

Review of solar photovoltaic/thermal (PV/T) air collector

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ABSTRACT

Growing concern with regard to energy sources and their usage has consequently increased significance of photovoltaic thermal (PV/T) collectors. A PV/T air collector is a system which has a conventional PV system combined with a thermal collector system. The system is able to produce electrical energy directly converted from sunlight by using photoelectric effect. Meanwhile, it also extracts heat from the PV and warms the fluid (air flow) inside the collector. In this review, solar PV system and solar thermal collectors are presented. In addition, studies conducted on solar PV/T air collectors are reviewed. The development of PV/T air collectors is a very promising area of research. PV/T air collectors using in solar drying and solar air heater.

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1. INTRODUCTION

Solar energy is the radiation produced as a result of the nuclear fusion reactions in the sun. This energy is radiated from sun in all directions. The solar energy from sun when beamed onto Earth for even an hour is sufficient to produce the global energy need for an entire year. Many technologies exist to harness the energy from sun and use it in application. The energy harnessed from sun can be used in two different forms; thermal and electrical. One such technology which utilizes radiation from solar energy to produce electrical and thermal energy is Solar PV/T technology and the device used in this technology is called a Solar PV/T collector. Solar PV/T collector is a hybrid system that deploy solar PV technology and solar heater technology. When a photovoltaic system is irradiated with solar energy, the cell temperature increases prominently. The greater the temperature difference between ambient temperature and temperature of the cell is, the less efficient the electrical efficiency and electrical output of the PV module becomes. In order to enhance the electrical efficiency, this excess heat is extracted by passing a heat extracting fluid (air or water) under the module. This integrated method, where electrical and thermal energy are generated simultaneously, is the basis of PV/T collectors [1]-[9].

The overall performance of the PV/T air collector can be evaluated based on the thermodynamic, environmental and economic impacts analysis. Enviroeconomic and exergoeconomic analyses for PV/T air collectors was studied [10]. Energy-exergy-economic-environmental analyses for different PV/T array systems was studied [11]. In this review, thermodynamic aspect is focused involving exergy analysis. Exergy has the characteristic that it is conserved only when all processes of the system and the environment are

reversible. Exergy is destroyed whenever an irreversible process occurs when an exergy analysis is performed on a system like PV/T system, the thermodynamic imperfections can be quantified as exergy destruction, which is wasted work or wasted potential for the production of work. By analyzing the exergy destroyed by each component in a process, it can be easily identified where the focus should be given to improve system efficiency. Exergy analysis is conducted by utilizing the first and second law of thermodynamics. Exergy analysis has become an essential tool in the system design, analysis, and optimization of thermal systems [12-20].

2. RESEARCH METHOD

The system which converts sunlight into electrical current by means of a photovoltaic (PV) cell is known as PV system. The process by which the PV cell converts sunlight to electrical current is called Photoelectric effect. Sunlight consists of photons. Billions of these photons continues to hit the earth every second. These photons contain large quantities of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a PV cell, they are either reflected, absorbed, or passed through. Electricity is generated by the photons that are absorbed.

The photons with energy greater than the band-gap energy of the semiconductor when absorbed creates some electron-hole pairs proportional to the incident irradiation. When such a photon is absorbed, the energy of that photon is absorbed by an electron in an atom of the semiconducting material of the PV cell. With the added energy, the electron can escape from its normal position (valence band) in the atom to become free by jumping to the conducting band leaving a hole behind. The electrical circuit is completed by the flow of these electrons and holes using electrodes. As millions of photons hits the PV cell, millions of electrons gain energy and become free to move along the conducting wires. Solar cells and modules consists of thin conducting wires and a built-in electric field to provide the voltage needed to move the current through an external load. The small quantity of current produced at each cell can be significantly increased by connecting several cells together and kept on large [21].

The PV system may include major components as; DC-AC power inverter, battery storage, system and battery controller, back-up energy sources and electrical loads [22]. The Figure 1 shows the main components of a Solar PV system. PV cells are the basic unit which converts the sunlight to energy. A PV module consists of PV cells arranged in frame to form a module. A PV module is constructed by connecting PV cells in series for high voltage and in parallel for high current. By connecting series of PV modules, a PV array is formed. The inverter is a device which converts direct current (DC power) into standard alternating Current (AC power) which can be used for the appliances in the home, synchronizing with utility power whenever the electrical grid is distributing electricity [23].

