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# Comparative simulation analyses on dynamic performances of photovoltaic–thermal solar collectors with different configurations

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ABSTRACT

The electrical efficiency of photovoltaic (PV) module can be increased by reducing the operating temperature of PV module. The hybrid photovoltaic/thermal (PV/T) solar system consists of conventional PV module and attached heat transfer pipe with internal working fluid flowing to extract heat energy from PV module. This article presents a brief review on the latest researches and applications of the PV/T systems. Afterwards, based on energy-balance equations, mathematical models for several PV/T systems with different configurations are developed. Analytical expressions for both the electrical and thermal performance parameters are derived as functions of climatic and design parameters to conduct comparative analyses. The calculation results indicate that the changes in the PV/T configurations have influences on electrical and thermal performances of the PV/T system. Further suggestions on configurations optimization for practical applications are propounded.



## 1. Introduction

With the increasingly serious crises of fossil energy depletion, global warming and environmental pollution in recent years, the whole world, especially the developing countries have been dedicating to exploiting the new energy resources. According to the International Energy Agency (IEA), China will become the country with the biggest increase in electricity production from new energy sources over the next decades, which exceeds that of the European Union, United States combined and Japan. As a promising green and renewable energy resource, the solar energy has received worldwide attention. Advantages of abundant solar energy resource and policy support [1] in China create significant conditions for the development of photovoltaic (PV) industry. PV is a method of converting solar radiation into direct current electricity via the photovoltaic effect of semiconductors modules. The operating temperature plays a significant role in the PV conversion process. The electrical performance of a PV module has a negative linear correlation with temperature [2]. In practical applications, a large portion of solar radiation is absorbed by PV modules in form of heat, which is difficult to be eliminated by natural convection. The resulting rising operating temperature leads to a declining electrical efficiency consequently. Aiming to improve the electrical performance, utilizing attached heat transfer pipes is an efficient approach to eliminate waste heat from PV modules by means of heat transfer via working fluid flow, e.g. water and air. This kind of hybrid photovoltaic/thermal (PV/T) [3] solar systems integrating heat transfer pipes with PV modules can achieve a higher conversion efficiency of solar radiation than conventional PV systems, and simultaneously produce heat and electricity, as shown in Fig. 1.

A significant amount of theoretical and experimental work on hybrid PV/T system has been carried on since the mid-1970s. Wolf [4] and Florschuetz [5] introduced earliest the concept of hybrid PV/T system. As the issues of energy and environment become increasingly prominent in recent years, related researches on hybrid PV/T systems have been more and more significant. Huang et al. [6] conducted a comparative study between an integrated PV/T system consisted of a commercial polycrystalline PV module and a conventional solar water heater. The evaluation results based on the concept of primary-energy saving efficiency indicated that the thermal performances of PV/T collector with a corrugated polycarbonate panel were improved well. Via Transient Systems Simulation (TRNSYS), Kalogirou and Tripanagnostopoulos [7] developed a hybrid PV/T thermosyphonic system and a larger active system for domestic hot water applications, and experimentally estimated the electrical and thermal performances in three locations at different latitudes. In order to estimate the thermal and electric performances of a PV/T solar hybrid system, Robles-Ocampo et al. [8] constructed an experimental model of an original PV/T water-heating collector with a bifacial PV module to enhance electric energy production of hybrid PV/T systems. Via finite difference

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**Nomenclature**

| | |
|---|---|
| $c$ | specific heat capacity, kJ/kg K |
| $D$ | equivalent diameter, m |
| $F$ | packing factor |
| $h$ | convective HTC, W/m$^2$ K |
| $H$ | height, m |
| $I$ | solar radiation intensity, W/m$^2$ |
| $L$ | length, m |
| $\dot{m}$ | mass flow rate, kg/s |
| $T$ | temperature, K |
| $U$ | overall HTC, W/m$^2$ K |
| $v$ | flow velocity, m/s |
| $W$ | weight, m |
| $x$ | distance in flowing direction, m |

*Greek letters*

| | |
|---|---|
| $\alpha$ | absorption coefficient |
| $\sigma$ | Stefan–Boltzmann constant |
| $\varepsilon$ | emissivity |
| $\delta$ | thickness, m |
| $\mu$ | dynamic viscosity |
| $\eta$ | photovoltaic efficiency |
| $\lambda$ | thermal conductivity, W/m K |
| $\tau$ | transmission coefficient |
| $\nu$ | kinematic viscosity, m$^2$/s |

