Numerical investigation of the thermal and electrical performances for combined solar photovoltaic/thermal (PV/T) modules based on internally extruded fin flow channel

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Abstract. A solar photovoltaic/thermal (PV/T) module based on internally extruded fin flow channel was investigated numerically in this paper. First of all, the structures of the thin plate heat exchanger and the PV/T module were presented. Then, a numerical model of the PV/T module considering solar irradiation, fluid flow and heat transfer was developed to analyze the performance of the module. Finally, the steady electrical and thermal efficiencies of the PV/T module at different inlet water temperatures and mass flow rates were achieved. These numerical results supply theory basis for practical application of the PV/T module.

1. Introduction
Energy crisis and environmental pollution have attracted broad attention. Therefore, adjustment the energy composition and development renewable energy have gradually become an important part of human sustainable development. In all kinds of renewable energy resources, solar energy has the advantages of enormous energy, longevity, cleanness, and cheapness. And in various application techniques of solar energy, the solar photovoltaic generation has been considered to be one of the best among the known electricity generation owing to the highest electricity energy levels.

The important technologies for the application of photovoltaic (PV) cell include the following two points: First, gain the high efficient and low-cost photovoltaic materials. Second, provide using conditions for the PV cell to reach optimal conversion efficiency. The former belongs to the PV materials technology, while the latter could be realized by high efficient heat transfer technology. Several researchers conducted material feature studies to improve the electrical performance of the PV cell. Ghanwat, et al [1,2] successfully obtained hierarchical TiO2 nanostructures and synthesized SnS2 thin film to improve the PV electrical efficiency. However, several researchers conducted PV heat dissipation and waste heat recovery, which is solar PV–thermal (PV/T) technology, to make the PV work at the optimal conditions. In the commercial applications, the electricity efficiency of a monocrystalline silicon solar PV cell is about 6~15%, whereas the remaining radiant energy of the sun is absorbed by the PV cell and converted into heat, which makes the PV electrical efficiency decrease with the increasing PV temperature. Moreover, the service life of a PV cell also decreases at elevated temperature. If the PV could had been cooled in time, the waste heat could had been collected and utilized, which might have improved the electrical efficiency, might have greatly increased the integrated use efficiency of the solar energy, and might have extended the lifespan of the PV cell.

Nowadays, the main PV/T technology is to make circulating water flow the copper or aluminium...
tubes welded on the PV panels to co-generate heat and electricity. Chow [3] analyzed the performance of a single glazed flat plate PV/T collector by an explicit dynamic model. Touafek, et al [4] studied a galvanized steel tube-sheet PV/T module. Moreover, several scholars conducted studies for improving the performance of the tube-and-sheet PV/T system. Zondag, et al [5] analyzed nine different designs of the PV/T modules. The results showed that the channel-below-transparent-PV design had the best efficiency, but the PV-on-sheet-and-tube design was considered to be a better alternative owing to the higher annual efficiency and easier manufacture. Tripanagnostopoulos [6] and Abu Bakar, et al [7] studied the performance of the different forms of the PV/T collectors with water or air circulation. Liang, et al [8] tested the efficiency of the PV/T collector filled with graphite. The experimental results showed that the mean electrical efficiencies of the PV/T collector filled with graphite and the traditional PV module were 6.46% and 5.15%, respectively. Ibrahim, et al [9,10] analyzed the performance of the spiral flow tube sheet PV/T system. It produced a thermal efficiency of 54.6%, a PV electrical efficiency of 13.8%, and a PV/T total efficiency of 68.4%. To further increase the performance, numerous new types of PV/T modules have been developed. Chow, et al [11-13] proposed a flat-box metallic absorber to replace the tube-and-sheet design to get higher efficiency and durability. Pei, et al [14,15] studied the performance of the heat-pipe PV/T system under different operating and structural conditions by experiment and simulation. Moradgholi, et al [16] investigated the performance of the thermosiphon-type heat-pipe PV/T system when the heat pipes were filled with different working fluids. Deng, et al [17] presented a novel PV/T module based on the micro heat pipe array. The PV/T technology offers the benefits of high efficiency, high reliability, light weight, and frost-resistance during winter. Ziapour and Khalili [18] performed the performance study to verify the new design of the PV panel combined with the type of the wickless heat pipe solar water heater. In this enhanced design, each wickless heat pipe is assumed in the shape of the loop mini tube comprised of the flow boiling process in it.

