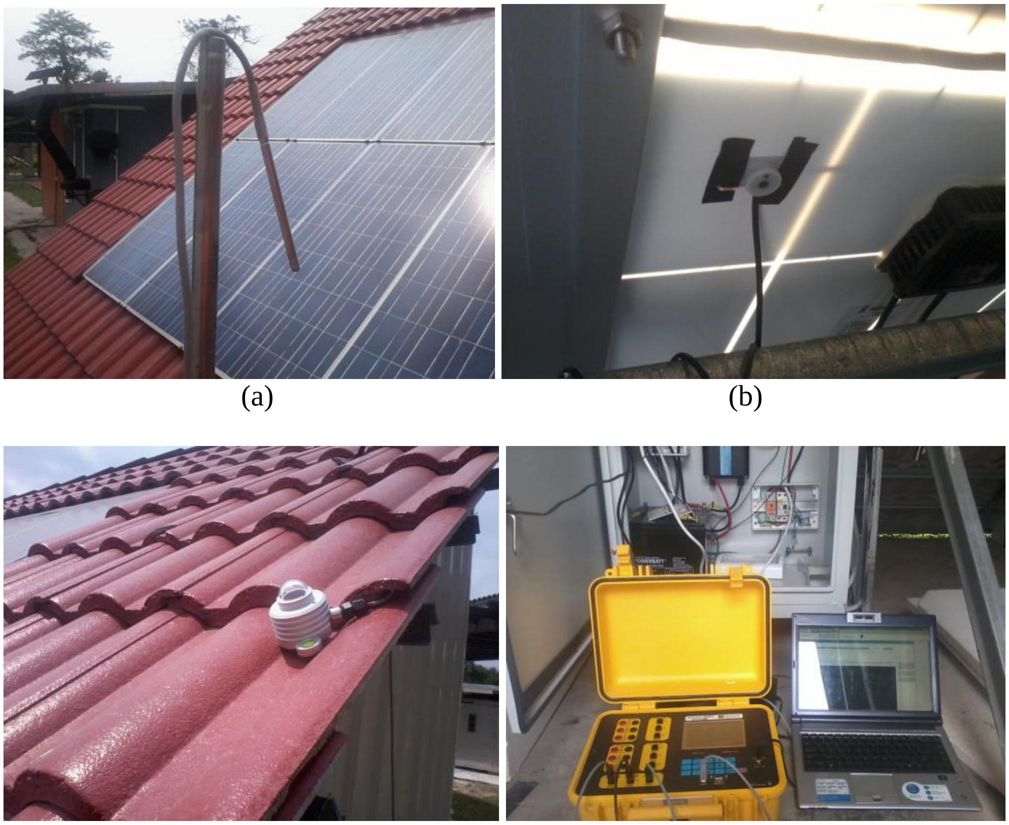


Figure 3: Heat transfer for the PV

A calibrated copper–constantan thermocouple was embedded on the FTV Test 100 equipment and used to measure the ambient and back surface temperatures. Temperatures were determined with a digital thermometer with an accuracy of 0.1 °C. The irradiance on the PV was measured every minute using a pyranometer with an accuracy of 20 W/m^2. This tool was installed on the FTV Test 100 equipment as well, and it was placed on the same plane as the PV was on the roof. The experiment was conducted in March and April 2014 at Solar Park, Bangi, Selangor, Malaysia. The following parameters were measured every minute during the experiment and Figure 4 (a-d) shows the arrangement of the experimental setup.

1. Ambient temperature
2. Back surface temperature
3. Irradiance



(a) (b) (c) (d)

Figure 4 (a): Measuring ambient temperature, (b) Measuring back surface temperature, (c) Measuring the irradiance, (d) Data logger system

2.1 Thermal modeling

To develop the energy balance equation for PV and simplify the analysis, the following assumptions were made:

a) Wind velocity is constant at 1.5 m/s.
b) The heat transfer coefficients at the top and bottom surfaces are the same.
c) The system is in a quasi-steady state.
d) Only one dimension is analyzed.
e) Ethylene vinyl acetate is 100% pure.

