A parametric study of a novel PV/T system model which includes the greenhouse effect

Seyed Reza Maadi[1], Meysam Khatibi[1], Ehsan Ebrahimnia-Bajestan[2], David Wood[4]

[1] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[2]School of Engineering, University of British Columbia, Kelowna, BC, Canada V1V 1V7
[4]Dept Mechanical & Manufacturing Engineering, University of Calgary, Calgary, Canada, T2N 1N4

Summary

A 3D coupled thermal-optical model was used to simulate the solar ray-tracing, heat transfer, and fluid flow in a water-based photovoltaic/thermal (PV/T) module. All layers of the PV/T module were simulated along with their optical and thermal properties as well as the greenhouse effect between the glass cover and PV cells. The Navier-Stokes and energy equations were solved in the thermal model and, simultaneously, the discrete ordinate (DO) model using a two-band radiation model was employed for the optics. Then, the effects of different operating conditions including the coolant mass flow rate, solar heat flux, and ambient temperature at different number of tubes in the cooling part of the PV/T module were studied. The results showed that increasing the number of tubes containing the water from 5 to 16, the performance of the modules improved dramatically; however, afterward, the thermal and electrical efficiencies increase only slightly.

Keywords: Photovoltaic/thermal module (PV/T), Thermal model, Optical model, Discrete ordinate (DO) model, Number of tubes, Greenhouse effect

1. Introduction

Solar energy is one of the most valuable renewable energies due to its eco-friendliness and availability. Because of the depletion of fossil fuels, and global warming issues, its implementation is growing widely. By employing photovoltaic (PV) modules, the solar irradiance is converted to electrical power, but most of the received solar irradiance is turned into thermal energy which is wasted. Photovoltaic/thermal (PV/T) technology—the combination of photovoltaic modules and solar collectors—has been proposed to simultaneously convert solar energy to thermal and electrical energies. This method also improves the electrical efficiency of the PV module by reducing the solar cell temperature. Many researchers have attempted to numerically investigate the effects of various geometric parameters, operating conditions, and material properties on the efficiency of these solar systems. Almost all models have focused on the thermal modeling or optical modeling of PV module separately, using one-dimensional (1D) models. For instance, Yazdanifard et al. (2017) applied a 1D heat balance model using a thermal-resistance approach. This is a cost-effective and quick method to evaluate PV/T systems (Spertino et al., 2016). To achieve more accuracy and details in modeling such as the temperature distribution in the module, some researchers have investigated the PV/T performance by employing a 2D (Maadi et al., 2017; Wu et al., 2019) and 3D simulation (Hosseinzadeh et al., 2018).

Based on the authors' knowledge, most of the studies on PV/T systems have simply modeled optical losses by considering wavelength-independent-optical properties for the glass cover and PV cells. However, the glass cover and PV cells have different optical functions at different solar wavelengths, whereby the short wavelengths pass through the glass and long wavelengths are trapped between the glass and PV cells. This is called the 'greenhouse effect'. For the simulation of PV/T systems, particularly glazed systems, it is necessary to consider the wavelength dependent properties and thermal modeling simultaneously. Therefore, this study aims to numerically investigate the performance of a water-based PV/T module considering all module layers and wavelength-dependent optical properties for the glass cover and PV cells. For this purpose, the discrete ordinates (DO) radiation model, using a two-band radiation model, is used. In addition, a solar ray tracing algorithm is used to calculate the absorbed energy in the solid layers which is coupled as a source term in the

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energy equation. The proposed model is employed to parametrically scrutinize the effects of the various coolant flow rates, solar heat fluxes, and ambient temperatures along with varying number of tubes on the electrical and thermal efficiencies as well as the proportion of thermal-optical losses to total received energy.

The rest of this paper is arranged as follows. The numerical model is discussed next, followed by the results and their discussion. The final Section summarizes the conclusions and gives recommendations for future studies.

