Fluid flow and heat transfer analysis of a photovoltaic module under varying environmental conditions

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Abstract. The objective of this work is to evaluate fluid flow and heat transfer from a standard photovoltaic module by means of comprehensive analysis for the polycrystalline photovoltaic modules by using three-dimension CFD numerical modelling and experimental measurement. The analysis shows that PV module temperature is incident solar radiation $G_t$ and ambient temperature $T_a$ dependent but also depends on the wind speed as well as wind direction. It has been additionally shown that the mounting conditions which are not included in any advanced mathematical model also plays a significant role. Base on presented results the already existing models for PV module temperature evaluation can be tuned in order to determine the PV module temperature accurately. The experimental and numerical results that were obtained enable the development of a model for the module operating temperature evaluation under varying real environmental conditions.

1. Introduction

In the last decades, solar energy become considered as an attractive option among renewable energy [1]. Manufacturing of photovoltaic modules uses very modern technologies and keeps a lot of challenge to turn solar radiation into electricity with high efficiency. Recently a considerable effort has been made by researchers to improve photovoltaic (PV) module performance mainly due to maximizing solar absorption and minimizing the optical losses as well as introducing new materials. The photovoltaic cell temperature is one of the critical parameters for assessing the module efficiency and for long-term performance and lifetime. The PV module temperature depends on many parameters such as solar irradiation, installation type and climatic conditions, modules configuration, cells types and thermal properties of materials used in module encapsulation [2] and many more for example dust layer. The effects of the PV module temperature on the power production under environmental condition was studied by Hussain et al. [3]. Authors found that the cell temperature increase, reduced significant the amount of generating electrical produced. The solar cells performance decreases with cell temperature increase, mainly due to increased internal carrier recharge rates, resulting from increased concentrations of carrier [4,5]. In the literature, various authors have developed thermal models relating to the PV module thermal flow and heat transfer mechanisms based on the environmental variables. In the most cases, their prediction due to a large number of arbitrarily selected parameters is poor and new more correlations should be developed. A review of the sensitivity analyses for correlations for PV module thermal process and heat transfer mechanisms has been presented by Coskun et al. [6]. Thermal analysis of wind incident angle on photovoltaic module temperature was studied by Kaplani and Kaplanis [7].
Authors results demonstrated a need for accurate evaluation of the wind velocity and wind incidence angle. It observed that the photovoltaic temperature slightly decreases with increasing wind incidence angle, particularly at high wind velocities. Al-Sabounchi [8] investigate the module tilted angle effect on the PV cell thermal behavior in the countries with hot climate. The investigation takes into account the ambient temperature, solar radiation, module manufacturing properties and other parameters. It was found that module tilted angle has a significant effect on the cell temperature. Jubayer et al. [9] studied the convective heat transfer from a ground mounted stand-alone PV modules. The result shows that the heat transfer rate is higher for solar panels installed on the ground than the solar panel mounted on a tilted surface, mainly due to poor ventilation from the back side. In the research study performed by Lobera and Valkealahti [10] thermal model based on the total energy balance in the PV component has been developed. Similar model for a double-glass multi-crystalline PV module based on the various thermal considerations was developed in [11]. Ju et al. [12] presented an improved method for estimating the temperature of solar cells which can be used for wide range of operating conditions. The photovoltaic module temperature under different wind speeds was analysed by Armstrong and Hurley [13]. Authors shown that there was a parasite difference in convective and radiative heat loss from the module at different wind speeds. Hassan et al. [14] analysed the temperature effect on the efficiency of the PV system and power generation. The results confirmed that the operating temperature of a module plays a significant role in the conversion process and the power output is significantly influenced by the temperature. Based on the thermal efficiency five different analytical models for module temperature evaluation has been verified by Tomar et al. [15]. The environmental effect on the PV temperature has been examined also in other studies [16-19].

The main objective of this research is to model the fluid flow and heat transfer from a standard PV module by using three-dimension CFD numerical modelling and experimental measurement. The obtained results will enable the development of a model for the PV operating temperature evaluation under varying real environmental conditions. By using this type of models, the operating temperature of working PV modules under different actual environmental conditions can be predict. Additionally base on presented results the already available theoretical models can be tuned in order to determine the module temperature with higher accuracy.

2. Experimental set-up

The experimental measurement was conducted using polycrystalline Sharp ND-RJ260 photovoltaic modules (temperature coefficient of power -0.42 %/°C and 1.6 m² of surface area, white colour back sheet, tilt angle β=15°) and BrukBet BEP260W (temperature coefficient of power -0.40 %/°C and 1.62 m² of surface area, white color back sheet, tilt angle β=35°). The nominal module power is equal to 260W. The azimuth for all PV modules was the same γ=20° West. The main hardware components of the data acquisition system for temperature and solar irradiation measurement consist of 4 Advantech ADAM4018 DAQ, 16-bit, an 8-channel analog input module that provides programmable input ranges on all channels, RS485 transceiver, computer with data acquisition software and data storage.

