Thermal/Electrical Modeling of a PV Module as Enhanced by Surface Cooling

A. Elnozahy, Ali K. Abdel Rahman, Ahmed Hamza H. Ali, Mazen Abdel-Salam, and S. Ookawara

***Abstract*—The present work is aimed at developing thermal and electrical models which are capable of estimating the two dimensional thermal and electrical performance of a PV module under given meteorological conditions. The thermal modeling has been developed in COMSOL Multiphysics software environment and the electrical modeling has been carried out in PSIM software environment. The main objective of the electrical model is to investigate the I-V and P-V characteristics of an 80W thin film PV module with and without cooling at varying surface temperature and irradiation. In the thermal model, the dependence of module surface temperature, electrical efficiency, and thermal efficiency on water flow velocity is investigated. The results obtained from the proposed electrical and thermal models are validated experimentally. The results showed that the maximum electrical, thermal and net energy efficiency values of cooled PV module are 9.92%, 55.6%, and 65.4%, respectively. Variation of water flow velocity experiences no significant temperature change in the coolant water exiting the module and results in a slight change of both the module surface temperature and electrical efficiency.**

***Index Terms*—COMSOL software, cooling system, electrical model, PSIM software, PV module, and thermal model.**

I. Introduction

Photovoltaic technology provides the direct method to convert solar energy into electricity. Modeling and simulation plays a very important role in the development of PV modules as well as in the design of PV systems. Photovoltaic (PV) system performance models are relied upon to provide accurate predictions of energy production for proposed and existing PV systems under a wide variety of environmental conditions.

Park *et al*. [1] investigated the electrical and thermal performance of a semi-transparent PV module that was designed as a glazing component.

The study evaluated the effects of the PV module's thermal characteristics on its electrical generation performance. The experiment was performed under both Standard Test Condition (STC) and outdoor conditions. The results showed that the power decreased about 0.48% (in STC with the exception of the temperature condition) and 0.52%(in outdoor conditions, under 500 W/m^2) per the 1^{o}C increase of the PV module temperature. It was also found that the property of the glass used for the module affected the PV module temperature followed by its electrical performance.

Lobera and Valkealahti [2] presented a dynamic thermal model based on the total energy balance in the PV module. Main heat transfer mechanisms between the module and its environment were modeled theoretical. The model was verified by the measurements data of the solar photovoltaic power station research plant.

A three dimensional numerical model to predict thermal and electrical performance of the PV module with and without cooling for given environmental and operating conditions was presented and validated. Results showed that the performance of the PV module with cooling had very little influence of increasing absorbed radiation (200–1000 W/m^2) at a constant ambient temperature (25^{o}C) and increasing ambient temperature (0– 50^{o}C) at an absorbed radiation of 800 W/m^2. For the same variation in conditions, the performance of the module without any cooling reduced significantly [3].

Brano and Ciulla [4] presented a fully analytical model to predict the electrical performance upon solar irradiance intensity and PV module temperature. The model refereed essentially to an equivalent circuit governed by five parameters and the extraction of them permitted to describe the I–V curve of the PV module and consequently permitted to assess the energy output of PV modules. The proposed model extracted the five characteristic parameters using only exact analytical relationship and tabular data always available such as short-circuit current, open circuit voltage, and the Maximum Power Point (MPP).

A photovoltaic module with a heat extraction system was studied. Hybrid electric thermal PV modules have been built using a layer of water superimposed to the module and confined in a polycarbonate box. Simulations of the thermal and electric behavior were developed with particular care to the efficiency of the system and to its transient behavior. An extended concept of thermal and electric efficiencies was introduced. Experiments done during a period of eight months confirmed the simulation analysis [5].

Kim *et al.* [6] investigated the thermal characteristics of a PV module by change of ambient temperature from 25^{o}C in minimum to 50^{o}C in maximum through a thermal analysis simulation program. In addition, a simulation method to attach fins to the backside of PV module was discussed. This work showed the comparison of the thermal characteristics between a PV module with and without fins. The results showed that the temperature of PV module to attach fins to the backside of PV module was lesser than without fins because heat was emitted at the fins.

The mathematical analysis of the single diode model was

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done. The I-V and P-V characteristics were verified for the PV module for the constant Irradiation (1000W/m^2) and constant temperature (25^{o}C). Similarly the I-V and P-V characteristics were observed for different irradiations (600W/m^2, 200W/m^2) and different temperatures (50^{o}C and 75^{o}C) [7].

