Simulation study on photovoltaic panel temperature under different solar radiation using computational fluid dynamic method

Leow W Z1, Irwan Y M1,2, Safwati I1,3, Irwanto M1,4, Amelia A R1, Syafiqah Z1, Fahmi M I1 and Rosle N1

1Centre of Excellence for Renewable Energy (CERE), School of Electrical System Engineering, Universiti Malaysia Perlis, Pauh Putra Campus 02600 Arau, Perlis, Malaysia.
2Centre of Diploma Studies, Universiti Malaysia Perlis, Sungai Chuchuh Campus, 02100 Padang Besar, Perlis, Malaysia.
3Institute of Engineering Mathematics, Universiti Malaysia Perlis, Malaysia.
4Department of Electrical Engineering, Medan Institute of Technology, Indonesia.

Email: leowwai@unimap.edu.my

Abstract: The electrical production is the primary performance of any solar photovoltaic (PV) system. The PV panel operating temperature is inversely proportional to the electrical production of the PV panel. The operating temperature of PV panel is influenced by solar radiation absorbed and the ambient temperature. In the present work, Computational Fluid Dynamics (CFD) method is used to investigate a three-dimensional (3-D) model of a PV panel. It is also essential to estimate the thermal behaviour of the PV panel under various environmental conditions. The primary purpose of this current work is to analyse temperature distribution from the PV panel under given operating conditions. The model geometry is built by using CATIA design software. ANSYS software was simulated the different intensity of solar radiation that applied to the PV panel in order to observe the temperature distribution on each layers of the PV panel. The ambient temperature of the simulation is fixed 35 °C according to the maximum ambient temperature captured in Malaysia. The simulation results show that an increase in solar radiation intensity along with the PV panel operating temperature increase.

1. Introduction

At present, solar energy is the main focus of many researchers on solving the issue of non-renewable energy among all renewable energy [1-4]. PV panel is absorbed solar radiation converted into electrical energy in a PV system. According to the type of PV panel, the electrical efficiency of the commercially available PV panel is in the range of 13 % until 20 % according to the Standard Test Condition (STC) [5]. The rest of solar radiation absorbed in the PV panel is converted into the waste heat energy[6]. This is lead to increment in the operating temperature of PV panel. Therefore, it can be observed that the increase in PV panel operating temperature is linearly proportional to the solar radiation and ambient temperature. It can be observed that the electrical energy of the PV panel is significantly affected by the PV panel operating temperature in the actual environmental condition [7]. Skoplaki and Playvos [8] mentioned that negative impact of high operating temperature on a reduction in the band-gap of PV panel. This leads to a decrease in the open-circuit voltage, output power generated, and fill factor of the PV panel [9-10].

Several thermal models have been constructed and simulated to predict the temperature distribution of PV panel model under provided environmental conditions. More advanced software typically deals with thermal model to optimize the performance of the model. In the study by P.W. Ingle et al. [11], the solar collector has been simulated through the use of CFD method to understand the capabilities of heat transfer within the solar collector. In that result of simulation, it can be simpler to figure out the distribution of temperature and flow behaviour of air in the solar collector. Nyanor Peter et al. [12]...
constructed a finite-element model that stands for a standard PV panel to evaluate the operating temperature of PV panel working with COMSOL Multiphysics. The material properties of the PV panel construction are determined from the COMSOL material library and literature.

The work of G. Acciani et al. [13] carried out the thermal behaviour of PV panel was analysed through the use of Finite-Element Method (FEM) approach under several operating conditions. A three-dimensional model of the two various types of PV panel has been conducted as outlined by geometry and physical features of commercial PV panel into a COMSOL Multiphysics environment. The result of the simulation is accepted as true with experimental results in the actual PV panel. G. M. Tina and Abate R. [14] have conducted some investigation to determine the thermal behaviour of a PV panel. The PV panel is composed of three layers which are front, central and back layers. It showed that different segments of PV panel obtained various operating temperatures.

In this paper, this research aims to develop a 3-D model of PV panel under the different intensity of the solar radiation. This outcome of this paper is to discuss the PV panel thermal behaviour and analyse its temperature distribution on each layer within the PV panel. The model geometry is built through the use of CATIA software. The temperature distribution of PV panel can be predicted by the CFD method using ANSYS Transient Thermal simulation software.

