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A Detailed Mathematical Modelling and Experimental Validation of Top Water Cooled Solar PV Module

In this research article, an analytical model has been developed to examine the electrical and thermal behaviour of a solar photovoltaic module with top water cooling. Mathematical calculations have been performed under India, Chennai (latitude: 13.06° N and longitude: 80.11° E) prevailing weather conditions. Three modes of heat transfer mechanisms are considered in the thermal model and computed using improved correlations. The model validation against the experimental data exhibited a good agreement. Daily average electrical and overall thermal efficiency of a PV module with top water flow have been found to be 14.29% and 45.44% respectively. Water flows on top side of the PV module decreases the average module temperature of a day from 56.67°C to 39.44°C, and the average daily module electrical efficiency is increased up to 14.29%, compared to 12.74% efficiency of PV module without cooling.

Keywords: *Analytical modelling, Top water cooling, PV cell temperature, Efficiency.*

1. INTRODUCTION

In recent years, solar technology has been promoted as a viable power source vigorously. Solar energy can be utilised using two types of technologies, solar-thermal and photovoltaic. In a solar-thermal system, the solar energy is converted into thermal energy, and on the other hand, the photovoltaic technology directly converts the solar energy into electrical energy. Usually, electrical energy and thermal energy are generated separately. However, latest research studies on making electrical and thermal energy simultaneously by using a coupled apparatus are designed and are commercially known as Photovoltaic-Thermal or PV/T collectors. They are used to generate electrical power and retrieve the thermal energy thereby decreasing the photovoltaic module temperature. According to the type and climate conditions, a photovoltaic panel converts 6-20% of the incident solar insolation into electric power. The majority of the incident solar energy on PV module is mutated into heat which elevates the PV cell temperature, and which motives to diminishing in its electrical power generation consequently. The increase in temperature of PV cell causes a substantial drop in open circuit voltage (V_{oc}) that results in a great loss in electrical efficiency. For a solar cell made of crystalline silicon, the short-circuit current (I_{sc}) increases slightly whereas, the V_{oc} drops significantly by about 2.3 mV/°C. Due to this fact, the electrical yield was reduced by about 0.4%/°C–0.5%/°C for multi and mono-crystalline silicon solar cells. Another essential factor that impacts the electrical output of the PV module is solar insolation reflection loss. The reflection loss of solar radiation yields around 4–5% if it strikes a glass covered PV-panel at a perpendicular incidence angle. Numerous ideas are proposed to reduce the reflection, yet many possess disadvantageousness: anti-reflective coatings are certainly not robust, and surface structuring is expensive, accumulate dust and dirt are hard to clean. However, the water refractive index is 1.3, and it is in between glass (n_g = 1.5) and air (n_{air} = 1.0). Water cooling on top of the module reduces reflection by 2–3.6% and simultaneously decreases the cell temperature. Krauter et al. [1] experimentally analysed the PV module performance by flowing the water over the top side of the module. Typically, the reflection irradiance reduces the electrical yield of PV modules by 8–15%. They concluded by flowing water on top of the PV module the reduction in reflection and cell temperature up to 3.6% and 22°C respectively. Also, the electrical output is increased up to 10.3%. Abdolzadeh et al. [2] studied the state of enhancing the efficiency of a water pumping PV system by spraying water over the PV module. He found that the optical performance and average PV cell efficiency is increased by 1.8% and 12.5% respectively due to spraying water over the cells. Kordzadeh et al. [3] studied the effects of PV array for PV water pumping system with the surface of array covered by a thin water film. He concluded this method improves the PV panel and whole system efficiency. Moharam et al. [4] developed a mathematical model to evaluate the cooling rate of the PV panel by spraying water on top of the panel. The cooling rate of the solar cell is found to be 2°C/min. This model is used to minimise the quantity of water and energy required for cooling the PV panel. Gaur et al. [5] experimentally and theoretically investigate the cooling of the thin film amorphous silicon PV module by flowing water on top. The theoretical model results are validated with experimental results and found good

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agreement between them. He concluded that the electrical and thermal efficiency of the water-cooled PV module is found to be 7.36% and 22.1% respectively. Irwan et al. [6] performed a comparative study on PV panel with and without the water cooling mechanism by using the solar simulator. A DC water pump used to spray the water over the PV module which consequently reduces the operating temperature and reflection of the PV panel. The experimental result shows that the reduction in operating temperature was found to be 5 - 23˚C and the increase in electrical power were found to be 9 - 22 %. Nizetic et al. [7] developed an experimental system to investigate the optimal cooling of the PV module by spraying the water on the bottom, top and side of the module. He reported the average reduction in PV module temperature from 52°C to 24°C and the electric power output is increased up to 14.1% is obtained. So far, no comprehensive mathematical model is available to predict the thermal and electrical behaviour of the photovoltaic module by top water cooling technology. In the present paper, a detailed analytical model is developed to analyse the performance of the photovoltaic module when a thin film of water is flowing over the top side of the module. Detailed steady-state energy balance equations are simultaneously solved to determine the temperature of every layer of the system. The overall thermal efficiency, gain in energy and exergy calculations have also been investigated. Experimental analysis was conducted to validate the present mathematical model results.