The energy balance for the solar cell is expressed as follows [10, 11]:

PV module:

$$\tau_G[\alpha_c I(t)\beta_c + (1-\beta_c)\alpha_T I(t)]dx = [U_T(T_c - T_a) + h_T(T_c - T_{bs}) + \eta_c\tau_G I(t)\beta_C]bdx \quad (1)$$

Rearrange eq (1), expression for cell temperature is

$$T_c = [(\alpha\tau)_{eff}\, I(t) + U_T T_a + h_T T_{bs}]/(U_T + h_T) \quad (2)$$

where,

$$(\alpha\tau)_{eff} = \tau_G[\alpha_c\beta_c + (1-\beta_c)\alpha_T - \eta_c\beta_C] \quad (3)$$

$$U_T = [L_G/K_G + 1/h_o]^{-1} \quad (4)$$

$$h_T = [L_T/K_T]^{-1} \quad (5)$$

Back surface of tedlar:

$$h_T(T_c - T_{bs})bdx = h_o(T_{bs} - T_a)\ bdx \quad (6)$$

Taking $h_o = 5.7 + 3.8\ V$ [11] (7)

Insert eq (2) in eq (6). The expression of back surface temperature is

$$T_{bs} = [hp_1(\alpha\tau)_{eff}\ I(t) + (hp_1U_T + h_o)T_a]/\ [U_Thp_1 + h_o] \quad (8)$$

where,

$$hp_1 = [h_T/(U_T + h_T)] \quad (9)$$

2.2 Statistical analysis

To compare the calculated results with the experimental ones, the correlation coefficient (*r*) and the percent deviation of root mean square (*e*) were evaluated using the following expressions [12]. These equations were applied under both conditions, that is, with and without sudden irradiance fluctuation in the experimental data.

$$r = N \sum X_iY_i - (\sum X_i)(\sum Y_i) \ /\ \sqrt{}N\sum X_i^2 - (\sum X_i)^2\sqrt{}N\sum Y_i^2 - (\sum Y_i)^2 \quad (10)$$

$$ei = [X_i - Y_i / X_i] \times 100 \quad (11)$$

3.0 RESULTS

Equation 8 was solved with Microsoft Excel software to evaluate the back surface temperature of the given design and the climatic parameters for a given day from the period of March 2014 to April 2014. The variations in the theoretical and experimental results are shown in Figs. 4 and 5, respectively. Moreover, *r* and *e* were calculated using Eqs. 10 and 11. The theoretical and experimental values agree under the condition of no sudden fluctuation, with *r* and *e* values of 0.931 and 12.3%, respectively. Under the condition of sudden fluctuation, *r* and *e* values are 0.345 and 58.5%, respectively.

4.0 DISCUSSIONS

In the case without sudden irradiance fluctuation, the thermal model and experimental results vary by 12.3%. Several assumptions contribute to the error. In particular, the disregard of the edge losses and of the fact that the estimated wind speed under the PV is similar to the wind speed on the top surface were suspected to be major causes of this variance. In addition, the de-rating factor of the PV modules as generated by the dust effect and the number of thermocouples on the PV may not represent the average temperature of the PV modules because only one thermocouple was installed under the PV to denote the temperature of the PV array. Therefore, the considered percentage error was acceptable because the experimental setup and the thermal modeling approach are simplified. Figure 4 show the back surface temperature of photovoltaic without sudden fluctuation.

In the case involving sudden irradiance fluctuation, the low *r* value is mainly a result of the heat capacitance effect. When the irradiance dimmed rapidly, the PV still stored heat given its heat capacitance. Thus, the temperature of the back surface did not decrease quickly during the experiment. This temperature began to decrease according to the irradiance fluctuation following the PV time constant. This occurrence increases *e* value and decreases *r* value. Sudden fluctuations normally occur under cloud shading or as a result of unexpected rain for a few hours, especially in countries with tropical climate. Figure 5 shows the back surface temperature of photovoltaic for sudden fluctuation.