2. Methodology

According to the PV technology used, the PV panel is made up of a number of various layers. In this research, the type of PV panel is the monocrystalline SNM-100P. There are six major layers within PV panel, which is a top glass covering, Ethylene Vinyl Acetate (EVA) layer 1, PV cells, EVA 2, tedlar layer and metal back sheet (aluminum). The PV cells used in that PV panel are monocrystalline silicone. All of these layers are assembled to each other and mounted in a metal back sheet. The material properties of the PV panel model are displayed in Table 1.

Geometry Model
Geometry model is built by utilized CATIA software. Firstly, the model of PV panel is created with the dimension of length as 120 cm, breadth as 54 cm and height as 3 cm based on the manufacturer datasheet of PV panel dimension. The model of PV panel has consisted of six layers. Table 1 displays each thickness layer within the PV panel model. After completed sketching the PV panel model, then save the design model into the CATIA product model as shown in Figure 1(a). Furthermore, the PV panel model was imported to the ANSYS Transient Thermal simulation software.

| No. | Material (Layer) | Thickness (cm) | Thermal Conductivity (W/m°C) | Specific Heat Capacity (J/kg°C) | Density (kg/m^3) |
|-----|-----------------|-------------|-----------------------------|-----------------------------|-----------------|
| 1.  | Glass Covering  | 0.3         | 1.8                         | 500                         | 3000            |
| 2.  | EVA             | 0.05        | 0.35                        | 2090                        | 960             |
| 3.  | PV Cell         | 0.04        | 148                         | 677                         | 2330            |
| 4.  | Tedlar          | 0.01        | 0.2                         | 1250                        | 1200            |
| 5.  | Aluminum Frame  | 2           | 204                         | 996                         | 2707            |

Transient Thermal Simulation
ANSYS software is used to analyse the temperature distribution of the entire PV panel with reduce time and cost consuming. ANSYS is universal finite-element software used to present computer simulation such as fluid dynamics, physical, structural, vibration and heat transfer fields of engineering analysis. Furthermore, ANSYS is possible to simulate tests or operation condition, allowing for testing in a virtual environment before developing product prototypes. ANSYS can work built-in along with a different employed engineering software program on the computer with the addition of CAD and FEA connection modules. ANSYS software can import PV panel model from the CAD program and can also create geometry in the pre-processing steps. Figure 1(b) shows the flowchart of operations.
ANSYS Transient Thermal is utilized in this simulation process. Typically, the transient behaviour can be initiated or turned off at the beginning of the system. In this simulation, the heat flux changes over time, causing the temperature changes that affect the performance of the PV panel model. Therefore, it is necessary to investigate the transient thermal behaviour of the system to figure out the scope of deviation from the normal situation [16-17].

The following is a list of processes used by ANSYS Transient Thermal simulation software to simulate a PV panel.

- Imported the geometry from the CATIA software to Design Workbench in ANSYS Transient Thermal.
- Defined material properties of each layer of the model in Engineering Data.
- Named each layer of the model in Geometry section.
- Create an automatic mesh in the Model section (Make sure select “CFD” in the Physics Preference and “Thermal” in the Solver Preference).
- Set a fixed 35 °C in the initial temperature with uniform applied to the model in Setup section.
- Applied the convection coefficient as 15.2 W/m²°C on the model.
- In the Analysis Settings part, set the step end time as 3600 seconds which the simulation of the model was conducted from one hour with all initial conditions.
- After set the environment condition, the simulation results of PV panel model temperature can be obtained in a form of contour plot.
- Analysis the operating temperature of the PV panel model based on variety of the solar radiation amounts.

The starting temperature of the PV panel model is set at 35 °C, which is the average daily temperature captured in Malaysia [18]. According to Newton’s Law of Cooling, the convective heat transfer coefficients can be calculated by using equation (1)[19].

\[ h = 5.7 + 3.8 \times Vm \]  \hspace{1cm} (1)

Where \( h \) represents the convective heat transfer coefficients and \( Vm \) is present in the wind speed value. In the research conducted by M. Irwanto et al. [20], the average wind speed of Kangar, Perlis is 2.5 m/s. Thus, the calculated convective heat transfer coefficient was applied to the model is 15.2 W/m²°C. Figure 2 depicts the PV model.
3. Results and Discussion

The results obtained from the CFD model analysis of a PV panel are presented in this section. As a way to investigate the effect of varying intensity of solar radiation applied to the PV panel; a model was created to simulate a PV panel under different solar radiation amounts. The selected different of solar radiation is taken from 200 W/m$^2$ until 1000 W/m$^2$ with an interval of 200 W/m$^2$. The model was simulated within one hour (3600 second) under all initial conditions.