Based on this background, this paper is aimed at developing thermal and electrical models which are capable of estimating the two dimensional thermal and electrical performance of a PV module under given meteorological conditions. The thermal modeling has been developed in COMSOL Multiphysics software environment and the electrical modeling has been carried out in PSIM software environment. The main objective of the electrical model is to investigate the I-V and P-V characteristics of an 80W thin film PV module with and without cooling at varying surface temperature and irradiation. In the thermal model, the dependence of module surface temperature, electrical efficiency, and thermal efficiency on water flow velocity is investigated. The results obtained from the proposed electrical and thermal models are validated experimentally.

II. Electrical Model

The equivalent circuit of a photovoltaic cell is shown in Fig. 1 [8] where R_s is the very small series resistance, R_{sh} is the quite large shunt resistance, and D is the ideal P–N diode. I_{ph} is the generated photocurrent source which is influenced by the surface temperature and irradiation. V and I represent the output voltage and current of the cell, respectively.

A. Governing Equations

According to the physical property of P–N semiconductor, the I-V characteristic of a module consists of series-parallel combination of n cells is expressed as follows [8]:

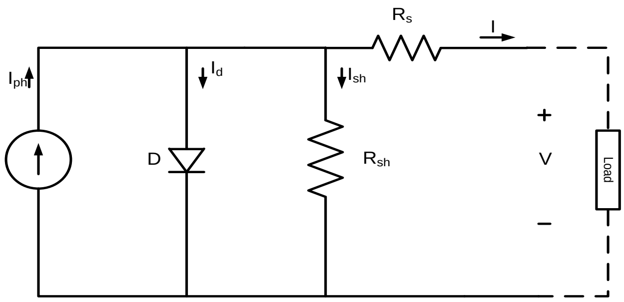


Fig. 1. Equivalent circuit of PV cell.

$$I = n_p I_{ph} - n_p I_o \left[\exp\left\{ \frac{q}{AkT}\left(\frac{V}{n_s} + IR_s \right) \right\} - 1 \right] - \frac{V - n_s}{R_{sh}} \qquad (1)$$

where

$$I_{ph} = \left\{ I_{sc} + k_{sc}\left(T - T_{ref}\right) \right\} \frac{q_{rad}}{1000} \qquad (2)$$

$$I_o = I_r \left(\frac{T}{T_r} \right)^3 \exp\left\{ \frac{qE_{gap}}{kA}\left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right\} \qquad (3)$$

In (1), q is the electron charge (1.602×10−19, C); k represents the Boltzmann constant (1.38×10−23 J/◦K), T is the surface temperature of module, A is the ideality factor (A = 1–5), n_s is the number of cells connected in series, and n_p is the number of cells parallelly connected so $n = n_s n_p$. I_{sc} is the short-circuit current, k_{sc} is the temperature coefficient of the short-circuit current, and q_{rad} is the solar radiation in W/m^2. The module reverse saturation current I_o is expressed in (3), where E_{gap} is the energy of the band gap for silicon (E_{gap} =1.1 eV) and T_{ref} is the reference temperature of PV module.

B. PSIM Based PV Module Modeling

Fig. 2 shows the electrical model of SF80-A PV module formed from the PSIM software package. The series resistance is always neglected in conventional mathematical model to form a simple equation. However, in the proposed PSIM model, the series and shunt resistance are taken into consideration. Therefore, the proposed model can be considered significantly more accurate than the conventional model in simulating the PV module characteristics. The components of both the main circuit and subcircuit of the proposed electrical model are described in Appendix A.