2. ANALYTICAL MODELLING

2.1 Thermal modelling

Thermal analysis has been carried out by solving the energy balance equations for top water cooled PV panel to calculate the thermal parameters and thermal efficiency of the present system. Figure 1 shows the schematic cross - sectional diagram of top water-cooled PV module. The various design parameters of the PV/T system and other parameters used in this study are given in Table 1.The following assumptions are considered to write the energy balance equations for various layers of the solar PV/T system:

- The system is in quasi-steady-state condition.
- One dimensional heat conduction.
- The ohmic losses in the photovoltaic solar cells are negligible
- Water flowing is uniform along the length of PV module.
- The ambient temperature is same on all area exposed to the environment.
- The reference temperature and pressure are 25°C and 101325 Pa.

The thermal parameters and thermal efficiency of a top water-cooledphotovoltaic module system are obtained if the energy balance equation is written for each layer of a PV/T system.

For water layer on top:

[Convective heat transfer from glass top-water flow] = [Flowing water heat gain rate] + [Heat loss rate from flowing water-ambient]

$$h_{c,g-w}\left(T_g - T_w\right)Bdx = \dot{m}C_w\left(\frac{dT_w}{dx}\right)dx + \\ +h_{tot,w-a}\left(T_w - T_a\right)Bdx \tag{1}$$

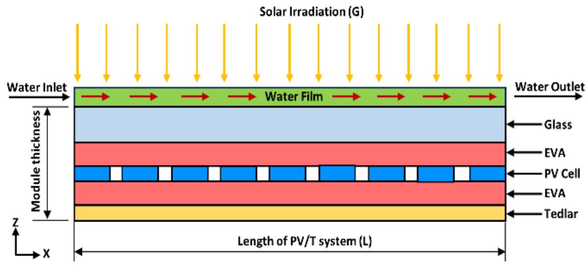

Figure 1. Schematic diagram of PV/T system

Table 1. Design parameters used in the present analytical modelling

Parameter	Value	Parameter	Value
L	1.5 m	V_{wind}	1.0 m/s
B	0.66 m	ρ	1000 kg/m^3
C_f	0.36	k_w	0.575 W/(mK)
α_g	0.04	k_g	2 W/(mK)
α_e	0.08	k_e	0.311 W/(mK)
α_c	0.9	k_c	130 W/(mK)
α_t	0.128	k_t	0.15 W/(mK)
τ_g	0.92	L_g	0.003 m
τ_e	0.9	L_e	0.0005 m
τ_c	0.02	L_c	0.0002 m
τ_t	0.012	L_t	0.0003 m
ε_w	0.98	μ_f	0.764x10^{-3}Ns/m^2
β_c	0.83	γ	0.68

For glass top side:

[The rate of solar energy available on glass] + [Conductive heat transfer from EVA-1-glass] = [Convective heat transfer from glass-flowing water]

$$\alpha_g G + U_g\left(T_{e,1} - T_g\right) = h_{c,g-w}\left(T_g - T_w\right) \tag{2}$$

For upper EVA (EVA-1):

[The rate of solar energy available on upper EVA] + [Conductive heat transfer from PV cells-upper EVA] = [Conductive heat transfer from upper EVA-glass]

$$\alpha_{gg} G + U_{ec}\left(T_c - T_{e,1}\right) = U_g\left(T_{e,1} - T_g\right) \tag{3}$$

For solar PV Cell:

[The rate of solar energy available on PV cells] = [Rate of electrical power produced] + [Conductive heat transfer from PV cells-upper EVA] + [Conductive heat transfer from PV cells-lower EVA]

$$\alpha_{cegc} G = E_p + U_{ec}\left(T_c - T_{e,1}\right) + U_{cc}\left(T_c - T_{e,2}\right) \tag{4}$$

For lower EVA (EVA-2):

[The rate of solar energy available on lower EVA] + [Conductive heat transfer from PV cells-lower EVA] = [Conductive heat transfer from lower EVA-tedlar]

$$T_{w,out} = W.\left[1-\exp\left(-W_1 L\right)\right] + T_{w,in}\exp\left(-W_1 L\right) \quad (5)$$