The charge controller regulates the flow of electricity from the PV modules to the battery and the load. It enables the battery to be fully charged without overcharging. When the load is consuming power, the controller allows electricity to flow from the modules into the battery or the load. When the battery is full the controller senses that and stops the flow of charge from the modules. At night time, and/or if the demand exceeds the power produced from Solar PV during the day and battery, electricity is provided through utility power source. The utility meter spins backwards when solar power production exceeds house demand. This allows the user to credit any excess electricity in future utility bills [24]. The storage battery is used to store any excess energy produced by PV modules and deliver it back for consumption when in demand [25].

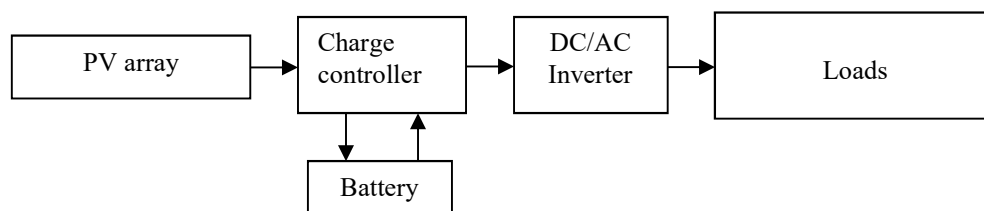


Figure 1. Schematic of PV system

Generally, PV systems can be classified based on their function and operational needs, their component configuration and the way other power sources and appliances are connected to the PV system. There are three types of solar PV systems. Stand-alone system or off-grid systems are systems which generate power and consume the power generated within the system and does not interact with the main electrical grid.

In a hybrid system, in addition to solar energy, one or more source of energy is hybridized in the solar PV system such as such as wind, biomass or diesel to provide the required power. This increased the reliability and efficiency in a cost effective way [25].

3. SOLAR THERMAL COLLECTORS

A solar thermal collector converts solar energy into useful thermal energy which is then transferred to the working fluid flowing through the collector such as water and air. The thermal energy collected can be used for various applications such a water or space heating, to generate steam. It can also be stored in a thermal storage for later use. Based on the working principle and other factors, solar thermal collectors can be categorized in various ways. One of the common categorization is (i) non-concentrating (for example, flat plate collectors) and (ii) concentrating (for example, compound parabolic concentrators). Another common way to categorize it is based on the working fluid (heat transfer fluid) used inside the collector as heat extraction such as into liquid heating and air heating types. For applications at low to medium temperature of about 100oC, the type of solar collectors that are usually used is stationary collectors which do not use solar tracking mechanism. They are generally used for air and water heating applications. Whereas concentrating collectors which use solar tracking system is commonly used for applications at medium to high temperature of about 200-2500oC such as solar thermal power generation and high temperature heating [1].

The main difference in the design of flat plate air collector from water collector is air plate collectors lack the flow tubes that are attached to the absorber plate. The main parameter to enhance the performance of solar air collector is the heat transfer rate between the absorber surface and the flowing air. In order to achieve this objective, various modification have been proposed in the design and air movement in solar air collectors including the use of corrugated, finned absorbers and multiple-pass air flow configurations as shown in the Figure 2.