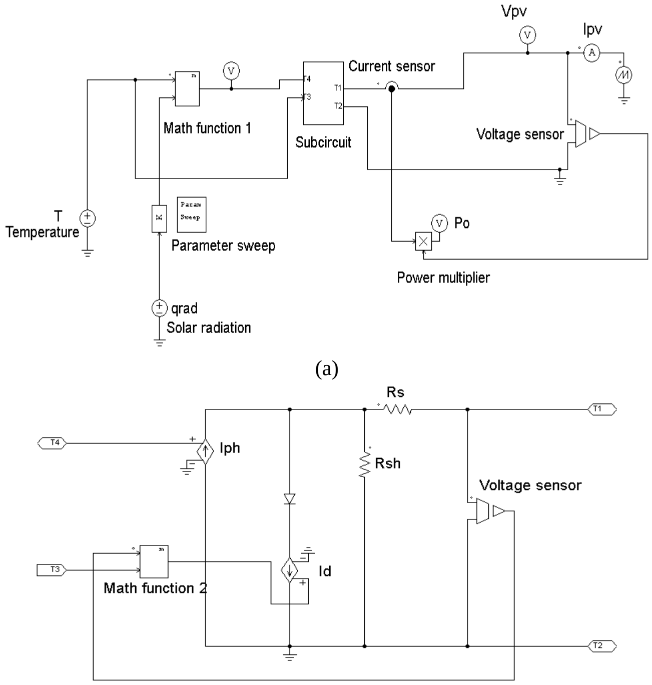


Fig. 2. Schematic diagram of PSIM based PV module (a) main circuit and (b) inner subcircuit.

III. Thermal Model

The thermal performance of the PV module is evaluated using COMSOL Multiphysics software. A water film, glass and silicon layers are modeled in COMSOL for the tested PV module being cooled by water as shown in Fig. 3. The coolant water film flows over the surface of the module at a constant thickness.

A. Geometry and Material Properties

The geometry of the system is divided into the following subdomains:

1) *Solid Subdomains:* The glass of the cover layer has length and thickness of 1230 mm and 3 mm, respectively.

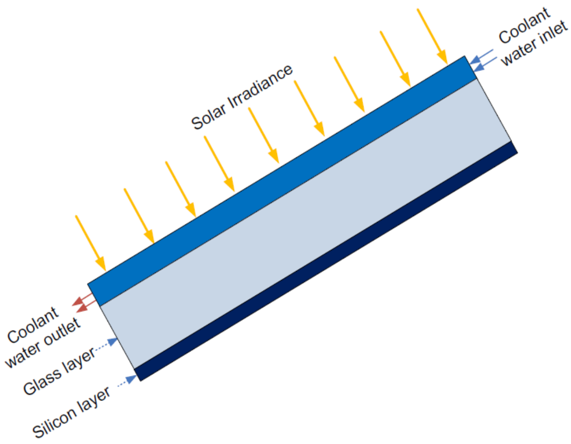


Fig. 3. A schematic of water film, glass and silicon layers.

The silicon layer has length and thickness of 1230 mm and 0.4 mm, respectively.

2) *Fluid Subdomain:* The thickness of the water film is 1mm.

The tilt angle of the three-forming layers of the module is 30 °with respect to the horizontal plane as shown in Fig. 4. All material properties are provided by COMSOL data base at each time step in the simulation, including temperature dependent properties for water.

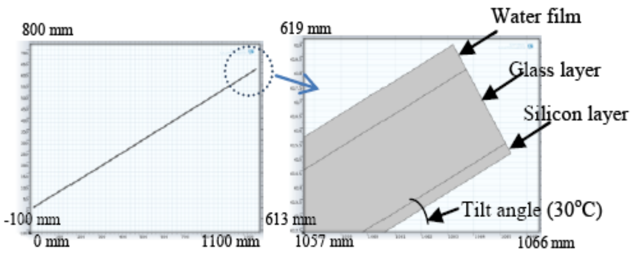


Fig. 4. Geometry of PV module with film of water as built in COMSOL.

B. Simplifying Assumptions and Data Input of PV Module Model

Several simplifying assumptions are made to perform this study regarding the conceptual PV module construction, atmospheric conditions, water flow characteristics, and other factors, which impact this thermal analysis:

1) All solar irradiance that is not used to produce electricity in the PV module will be developed into heat.
2) No dust or any other agent is deposited on the module surface affecting the absorptivity of the PV module.
3) The flow through the top surface of the module is considered to be fully laminar and incompressible at uniform temperature.
4) The coolant water temperature at inlet is equal to the ambient temperature surrounding the PV module (= 298 K).

The PV module is commercial grade thin film silicon module with dimension of length, width and thickness of 1235, 641 and 35 mm, respectively. The electrical efficiency, η_{Tref} at reference conditions (T_{ref} = 25°C and q_{rad} =1000W/m^2) is 10% with a thermal coefficient, β_{ref} , of 0.3% (1/K) to express the degradation of the output of PV module per degree of temperature [9].