The current study presents a PV/T technology based on the thin plate heat exchanger with internally extruded fin flow channel [19]. The simulations of the fluid flow and heat transfer were conducted on the PV/T module to achieve the electrical and thermal performance. The simulation results were analyzed to supply the basis for the practical application of the PV/T module.

2. PV/T module

![Figure 1. Structure schematic of the PV/T module.](image1)

![Figure 2. Structure schematic of the thin plate heat exchanger.](image2)

The basic configuration of the PV/T module with internally extruded fin flow channel is shown in figure 1. It combines PV module, thin plate heat exchanger, insulation layer, and frame. When the PV/T module is in operation, the thin plate heat exchanger transfers the heat absorbed by the PV module to the circulating water. The thin plate heat exchanger is shown in figure 2. It constructed by two parallel metal thin plates, one of which forms arrays of pin-fin corrugations through machinery
mould extrusion, while another thin sheet remains smooth and is fixed with the PV panel by the metal retaining clip. Two thin plates join together by laser-welding technology, and forming a water flow channel. One fluid inlet at the bottom and one fluid outlet on the top of the thin plate heat exchanger respectively connects with the water pipes. Therefore, the thin plate heat exchanger has a better heat transfer property owing to the absorber with fins and the cross flow over the pin fins.

3. Numerical simulation of the PV/T module

The heat transfer mechanisms of the PV/T are shown in figure 3. When a light ray solar cell surface, some of the solar radiation energy converts into electricity, some is reflected by the PV surface, and some converts into heat. Part of the heat is transferred to the water inside the thin plate heat exchanger, and part of the heat is transferred to the surroundings through convection and radiation. The simulation of the PV/T with water flow was set up, which included the CFD modelling of the solar irradiation, the circulating water flow and the heat transfer inside the heat exchanger, the conduction of the insulation layer, and the heat exchange with the surroundings. Figure 4 shows the model geometry of the PV/T module, while the specifications of the different components of the PV/T studied are summarized in table 1.

![Figure 3. Schematic diagram of the heat transfer in PV/T module.](image)

![Figure 4. Model geometry.](image)

### Table 1. Basic characteristics and specifications of the PV/T module.

| Components            | Dimensions: 1580×808×50 mm |
|-----------------------|-----------------------------|
| PV module             | Glass cover Material: low iron tempered glass Dimensions: 1580×808×3 mm |
| Monocrystallinesilicon solar cell | Solar cell temperature coefficient: 0.0045 K⁻¹ Thickness: 1 mm Absorbability of solar energy: 0.95 Electrical efficiency in standard conditions: 15% |
| TPT                   | Dimensions: 1580×808×3 mm Thickness: 3 mm |
| EVA                   | Thickness: 0.5 mm |
| Thin plate heat exchanger | Type: With internally extruded pin–fin flow channel |
Material: Stainless steel
Thickness: 5 mm
Inlet/Outlet pipe diameter: 20 mm

Insulation layer
Material: polyurethane
Thickness: 40 mm

Framing
Material: aluminium

3.1. Numerical model
The conservation of mass equations, momentum equations and energy equations are established, and the standard k-epsilon two-equation turbulent model is employed. The thermo physical properties of different components of the PV/T module are shown in table 2.

| Physical property         | Glass | EVA | PV | TPT | Stainless steel | Insulation | Aluminium |
|---------------------------|-------|-----|----|-----|-----------------|------------|-----------|
| Density (kg/m³)           | 2500  | 900 | 1650 | 1475 | 7930            | 30         | 2719      |
| Heat capacity (J/kg·K)    | 840   | 2300 | 700 | 1130 | 500 | 1380 | 871      |
| Heat conductivity coefficient (W/m·K) | 0.76  | 0.5 | 150 | 0.614 | 16.3 | 0.04 | 202.4 |

