Energy and Buildings 66 (2013) 485–494

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

# Dynamic performances modeling of a photovoltaic–thermal collector with water heating in buildings

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ARTICLE INFO

*Article history:*
Received 13 June 2013
Accepted 26 July 2013

*Keywords:*
Building integrated photovoltaic–thermal
Photovoltaic–thermal collector
Water heating
Dynamic performances

ABSTRACT

The photovoltaic and thermal performances of a photovoltaic–thermal (PVT) collector with water heating in buildings are presented in given climate conditions. According to energy balance equations, some performance parameters can be determined, including the photovoltaic efficiency, the temperature of solar cell and the outlet temperature of water, as well as the photovoltaic power and heat transfer rate. The influences of the series-connected PVT module number, the inlet temperature of water and the mass flow rate of water on the photovoltaic and thermal performances were discussed and analyzed. The approaches of improving the photovoltaic and thermal performances were concluded. The results indicated that the less series-connected PV modules, the lower inlet temperature of water and the higher mass flow rate of water resulted in the high photovoltaic efficiency.



## 1. Introduction

With industrial development and population expansion in recent decades, the energy demand on a global scale, especially in developing countries, has been growing rapidly. According to International Energy Agency (IEA), the traditional fossil fuels, a kind of non-renewable energy source with limited reserves including coal, oil and natural gas, represented approximately 80% of global energy supply during 2011. However, excessive consumption of fossil fuels will inevitably lead to exhaustion of energy in the near future. Moreover, as the main cause of global warming, emissions of greenhouse gases produced by burning fossil fuels have received worldwide attentions. In response, more and more countries and organizations are turning to the development of new renewable energy sources technology [1]. As a major renewable energy source with the most prominent characteristics of inexhaustibility and environmental friendliness, solar power has great research values and broad application prospects. The solar power technology has obtained significant development over recent years.

Photovoltaic, a direct conversion of solar radiation to electric energy by semiconductor modules, is one of the most promising utilization technologies of solar power [2]. The photovoltaic efficiency of a common solar cell is normally between 4% and 17%, and it can be adversely influenced by working temperature. Tests show that every 1 °C rise in working temperature for crystalline silicon cells reduces the photovoltaic efficiency by 0.4% [3]. Actually in practical applications, a large proportion of solar power will be absorbed by solar cell in the form of heat energy, which is extremely difficult to be removed from solar cell by natural convection. The resulting high working temperature of solar cell finally leads to a drop of photovoltaic efficiency. Solar thermal is another practical utilization technology of solar power [4]. Via heat collector, the core component of a solar thermal system, the solar thermal power can be used for heating working fluid. Heat collectors are usually classified into the non-concentrating ones for utilizations of low-temperature heat energy and the concentrating ones for utilizations of high-temperature heat energy. Generally, the low-cost solar thermal technology has a poor photo-thermal efficiency.

In conclusion, while heat energy is the negative factor needed to be weakened for a photovoltaic system, it is also the targeted product of a solar thermal system. The hybrid photovoltaic–thermal (PVT) system, as a combination of photovoltaic and solar-thermal technology, is born. The basic principle of a hybrid PVT system is to collect needless heat energy from its PV module by working fluid, and then use this part of heat energy in other ways. The schematic diagram of the photovoltaic–thermal collector with water heating is shown in Fig. 1, which consists of a PV module and an attached duct for working fluid flowing.

The hybrid PVT systems can be classified according to the used type of working fluid, commonly PVT air heating systems (PVT/a) and PVT water heating systems (PVT/w). Some theoretical and experimental researches on these two types of hybrid PVT systems have been conducted in recent years. Hegazy [5] evaluated the performances of four popular designs of PVT/a systems including the air flowing over the absorber or under it, and on both sides of the absorber in single pass or double pass mode, this study provided

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http://dx.doi.org/10.1016/j.enbuild.2013.07.067

**Nomenclature**

| | |
|---|---|
| $A$ | area of solar cell |
| $b$ | width of solar cell (m) |
| $C$ | specific heat capacity (J/kg °C) |
| $h$ | convective heat transfer coefficient (W/m$^2$ °C) |
| $I(t)$ | solar radiation intensity (W/m$^2$) |
| $k$ | heat transfer coefficient (W/m$^2$ °C) |
| $L$ | length of solar cell (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $n$ | number |
| $\dot{Q}$ | power (kW) |
| $t$ | time |
| $T$ | temperature (°C) |
| $x$ | distance in flowing direction (m) |
| *Greek letters* | |
| $\alpha$ | absorption coefficient |
| $\beta$ | packing factor |
| $\delta$ | thickness (m) |
| $\eta$ | photovoltaic efficiency |
| $\lambda$ | thermal conductivity (W/m °C) |
| $\tau$ | transmission coefficient |
| *Subscripts* | |
| $a$ | ambient |
| $b$ | backplane |
| $C$ | solar cell |
| 1, 2 | EVA |
| $g$ | glass |
| $P$ | photovoltaic |
| $T$ | thermal |
| $w$ | water |