C. Governing Equations

All three modes of heat transfer are involved when considering the heat flow through the PV module. Heat is transferred within the PV module and its structure by conduction. Heat is transferred to the PV module surroundings by both free and forced convection. Heat is also removed from the module in the form of long-wave radiation [10]. COMSOL numerically solves the continuity and momentum equations, which are the governing equations for the fluid flow as expressed by (4) and (5), respectively [11].

$$\nabla \cdot (\rho u) = 0 \tag{4}$$

$$\rho u \cdot \nabla u = -\nabla p + \nabla \cdot \left(\mu\left(\nabla u + (\nabla u)^T\right)\right) \tag{5}$$

where ρ , u, p , and μ are density, velocity, pressure, and dynamic viscosity of water film on the front face of the module, respectively.

The conduction-convection equation is also solved for the heat transfer in the flowing water as expressed by (6).

$$\rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) \tag{6}$$

where C_p and k are the specific heat capacity and thermal conductivity of water, respectively.

The long-wave radiation heat loss is expressed by (7), [12].

$$q_{lw} = \varepsilon \cdot \sigma \cdot \left(T_{pv}^4 - T_{amb}^4\right) \tag{7}$$

where ε , σ , T_{pv} , and T_{amb} are surface emissivity, Stefan–Boltzmann Constant ($=5.67\times10^{-8}\,\mathrm{W/m^2K^4}$), module surface temperature, and ambient temperature, respectively.

The amount of energy converting into electric power in the PV module is a function of the PV module efficiency, η_{elec} as expressed by (8), which satisfies assumption 1 above.

$$q_{heat} = q_{rad}\left(1 - \eta_{elec}\right) \tag{8}$$

The module electrical efficiency (η_{elec}) is expressed in (9), as a function of its efficiency (η_{Tref}) at reference conditions, the PV module surface temperature (T_{pv}), and the PV module thermal coefficient (β_{ref}) [13].

$$\eta_{elec} = \eta_{Tref}\left[1 - \beta_{ref}\left(T_{pv} - T_{ref}\right)\right] \tag{9}$$

The total amount of energy received by the module due to its expose to solar irradiance is calculated as follows:

$$E_{in} = q_{rad} \cdot A \tag{10}$$

The thermal energy extracted by the cooling water is calculated as:

$$E_{water} = m_{water} C_p \left(T_{outlet} - T_{inlet} \right) \tag{11}$$

The mass flow rate of the water (m_{water}) passing on the top of the module is calculated as the product of the density (ρ) and flow rate (Q) of the water. The thermal efficiency is simply expressed as:

$$\eta_{th} = \frac{E_{water}}{E_{in}} \tag{12}$$

The input energy which is converted to electrical energy (E_{pv}) is obtained by multiplying (9) and (10).

$$E_{pv} = \eta_{elec} E_{in} \tag{13}$$

The net efficiency of the PV module is calculated as:

$$\eta_{tot} = \frac{E_{water} + E_{pv}}{E_{in}} \tag{14}$$

It was verified that all the flow velocity values used would produce laminar flows, rather than turbulent flows, by calculating the Reynolds number, Re, from (15), shown below at characteristic distance (D) and confirming that was less than 2300 to satisfy assumption 3.

