Combining CFD simulations with block-oriented heatflow-network model for prediction of photovoltaic energy-production

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Abstract. The exterior factors which influencing the working circumstances of photovoltaic modules are the irradiation, the optical air layer (Air Mass – AM), the irradiation angle, the environmental temperature and the cooling effect of the wind. The efficiency of photovoltaic (PV) devices is inversely proportional to the cell temperature and therefore the mounting of the PV modules can have a big affect on the cooling, due to wind flow-around and naturally convection. The construction of the modules could be described by a heatflow-network model, and that can define the equation which determines the cells temperature. An equation like this can be solved as a block oriented model with hybrid-analogue simulator such as Matlab-Simulink. In view of the flow field and the heat transfer, witch was calculated numerically, the heat transfer coefficients can be determined. Five inflow rates were set up for both pitched and flat roof cases, to let the trend of the heat transfer coefficient know, while these functions can be used for the Matlab/Simulink model. To model the free convection flows, the Boussinesq-approximation were used, integrated into the Navier-Stokes equations and the energy equation. It has been found that under a constant solar heat gain, the air velocity around the modules and behind the pitched-roof mounted module is increasing, proportionately to the wind velocities, and as result the heat transfer coefficient increases linearly, and can be described by a function in both cases. To the block based model the meteorological parameters and the results of the CFD simulations as single functions were attached. The final aim was to make a model that could be used for planning photovoltaic systems, and define their accurate performance for better sizing of an array of modules.

1. Introduction
There are mainly two factors, which influences the power output of the photovoltaic modules, they are the temperature of the solar cells and the irradiation, which comes from the Sun. The quantity of the radiation arriving from the Sun influences the first factor, what between the average Earth-Sun distance, outside the atmosphere of the Earth on a perpendicular surface is 1353 Wm\textsuperscript{-2}, but a part of this in the atmosphere is absorbing or reflecting. The moisture content of the air and the clouding influences this parameter, while at clean weather, the radiation coming to the ground surface through the atmosphere is around 1000 Wm\textsuperscript{-2}, till in cloudy time it could be only 200 Wm\textsuperscript{-2} or less.
The other factor is the temperature of the solar cells. The performance of Si solar cells decrease with the increase of the temperature, averagely in a direct proportion with 0.2% (figure 1). The solar modules which can be bought in trade, are only tested on 25°C, but the cells’ temperature may attain 60-70°C and in some cases above 100°C in the practice.

![Figure 1. Effect of temperature on the current-voltage characteristics of a solar cell.](image)

This temperature is beside certain circumstances artificially reducible, this could be made by many ways, starting with the extreme cases like fluent hydrogen refrigeration, ventilation, etc., but it was proven already, that the performance increase gained by these, is not in a proportion with the expenses. The repository of the passive refrigeration opportunities is wide. In this case the cooling medium is air, refrigeration happen due to convection, which may be natural (when the density difference causes the substance flow) or may be artificial.

Natural convection cooling is mainly used by pitched roofs or by PVs integrated in vertical facades, where the energy of the cooling medium will be used for heating the building.

The cooling effect at free standing PV modules is usually the wind and the buoyancy driven flows. In this work we examine the flow properties at free standing solar modules with the help of computational fluid dynamics (CFD).

The upwarming can be reduced with the suitable setup of the modules, taking the meteorological parameters into consideration: the prevailing wind direction and hereby the air circulation around the modules. To let us be able to calculate with this, it is necessary to examine the regional meteorological parameters, which will be the boundary conditions in the simulation case.

The performance of solar cell is normally evaluated under the standard test condition (STC), where an average solar spectrum at AM 1.5 is used, the irradiance is normalized to 1000Wm\(^{-2}\), and the cell temperature is defined as 25°C. To satisfy the requirement of temperature and insulation in STC, the test usually needs specified environment and some special testing equipment, such as an expensive solar simulator. In fact the modules temperature can reach 80-90°C between naturally conditions, where the efficiency looses either 20-30% from its originally given value. Some manufacturers give a number called NOCT (Nominal Operating Cell Temperature), which can better describe the operating conditions of a module. The NOCT number of a module will be determined at irradiation 800Wm\(^{-2}\), at temperature 20°C and wind velocity 1ms\(^{-1}\), while it is assumed that wind can flow around it.
\[ T_{PV\text{cel}} = T_{\text{air}} + \frac{NOCT - 20}{80} I \]  

Substituting the proper values in it, where \( T_{\text{air}} \) is the environmental temperature in °C and \( I \) is the irradiation in mWm\(^{-2}\), we can get the actual operating temperature of our module.

