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Investigation of Temperature Effects in Efficiency Improvement of Non-Uniformly Cooled Photovoltaic Cells

Anas Al Tarabsheh[*,a], Spyros Voutetakis[b], Athanasios I. Papadopoulos[b], Panos Seferlis[b,c], Issa Etier[a], Omar Saraereh[a]

[a]Hashemite University, Electrical Engineering Department, 13115 Zarqa, Jordan.
[b]Chemical Process and Energy Resources Institute (CPERI), Centre for Research and Technology Hellas (CERTH), P.O. Box 60361, Thermi-Thessaloniki 57001, Greece.
Department of Mechanical Engineering, Aristotle University of Thessaloniki, P.O. Box 484, 54124 Thessaloniki, Greece
atarabsheh@hu.edu.jo

This study investigates the performance of photovoltaic (PV) modules with respect to temperature and proposes pipe layouts enabling efficient cooling. The operating temperatures of the PV cells are not equal since the fluid flowing through the cooling pipes has a temperature difference between the inlet and the outlet of the pipes. The warm atmosphere affects the current density/voltage *J*/*V* characteristics of the PV modules. Therefore, the PV cells under cooling tend to operate at a relatively lower temperature resulting in an enhancement in their efficiencies. This paper calculates the *J*/*V* characteristics of each PV cell depending on its operating temperature. Then the overall *J*/*V* characteristics of the PV module are recorded. The module is cooled by a fluid flowing through pipes underneath the PV module backside. The fluid serves as both heat sink and solar heat collector. In contrast to the existing models, where a PV module and its PV cells are assumed to be having the same operating temperature, our model tries to address the non-uniform distribution of the operating temperatures of the PV cells. The main idea of this paper is to consider the effect of the cooling process on the performance of each PV cell independently in order to more accurately calculate the effect of temperature on the PV parameters of the module. Different designs of cooling pipes are also introduced in this work to find the effect of pipe geometries on the performance of the PV modules. The geometry can improve the PV cell parameters and consequently the performance of the PV module. In all designs, the flow rate of the fluids must be kept the same in order emphasize the effect of geometry only. The best design is the one which keeps the operating temperature of the PV cells as minimum as possible resulting in a maximum energy yield of the PV cells.

1. Introduction

The photovoltaic (PV) cells are able to produce energy from the abundant resource of sunlight. Since the PV modules are exposed to sunlight they generate heat as well as electricity. Typically a PV module converts only 10-15% of the incident power to electricity, while the remaining power is largely rejected as heat. The warm atmosphere affects the current density/voltage *J*/*V* characteristics of the PV modules where their electrical efficiencies η are adversely affected by the significant increase of cell operating temperature during absorption of solar radiation (Teo et al., 2012). Applying a cooling system to a PV module reduces the cost of solar energy in three ways. First, cooling improves the electrical production of PV modules. Second, cooling makes possible the use of concentrating PV systems by keeping the PV cells from reaching temperatures at which irreversible damage occurs, even under the irradiance of multiple suns. This makes it possible to replace PV cells with potentially less expensive concentrators. Finally, the heat removed by the PV cooling system can be used for building heating or cooling, or in industrial applications. To this end, hybrid photovoltaic/thermal (PV/T) solar systems have been investigated as a means of decreasing the temperature of PV modules and boost their electrical efficiency. Work by Nualboonrueng et al. (2012) investigates the effects of amorphous and multi-crystalline silicon materials in the performance of PVTs, work by Beccali et al. (2009) highlights the increased energy savings due to the use of PVTs, while work by Hasan et al. (2012) addresses the development of hybrid PVT-Biogas systems for power generation.

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Although PVTs present a promising option to maintain low PV temperatures, the use of fluid-based cooling is considered to be the least expensive method to improve PV panel performance (Odeh and Behnia, 2009). The temperature of the cooling fluid at the outlet of the PV module is higher than that at the inlet due to heat exchange between the backside of the module and the pipes. Therefore, the temperature of the pipes increases gradually from the inlet toward the outlet resulting into a non-uniformly cooled PV module. In other words, each PV cell in the module has a different operation temperature leading to different *J*/*V* characteristics of each cell. In contrast to the existing models (Odeh and Behnia, 2009) where the PV module is assumed to be cooled to a specific temperature and then assuming that all cells have the same temperature, our model tries to address the non-uniform distribution of the operating temperatures of the PV cells.

2. Method and model

The PV cells can be combined and connected together in such a way that they deliver exactly the required power. In this work, each PV panel composed of *N* series-connected solar cells is evaluated using MATLAB^{TM} software, from which the *J*/*V* characteristics of each cell n $(1 \leq n \leq N)$ are calculated for different cell operating temperatures T_n.