2. Numerical modeling

The simulated layers in PV/T module are shown in Fig. 1(a). The layers are: the poly-crystalline silicon cells (pc-Si) encapsulated by two transparent layers above them, an Ethylene-vinyl acetate (EVA) and anti reflective coating (ARC), and two layers of EVA and Tedlar polyvinyl fluoride (Tedlar) underneath. The operating conditions for the base case are: water inlet temperature ($T_{W,in}$) and coolant (water) flow rate ($\dot{m}$) of 311 K and 0.044 kg/s, respectively, wind velocity of 1 m/s, ambient temperature of 303.15 K, solar irradiance of 700 W/m^2 (G_{sun}), and pump efficiency of 80% (η_{pump}). Other geometrical specifications, thermo-physical and optical properties along with operating conditions can be found in Maadi et al. (2019).

Thermal modeling. The laminar convective heat transfer of air inside the air gap, and water flowing through the tubes, are governed by the continuity, Navier-Stokes, and energy equations. However, the energy equation for the solid components of the PV/T is:

$$k_s \nabla^2 (T_s) + \gamma \dot{E}_{elec} + S_h = 0 \tag{1}$$

In Eq. (1), $\gamma = 1$ for the PV cells (i.e., pc-Si layer) and zero otherwise. The subscript s indicates the solid layers. $\dot{E}_{elec}$ is the electrical power as discussed by Yazdanifard et al. (2017). Moreover, S_h is a heat source, which represents the amount of solar irradiance absorbed by each solid layer. To determine S_h, the Radiative Transfer Equation (RTE) must be solved coupled with the other conservation equations of mass, momentum, and energy.

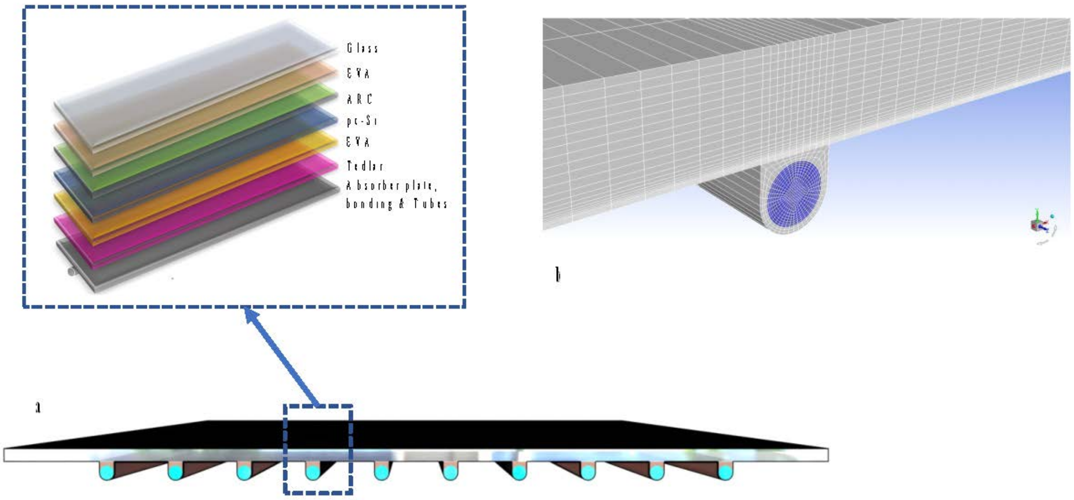


Fig. 1: (a) Schematic of the PV/T module, heat conduction tubes, and simulated layers; (b) Computational mesh with the water flow highlighted in blue.

Optical Modeling. For solving the RTE, the DO radiation model is employed. The RTE for the spectral intensity $I_\lambda(\vec{r}, \vec{s})$ at position $\vec{r}$ in the direction $\vec{s}$ is written as:

$$\vec{\nabla}.\left(I_\lambda(\vec{r},\vec{s})\vec{s}\right) + (\sigma_\lambda + \sigma_s) I_\lambda(\vec{r},\vec{s}) = \sigma_\lambda n^2 I_{\mathrm{b}\,\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r},\vec{s})\,\Phi(\vec{s}.\vec{s}')\,d\Omega' \tag{2}$$