(a) 200 W/m$^2$ of solar radiation.
(b) 400 W/m$^2$ of solar radiation.
(c) 600 W/m$^2$ of solar radiation.
(d) 800 W/m$^2$ of solar radiation.
Figure 3. Temperature distribution of the model when solar radiation as 200, 400, 600, 800 and 1000 W/m² applied to the PV panel model.

Figure 3 indicates a contour plot of the temperature distribution of the PV panel model when applied to the solar radiation of 200, 400, 600, 800 and 1000 W/m² on that model. It can be seen that each model applies on the different intensity of solar radiation was obtained the similar contour plots of the model temperature distribution. From the color distribution, the bright-red color is representing the hottest (maximum temperature of the model), and the dark-blue color is representing the coldest (minimum temperature of the model). It can be seen that the maximum temperature is obtained at the center of the top glass covering whereas the aluminum frame comprised of minimum temperature among all materials of the PV panel model.

Figure 3(a) shows the range of model temperature distribution is between 39.12 °C until 43.13 °C when the 200 W/m² of solar radiation applied to the model. The solar radiation of 400 W/m² was applied on the model as demonstrated in Figure 3(b). It can be seen that the maximum temperature of the model is at 51.26 °C while the minimum temperature is captured at 43.36 °C. Figure 3(c) presents the temperature distribution performance of the model when the model applied by solar radiation of 600 W/m². The operating temperature for that model ranges from 47.55 °C to 59.39 °C. On the other hand, the range of operating temperature is from 51.73 °C to 67.52 °C when the selected solar radiation of 800 W/m² applied on the model as shown in Figure 3(d). As seen in Figure 3(e), the contour plot for temperature distribution of the model is the solar radiation of 1000 W/m² applied on the model. The maximum temperature of model is 75.66 °C while the minimum temperature is recorded at 55.91 °C. All the range of model temperature distribution is listed in Table 2.

| Solar Radiation | Minimum Temperature (°C) | Maximum Temperature (°C) |
|-----------------|--------------------------|--------------------------|
| 200 W/m²        | 39.19                    | 43.13                    |
| 400 W/m²        | 43.36                    | 51.26                    |
| 600 W/m²        | 47.55                    | 59.39                    |
| 800 W/m²        | 51.73                    | 67.52                    |
| 1000 W/m²       | 55.91                    | 75.66                    |

Figure 4 shows the relationship between the maximum temperature and time of the model at different solar radiation intensity levels. The selected several of solar radiation is taken as 200 W/m², 400 W/m², 600 W/m², 800 W/m² and 1000 W/m². The model was simulated one hour under all initial conditions. As we can be seen from the Figure 4, the temperature of the model at solar radiation of 1000 W/m² is higher than other amounts of solar radiation. On the other hand, the temperature of the model at solar radiation of 200 W/m² is the lowest among all the different intensity of solar radiation. It can be found out that solar radiation is linearly the proportion to the PV panel temperature. The increase in solar radiation amounts along with the temperature of PV panel increases.
It can be observed that the different model layers consisted of different value of temperature as displayed in Figure 3. This is due to the physical properties of each layer of the PV panel various densities of layers, thermal conductivities, specific heat capacity and thickness of each layer. The thermal resistance was occurred between layer and layer as the heat transfer across a composite plate. Thermal resistance is a measurement of a temperature difference by which a material resists a heat flow called as thermal resistance. Clearly, the thermal conductivity of the aluminum is higher than that of other material layers and combination the effects of conductive and convective dissipate the heat away to the atmosphere at a much faster speed. Therefore, the coolest of the entire PV panel model is an aluminum frame. And also, the existing of the aluminum frame assists in cooling the PV panel. It can be concluded that higher thermal conductivity of the material is moves the heat very quickly compared to lower thermal conductivity.