$$\mathrm{Re} = \frac{\rho u D}{\mu} \tag{15}$$

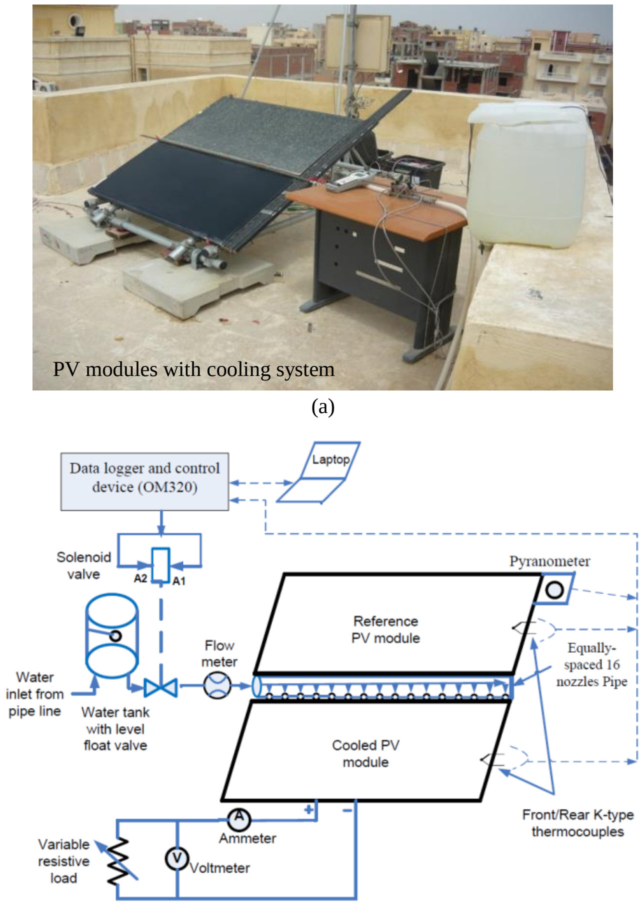
The COMSOL software model the flow through the water film by simultaneous solution of the continuity, momentum, and energy equations in an iterative procedure where the boundary condition of the outer surface of the water film is selected as slip-wall. At each iteration in the simulations performed, the PV module efficiency, η_{elec} is calculated from (9), from the user input values for β_{ref} , η_{Tref} , and T_{ref} . The COMSOL solve the describing equations to predict a value for the surface module temperature, T_{pv}. The amount of solar irradiance, q_{rad} , which is transformed into heat, q_{heat} , is then calculated from (8). Values for the thermal efficiency of the module are calculated iteratively by COMSOL using (10)-(12). Post processing of the data recorded in the simulations is required to calculate the thermal efficiency, η_{th} of the PV module.

IV. Experimental Setup

An experimental setup has been developed to study the performance of the tested PV module as enhanced with cooling system and validate the proposed thermal and electrical models with experimental results. The electrical and thermal performance of thin film PV module with surface cooling is evaluated using PSIM and COMSOL Multiphasics software, respectively. According to [14] a cooling system consists primarily of a copper pipe with 16 equally–spaced nozzles mounted opposite to the front side of PV module. Through the pipe, water flows to cool the module from the front side rather than using water reservoir to cool the module on the backside. The flow of water on the PV module surface is controlled using a solenoid valve [14] as shown in Fig. 5.

Two SF80-A thin film PV modules were used in this study. The reference one is located in upper side to the module with cooling system as shown in Fig. 5a. The measurements were recorded during a clear day (10th of April 2014) on the roof of the Energy Resources Engineering (ERE) department building at Egypt-Japan University of Science and Technology (E-JUST) temporary campus in new Borg El-Arab city, Alexandria-Egypt.

Irradiance was measured by a pyranometer at the same incidence plane of the modules: south at an elevation angle of 30°.



(b)

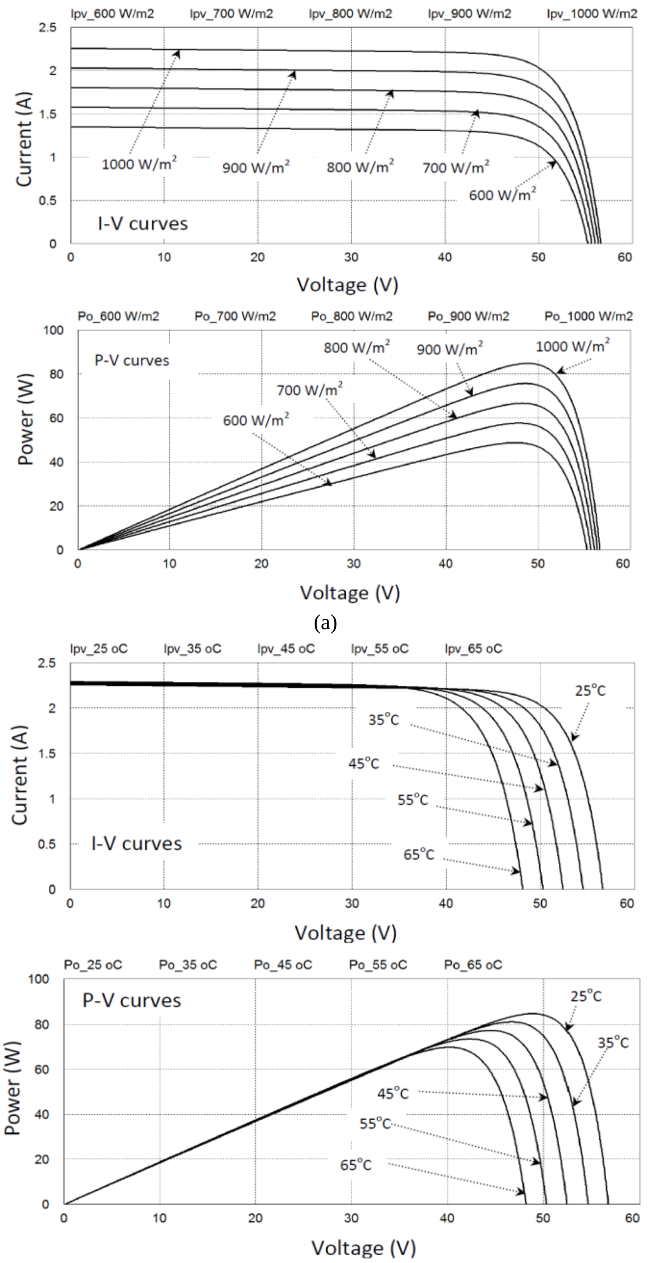
Fig. 5. PV modules with surface cooling system (a) Photograph of PV system (b) Schematic diagram [14].