where $\overrightarrow{s'}$ and σ_s are scattering direction vector and scattering coefficient, respectively. σ_λ , n, Φ, and Ω' denote spectral absorption coefficient, refractive index, phase function, and solid angle, respectively. $I_{\mathrm{b}\lambda}$ is also the blackbody intensity given by the Planck function. The non-gray model was applied by dividing the radiation spectrum into two wavelength bands (i.e. two-band model) as 0–4.25 μm and greater than 4.25 μm for a typical glass (Moghimi et al., 2015) with absorption coefficients of 26 m^{-1} and 1100 m^{-1}, respectively.

The boundary conditions of the tubes are mass flow inlet and zero gradients at the outlet. The boundary of the exterior surface of the glass were simulated by standard convection and radiation boundary conditions. ANSYS-Fluent 18.1 was used to solve the governing equations using the SIMPLE scheme, second order upwind discretization, and the PRESTO scheme for pressure. The sun's rays that enter the computational domain were modeled by the ray tracing algorithm. The mesh is shown in Fig.1(b). More details about the governing equations, assumptions, and numerical procedure are given in Maadi et al. (2019).

Performance of PV/T module. To evaluate the performance of the PV/T module, the thermal efficiency (η_{th}), electrical efficiency (η_{elec}), and overall efficiency (η_{ov}) are defined as (Yazdanifard et al., 2016):

$$\eta_{th} = \frac{\dot{m}C_{p,w}\left(T_{W,out} - T_{W,in}\right)}{AG_{sun}} \tag{3}$$

$$\eta_{elec} = \frac{E_{elec} - P_{pump}}{AG_{sun}} \tag{4}$$

$$\eta_{ov} = \eta_{elec} + \eta_{th} \tag{5}$$

where, $T_{W,out}$, $T_{W,in}$, $C_{p,w}$, and A are the outlet and inlet water temperature flowing through the tubes, heat capacity of water, and module area. E_{elec} and P_{pump} are calculated as follows:

$$P_{pump} = \frac{N\dot{m}\Delta p}{\rho_w \eta_{pump}} \tag{6}$$

$$E_{elec} = \tau_g\, \bar{\alpha}_{pv}\, AG_{sun}\, \eta_{ref}\, (1\text{-}\beta_{ref}\, (T_{pv} - T_{ref}))\, P_a \tag{7}$$

In order, η_{ref}, β_{ref}, T_{ref}, N and Δp are reference values for cell efficiency, temperature coefficient, temperature, the number of the tubes, and the pressure loss in one tube, respectively. τ_g and $\bar{\alpha}_{pv}$ are transmittance of the glass and effective absorptance of the PV cells.

3. Results and Discussion

To examine the accuracy of the proposed thermal-optical model, the thermal (η_{th}) and electrical (η_{elec}) efficiencies predicted by this model were compared to the experimental data of Bhattarai et al. (2012) for a similar PV/T module at different solar irradiances. Table 1 shows a reasonable agreement between the numerical results and measured data.

The validated model can now be used to study the effects of different geometrical, operational, environmental and material factors on the performance of PV/T module. In the present study, the results on the effects of the mass flow rate, solar heat flux, and ambient temperature as well as the number of tubes are presented and discussed.

Table 1: Validation study of efficiencies from present numerical study and available experimental study (Bhattarai et al., 2012).

$\frac{(T_{w,in} - T_{amb})}{G_{Sun}}$ (m^2K/W)	$\eta_{th,numerical}$ (%)	$\eta_{th,experimental}$ (%)	$\eta_{elec,numerical}$ (%)	$\eta_{elec,experimental}$ (%)
0.01	53.68	51.3	12.73	13.2
0.02	48.28	46	12.36	12.7
0.03	41.38	40	11.99	12.3