For Tedlar inner Side:

[The rate of solar energy available on tedlar] + [Conductive heat transfer from lower EVA-tedlar top] = [Conductive heat transfer from tedlar top-tedlar bottom]

$$\begin{aligned}&\alpha_t \tau_c \tau_e^2 \tau_g \beta_c G + \left(1-\beta_c\right)\alpha_e \tau_e^2 \tau_g G + \\ &+U_e\left(T_{e,2} - T_{t,top}\right) = U_t\left(T_{t,top} - T_{t,btm}\right)\end{aligned} \quad (6)$$

For Tedlar outer side:

[Conductive heat transfer from tedlar top-tedlar bottom] = [Convective heat transfer from tedlar bottom-ambient]

$$U_t\left(T_{t,top} - T_{t,btm}\right) = h_{wind}\left(T_{t,btm} - T_a\right) \quad (7)$$

2.2 Dimensionless numbers and heat transfer coefficients

The following innumerable dimensionless quantities are desired to estimate the heat transfer coefficient.

The Reynolds number for water flow over the PV panel is:

$$Re = \frac{ww L}{\mu_w} \quad (8)$$

where u_w is the velocity of water on PV module top surface is given by:

$$u_w = \frac{\dot{m}}{\rho_w \frac{\pi}{4} d^2 n} \quad (9)$$

where $\dot{m}$ is the water flow rate and it is computed using the equation below:

$$\dot{m} = \frac{Mass\, of\ water\ filled\ per\, minute}{60} \quad (10)$$

The Prandtl number for flowing water in PV/T system is:

$$Pr = \frac{\mu_w C_w}{k_w} \quad (11)$$

The Nusselt number for laminar water flow over a glass of the PV module is estimated using equation [9]:

$$Nu = 0.332\left(Re^{1/2}\right)\left(Pr^{1/3}\right) \quad (12)$$

The convective heat transfer coefficient h_{wind} due to ambient air flowing below the tedlar surface is computed from [10]:

$$h_{wind} = 2.8 + 3V_{wind} \quad (13)$$

where V_{wind} is the wind velocity.

The heat transfer coefficient due to convection from the glass top to flowing water can be estimated via

$$h_{c,g-w} = \frac{Nu.k_w}{L} \quad (14)$$

The total heat loss from flowing water-ambient is:

$$h_{tot,w-a} = h_{c,w-a} + h_{r,w-a} + h_{e,w-a} \quad (15)$$

The convective heat transfer coefficient between the water layer to ambient is given by [11]:

$$h_{c,w-a} = \left(0.321 + 0.425V_{wind}\right)\times 11.574 \quad (16)$$

The radiation heat transfer coefficient for the wetted surface to ambient is expressed as [12]:

$$h_{r,w-a} = \frac{\left(T_w^4 - T_{sky}^4\right)}{\left(T_w - T_a\right)} \quad (17)$$

The effective sky temperature T_{sky} is calculated from the following empirical relation [13]:

$$T_{sky} = T_a \sqrt[4]{0.711 + 0.0056T_{dp} + 0.000073T_{dp}^2 + 0.013\cos(15t)} \quad (18)$$

where T_{dp} is the dew point temperature in (°C) and t is time (hr) from midnight.

The heat transfer coefficient due to evaporation can be estimated by [14]:

$$h_{e,w-a} = 0.016276 \times h_{w,a} \frac{\left(p_g - .p_a\right)}{\left(T_g - T_a\right)} \quad (19)$$

where p_g and p_a are partial vapour pressure at glass surface and ambient respectively as given below,

$$p_g = exp\left[25.317 - \frac{5144}{T_g}\right] \quad (20)$$

$$p_a = exp\left[25.317 - \frac{5144}{T_a}\right] \quad (21)$$

The conductive heat transfer coefficients in Eqs. (2)-(6) are:

$$U_g = \frac{k_g}{L_g} \quad (22)$$

$$U_e = \frac{k_e}{L_e} \quad (23)$$

$$U_c = \frac{k_c}{L_c} \quad (24)$$

$$U_t = \frac{k_t}{L_t} \quad (25)$$

where k_g, k_e, k_c and k_t are the thermal conductivity of glass, EVA, PV cell and tedlar respectively. Where L_g, L_e, L_c and L_t are the thickness of glass, EVA, PV cell and tedlar respectively.