significant information about the design and operation of such types of PVT systems. Tonui et al. [6,7] improved the performance of PVT/a system by reasonable structural modifications to enhance heat abstraction process. By model analysis and experimental verification, Tiwari et al. [8] evaluated the overall efficiency (electrical and thermal) performance of a PVT/a system on climatic conditions in India. Afterwards, Raman and Tiwari [9,10] conducted further analyses based on energy and exergy for a double-pass hybrid PVT collector on different climatic conditions in India. Sarhaddi et al. [11,12] evaluated the thermal, electrical and exergetic performance of a typical PVT/a system by a series of detailed energy and exergy analytical approaches. Kumar et al. [13] performed a comprehensive steady state analysis to evaluate and compare the thermal and electrical performance of a double-pass PVT/a system with and without specific configuration of vertical fins. Recently, Al-Alili et al. [14] proposed a hybrid desiccant assisted air conditioner system powered by PVT collector. The simulation and computation results showed such a proposed system could meet the corresponding requirements of buildings in humid and hot climates. Compared with other solar air conditioners, the overall performance of this air conditioner system was improved.

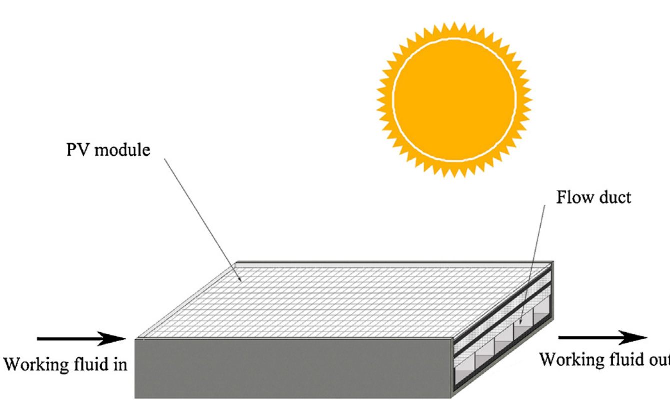


**Fig. 1.** Schematic diagram of a photovoltaic–thermal collector with water heating.

Besides, Huang et al. [15] analyzed the performance of an integrated PVT solar water heater with a commercial polycrystalline PV module. Using the concept of primary-energy saving efficiency, the performance of this system was evaluated and measurements for performance improvements were mentioned. By developing a series of steady and dynamic simulation models, Zondag et al. [16,17] conducted energy performance analyses for a PVT/w system. Kalogirou et al. [18] presented TRNSYS simulation results for a hybrid PVT solar systems for domestic hot water applications working with either passive (thermo-syphon) or active (pump circulating) mode. Ji et al. [19] constructed a flat-box aluminum-alloy PVT/w system designed for natural circulation, conducted outdoor tests and performed dynamic simulations on an improved prototype in a moderate climate region. Chow et al. [20] experimentally analyzed a facade-integrated PV/water-heating system, with which tremendous energy savings can be achieved. Suggestions on further performance improvements of this system were given consequently. Robles-Ocampo et al. [21] constructed an experimental model of a hybrid PVT/w system with the application of a specific bifacial PV module for enhancing electric energy production and estimated the overall solar energy utilization efficiency of this system. Erdil et al. [22] constructed a hybrid PVT domestic water pre-heating system and made experimental measurements for this system in Cyprus. The pay-back period was estimated considering the required modification costs on PV module. It was concluded this low-cost hybrid system with a relatively short pay-back period was economically attractive. With a theoretical model, Dubey et al. [23] evaluate the thermal, exergetic and electrical performance of PVT flat plate water collectors by changing the number of collectors connected in series, alternative series/parallel combination modes and different weather conditions of India. Results showed the flat plate water collectors partially covered by PV module were beneficial for those users whose priority requirements were hot water generation, and those fully covered were beneficial for users whose priority requirements were electricity generation. With numerical simulations, Santbergen et al. [24] constructed a one-cover sheet-and-tube PVT system for domestic hot water heating. The mechanisms determining the electrical and thermal yields were analyzed and improvement measures were proposed in this work. Pei et al. [25] designed a detailed simulation model of a heat-pipe PVT system, analyzed and compared the annual electrical and thermal performance of such HP-PVT systems with and without auxiliary heating equipment in different climate conditions of China.

Solar energy applications in building can be classified into two categories: thermal systems and photovoltaic systems. Normally, both types of collectors are used separately. In the solar thermal system, conventional electrical energy is used to circulate working liquid through a collector. If both types of collectors, thermal and photovoltaic, are combined in a hybrid unit (called a photovoltaic–thermal collector), The use of conventional electrical energy can be avoided for circulating working liquid through a collector. The photovoltaic–thermal collector in building can produce thermal and electrical energy simultaneously. A number of theoretical and experimental studies have been made on the hybrid PV/T collectors with air or water as the working fluid. Performance evaluations of a building integrated semitransparent photovoltaic–thermal system for roof and façade have been carried