The optical modeling of the glass cover in the glazed PV/T modules is a challenge due to the changing behaviors of its optical properties as the wavelength of the solar radiation changes (as previously stated in section 2). On the other hand, capturing the greenhouse effect, i.e., trapping the long wavelengths of the radiation through the air gap between the glass and PV layers, and modeling the reflection of each part could play an important role in the performance of a PV/T module and are included in our model. Fig. 2 demonstrates the ray tracing of the incident radiation. Due to the greenhouse effect, a part of the incident radiation is trapped between the PV module and glass cover, and leads to a temperature rise in the PV module. Therefore, considering the greenhouse effect in the simulation decreases the optical losses (shown in Fig. 2), which in turn can increase the thermal efficiency of the module. For instance, at solar irradiance of 300 W/m^2, applying the greenhouse effect results in the thermal efficiency increasing by 12% compared to the case without this effect (Maadi et al., 2019).

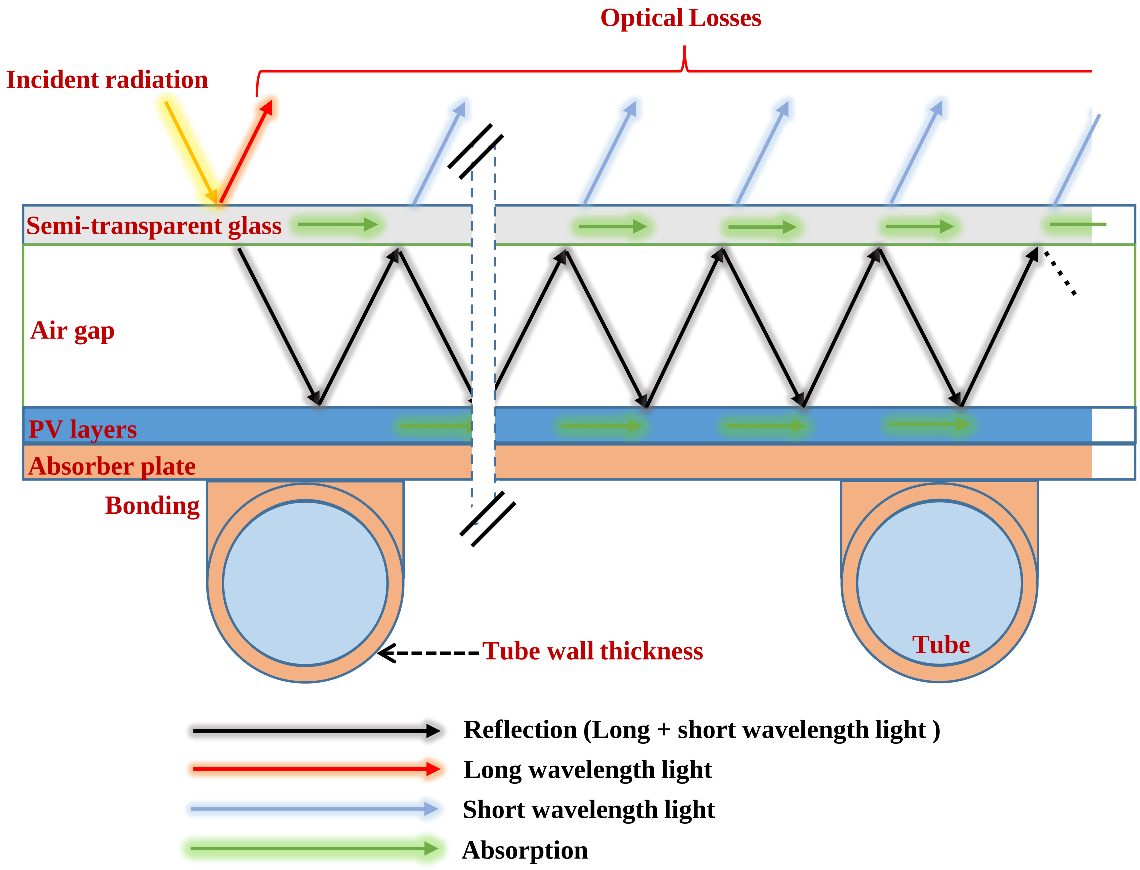
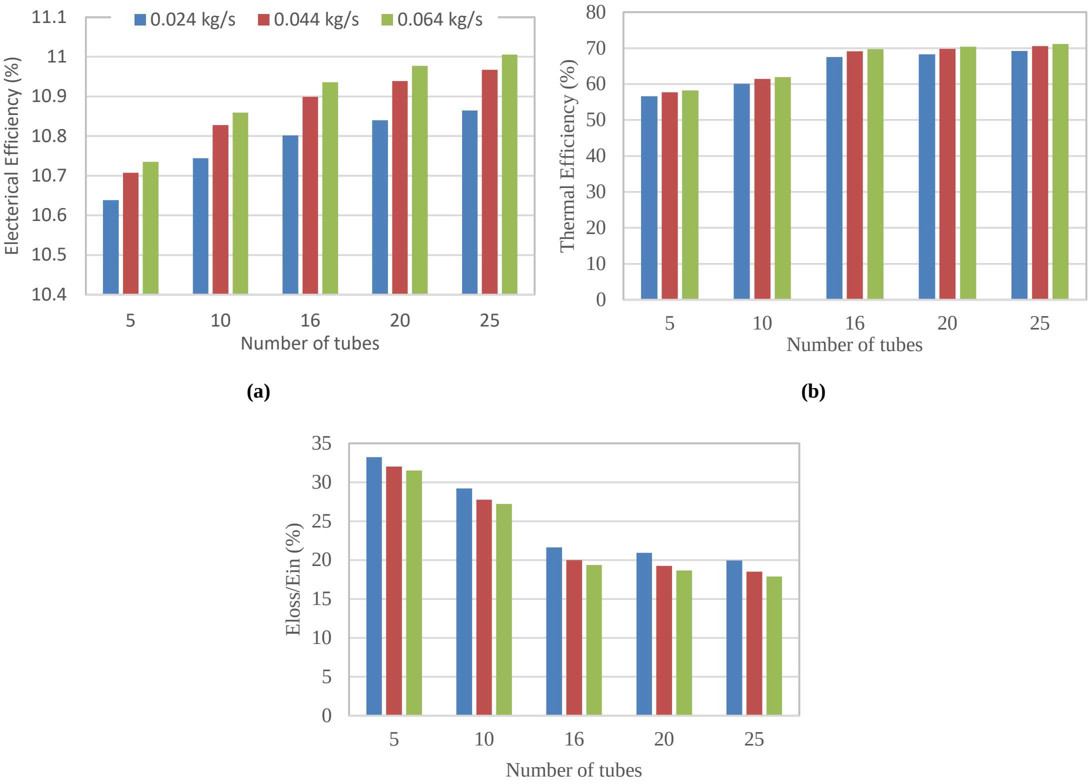