2.3 Flowing water temperature above PV module

An ordinary differential equation (ODE) for the flowing water temperature (T_w) above the PV module glass from equation (1) is given by:

$$\frac{dT_w}{dx} = \frac{B}{\dot{m}C_w} h_{c,g-w}\left(T_g - T_w\right) - h_{c,w-a}\left(T_w - T_a\right) - -h_{e,w-a}\left(T_w - T_a\right) - h_{r,w-a}\left(T_w - T_a\right) \tag{26}$$

The expression for flowing water temperature above the PV panel glass can be obtained by integrating Eq. (26) with the following boundary conditions is given by,

Boundary condition: $T_w = T_{w,in}$, at $x = 0$

$$T_w(x) = W.\left[1 - exp\left(-W_1 x\right)\right] + T_{w,in} exp\left(-W_1 x\right) \tag{27}$$

where,

$$W = \frac{h_{c,g-w}T_g + h_{c,w-a}T_w + h_{e,w-a}T_a + h_{r,w-a}T_a}{h_{c,g-w} + h_{c,w-a} + h_{e,w-a} + h_{r,w-a}} \tag{28}$$

$$W_1 = \frac{B.h_{c,g-w} + h_{c,w-a} + h_{e,w-a} + h_{r,w-a}}{\dot{m}C_w} \tag{29}$$

The expression for flowing water outlet temperature ($T_{w,out}$) can be obtained by substituting the following boundary conditions in Eq. (27) is given by,

Boundary condition: $T_w = T_{w,out}$, at $x = L$

$$T_{w,out} = W.\left[1 - \exp\left(-W_1 L\right)\right] + T_{w,in}\exp\left(-W_1 L\right) \tag{30}$$

The expression for average water flowing temperature over the full length of PV panel is given by,

$$\overline{T}_w = \frac{1}{L}\int_{x=0}^{L} T_w(x)\,dx \tag{31}$$

$$\overline{T}_w = W.\left[1 + \frac{\exp\left(-W_1 L\right)}{W_1 L} - \frac{1}{W_1 L}\right] + +\frac{T_{w,in}}{W_1 L}\left[1 - \exp\left(-W_1 L\right)\right] \tag{32}$$

2.4 Thermal energy and efficiency

The rate of useful thermal energy delivery of the PV/T top water cooling module is given by,

$$\dot{Q}_{del} = \dot{m}C_w\left(\Delta T\right) \tag{33}$$

where ΔT is the rise in temperature of flowing water over the PV module.

The thermal efficiency of the photovoltaic module with top water cooling is defined as

$$\eta_{th} = \frac{\dot{Q}_{del}}{BLG} \tag{34}$$

The electrical efficiency of a PV module has been evaluated by [15,16].

$$\eta_{ele} = \eta_{ele,ref}\left[1 - 0.0045\left(T_c - T_a\right)\right] \tag{35}$$

The thermal equivalent electrical efficiency is defined as

$$\eta_{ele,th} = \frac{\eta_{ele}}{C_f} \tag{36}$$

where $C_f = 0.36$ is the thermal power plant conversion factor for India [17].

The total thermal energy efficiency of PV panel with top water cooling is given by

$$\eta_{th,ovl} = \eta_{th} + \eta_{ele,th} \tag{37}$$

2.5 Exergy analysis

The exergy analysis is dependent on the 2nd law of thermodynamics, which includes (i) exergy inflow, (ii) exergy outflow and (iii) exergy destructed from the system.The general exergy balance equation for a control volume is written as [16],

$$\sum \dot{E}x_{w,in} - \sum \dot{E}x_{w,out} + \sum \dot{E}x_{Q,sun} - \sum \dot{E}x_{ele} = \dot{I} \tag{38}$$

where $\dot{E}x_{w,in}$, $\dot{E}x_{w,out}$, $\dot{E}x_{Q,sun}$, $\dot{E}x_{ele}$ and $\dot{E}x_{des}$ are the exergy rate of inlet water flow, the exergy rate of outlet water flow, heat exergy rate, work exergy rate and irreversibility rate in control volume, respectively.

The exergy rate of inlet and outlet water flow are given by [16]:

$$\sum \dot{E}x_{w,in} = \dot{m}C_p\left(T_{w,in} - T_a - T_a\,ln\left(\frac{T_{w,in}}{T_a}\right)\right) \tag{39}$$

$$\sum \dot{E}x_{w,out} = \dot{m}C_p\left(T_{w,out} - T_a - T_a\,ln\left(\frac{T_{w,out}}{T_a}\right)\right) \tag{40}$$

The heat exergy rate includes solar radiation intensity exergy rate. According to the Petela theorem, it is given by [16]

$$\sum \dot{E}x_{Q,sun} = BLG\left[1 - \frac{4}{3}\left(\frac{T_a}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4\right] \tag{41}$$