![Figure 1. An experimental set-up with thermocouples arrangement](image-url)
As temperature sensors, calibrated Copper-Constantan (T-type) thermocouples were used. Each module has been equipped with four thermocouples attached to the back sheet in the recommended by standard arrangement (see Figure 1). Signals from all thermocouples were acquired every second and the five minutes average value has been stored for analysis. The ambient temperature, air speed and solar irradiation (global and diffusive components), were also obtained from the local sensors, at location AGH University of Science and Technology in the city center of Kraków, Poland. The signals from weather station sensors were acquired every second and 5 minutes average value has been stored.

3. Numerical model

In this work, a three-dimensional model of the photovoltaic module with mounting system and surrounding area has been created to analyse fluid flow and heat transfer. The sketch of the analysed geometry and main heat transfer components are presented in Figure 2. The photovoltaic module size under consideration was 1.654 x 0.989 x 0.04m (length, width and thickness). However, it should be noticed that glass thickness was only 5mm. Due to the small thickness of layers, the averaged heat conduction coefficient was calculated. The size of the computational domain was equal to 4.2 x 2.8 x 2.2m, and an unstructured hex-dominant mesh was generated for the domain. The fluid flow domain contains boundary layer with prismatic cells for the photovoltaic module near-wall region. The area with the high impact of turbulence has a locally much finer mesh. Before a set of final CFD analysis were performed different meshes have been tested to obtain mesh independent solution. Based on tests mesh with 300,000 - 500,000 high-order elements has been found to give mesh-independent solution.

![Figure 2. An analysed geometry and main heat transfer components](image)

In this work, it assumed that temperature is a passive scalar and have no influence on the air flow. The considerations for the mathematical model eq. (1)-(3) are: steady state, newtonian fluid, negligible viscosity dissipation and the use of the Boussinesq approximation. The time averaged governing equations for continuity, momentum and energy in tensor notation, are as follows:

\[
\frac{\partial \bar{U}_i}{\partial x_i} = 0
\]

\[
\bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j^2} - \frac{\partial}{\partial x_j} \left( \bar{u}_j \bar{u}_i \right)
\]

\[
\bar{U}_j \frac{\partial \bar{T}}{\partial x_j} = \kappa \frac{\partial^2 \bar{T}}{\partial x_j^2} - \frac{\partial}{\partial x_j} \left( \bar{u}_j \bar{T} \right)
\]

where \(x_i, x_j\) are the Cartesian coordinates of the system, \(\bar{U}, \bar{P}, \bar{T}\) are the mean velocity, dynamic pressure and temperature; \(\nu, \kappa\) are fluid viscosity and thermal diffusivity. In order to model turbulent flow the realizable \(k-e\) model which is a modification of the standard \(k-e\) model was used. Model is a semi-empirical 2-equation eddy viscosity model, which is based on the Boussinesq hypothesis - Reynolds
stresses can be expressed in terms of mean velocity gradients and that the turbulent eddy viscosity is related to the turbulent kinetic energy and the dissipation rate of turbulent kinetic energy. The \( k-\varepsilon \) turbulence models incorporate, on average, the influence of turbulent eddies (Reynolds stresses) through turbulent viscosity, which is related to the fluid rate of strain according to:

\[
-\rho \mu \frac{\partial \tau_{ij}}{\partial x_j} = \mu_T \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) = 2 \mu_T S_{ij} - \mu_T \frac{k^2}{\varepsilon}; \quad \mu_T = \rho C_\mu \frac{k^2}{\varepsilon}; \quad \mu_T = \frac{\mu_T}{\kappa} \frac{\partial T}{\partial x_i} \left( \frac{\partial \theta}{\partial x_i} \right)
\]  

Realizable \( k-\varepsilon \) model contains a improved formulation for the turbulent viscosity. The model equation for the turbulent kinetic energy and for the dissipation rate can be written as follows:

\[
\frac{\partial}{\partial x_i} \left( \bar{U} k \right) = \frac{\partial}{\partial x_i} \left( \frac{\nu_{eff}}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + P_k - \varepsilon
\]

\[
\frac{\partial}{\partial x_i} \left( \bar{U} \varepsilon \right) = \frac{\partial}{\partial x_i} \left( \frac{\nu_{eff}}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + C_1 \varepsilon \bar{S} - \frac{C_2 \varepsilon^2}{k + \sqrt{\varepsilon}}
\]

where \( k \) and \( \varepsilon \) are turbulence kinetic energy and dissipation rate, \( P_k \) represents the turbulent kinetic energy production as function of turbulent kinematic viscosity, \( \mu_{eff} = \mu + \mu_T \) and \( \nu_{eff} = \mu_{eff} / \rho \) are turbulent effective viscosity. The turbulent model constants are as follows:

\[
C_1 = \text{max} \left[ 0.43, \frac{\eta}{\eta + 5} \right]; \quad \eta = \frac{S k}{\varepsilon}; \quad S = \sqrt{2S_i S_j}; \quad C_\mu = \frac{1}{A_0 + A_S} \frac{1}{k S_{ij} S_{ij} + 0.41 \beta_{ij} \beta_{ij}}; \quad S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

\[
\widetilde{\Omega}_{ij} = \Omega_{ij} - 2 \varepsilon_{ijk} \omega_k; \quad \Omega_{ij} = \tilde{\Omega}_{ij} - 2 \varepsilon_{ijk} \omega_k; \quad A_0 = 4.04; \quad A_S = \sqrt{\varepsilon} \cos \phi; \quad \phi = \frac{1}{3} \cos^{-1} \left( \sqrt{6} W \right)
\]

\[
C_{1} = 1.44; \quad \sigma_\varepsilon = 1.0; \quad \sigma_k = 1.2; \quad W = \frac{S_{ij} S_{jk} S_{ki}}{S^3}
\]

Presented heat transfer model includes solar model and radiation heat transfer model. For the radiative heat transfer Surface-to-Surface (S2S) radiation model has been used:

\[
q_{out,k} = \varepsilon_k \sigma T_k^4 + \rho_k q_{in,k}
\]

\[
A_k q_{in,k} = \sum_{j=1}^{N} A_j q_{out,k} F_{jk}
\]

where \( q_{out,k} \) and \( q_{in,k} \) are energy flux leaving the surface and energy flux incident on the surface from surroundings; \( A_k \) is an area of \( k \)-surface, \( F_{jk} \) is view factor between \( k \)-surface and \( j \)-surface. As a numerical solver Fluent v.18 was used with fluid and solid properties presented in Table 1.

**Table 1. Fluid and solid properties.**

| Material name | Specific heat (J/kgK) | Density (kg/m³) | Viscosity/Emmissivity (kg/ms) / (-) | Thermal conductivity (W/mK) |
|---------------|----------------------|----------------|----------------------------------|---------------------------|
| Air           | 1006.43              | 1.225          | 1.78*10⁻⁴                       | 0.0242                    |
| Panel         | 700                  | 2700           | 0.92                            | 197                       |
| Soil          | 1600                 | 1600           | 0.95                            | 2                         |

Mean wind speed and turbulence intensity profiles for aerodynamics roughness length 0.03 m are employed at the domain entrance as an inlet boundary conditions. Five different wind speeds in the range 0.5-5m/s are selected. At the domain exit, a uniform zero gauge pressure boundary condition is used. Side walls of the computational domain have pressure outlet boundary condition applied. The bottom wall of the domain has been treated as a rough wall with no-slip boundary condition. For the thermal boundary conditions, at the inlet plane of the domain the air temperature \( T_0 \) equal to the values obtained from measurements have been applied in the range 2-16°C (spring season). Solar radiation is applied to the thermal radiation model as an incident solar radiation in the range 100-1000W/m².
4. Results and discussion

Presented results show the effect of solar radiation, air temperature, air velocity and direction as well as module inclination and mounting conditions on the module operating temperature $T_c$. The incident solar irradiation $G_T$ was in the range 100-1000 W/m² while the air velocity $V_w$ was between 0.0-5.0 m/s. The mathematical model and numerical schemes were validated against experimental measurement and the results of the analysis can be found in [20]. In this paper only selected experimental results for the module tilt angle $\beta=15^\circ$ are presented in Figure 6.

The flow field around the PV module for the air velocity $V_w = 3.1$ m/s is shown in Figure 3(a)-3(d). For the configuration presented in Figure 3(a), 3(c)-3(d) the wind direction is opposite to the X-axis direction while in Figure 3(b) air direction is opposite to the Z-direction (is from the module left side). It is worth to notice that for the configuration Figure 3(d) module tilt angle is $\beta=0^\circ$ and the space under the module is closed (the air flow can’t flow under the module) which reduces cooling conditions. The module temperature for the configuration presented in Figure 3(a)-3(d) and for air temperature equal to $T_a=8^\circ$C is shown in Figure 4(a)-4(d). Depend on configuration temperature distribution and mean module temperature varied significantly. Due to poor cooling conditions, the highest temperature has been obtained for module mounted horizontal ($\beta=0^\circ$). In contrast, the lowest temperature was obtained for the case 4(b) with $\beta=15^\circ$ and side cooling (air flow from the side).