Fig. 2: A schematic of the incident radiation interaction and trapped wavelength between encapsulated PV layers and glass cover (greenhouse effect). Figure taken from Maadi et al. (2019).

3.1 Coolant flow study

Fig. 3(a-c) illustrate the variations in the electrical efficiency, thermal efficiency, and ratio of energy loss over total received energy in terms of water mass flow rates (in laminar flow) and different number of tubes, *N*, respectively. It should be mentioned that the calculated energy loss contains both thermal and optical losses including convection to the ambient, thermal radiation to the sky, the reflectance of solar irradiance from the glass surface to the ambient, and the escape of some reflected light from the PV cells through the glass to the ambient. Considering Fig. 3(a), for a given total water mass flow rate in the tubes, increasing *N* leads to an increase in electrical efficiency of the PV/T module due to a reduction in the average temperature. An electrical efficiency improvement is also experienced when the water flow rate increases. Increasing the water flow rate increases the heat transfer coefficient inside the tube, which in turn increases the heat transfer rate from the solid layers to the coolant, reducing the PV plate temperature and improving the electrical efficiency. Similarly, the thermal efficiency of the PV/T module increases with *N* and the water flow rate (see Fig. 3(b)). The results also indicate that the improvement in the performance of the PV/T module is more considerable when *N* increases to 16, but a further increase has no significant effect. Therefore, *N* = 16 is likely to be an optimum value, when economical and technical issues are taken into account. In Fig. 3(c), the ratio of energy loss over the total received energy is observed, where increasing *N* and flow rate reduce the energy loss as higher amounts of absorbed energy are transferred to the water.