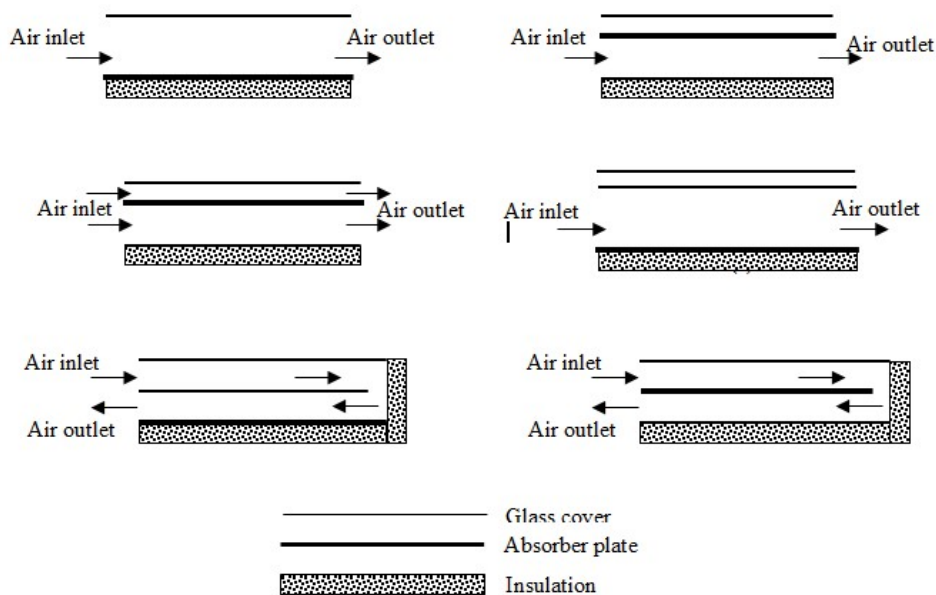


Figure 2. Different air flow designs for solar air collectors

The thermal efficiency of solar thermal collectors is a ratio of the useful thermal energy, Q_u to the overall incidence irradiations, I . Where the heat collected by the flat plate air collector can be measured by result of average mass flow rate, \dot{m} heat capacity of flowing medium, C_p and a temperature difference of the medium at the collector inlet, T_i and outlet, T_o [26]-[29].

$$\eta_{th} = \frac{Q_u}{I} = \frac{\dot{m}C_p(T_o - T_i)}{I}$$

4. SOLAR PV/T AIR COLLECTORS

In 1978, Kern and Russel introduced the concept of PV/T collectors using water or air as a heat removal fluid. As such PV/T collectors can be classified into three categories based on the type of working fluid used. Namely, PV/T water collector, PV/T air collector, and PV/T water/air combination collector [30]. Due to the dual functions of a PV/T collector, this type of collectors maximizes the use of solar energy resulting in a higher overall solar conversion rate than that of solely PV or solar collector. The PV cells composed of semiconductor material convert highenergy photons of incident solar radiation into electricity. The lower energy photons are absorbed by the PV panel and generate heat within the cells [31]. The generation of heat within the cell reduces the efficiency of the cells.

The photovoltaic thermal (PV/T) technology extract a great percent of this heat and utilize it for practical applications. The removal of heat from the cell and transferring it to the working fluid increases the electrical efficiency of the PV module while simultaneously producing hot fluid which can be used for thermal applications. Since PV/T offers an improved method of utilizing solar energy, the overall efficiency of the system is higher. The major advantages of using PV/T is as follows [32]: (i) It is dual-purpose: a system which can be used to produce thermal and electricity output, (ii) It has a wide application: the thermal output can be used for drying, heating and cooling (desiccant cooling), (iii) It is flexible and efficient: the combined efficiency is always much higher than using two individual systems and is especially attractive when roof-panel spacing is limited, and (iv) It is practical and cheap: it can be easily integrated to building with minor modification. Furthermore, by replacing the roofing material with the PV/T system, the payback period can be reduced.

Recently, Fudholi *et al.* [33] studied theoretical and experimental of PV/T air collector with ∇ -groove. They reported that PV/T exergy efficiencies of were 12.66-12.91% and PV/T energy efficiencies were 31.21-94.24%. The thermal and PV efficiency was 21.3-82.9% and 9.87-11.34% respectively. In 2016, Hazami, *et al.* [34] studied theoretical and experimental of PV/T air collector using energy and exergy analysis. They reported that PV/T exergy efficiencies of was 14.8%. From energy analysis, the PV and thermal efficiency was 15% and 50% respectively. Slimani *et al.* [35] studied theoretical and experimental of PV/T air collector for an indirect solar dryer. They reported that PV, thermal and PV/T efficiencies were 10.5%, 70% and 90%, respectively. Gholampour and Ameri [36] studied energy and exergy analysis of PV/T flat transpired collectors based on theoretical and experimental study. They reported that PV/T exergy efficiencies of was 8.66%. From energy analysis, the thermal and PV/T efficiency was 69.9% and 55% respectively. In 2015, Li, *et al.* [37] studied theoretical and experimental of PV/T air collector in the hot summer and cold winter zone. They reported that PV, thermal and PV/T efficiencies were 11.9-12.4%, 50% and 77.7%, respectively.