![Flow field at different module inclination $\beta$ and air flow direction.](image)

**Figure 3.** Flow field at different module inclination $\beta$ and air flow direction.

![Temperature distribution on the module surface.](image)

**Figure 4.** Temperature distribution on the module surface.
As can be seen the temperature distribution at module surface is highly non-uniform and vary significantly during the day depends on wind speed and the Sun position. The effect of the Sun position on the module temperature distribution for incident solar irradiation \( G_T = 470 \text{ W/m}^2 \), wind speed \( V_w = 1.0 \text{ m/s} \), ambient temperature \( T_a = 8 \text{ °C} \), inclination \( \beta = 0\text{°, 15\°} \) and for different time (at day 12.04.2018) is presented in Figure 5.

![Figure 5. The PV module surface temperature during the day \( G_T = 470 \text{ W/m}^2, V_w = 1.0 \text{ m/s, } T_a = 8\text{°C} \).](image)

Two of the three essential parameters which influence module temperature are the wind speed \( V_w \) and ambient temperature \( T_a \). The effect of those parameters on the mean module temperature for \( \beta = 15\text{°, 30\°} \) are presented in Figure 6(a)-6(b). It can be seen that for low wind speed heat loss is weak and the module temperature becomes very high which decrease module efficiency about 20%. The presented data compared with the experimental measurement.

![Figure 6. The effect of wind speed \( V_w \) (a), ambient temperature \( T_a \) (b), solar irradiation \( G_T \) (c) and mounting configuration (d) on the average module temperature \( T_c \).](image)

The third important parameter which directly influenced PV module temperature is incident solar irradiation \( G_T \). The effect of solar irradiation on module temperature for different wind speed \( V_w \) at
two module angles $\beta = 15^\circ, 30^\circ$ is shown in Figures 6(c). The last (fourth) important parameter is related to the module mounting configuration. Usually module front surface is well cooled, but the module back side heat transfer can vary significantly. For the cases when the modules back surface is under good cooling conditions air flow from two sides can be nearly the same and the module temperature become lowest. However, when cooling conditions become poor the temperature an increase about 2.6-3.6°C in reference to the normal flow condition is observed. On the other hand when the module is mounted horizontally poor cooling condition cause additional module temperature increase about 10.0-11.2°C (see Figure 6(d)).

In the literature, several correlations have been proposed to evaluate PV module temperature. However, most of them use two or three parameters only. In the present work modification of the one of most popular correlation for the module $T_c$ operating temperature evaluation will be used [21]:

$$ T_c = T_a + kG_T $$

As can be seen in this linear expression no wind speed $V_w$ is included. The mounting conditions are taken into account and depend on the single dimensional parameter $k$, known as the Ross coefficient. Reported values for $k$ are in the range 0.02–0.04 Km²/W [21]. In the literature, a few models can be found which include the effect of wind speed but without mounting conditions consideration [22]:

$$ T_c = 0.943T_a + 0.028G_T - 1.528V_w + 4.3 $$

In the present paper with the use of numerical data and experimental data new correlations is proposed which takes into account four - all key - parameters (solar irradiation, ambient temperature, wind speed and mounting configuration) as the follows:

$$ T_c = T_a + kG_T + e^{(3.75-0.75V_w)} $$

where $T_a$ and $G_T$ are ambient temperatures and incident solar radiation, $V_w$ is the wind velocity, $k$ is the Ross coefficient. The equation coefficients were evaluated using the least squares method. This correlation gives a possibility to take into account ambient temperature, solar radiation, wind speed and mounting scheme or another PV configuration arrangement. The correlation eq.(11) accuracies have been assessed using: root mean square error (RMSE), the mean bias error (MBE), the coefficient of determination ($R^2$) presented in Table 2.

| Model                  | MBE  | RMS  | $R^2$ |
|------------------------|------|------|-------|
| Model Eq. (9)          | 1.52 | 4.57 | 0.613 |
| Model Eq. (10)         | 3.06 | 5.34 | 0.467 |
| Model current Eq. (11) | 0.72 | 2.71 | 0.933 |

5. Conclusions

The temperature of the photovoltaic panel is an important issue and it is directly related to the PV system performance. The present paper shows the fluid flow and heat transfer from a PV module by means of experimental measurement and three-dimensional simulation for determining the temperature of the module. Presented results contribute to a better knowledge of the module behaviour influenced by the various environmental conditions as well as mounting conditions. The analysis shows that PV module temperature depends on: incident solar radiation $G_T$, ambient temperature $T_a$, wind speed $V_w$ and wind direction. It has shown that the mounting conditions (which are not included in any advance model) play a significant role and may cause an additional module temperature increase in the range 10.0-15.5°C. Such temperature additional increase can cause mono and polycrystalline module efficiency decrease about 3.8-6.5%. The presented experimental and numerical results enable the development of an improved model for the PV module temperature related with the environmental and mounting conditions. The presented model is much sought after by the computer software, malfunction detection tools, and system designers.
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