The work exergy rate includes only the outlet electrical power of PV module [16]

$$\sum \dot{E}x_{ele} = \eta_{ele}BLG \tag{42}$$

Exergy efficiency of the top water cooled solar photovoltaic module is defined as the ratio of net output exergy rate to the net input exergy rate [16]:

$$\eta_{exy} = \frac{\sum \dot{E}x_{w,out} - \sum \dot{E}x_{w,in} + \sum \dot{E}x_{ele}}{\sum \dot{E}x_{Q,sun}} \tag{43}$$

Substituting Eqs.(39)-(42) into (43), the exergy efficiency of the solar photovoltaic panel with top water cooling is obtained as follows:

$$exy = \left[\frac{\dot{m}C_p\left(T_{w,out} - T_{w,in} - T_a\,ln\left(\frac{T_{w,out}}{T_{w,in}}\right)\right) +_{ele} BLG}{BLG\left[1 - \frac{4}{3}\left(\frac{T_a}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4\right]}\right] \tag{44}$$

3. EXPERIMENTAL WORK

A polycrystalline silicon PV module is mounted on a rigid steel frame for the stability of the system and ease of inclination angle adjustment. The water layer over the PV panel was produced by making 100 holes in a circular PVC pipe of diameter 2.5 mm and placed on top of the PV panel. The mass flow rate of water was controlled by a valve placed in between inlet of the feeding tube and water tank.

The specifications of the PV module used in this study are given in Table 2. The outdoor experiment was conducted at Chennai, India (13.06° N, 80.11° E) and the experiment rig of a PV module with top water cooling is shown in Figure 2. The test was carried out from 8.00 am to 4.00 pm on a sunshiny day. Experiment tests had been performed for PV module without cooling (WOC) and the PV module with top water cooling (WWC) concurrently. The optimal slope angle of the PV panel throughout the test period is set as 13° facing towards the South. The solar radiation is measured by digital solarimeter installed parallel to the PV module plane. Well-calibrated k-type thermocouples are utilised to measure the numerous temperature of the PV/T system. The wind velocity is measured by using an anemometer. Digital multimeter (DMM) has been used to measure the current and voltage of the PV module.

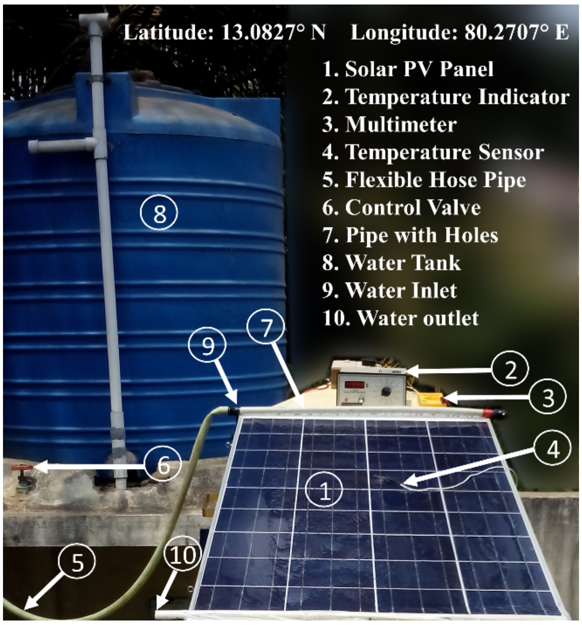

Figure 2. Experimental rig of the PV/T system

Table 2. Specifications of PV module

Parameter	Value
Module dimensions	1500 x 0.66 x 38.5 mm
No. of cells	36
Peak power, P_{mp}	150 W
Rated voltage, V_{mp}	17.84 V
Rated current, I_{mp}	8.4 A

4. RESULTS AND DISCUSSION

4.1 Experimental validation

The present mathematical model results have been validated by their corresponding experimental values. The root means square percentage error (RMSE) and R-squared (R^2) values are computed by evaluating the simulated results with experimental outcomes. It is obvious from the errors that the present mathematical model results are in good agreement with the experimental outcomes.

The simulated values are compared with the experimental values during the test day, and proportionate error values are generated are given in Table 3. Figure 3 shows the hourly values of simulated and experimental top side glass temperature for top water-cooled solar PV module. The RMSE and R-squared value for top glass temperature are found to be 2.29% and 0.9889 respectively. The Figure 4, 5 and 6 shows the experimental and simulated hourly values of PV cell, tedlar bottom and outlet water temperature respectively. The RMSE of these parameters is 2.31%, 2.98% and 1.04% respectively with the corresponding R^2 as 0.9890, 0.9899 and 0.9985 respectively. It is observed that the simulated values of the present thermal parameter values are good agreement with present experimental results. Thus, the present mathematical model is confidently used to simulate and predict the behaviour of the PV/T TWC system.