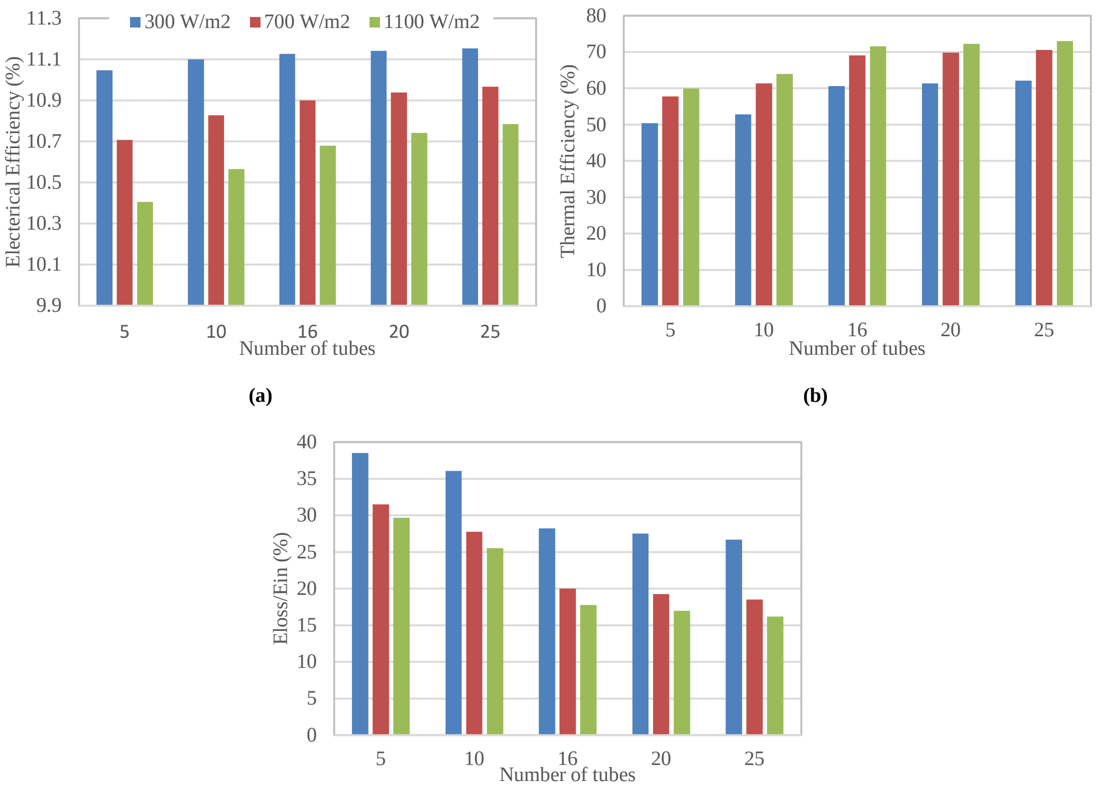
(a) **(b)**

(c)

Fig. 3: Effects of water mass flow rate at different number of tubes on the (a) electrical efficiency, (b) thermal efficiency, and (c) ratio of energy loss over total received energy (At solar heat flux of 700 W/m^2 K and ambient temperature of 303.15 K).

3.2 Solar heat flux study

Fig. 4 shows the simultaneous effects of solar heat flux and number of tubes on (a) the electrical efficiency, (b) thermal efficiency, and (c) ratio of energy loss over total received energy. As expected, by increasing the solar heat flux, the cell temperature increases. As a result, the thermal and electrical efficiencies of the module increase and decrease, respectively. However, these variations are more pronounced when the solar heat flux increases from 300 to 700 W/m^2. According to Fig. 4(b) and considering a constant solar heat flux (e.g. 1100 W/m^2), the thermal efficiency initially experiences a dramatic rise by increasing N from 5 to 16 which is followed by a level off (reaching nearly 73% at 25 tubes). Although by increasing the solar heat flux the energy loss increases, the results show that the proportion of energy loss to total received energy decreases (see Fig. 4(c)).