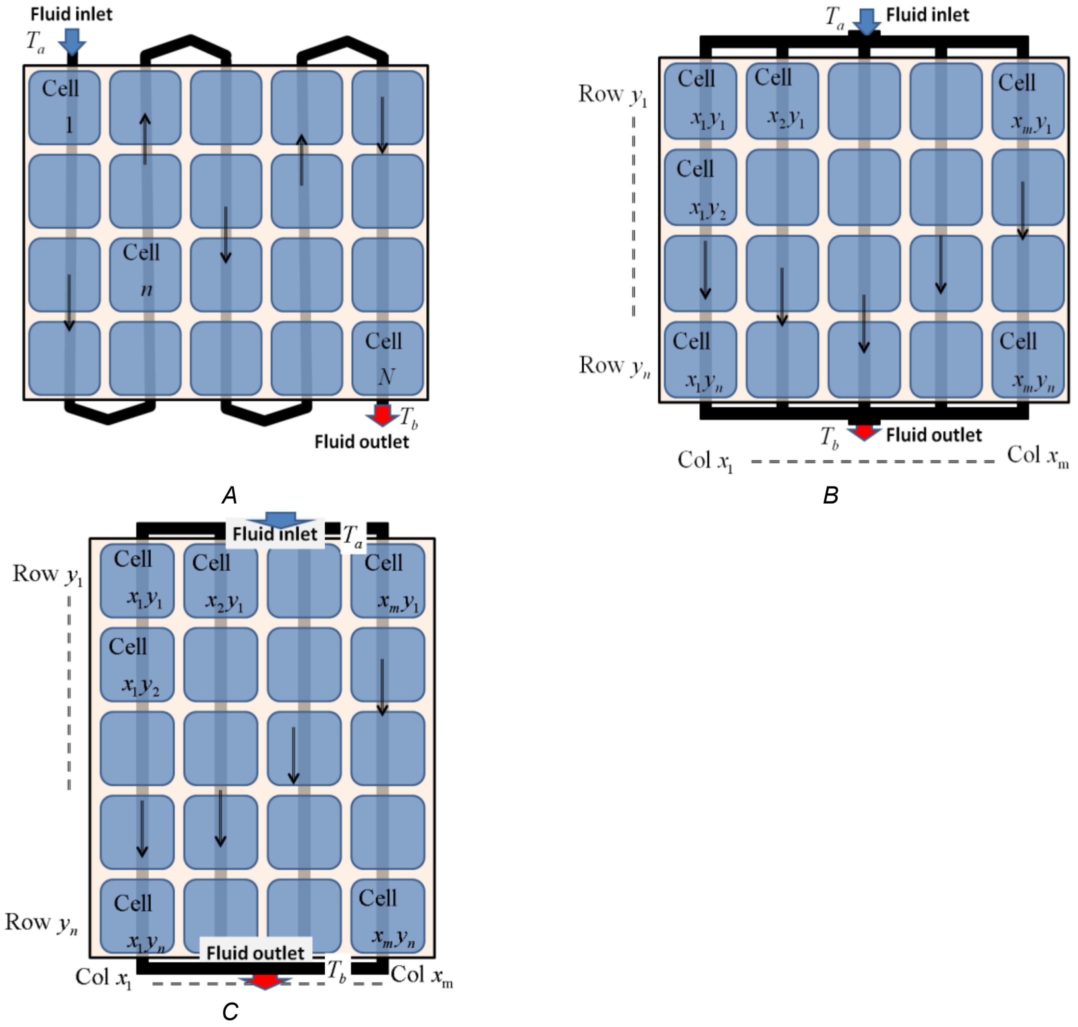

Figure 1: Design A, B and C of cooling pipes of a PV panel consisting of N series-connected solar cells

Figure 1 shows different geometry-designs of cooling pipes considered in this work for a PV panel where the fluid inlet of temperature T_a is underneath cell 1 while the fluid outlet of temperature T_b is at backside of the cell *N*. The fluid serves as both heat sink and solar heat collector (Fontenault and Gutierrez-Miravete, 2012). The arrows indicate the direction of the fluid flow along the backside-attached pipe whose inlet and outlet temperatures are T_a and T_b. In Design A the cooling medium passes from all cells columnwise. Therefore, higher temperatures are observed in the cell columns towards the cooling medium outlet. The PV panels in designs B and C have $m \times n$ serially-connected solar cells where each row $y_{(1 \cdots n)}$ has the same operating temperature while the temperature is different for each column $x_{(1 \cdots m)}$. In both Designs B and C the cooling medium flow is divided equally in m channels with each channel cooling one column of cells. The highest temperatures are observed at the rows closer to the cooling medium outlet. Designs B and C are applied on non-square PV panels and the difference is on the number of channels used for the cooling of the cells. The choices are to use a large number of short channels or small number of larger channels.