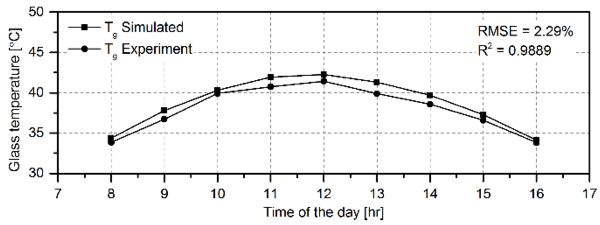

Figure 3. Top glass temperature

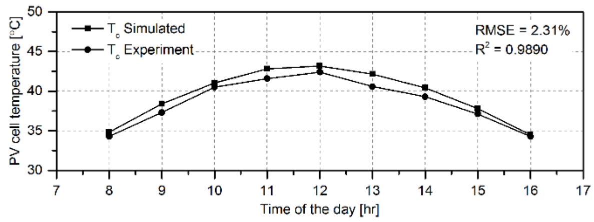

Figure 4. PV cell temperature

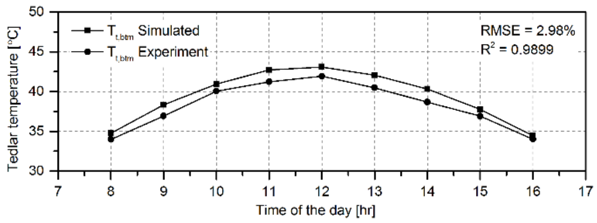

Figure 5.Tedlar temperature

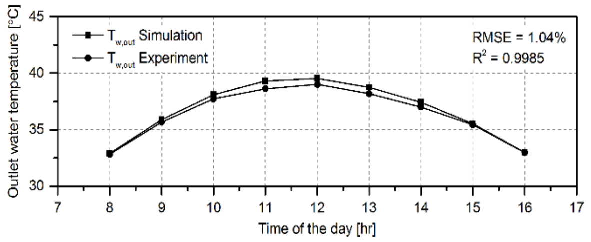

Figure 6. Outlet water temperature

Table 3. Error values of present analytical model

Parameter	RMSE%	R^2
Glass temperature, T_g	2.29	0.9889
PV cell temperature, T_c	2.31	0.9890
Tedlartemperature, $T_{t,btm}$	2.98	0.9899
Outlet water temperature, $T_{w,out}$	1.04	0.9985

4.2 Timely variation of performance

The timely variations of ambient temperature, sky temperature and solar insolation in the environmental conditions of Chennai for a typical sunny day have been shown in Figure 7. The hourly simulated top glass, PV cell, tedlar bottom, and outlet water temperature on their corresponding ambient temperature are plotted in Figure 8. The lowest and highest outlet water temperature was 32.90°C and 39.53°C at 8 hr and 12 hr respectively. The peak simulated top glass and PV cell temperature was found to be 42.26°C and 43.16°C atnoon respectively. At 12 hours the simulated tedlar bottom temperature reaches a maximum value of 43.08°C and at 16 hr it attains a minimum value of 34.45°C. Due to the top water cooling, more heat transfer occurs on the top glass of the PV module to flowing water and hence always the glass temperature was less than that of tedlar temperature. The maximum difference between PV cell temperature and ambient temperature was found to be 5.55°C atnoon and the minimum difference was found to be 2.13°C at 16 hr.