Ambient temperature was measured by K-type thermocouple. This is in addition to four K-type thermocouples installed on the two modules to measure the actual modules temperatures. Two thermocouples are installed on the front face of the two modules. The other two are installed on the rear face of the two modules. As shown in Fig. 5b, the five K-type thermocouples are connected to the OM320 data logger and control whereas the data is reordered every one hour during 06:00 AM to 06:00 PM period. Tracking of the ‘‘maximum power point’’ is done manually by utilizing the variation of an ohmic load and measuring output voltage and current [14].

V. Results and Discussion

Fig. 6 shows the I–V and P–V characteristic curves of tested SF80-A PV module as obtained by the proposed PSIM electrical model at varying irradiance, q_{rad} and temperature, T. The dependence of the short circuit current on the irradiance is shown in Fig. 6a. The effect of temperature on the open circuit voltage is shown in Fig. 6b.

Fig. 7 shows the experimental I-V and P-V curves of tested PV module against those obtained by the PSIM model. The experiment results validate the proposed model. This is because of there is a satisfaction agreement between these results and those obtained from the model for the tested PV module with and without cooling, as shown in Fig. 7. It is clear that, the module surface temperature has a significant effect on the open circuit voltage (62.3 V for cooled module against 59 V for module without cooling) while it has less effect on the short circuit current, Fig. 7.

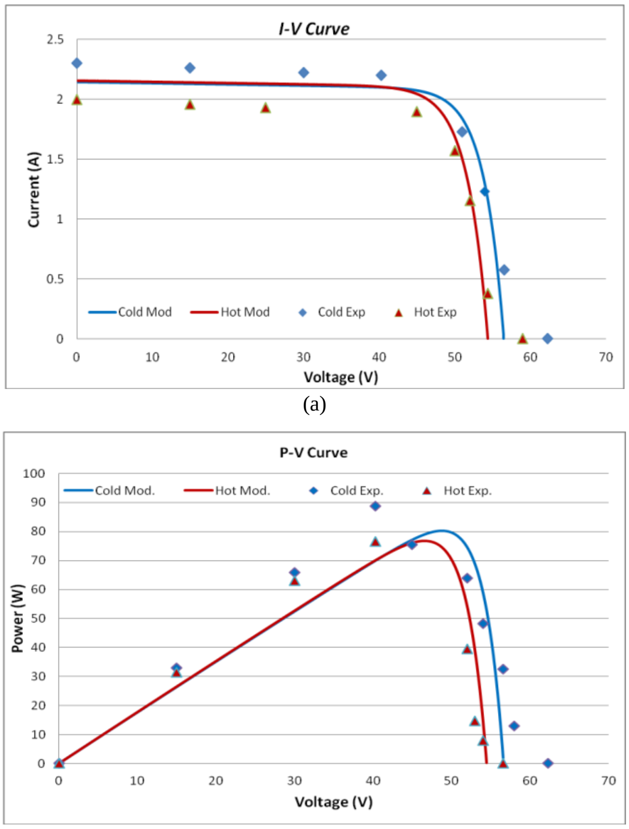


(a)

(b)

Fig. 6. I-V and P-V curves of the PSIM based PV module model at varying (a) irradiance at $T = 25^{o}$C and (b) temperature at $q_{rad} = 1000 W/m^2$.