3.2. Boundary conditions
The equations are subjected to several boundary conditions as follows:

- The glass cover is convective thermal boundary condition, which allows considering the effect of the convective flow outside the PV/T and the heat radiation between glass cover and sun. This is done by calculating the convective heat transfer coefficient dependent on the outside velocity as follows:

  \[ h = 5.7 + 3.8 \nu \]

  Where \( h \) is the convection heat transfer coefficient, W/m²·K; \( \nu \) is the ambient wind speed, m/s.

- For the power generation of the solar cell, the following empirical formula is used.

  \[ E = G \eta_N [1 - \phi_a (T_b - 25)] \]

  Where \( G \) is the solar irradiance, W/m²; \( \eta_N \) is the electrical efficiency in standard conditions, namely the PV cell electrical efficiency under the condition of solar irradiance of 1000 W/m² and ambient temperature of 25°C, %. \( \phi_a \) is the PV cell temperature coefficient, K⁻¹. \( T_b \) is the PV cell temperature, °C.

  Except converting into electricity, all the solar irradiation that is absorbed presents in the PV cell as internal heat sources in the simulation process. The internal heat sources are determined by the way of iteration.

  - The boundary condition for the water inlet is "mass flow rate" and the outlet is "outflow".
  - For the side walls and bottom walls, the boundary conditions are considered to be convective boundary condition. These walls don’t participate in solar radiation and heat radiation.
  - All other surfaces are "wall", and the walls between the two zones are defined as "coupled".

3.3. Mesh formation
The grid is generated by CFD pre-processor. Through independent verification for the grid, a grid with 694406 cells is used for the current work.

3.4. Numerical method
A commercial computational fluid dynamics program is used to solve the coupled equations. The
The segregated solver is used, and the SIMPLE algorithm is used for calculating the pressure-velocity coupling. The second-order is selected as the discretization method for pressure, and the second order-upwind discretization method is used for solving momentum, energy, and turbulence equations.

3.5. Data processing
The thermal and electrical performances of the PV/T module are described by the thermal efficiency $\eta_a$ and the electrical efficiency $\eta_e$. Based on the simulation results, the calculation formulas are as follows.

$$
\eta_e = \frac{E}{AG} \frac{G\eta_a[1-\vartheta_a(T_b-25)]}{AG} \quad (3)
$$

$$
\eta_a = \frac{Q_u}{AG} \quad (4)
$$

The performance of the PV/T module is described as the total efficiency $\eta_o$, which sums the thermal and electrical efficiencies. The calculation formula is as follows.

$$
\eta_o = \eta_e + \eta_a \quad (5)
$$

Where $E$ is the generated power of the PV/T module (W); $A_e$ is the aperture area (m$^2$); $G$ is the solar irradiance (W/m$^2$); $Q_u$ is the useful heat transferred to the circulating water.

4. Results and discussion
The steady state fluid flow and heat transfer in the PV/T module at different water temperatures (20, 30, 40°C) were simulated with the CFD models. The PV/T module is placed at a tilt angle of 45°. The ambient air temperature, wind speed, solar irradiance and mass flow rate are 20°C, 2 m/s, 800 W/m$^2$ and 0.02 kg/(m$^2$·s), respectively. The results of simulation on the heat transfer were obtained in detail, and the efficiencies could be calculated at different inlet cooling water temperatures. The simulation results are shown in figures 5 and 6.

![Figure 5](image1.png)  
**Figure 5.** Efficiency curves of the PV/T module at different inlet water temperatures.  

![Figure 6](image2.png)  
**Figure 6.** Instantaneous efficiency curve of the PV/T module.