The above formula is experimental and simplified, the convection and the heat conduction are taken into consideration, but presupposes it, that the heat conduction coefficient of the substance does not change powerfully with the temperature.

To calculate the modules accurate temperature, we have to know at least the surface heat transfer coefficients (\( \alpha \)) at various flow rate, which defines the leaving quantity of heat from the modules.

Along an L surface, which has \( T_s \) temperature, the mediums temperature is \( T_w \) and a flow with \( v \) velocity, the upcoming heat flow hangs on many parameters. Either we have to solve the continuity equations of Fourier–Kirchhoff, Navier–Stokes and Reynolds, or through calculating or measuring the Nusselt-number and expressing from the expression (2) [1].

\[ Nu = \frac{\alpha L}{\lambda} \]  

In this case, on the other hand, determining the Nusselt number is necessary, which is possible if the questionable flow space is known, while \( Nu = f(Gr, Pr, Re) \), so it depends on the Prandtl-, Reynolds- and Grashof criteria.

The problematic of the determination of the Nusselt number, was examined in several works already, in case of photovoltaic modules. One of the most accurate and most detailed models, which are based on measuring an artificially heated plate, is the work Sharples és Charlesworth (1997) [2].

\[ Nu_L = 0.664 \frac{Re^0.5}{Pr^{0.33}} \]  

Into the above formula replacing the physical parameters of the air, at a surface area of \( 1.8 \times 0.9 \text{m}^2 \) with 325K surface temperature, the modules heat transfer coefficient – at 300K environmental temperature – with the under mentioned context can be calculated, where \( v \) is the flow velocity of the air:

\[ \alpha = 4.01v_\infty^{0.5} \]  

2. Methodology

2.1. Preparation

The Nusselt number and the heat transfer coefficient will be defined through CFD simulations, in our case. The reliability of CFD modelling was proven by Moshfegh and Sandberg. [3] They made a model, which was validated for buoyancy-induced flow and heat transfer in a tall open air cavity. The average difference between the predicted and measured velocities and for heat fluxes at and above 100Wm\(^{-2}\) was less than 3%.

The Hungarian meteorological parameters were examined, principally the environment temperature and the wind, which has a strong influence on the power generation of the solar cells. We wanted to examine what happens at the highest levels of these parameters, this is because the irradiance was set automatically to 1000 Wm\(^{-2}\), and at the other parameters we were searching for the highest averages. The average air temperature at our latitude is at a sunny summer day at about 21°C, but in Pécs were measured the highest low temperature in a day (in Hungary), which was 26.9°C. The wind velocities are mostly between 1 and 3ms\(^{-1}\) but the wind has the biggest affect on the surface heat transfer coefficient so we made calculation from 0 to 7ms\(^{-1}\).

The PV modules were defined as solid in the calculations with one domain, so we made a thickness weighted average on the density, heat conductivity(\( U \)) and on the specific heat capacity(\( C \)). A typical
solar module stays from glass coverage, Ethylene-vinyl acetate (EVA) encapsulation for the cells and usually from a PVF, PVB or glass bracing on the backside. The thickness of the solar cells is usually 300µm, the glass has around 2mm thickness. The rest should be then about 7.7mm which are mainly plastics and have near the same conductivity and capacity for heat. Our calculations made out that the average values for our type of modules are: $\alpha = -1500\text{kgm}^{-3}, U = -0.5\text{Wm}^{-1}\text{K}^{-1}$ and $C = -400\text{Jkg}^{-1}\text{K}^{-1}$.

We do not want to specify the temperature of the modules, these numbers are to let us approach them in the course of calculations, because the buoyancy driven flows could be calculated more precisely this way. The buoyancy driven flows are important mostly in the lower or zero wind velocity calculations, where they are the only flow types near the wall of the modules, exactly in the wind-shaded areas.

The heat transfer coefficients, which will be served by the calculations, will be used at the heatflow-network model (figure 2) we presented in our previous works. [4] This network describes the material layer junctions of the photovoltaic module, represented with their heat resistance. This heatflow-network model was implemented in Matlab/Simulink, and this is a one-dimension steady state model which is able to describe the junction temperatures in the photovoltaic module.