Data extracted from COMSOL following each simulation include the average module surface temperature, T_{pv}, average water outlet temperature, T_{outlet}, average water density, ρ, and average water heat capacity, C_p. The values for η_{elec}, η_{th} and η_{tot} after each simulation are manually calculated in Microsoft Excel using (9)–(14).



(a)

(b)

Fig. 7. Electrical model validation with and without cooling using experimentally measured data at irradiance of 950 W/m^2 (a) I-V curve (b) P-V curve.

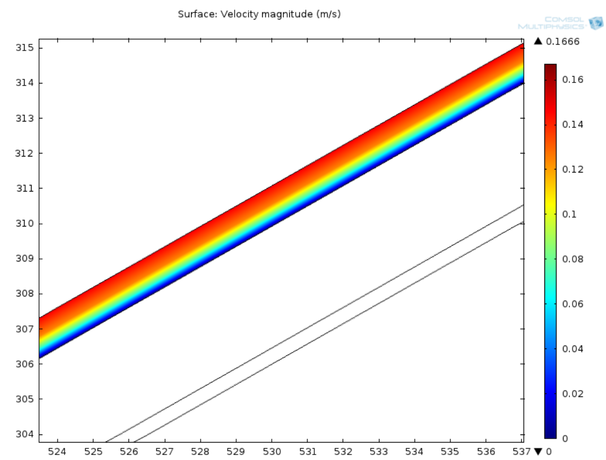


Fig. 8. Water laminar flow velocity profile.

By varying the flow velocity of water from 0.01m/s to 1m/s, a laminar flow profile of water film on the surface of the PV module is achieved at each flow velocity values as shown in Fig. 8. One can see the slip-wall boundary condition invoked on the outer wall of the water film, and the half parabolic flow profile that is created. As expected, the maximum flow velocity is at the outer surface of the water film as shown in

Fig. 8. The module surface temperature (T_{pv}) showed a drop from 303.5K to 300.5K against the drop of the water outlet temperature (T_{outlet}) from 303.3K to 301.3K as shown in Fig. 9. The electrical efficiency (η_{elec}) increased from 9.82% to 9.92 (which approaches10%, the efficiency at reference conditions). In contrast, the thermal and net efficiencies decreased by increasing the water flow velocity as shown in Fig. 10. The maximum values of the thermal and net efficiencies reached 55.6% and 65.4% respectively.

Therefore, the change in water flow velocity has slight effect on the surface temperature of the PV module and electrical efficiency. Although a high inlet velocity results in the lowering PV module surface temperatures and increasing the electrical efficiency. The coolant water exiting the module experiences no significant temperature change. The difference is 5°C between inlet and outlet water temperature inconformity to the experimental results (5.5°C at water flow velocity 0.17m/s). Therefore, it would not be entirely beneficial to utilize the water exiting the PV module for any practical application.

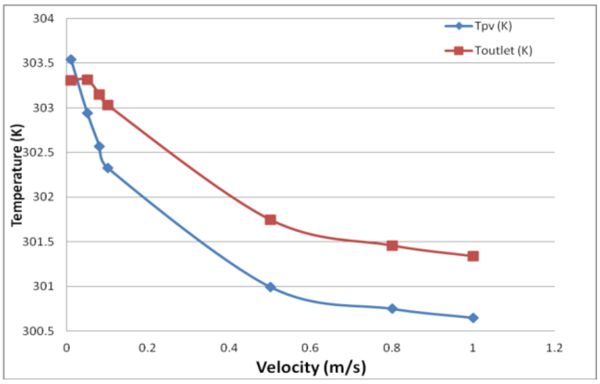


Fig. 9. Average module surface temperature and water outlet temperature as influenced by water flow velocity at inlet water temperature, T_{inlet} of 298 K.