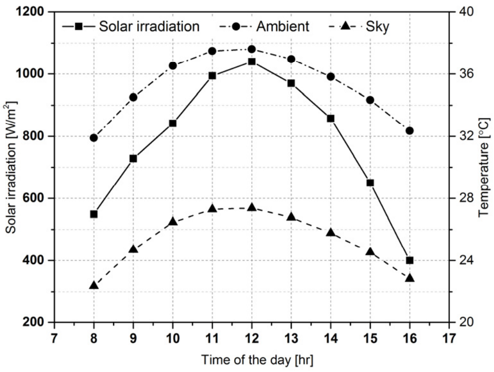

Figure 7.Timely variation of G, T_a and T_{sky}

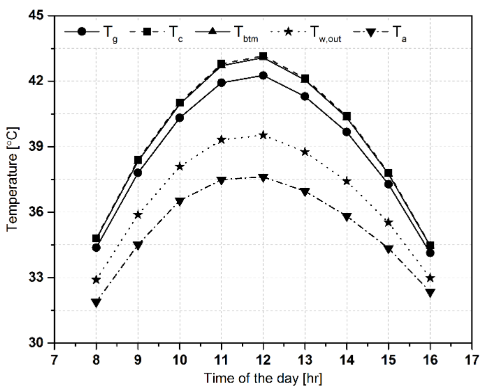

Figure 8.Timely variation of simulated temperatures

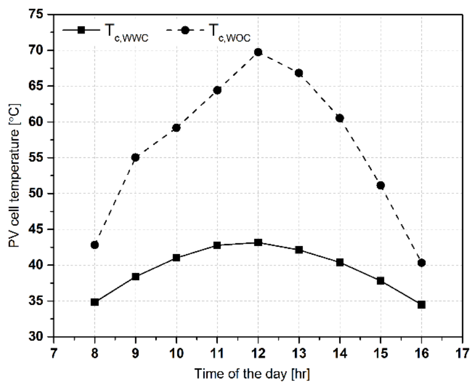

Figure 9.Timely variation of simulated T_c

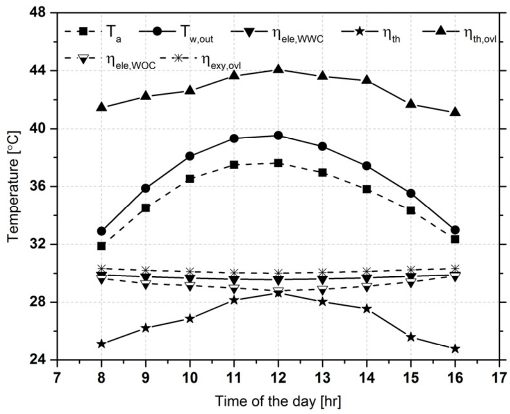

Figure 10.Timely variation of simulated efficiencies

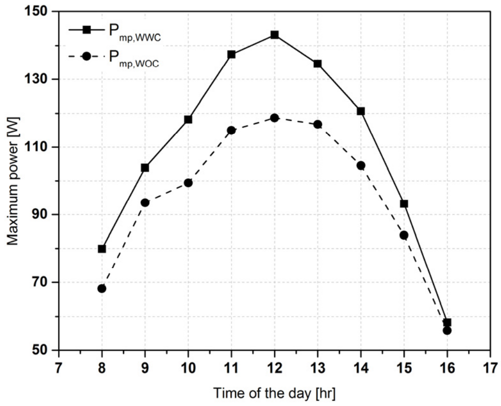

Figure 11.Timely variation of simulated P_{mp}

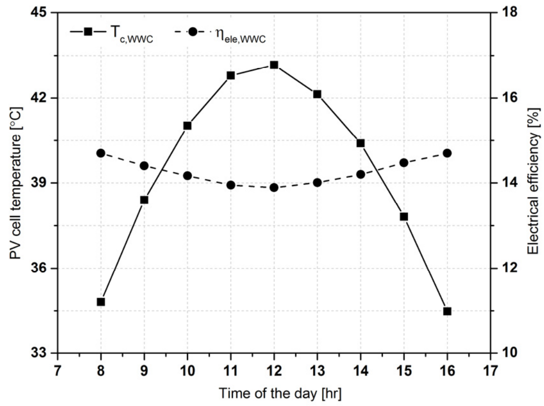

Figure 12.Timely variation of simulated T_c and η_{ele}

The simulated values of PV cell temperature for WWC and WOC PV module are shown in Figure 9. The maximum and minimum difference between WWC and WOC PV module cell temperatures are 26.56°C atnoon and 5.85°C at 16 hr respectively. Figure 10 shows the simulated hourly values of thermal, electrical and overall thermal and exergy efficiency. The electrical efficiency ranged between 13.89% and 14.69%. The thermal efficiency achieves a peak value of 11.58% at noon whereas for morning and evening the thermal efficiency is very low due to the outlet water and ambient temperature difference is very less. The overall thermal efficiency and exergy efficiency throughout the simulation time lies in between 50.16 – 42.76% and 15.04 – 15.82% respectively.

From Figure 10 it is found that the maximum thermal efficiency occurs where the electrical efficiency is minimum and vice versa. Also, the maximum overall exergy is found to be 15.82%. Figure 11 shows the simulated values of maximum power for WWC and WOC of the solar PV module. The minimum and maximum difference between P_{mp} for WWC and WOC are 2.37 W at 16 hr and 24.4 W at noon respectively. The simulated electrical efficiency concerning cell temperature for WWC PV module is shown in Figure 12. The electrical efficiency is maximum at minimum PV cell temperature and vice versa.