Figure 5 presents the electrical efficiency, thermal efficiency and total efficiency curves of the PV/T module at different inlet water temperatures. As shown in the figure, the efficiencies decrease with the increasing inlet water temperatures. When the inlet water temperature is 20°C, the electrical efficiency, thermal efficiency, and total efficiency are 14.86%, 68.54%, and 83.40%, respectively. When the inlet water temperature is 50°C, the electrical efficiency, thermal efficiency and total
efficiency are 13.12%, 26.63%, and 39.75%, respectively. The electrical efficiency and thermal efficiency fall by 11.71% and 61.15%, respectively. As the inlet water temperatures increase, the operating temperatures of the PV/T module increase, which makes the heat loss of the PV/T through the top surface increase and the useful heat reduces. Therefore, the thermal efficiency of the PV/T will reduce with the increasing inlet water temperatures. Similarly, the electrical efficiency will reduce with the increasing PV temperatures as shown formula (2).

By using a curve fitting technique, the numerical instantaneous thermal efficiency of the PV/T module is obtained in Figure 6. It is represented as a linear relation of the parameter \([(T_{in} - T_a)/G]\). The intercept of the efficiency line with the y-axis represents the maximum instantaneous thermal efficiency, while the slope represents the heat loss coefficient. The numerical maximum instantaneous efficiency is 68.57%, and the heat loss coefficient is 11.18 W/(m²·K). The thermal efficiency decreases rapidly with the increasing parameters \([(T_{in} - T_a)/G]\). The heat loss coefficient of the PV/T module is larger owing to the more heat loss between the glass cover and the surroundings. To decrease the heat loss, some studies had added the air gap between the glass cover and the PV cell, which could improve the thermal efficiency but impede the cooling of PV cell.

The steady state fluid flow and heat transfer in PV/T at different water mass flow rates \(0.02, 0.05, 0.10, 0.15, 0.20 \text{ kg/(m}^2\cdot \text{s})\) were simulated with the CFD models. The PV/T is placed at a tilt angle of 45°. The direct solar irradiance has an intensity of 800 W/m² perpendicular to the module. The ambient air temperature, wind speed and inlet water temperature are 20°C, 2 m/s and 30°C, respectively. The simulation results are shown in figures 7 and 8.

The figures show that the PV temperature decreases and the electrical efficiency increases with the increasing water mass flow rates. The PV temperatures at the mass flow rate of 0.02 kg/(m²·s) and 0.20 kg/(m²·s) are 35.7°C and 33.2°C, respectively, with a difference of 7.5%. When the mass flow rate is 0.02 kg/(m²·s), the electrical efficiency, thermal efficiency, and the total efficiency are 14.28%, 54.64%, and 68.92%, respectively. When the mass flow rate is 0.20 kg/(m²·s), the electrical efficiency, thermal efficiency, and the total efficiency are 14.45%, 58.55%, and 73.00%, respectively. The efficiencies increase with the increasing mass flow rates. The electrical efficiency increases 1.2%, the thermal efficiency increases 7.2%, and the total efficiency increases 5.9%. The increases of efficiency are limited. Therefore, the appropriate mass flow rate should not be too large, lest improve the pressure loss. The optimum mass flow rate is about 0.10 kg/(m²·s).

5. Conclusions
In order to increase the electrical and thermal efficiencies of the PV/T module, a solar photovoltaic

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**Figure 7.** PV temperatures and PV/T electrical efficiencies at different water mass flow rates.  **Figure 8.** Efficiencies of PV/T module at different water mass flow rates.
/thermal (PV/T) module with internally extruded fin flow channel was present in the study. Then, a numerical model of the PV/T module was developed to analyze the performance of the module. The numerical results show that the numerical maximum instantaneous efficiency is 68.57%, and the heat loss coefficient is 11.18 W/(m²·K). The electrical efficiency, thermal efficiency and total efficiency of the PV/T module decrease with the increasing inlet water temperatures, and increase with increasing mass flow rates. The optimum mass flow rate is about 0.10 kg/(m²·s).

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