Yang et al. (2012) attached thermal couples on the surface of the PV panels and found that the temperature distribution of the cells along the pipe in which fluids flow is linear. Therefore, the cell temperature T_n of a cell n can be expressed as follows:

$$T_n = T_a + \left(T_b - T_a\right)\left(\frac{n-1}{N-1}\right) \tag{1}$$

where the temperature difference $\left(T_b - T_a\right)$ depends on the fluid type, the fluid flow rate, the material and dimensions of the pipe, the efficiency of the cells, and the solar radiation. The temperature of PV cells increases by the absorbed solar radiation that is not converted into electricity, causing a decrease in their efficiencies. To minimize this effect, a suitable fluid is circulated to extract this heat. As the fluid flows it cools the backside of the cells and consequently the cells performance improves (Kalogirou and Tripanagnostopoulos, 2006). However, the observed improvement is not uniform throughout the panel due to the difference of the operating temperatures of the cells. This work takes into account the non-equal cell temperatures in order to more accurately describe the PV panel performance. Without cooling the PV cell temperature T_{PV} is governed by the ambient temperature T_{amb} and the incoming solar radiation (Lasnier and Ang, 1990). The current density/voltage *J*/*V* characteristics of each solar cell are given as:

$$J = J_s\left(\exp\left(\frac{V - JR_s}{n_{id}V_t}\right) - 1\right) + \frac{V - JR_s}{R_p} - J_{ph} \tag{2}$$

where R_p, R_s, J_{Ph}, n_{id} are the shunt resistance, series resistance, short-circuit current density and diode ideality factor (Pachpande and Zope, 2012). The origin of the series resistance is the resistance offered by the contacts and the bulk semiconductor material itself (Ramchandani et al., 2012). The origin of the shunt resistance is the non ideal nature of the p–n junction and the presence of impurities near the edges of the cell that can provide a direct path around the junction (Liu and Dougal, 2002). An added value of this work upon the previous ones is that the operating temperatures of the cells are different for every cell in the same PV module. The saturation current density J_s is expressed as follows (Salmi et al., 2012):

$$J_s = J_{s-nom}\left(\frac{T}{T_{nom}}\right)^3 \exp\left(\left(\frac{T}{T_{nom}} - 1\right)\frac{E_g}{n_{id}V_t}\right) \tag{3}$$

where T_{nom} is the nominal temperature considered to be 300 K and J_{s-nom} is the reverse-saturation current density at nominal temperature. The thermal voltage V_t equals to kT_{nom}/q (Rustemli and Dincer, 2011) and is considered to be 25.9 mV at 300 K. The band gap E_g is calculated based on the temperature dependence coefficient δ of the band gap, as follows:

$$E_g = E_{g-nom} - \delta\left(T - T_{nom}\right) \tag{4}$$

Eq(3) and Eq(4) indicate that different types of solar cells (amorphous silicon, crystalline silicon etc.) which have different values of n_{id} and E_g show different dependence on temperature.

3. Simulation and results

3.1 PV cell and module parameters

Based on Eq(1) the MATLAB code is developed for all given electrical parameters presented in Table 1 to calculate the current of the PV cell. Due to the low voltage produced by a PV cell, several PV cells are connected in series to form a PV module. The PV modules can be also connected in parallel to increase the generated current. In other words, the cells are connected in series and parallel to meet the desired output power.

3.2 Results considering PV modules with and without cooling

As a first step in simulation we assume no fluid flows into the pipes. Therefore, the PV cells in the module share the same temperature. The warm climates (i.e. high ambient temperatures) influence the *J*/*V* characteristics of each PV cell and the corresponding PV module which consists of 36 series-connected identical cells. Considering a cooling fluid as shown in Figure 1, the direction of fluid flow indicates that cell 1 is colder than cell *N* since the fluid serves as heat sink of the PV cells. Therefore, the temperature of the PV cells is not equal for all the cells, and the corresponding *J*/*V* characteristics of each PV cell will look different. Figure 2 compares between the *J*/*V* characteristics of a PV module without cooling (fixed T_{PV}=67 °C) and with cooling (T_a = 30 °C and T_b = 60 °C).