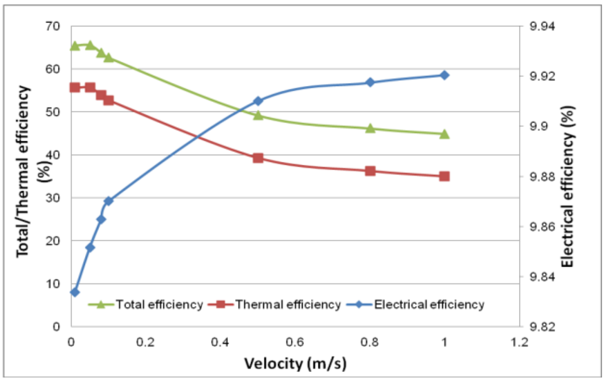
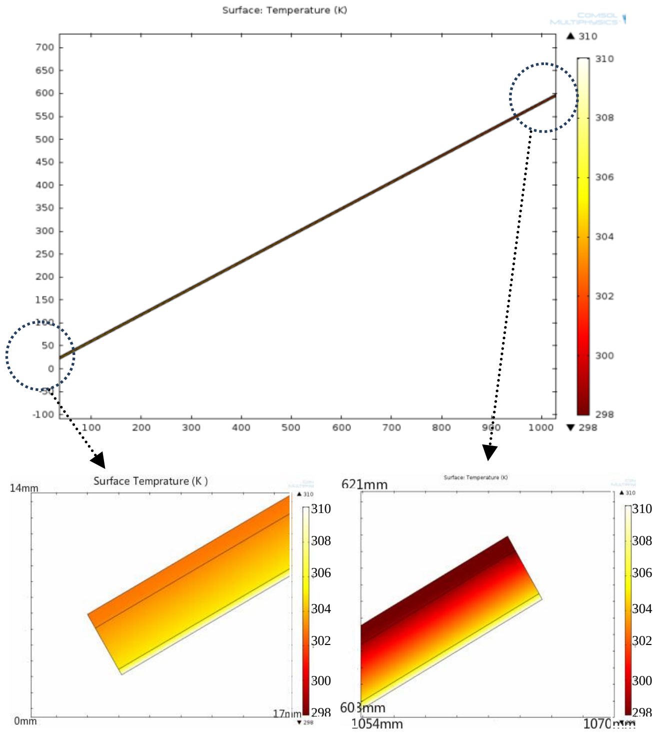


Fig. 10. Electrical, thermal and net efficiency values of the PV module as influenced by water flow velocity at inlet water temperature, T_{inlet} of 298 K.

A two-dimensional plot for the steady state solution of the temperature distribution along the PV module layers at water flow velocity 0.1m/s is shown in Fig. 11. It is clear that the water temperature at inlet is 298 K (equal the ambient temperature), Fig. 11a, and increases along the module length to reach the highest value of 303 K at the outlet, Fig. 11b. The gradient of the temperature across the module layers and water film is shown in Fig. 11, where the average temperature of the front surface of the PV module is 302 K and increases across the module to reach 310 K at the rear surface.



(a) (b)

Fig. 11. Two-dimensional surface plot of PV module temperature at water flow velocity 0.1m/s; (b) Outlet temperature at 303 K, (a) Inlet temperature at 298 K.

VI. Conclusions

In this study, the performance evaluation of a PV module as enhanced by surface cooling system is carried out. A detailed thermal and electrical model is developed to predict the I-V and P-V characteristics of the PV module as well as the electrical, thermal and net efficacies are calculated. From the study, the following conclusions are drawn.

1) The proposed electrical and thermal models are validated by comparison against experiment and proved to have a satisfactory agreement with the output characteristics of a tested PV module with and without cooling.
2) The module surface temperature has a significant effect on the open circuit voltage (62.3 V for cooled module against 59 V for module without cooling) while it has less effect on short circuit current.
3) Variation of water flow velocity results in a slight change of both the module surface temperature and electrical efficiency (η_{elec} increased from 9.82% to 9.92 when flow velocity increased from 0.01m/s to 1m/s.
4) The maximum electrical, thermal and net energy efficiency values of cooled PV module in the present study are 9.92%, 55.6%, and 65.4%, respectively.
5) Variation of water flow velocity experiences no significant temperature change in the coolant water exiting the module (the difference between maximum water outlet and inlet temperature is 5 degree).

Appendix

A. Main Circuit Components of Electrical Model as Shown in Fig. 2a

Math function 1 represents (2).

Parameter sweep represents the change in temperature and solar radiation.

Power multiplier represents the calculation of output power

Voltage/current sensors measure the output voltage and current of PV module.

B. Subcircuit Components of Electrical Model as Shown in Fig. 2b

Math function 2 represents (3).

Two voltage controlled current sources represent currents I_{ph} and I_o.

R_s and R_{sh} represent Series and shunt resistance of the PV module, respectively.

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