(a) **(b)**

(c)

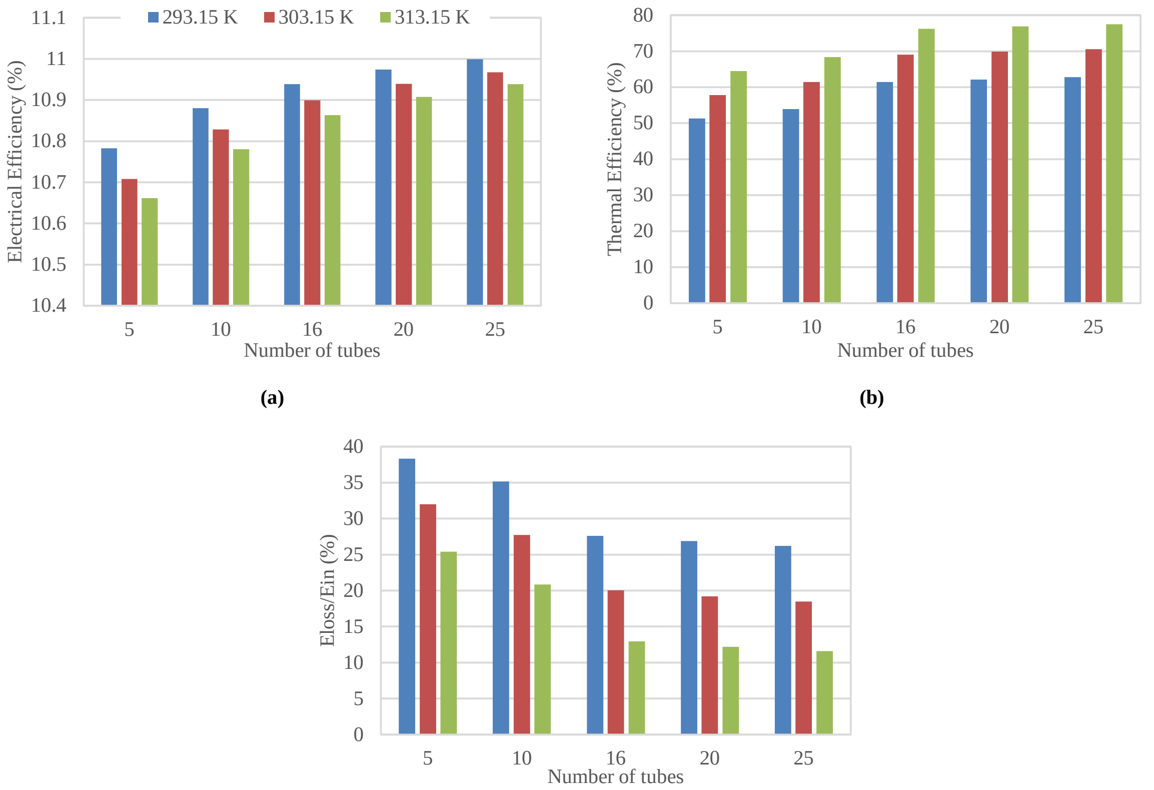
Fig. 4: Effects of solar heat flux at different number of tubes on the (a) electrical efficiency, (b) thermal efficiency, and (c) ratio of energy loss over total received energy (At total mass flow rate of 0.044 kg/s and ambient temperature of 303.15 K).

3.3 Ambient temperature study

A comprehensive investigation was conducted on the effects of ambient temperature along with *N* on the performance of the PV/T module as shown in Fig. 5(a-c). According to the results for *N* = 5, 10, 16, 20 and 25, increasing the ambient temperature from 293.15 to 313.15 K leads to an increase in the PV temperature by 2.51, 2.07, 1.56, 1.38 and 1.25 K, respectively. Therefore, at a constant *N*, increasing the ambient temperature reduces the electrical efficiency, which is more pronounced at lower *N* (see Fig. 5(a)).