*Subscripts*

| | |
|---|---|
| $a$ | airflow |
| $b$ | backplane |
| $c$ | solar cell |
| $e$ | environment |
| $g$ | glass cover |
| $s$ | sky |
| $w$ | wind |
| $ref$ | reference value at reference conditions |

control volume approach, Chow et al. [9] introduced a numerical simulation model of a building-integrated photovoltaic (BIPV) and water heating system to evaluate the system dynamic behavior under external excitations. The theoretical predictions were compliance with the measured values acquired from experimental facilities in Hong Kong. Ji et al. [10] presented a dynamic model of a novel PV/T solar-assisted heat pump (PV/T-SAHP) system with a specially designed PV evaporator to simultaneously produce heat and electricity. The spatial distributions of refrigerant conditions and the temperature distribution of the evaporator were derived under given solar irradiance and ambient temperature through the numerical model. The simulation results were in good agreement with the experimental measurements. Abdolzadeh and Ameri [11] investigated the possibility of improving the performance of a PV/T water pumping system by spraying water over the PV cells. Compared with traditional systems, experimental results indicated that the system performances were significantly improved. By using numerical simulations, Santbergen et al. [12] evaluated the electrical and thermal performances of a solar domestic hot water system with one-cover sheet-and-tube PV/T collectors to figure out the detailed mechanisms determining system performances. Daghigh et al. [13] considered that the liquid based PV/T collector systems were more desirable and effective than air based systems due to the less temperature fluctuation, and reviewed the available literature on PV/T collector systems adopting water and refrigerant as heat extraction medium for different applications. Pei et al. [14] developed a detailed simulation model of the heat-pipe PV/T (HP-PV/T) system to evaluate the electrical and thermal performances of this system in three typical climate areas of China. Compared with traditional water-type PV/T systems, two types of the HP-PV/T systems, including with and without auxiliary heating equipment, were studied under four different hot-water load conditions. Mishra and Tiwari [15] conducted a comparative analysis of hybrid PV/T water collectors under constant collection temperature mode with respect to the thermal and electrical performances of two different configurations, including the collector partially or fully covered by PV module. Shan et al. [16] studied the dynamic performances of a PV/T water heating system under given climate conditions. Based on energy balance equations, some performances parameters were derived, and the influences of design parameters on photovoltaic and thermal performances were analyzed for optimizing system designs as well. Mahjoubi et al. [17] presented an energy-balance model to estimate the real-time performances from a PV/T water pumping systems in Medenine, Tunisia. Theoretical results from this model were validated by experimental measurements and compared with those results in previous literatures. Fudholi et al. [18] estimated the electrical and thermal performances of PV/T water collectors under given solar radiation levels. The PV/T collectors were tested in term of the PV efficiency, thermal efficiency, and overall efficiency by changing mass flow rate. Hazi et al. [19] developed a mathematical model of PV/T systems for water heating in industry to evaluate the energy parameters and economic indicators as a function of three variables, including solar irradiance, air temperature and water supply temperature, under different climatic locations in Romania. Besides, Hegazy [20] performed an extensive investigation of the electrical, thermal and overall performances of four common flat plate PV/T systems designs, including the airflow either over or under the absorber, and on both sides of the absorber in a single pass or in a double pass. To evaluate the performances of the PV module integrated with air duct, Tiwari et al. [21] presented a detailed study of a hybrid PV/T system for composite climate of India. The theoretical results based on energy balance equations were consistent with experimental observations. Via developing a theoretical model of PV/T systems, Tonui and Tripanagnostopoulos [22] investigated two low cost modifications in system configuration to enhance heat extraction from the PV module, including the thin flat metal sheet and the finned back wall, theoretically and experimentally studied the effect of structural parameters on electrical and thermal

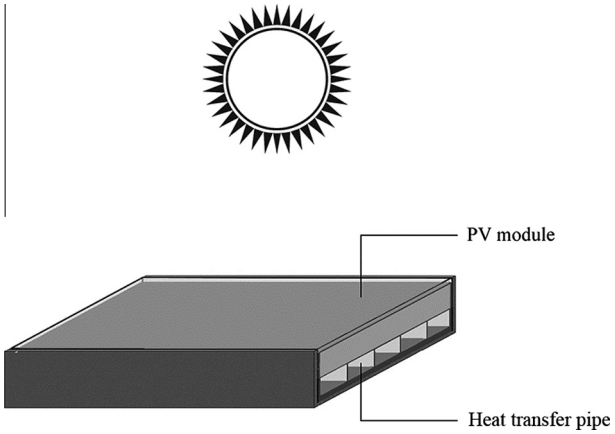


**Fig. 1.** The schematic diagram of the PV/T system.