![Figure 2. The heatflow-network model of a photovoltaic module.](image)

2.2. Pre-processing the cases

The quality of the numerical grid is important to the numerical calculation, in this consideration on the wall of the solar module, prism elements were generated with growing side longitude (figure 3), like this the boundary layer is conformed for using the k-ε turbulence model ‘Enhanced wall treatment’ option, so we can take advantage of the opportunity of modelling the boundary layer detachments and the wall nearly flows adequately. In the rest of the parts of the space we applied triangle elements, on unstructured construction. Near the module the side length of the triangle elements is 4mm, and is growing gradually receding from the wall. The skewness – as the grids’ qualitative indicator – comes to under a 0.6 value onto all of the grid which is relatively good for meshes containing triangular elements. The grid consist of 110 769 pieces of elements in the one module case and 233 730 pieces at the three modules. At the second case the finest smaller element region has a bigger extent, which is why it contains more elements.
Figure 3. The mesh distribution at the wall of the pv modules.

The basis of the physical models is the continuity equation (5) the momentum equation (6)(7) and the energy equation (8), and we made use of the Boussinesq approximation (9) for the determination of the density change of the air. The form of the equations in case of two-dimensional stationary applications:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{5}
\]

\[
u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = g\beta(T - T_0) - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right), \tag{6}
\]

\[
u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = g\beta(T - T_0) - \frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right), \tag{7}
\]

\[ho c_p \left( \frac{\partial T}{\partial x} + \nu \frac{\partial T}{\partial y} \right) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \tag{8}
\]

\[\rho = \rho_0 (1 - \beta \Delta T). \tag{9}\]

At the defining of the boundary conditions of the equations, the physical parameters of the air are constant, except the density (9). The environmental temperature is 300K, the temperature of the modules comes out from the radiation. At PV cells, most of the absorbed solar radiation is converted into heat, which increases the temperature of the cells. The solar heat gain by the PV modules was calculated from the insulation minus the reflection (5%) and the energy conversion into electricity (about 15%) [5]. A radiation model was used in the simulation case too, to calculate the radiation heat losses.

In all cases five different wind speeds were examined for the heat transmission of the modules, in order \(v_{\text{wind}} = \{0, 1, 3, 5, 7\}\) ms\(^{-1}\), based on the wind speeds occurring in Hungary mostly.
3. Results

An average of the values were made from the calculated heat transfer coefficients, hereby the biggest deflection was 2.54%. The linear function of the average values may be used in the heatflow network model, while its ingoing parameter is the wind velocity, which can be delivered from one of the initial values of the block oriented model.

- Pitched roof
  - $\alpha_{\text{avg-pitched-north}(v)} = 1.85x + 2.93$;
  - $\alpha_{\text{avg-pitched-south}(v)} = 3.62x + 2.93$;
- Flat roof
  - $\alpha_{\text{avg-flat-north}(v)} = 1.93x + 2.90$;
  - $\alpha_{\text{avg-flat-south}(v)} = 2.17x + 2.90$;
- Free standing modules
  - $\alpha_{\text{avg-array-north}(v)} = 4.188x + 2.90$;
  - $\alpha_{\text{avg-array-south}(v)} = 3.128x + 2.90$.

In figure (figure 4) of the schematic connections of the heatflow-network model we can see that other parameters are still missing like the wind speed, solar irradiation and the environmental temperature.

functions of the meteorological parameters were generated from the data’s of the Hungarian Meteorological Service (OMSZ). With these functions the energy production of the photovoltaic modules can be predicted.

$$t_w(\tau) = t_m \cos[(\alpha(\tau - \tau_0) + t_d)]$$ (10)
\[ I(\tau) = \begin{cases} 
I_m \cos[\beta(\tau - \tau_0)] \exp \left[ -\frac{\tau - \tau_0}{\tau_h} \right]^2, & \text{if } |\tau - \tau_0| \leq \tau_h \\
0, & \text{if } |\tau - \tau_0| > \tau_h 
\end{cases} \]  

(11)

\[ w(\tau_h) = e^{a(N_{\text{day}})(\tau_h - b(N_{\text{day}}))^2} + c(N_{\text{day}}). \]  

(12)

4. Conclusions

A method, with which the heat heat transfer coefficient of the modules can be defined with a good approach, got developed and implemented in the present work, that in the course of the later ones with measurements can be supported, but the calculated values appear suitable, based on the literatures. These values will be used in the mentioned Matlab/Simulik model [4]. Important, that the calculation can be parameterized, changes can be made in the temperature and examine the effect of the convective flow, or in case of the wind cooling. Similarly can be calculated other typical placement manners, like varying the distance from the ground, that may improve on the circulating quality.

5. References

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