Different geometries of cooling pipes are introduced in order to maximize the PV module's efficiency. Without cooling the achieved efficiency of the PV module is 14 %. Cooling the same module according to design A where one pipe is used, the efficiencies of the PV cells are improved and the corresponding efficiency of the module becomes 15.5 %. To improve upon the design of cooling pipes other designs (B and C) of cooling pipes for a PV panel (composed of $m \times n$ series-connected solar cells) are also introduced. The operating temperatures T_{PV} of PV cells according to Eq. (1) can be rewritten for design B and C as follows:

$$T_{x_i,y_j} = T_a + (T_b - T_a)\left(\frac{x_i - 1}{y_j - 1}\right), \quad i = 1 \cdots m, \quad j = 1 \cdots n \tag{6}$$

Table 1: Input electrical parameters for the test PV cell; these values are used to generate the J/V characteristics based on Eq (1)

Parameter	Value	Parameter	Value
E_g, eV	1.12	R_s, kΩ cm^2	0.5x10^{-3}
G, W m^{-2}	1,000	R_p, kΩ cm^2	7.3
δ, eV K^{-1}	2.8 10^{-4}	J_{ph}, mA cm^{-2}	33
A, cm^2	12.5x12.5	n_{id}	1.2
J_{s-nom}, mA cm^{-2}	3.5x10^{-8}	T_{amb}, K	290

Table 2: Output electrical parameters of the J/V characteristics for the test PV Module

Parameter	No cooling	Design *A*	Design *B*	Design *C*
$V_{oc}(V)$	20.39	21.89	22.81	22.65
$I_{sc}(A)$	5.16	5.16	5.16	5.16
$FF(\%)$	74.9	77.1	78.4	78.2
$\eta(\%)$	14	15.5	16.4	16.2

Design B splits the cooling medium flow into 9 channels with each channel used for the cooling of 4 cells in series. Design C splits the cooling medium into four channels with each channel used for the cooling of 9 cells in series. In all cases that a cooling medium is used the total cooling medium flow rate was constant. Figure 2 shows the efficiency of each PV cell cooled according to all geometries. The efficiency of the PV cells drops in the same direction as that of the fluid. The observed drop is clearly reduced in design B compared to C and A. Figure 2 also shows that implementing cooling pipes underneath each PV string improves the performance of the PV module due to the enhancement of the performance of the PV cells themselves. Table 2 presents the output electrical parameters of the test PV module cooled with different geometries where design B shows the best average electrical efficiency upon all other geometries. Design B achieved the lowest average cell temperature enabling the achievement of higher overall PV efficiency.

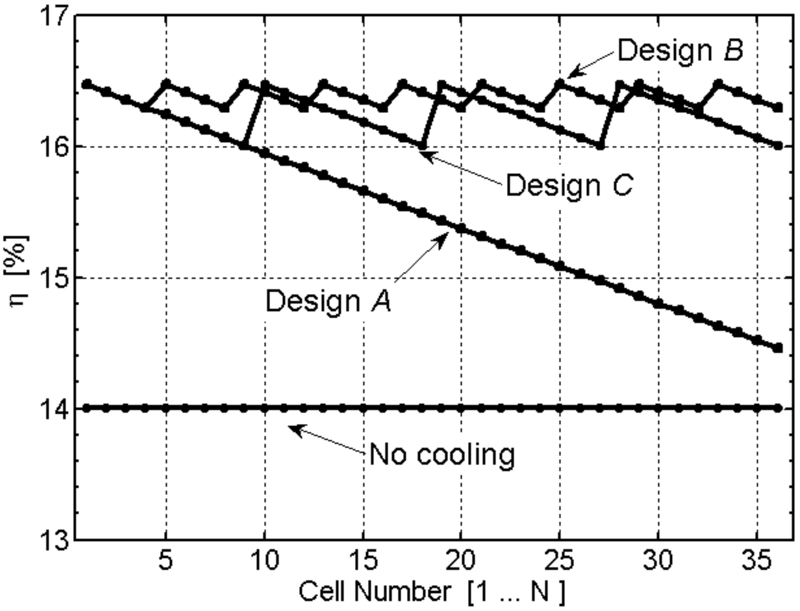

Figure 2: The electric efficiency η of each PV cell (N=1 to N=36) for the cooling configurations and the PV geometries shown in Figure 1

4. Conclusion

This paper examined the performance of PV modules whose PV cells operate under different temperatures since the fluid flowing through the pipes has a temperature gradient from the inlet toward the outlet. Therefore, this study introduced a more accurate evaluation of the PV modules performance. Implementing cooling pipes underneath each PV string improves the performance of the PV cells since they will not heat much in comparison with using one pipe for the entire PV module. Applying a cooling pipe for each string enhances much more the electrical efficiencies of the PV cells. The best design is the one which keeps the operating temperature of the PV cells as minimum and uniform as possible, resulting in a maximum energy yield of the PV cells.

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