Table 3 shows the temperature of each layers of the PV panel model in different intensity of solar radiation. It can be obvious that the difference in temperature between the layer to layer is not more than 5 °C. The reason for this is that the thickness of layers is very thin, contributing to a very small thermal resistance across the layers. It can be seen that the temperature of top glass cover is highest and aluminum frame is lowest temperature among all the layers of model as displayed in Table 3. When 200 W/m² and 400 W/m² applied on the model, the temperature difference between the glass and the aluminum frame is only 3.35 °C and 6.3 °C, respectively. On the other hand, the temperature difference between the glass and aluminum frame is exclusively 9.48 °C, 12.72 °C and 16.83 °C, respectively which occurred at 600W/m², 800 W/m² and 1000 W/m² of solar radiation. This is a good agreement with the theoretical study; increasing solar radiation is linearly proportional to the increasing temperature of the PV panel model.

| Solar Radiation | Top Glass (°C) | EVA 1 (°C) | PV Cell (°C) | EVA 2 (°C) | Tedlar (°C) | Aluminum Frame (°C) |
|-----------------|---------------|------------|--------------|------------|-------------|---------------------|
| 200 W/m²2       | 42.67         | 42.04      | 41.71        | 41.06      | 40.31       | 39.32               |
| 400 W/m²2       | 50.19         | 48.74      | 47.89        | 46.99      | 44.22       | 43.89               |
| 600 W/m²2       | 57.81         | 55.23      | 54.34        | 52.06      | 48.91       | 48.33               |
| 800 W/m²2       | 65.47         | 62.42      | 60.79        | 58.53      | 53.49       | 52.75               |
| 1000 W/m²2      | 74.05         | 71.85      | 68.90        | 67.23      | 63.69       | 57.22               |

4. Conclusion

A 3-D model of a PV panel was developed and analyzed by using ANSYS Transient Thermal simulation software. Compared to experiment-based, ANSYS simulation has the advantage of reducing delivery time and reducing the cost of new designs. The model has been constructed in accordance with the properties of the PV panel material such as densities of layers, thermal
conductivities, and specific heat capacity in the actual condition. The PV panel model was determined its temperature under the climatic condition of Malaysia, which fixed the 35°C of ambient temperature in the simulation model. Additionally, the average wind speed value of 2.5 m/s for Perlis, Malaysia is applied to the simulation. The selected different of solar radiation was taken as 200 W/m², 400 W/m², 600 W/m², 800 W/m² and 1000 W/m². The lowest operating temperature of PV panel model is 43.19°C under a solar radiation of 200 W/m² while the highest operating temperature of PV panel model is 75.66°C occurred at1000 W/m². It can be concluded that the operating temperature of the PV panel model increases along with the increase in solar radiation. In addition, the high temperature of PV panel can affect the performance and operation of the PV panel.

Acknowledgments
The authors gratefully acknowledge to the contributions and cooperation from member Centre of Excellence for Renewable Energy (CERE), School of Electrical Systems Engineering, Universiti Malaysia Perlis (UniMAP) for their work on the original version of this document.

References

[1] M. I. Fahmi, R. Kumar Rajkumar, W. Y. Wan, C. Lee Wai, R. Arelhi, and D. Isa. 2016. The Effectiveness of New Solar Photovoltaic System with Supercapacitor for Rural Areas, International Journal of Renewable Energy Development, Vol. 5, No. 3, pp. 249.

[2] L.H. Fang, S.I.S. Hassan, A.R. Rosemizi, and M.F. Malek.2016. A study of vibration energy harvester. ARPN Journal of Engineering and Applied Sciences, Vol. 11, No. 8, pp. 5028-5041.

[3] Y.M. Irwan, Z. Syafiqah, A.R. Amelia, M. Irwanto, W.Z. Leow, and S. Ibrahim. 2016. Design the Balance of System of Photovoltaic for Low Load Application. Indonesian Journal of Electrical Engineering and Computer Science, Vol. 4, No. 2, pp. 279 -285.

[4] L.H. Fang, A.R. Rosemizi, M. Isa, B.B. Ismail, and S.I.S. Hassan. 2018. Analysis of Batteries or Supercapacitor as an Energy Storage for Sound Energy Harvester System. IEEJ Transactions on Electrical and Electronic Engineering, Vol. 13, No.8, pp. 1-10.