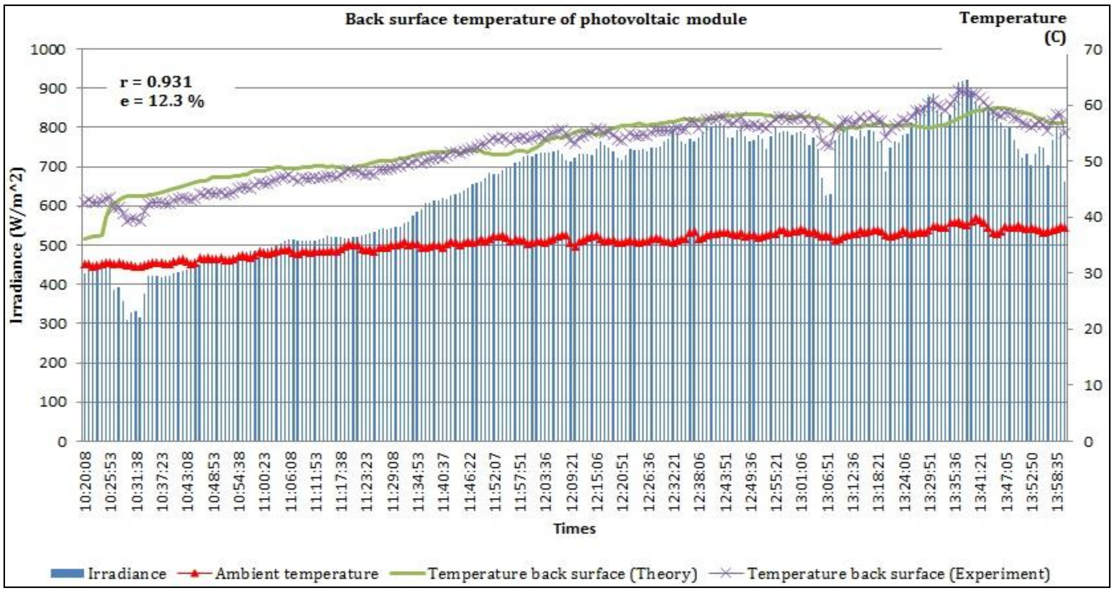


Figure 4: The back surface temperature of photovoltaic (no sudden fluctuation)

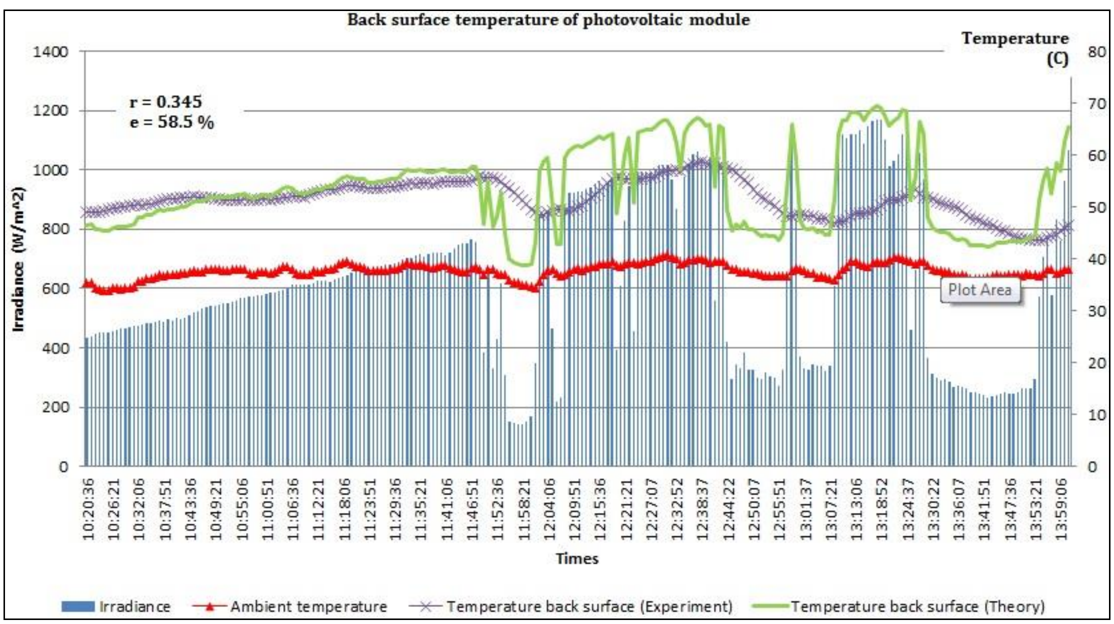


Figure 5: The back surface temperature of photovoltaic (sudden fluctuation)

5.0 CONCLUSIONS

In this study, the results of the thermal model for PV agree with those of the experiment under the condition without sudden irradiance fluctuation. The *r* and *e* values are 0.931 and 12.3%, respectively. In the event of sudden irradiance fluctuation, the back surface temperature of the PV module cannot be estimated suitably given the heat capacitance of the PV modules. The *r* and *e* values of 0.345 and 58.5% reflect this situation. Cell temperature can be predicted using Eq. 2 by incorporating the value of T_{bs} from Eq. 8. The result shows that T_{bs} is almost similar to T_c based on the equations presented previously for the simplification analysis that estimates the electrical efficiency of the PV.

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NOMENCLATURES

b	Width of module, m
hp1	Penalty factor
h	Heat transfer coefficient, $W/m^2.K$
I(t)	Irradiance, W/m^2
K	Conductivity, W/m.K
kWp	Kilo Watt Peak
L	Thickness, m
T	Temperature, K
U_T	Overall heat transfer coefficient between solar cell and ambient through glass cover, $W/m^2.K$
V	Velocity, m/s
X_i	Experimental value
Y_i	Theoretical value
Subscripts	
a	Ambient
bs	Back surface
c	Cell
G	Glass
T	Tedlar
o	From radiation and convection
Greek letters	
α	Absorptivity
$(\alpha\tau)_{eff}$	Effective transmittance-absorptance
β	Packing factor
τ	Transmittance
η	Efficiency

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