As depicted in Fig. 5(b), higher ambient temperature results in a higher thermal efficiency. For example, increasing the ambient temperature from 293.15 to 313.15 K increases the thermal efficiency by 13.14%, 14.42%, 14.72%, 14.75% and 14.68%, for *N* = 5,10,16, 20 and 25, respectively. Clearly, it can be seen that increasing *N* above 16 does not have a significant effect on the thermal efficiency. Based on the results, there is a direct correlation between the ambient temperature and thermal efficiency, whereas there is an indirect correlation between the ambient temperature and electrical efficiency. Due to these opposite behaviors, the overall efficiency should be taken into account in evaluating the performance of the system at varying ambient temperature. Fig. 6 indicates that higher ambient temperature increases the overall efficiency of the module, which similar to the results in previous sections. Increasing *N* to 16 shows a significant increase but for larger *N*, the efficiency is nearly constant.

As demonstrated in fig. 5(c), by increasing the ambient temperature, the ratio of the lost energy to the input energy decreases. For instance, at *N* = 16, changing the ambient temperature from 293.15 to 303.15 K and then to 313.15 K results in a significant reduction in overall heat loss to the environment and sky by 76.36% and 52.08%, respectively. Furthermore, this reduction is more pronounced at *N* = 16, which is consistent with Fig. 6.



(a) **(b)**

(c)

Fig. 5: The effects of ambient temperature at different number of tubes on the (a) electrical efficiency, (b) thermal efficiency, and (c) ratio of energy loss over total received energy (At a constant total mass flow rate of 0.044 kg/s and solar heat flux of 700 W/m^2).

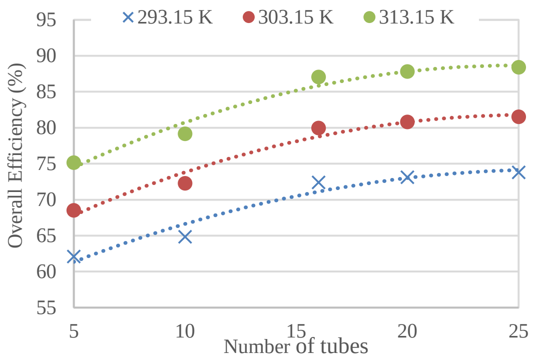


Fig. 6: Overall efficiency of the PV/T system in various ambient temperature and number of tubes (At a constant total mass flow rate of 0.044 kg/s and solar heat flux of 700 W/m^2).

4. Conclusion and recommendation for future studies

The performance of a PV/T module is examined using a detailed computational model which was validated against some recent experimental studies. The 3D coupled thermal-optical model directly determines the heat transfer in the coolant (water) flowing in the tubes on the back of the PV module and accounts for the effects of the greenhouse effect inside the air gap within the PV module. The effects of different operating conditions including the solar heat flux, ambient temperature, and mass flow rate of the coolant fluid at the different number of tubes in the cooling part of the PV/T module were investigated. Key findings of this numerical study are summarized as follows:

- Increasing the number of tubes from 5 to 16 at any studied condition leads to a significant increase in the thermal and electrical efficiencies of the module. Increasing the number of tubes above16, the module performance increases only slightly.

- The thermal and optical losses decrease by increasing the mass flow rate, which in turn improves the performance of the module.
- Increasing the solar heat flux and ambient temperature results in a temperature rise in the PV module. As a result, the electrical efficiency decreases and the thermal efficiency increases. Using a suitable number of tubes can improve both efficiencies.

According to the proposed model used in this study and the results, the following can be suggested as a subject of future studies:

- Investigate the influence of modeling greenhouse effect by scrutinizing different design parameters and optical properties like the solar angle and the effects of using two or three glass covers,
- Study novel PV materials to ascertain their thermal behavior and overall efficiency.
- Investigate different tube geometries to optimize heat transfer.

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