The simulated results of thermal parameters at noonare given in Table 4. The PV cell temperature and outlet water temperature at noon was found to be 43.17°C and 39.53°C respectively. The rate of useful thermal energy delivered, thermal efficiency and overall thermal efficiency at 12 noon was found to be 119.18 W, 11.58% and 50.16% respectively.

Table 4. Simulated results of thermal parameters at 12 noon

Parameter	Value	Parameter	Value
G	1040 W/m^2	$T_{t,btm}$	43.08 °C
T_{sky}	27.37 °C	$T_{w,out}$	39.53 °C
T_g	42.29 °C	T_w	39.21 °C
$T_{e,1}$	42.74 °C	Q_{del}	119.18 W
T_c	43.17 °C	η_{th}	11.58 %
$T_{e,2}$	43.16 °C	η_{ovl}	50.16 %

5. CONCLUSION

In this study, an enhanced layer by layer comprehensive analytical modelling of PV module with top water cooling has been carried out. The thermal model used in the present analysis provides more accurate results than that available in the literature. Further, it predicts the temperature of all layers of the PV module with top side water cooling. The electrical efficiency is sensitive to the PV module temperature, and it decreases as the temperature of the module increases. The operating temperature of top water cooled PV module is found drop significantly to about 30.4% and an increase of 12.1% in the electrical efficiency is observed concerning WOC. Based on RMSE percentage and R-squared errors the results of the present mathematical model are in good agreement with the experimental measurements. The analytical model developed are valuable tools which will be enclosed in the computational algorithm for the design and analysis of solar energy system facilities or to enhance the present facilities.

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NOMENCLATURE

B	- width of the collector, m
C_f	- conversion factor of a thermal power plant
C_w	- heat specific capacity of water, J/(kgK)
g	- diameter of hole, m

E_p	- outlet electrical power,W
$\dot{E}x$	- exergy rate, W
G	- solar radiation intensity, W/m^2
h	- heat transfer coefficient, W/(m^{2}K)
I	- current, A
$\dot{I}$	- irreversibility rate
k	- thermal conductivity, W/(mK)
L	- length of the collector, m
$\dot{m}$	- mass flow rate, kg/s
n	- number of holes / refractive index
Nu	- Nusselt number
P	- power, W
p	- partial vapor pressure, Pa
Pr	- Prandtl number
$\dot{Q}$	- heat transfer rate, W
Re	- Reynolds number
$RMSE$	- root mean square error percentage, %
R^2	- square of correlation
t	- time, h
T	- temperature, K
u	- conduction heat transfer coefficient, W/m^2 K
V	- voltage, V
V	- velocity of water over the module, m/s
V_{wind}	- wind velocity, m/s

Greek Symbols

α	- absorptivity
β_c	- packing factor of solar cells
γ	- air humidity
ΔT	- rise in temperature of flowing water, K
ε	- emissivity
η	- efficiency
μ	- viscosity of water, Ns/m^2
ρ	- density of water, kg/m^3
σ	- Stefan-Boltzmann's constant, W/(m^{2}K^4)
τ	- transmissivity

Subscripts

1	- top EVA
2	- bottom EVA
a	- ambient
btm	- bottom side
c	- solar cell / convective
dp	- dew point
del	- delivered
des	- destroyed
e	- EVA / evaporative
ele	- electrical
exy	- exergy
g	- glass
g - w	- glass to water
in	- inlet
out	- outlet
ovl	- overall
Q	- heat
ref	- reference
t	- tedlar
th	- thermal
tot	- total
top	- top side
w	- water
w - a	- water to ambient

ДЕТАЉНО МАТЕМАТИЧКО МОДЕЛИРАЊЕ И ЕКСПЕРИМЕНТАЛНА ЕВАЛУАЦИЈА СОЛАРНОГ PV МОДУЛА ХЛАЂЕНОГ ПОВРШИНСКИМ СЛОЈЕМ ВОДЕ

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Развијени математички модел има за циљ испитивање електричног и термичког понашања соларног фотонапонског (PV) модула са хлађењем површинским слојем воде. Математичка израчунавања су вршена у климатским условима Индије, у Ченеју (геогр. шир. 13,06^0, геогр. дуж. 80,11^0). Код термичког модела су размотрена три механизма преноса топлоте и израчунавања су обављена помоћу побољшаних корелација. Евалуација модела је показала добро слагање са експерименталним подацима. Просечна дневна електрична и укупна термичка искоришћеност PV модула са протоком површинске воде износила је 14,29% односно 45,44%. Проток воде на врху PV модула редукује дневну просечну температуру модула од 56,67^{0}C до 39,44^{0}C, док се просечна електрична искоришћеност модула повећава до 14,29% у поређењу са 12,74% без хлађења.