[5] M.U. Siddiqui and A.F.M. Arif.2013.Electrical, Thermal and Structural Performance of a Cooled PV Module: Transient Analysis Using aMultiphysics Model. Applied Energy,Vol. 112, pp. 300-312.

[6] M. I. Fahmi, R. K. Rajkumar, R. Arelhi, and D. Isa, Study on the effect of supercapacitors in solar PV system for rural application in Malaysia, in Proceedings of the Universities Power Engineering Conference, 2015.

[7] Y.M.Irwan, W.Z.Leow, M.Irwanto, Fareq.M, S.I.S.Hassan, I.Safwati and A.R.Amelia. 2017.Optimum Number of DC Fan as A Cooling Medium for Photovoltaic (PV) System. Journal of Engineering and Applied Sciences,Vol.12, No.15,pp.3824-3823.

[8] Skoplaki E, and Palyvos JA.2009. Operating Temperature of Photovoltaic Modules: A Survey of Pertinent Correlations. Renewable Energy, 24, pp. 23–29.

[9] M. I. Fahmi, R. Rajkumar, M. Shahrukh Adnan Khan, Lee Wai Chong, and D. Isa. Modern Load Profile for Standalone PV Rural Household in Malaysia, in 5th IET International Conference on Clean Energy and Technology (CEAT2018), 2019.

[10] L.H. Fang, S.I.S. Hassan, A.R. Rosemizi, M. Isa, and B.B. Ismail. 2017. Charaterization of Differences Dimension Piezoelectric Transducer for Sound Wave Energy Harvesting. Energy Procedia, Vol. 105, pp. 836-843.

[11] P.W.Ingle, A.A. Pawar, B.D. Deshmukh and K.C. Bhosale. 2013. CFD Analysis of Solar Flat
Plate Collector. International Journal of Emerging Technology and Advanced Engineering, Vol. 3, pp.337-342.

[12] Nyanor Peter, Oman Emmanuel Kabu, Kudadze Stephen, and Deku Anthony. 2015. 3D Finite Element Method Modeling and Simulation of the Temperature of Crystalline Photovoltaic Module. International Journal of Research in Engineering and Technology, Vol. 4, pp. 378-384.

[13] G Acciani, O Falcone, and S Vergura. Analysis of the thermal heating of poly-Si and a-Si photovoltaic cell by means of FEM. International Conference on Renewable Energies and Power Quality, 2010.

[14] G. M. Tina and R. Abate. Experimental Verification of Thermal Behavior of Photovoltaic Modules. 14th IEEE Medit. Electrotech. Conference, (2008), pp.579–584.

[15] S. Armstrong, and W.G. Hurley. 2010. A Thermal Photovoltaic Panels under Varying Atmospheric Conditions. Applied Thermal Engineering, Vol. 30, pp. 1488–1495.

[16] Bhowmik H, and Tou KW. 2005. An Experimental Study of Transient Heat Transfer from Discrete Heat Sources in Water Cooled Vertical Rectangular Channel. Journal of Electronic Packaging, Vol. 127, pp. 1993-1999.

[17] Z.Syafiqah, Y.M.Irwan, N.A.M. Amin, M.Irwanto, W.Z.Leowand A.R. Amelia. 2017. Thermal and Electrical Study for PV Panel with Cooling System. Indonesian Journal of Electrical Engineering and Computer Science. Vol. 7, No. 2, pp. 492-499.

[18] M. Z. Hussin, A. M. Omar, Z. MdZain, S. Shaari, and H. Zainuddin. 2012. Design Impact of 6.08 kWp Grid-Connected Photovoltaic System at Malaysia Green Technology Corporation. International Journal of Electrical and Electronic Systems Research, 5.

[19] J. Vlachopoulos and D. Strutt. Heat Transfer. In SPE Plastics Technicians Toolbox 2, (2002).

[20] M. Irwanto, N. Gomesh, M.R. Mamat, Y.M. Irwan. 2014. Assessment of Wind Power Generation Potential in Perlis, Malaysia. Renewable and Sustainable Energy Reviews, Vol. 38, pp. 296–308.