Researchers [38]-[40] studied experimental PV/T air collector. Rajoria *et al.* [38] reported that PV and thermal efficiencies were 3.1-9.1% and 12.1-28.1% respectively. Ahn *et al.* [39] reported that PV, thermal and PV/T efficiencies were 15%, 23% and 38% respectively. Good *et al.* [40] reported that PV and thermal efficiencies were 17.4% and 71.5% respectively. Amori and Abd-AlRaheem [41] studied experimental (field) of various PV/T air collectors. They reported that PV and thermal efficiencies were 8.3-10.4% and 46-62% respectively. In 2013, Rajoria *et al.* [42] studied theoretical and experimental of PV/T air collector. They reported that PV/T energy and exergy efficiencies of were 11.3% and 16.3%, respectively. In 2012, Agrawal *et al.* [43] studied theoretical and experimental of PV/T air collector connected in series.

They reported that PV and thermal efficiencies were 12.4% and 35.7% respectively. Amori and Al-Najjar [44] studied theoretical of thermal and electrical performance for PV/T air collector in Iraq. They reported that PV, thermal and PV/T efficiency were 9-12.3%, 19.4-22.8% and 47.8-53.6% respectively. In 2010, Agrawal and Tiwari [45] studied energy and exergy analysis of PV/T air collector under cold climatic conditions. They reported that PV/T energy efficiency was 53.7%. Sarhaddi *et al.* [46] [47] studied energy and exergy analysis of PV/T air collector. They reported that PV, thermal and PV/T efficiency were 10%, 17.18 and 45% respectively. PV/T exergy efficiency was 10.75%. Agrawal and Tiwari [48] studied theoretical and experimental of PV/T air collector. They reported that PV and thermal efficiency were 7.13% and 33.54% respectively.

5. CONCLUSION

Based on the present review, the following conclusions can be drawn: a) A number of research have been done on PV/T air collectors over the last four decades, exploring aspects such as efficiency enhancements by design development, numerical simulation, prototype design, experimental testing and testing methodologies for PV/T air collectors; b) The energy and exergy efficiency of PV/T air collector were 31% to 94% and 8.7% to 18%, respectively; c) The development of PV/T air collectors is a very promising area of research. Today, PV/T air collectors using in solar drying and solar air heater.

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Ahmad Fudholi, Ph.D, M.Sc obtained his S.Si (2002) in physics. He was born in 1980 in Pekanbaru, Indonesia. He has working experience about 4 years (2004-2008) as Head of Physics Department at Rab University Pekanbaru, Riau, Indonesia. A. Fudholi started his master course in Energy Technology (2005-2007) at Universiti Kebangsaan Malaysia (UKM). His M.Sc thesis was on Wind/PV Hybrid System and the Ph.D thesis was about the Finned Double-Pass Solar Collectors for Drying of Seaweed. His M.Sc and Ph.D thesis under supervisor by Prof Dato' Dr. Kamaruzzaman Sopian. After his master he became Research Assistant at UKM up to 2012. After his Ph.D (2012) in renewable energy, he became Postdoctoral in Solar Energy Research Institute (SERI) UKM up to 2013. He joined the SERI as a Lecture in 2014. More than USD 310,000 research grant (15 grant/ project) in 2014-2017 was involved. More than 25 M.Sc project supervised and completed. Until now, he managed to supervise 5 Ph.D (4 main supervisors and 1 Co. supervisor), 3 Master's student by research mode, and 5 Master's student by coursework mode, he was also as examiner (3 Ph.D and 1 M.Sc). His current research focuses on renewable energy, especially solar energy technology, micropower system, solar drying systems, and advanced solar thermal systems (solar assisted drying, solar heat pump, PVT

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Mariyam Fazleena Musthafa, M.Sc from Maldives. She graduated with the M.Sc (2017) in Energy Technology from Universiti Kebangsaan Malaysia (UKM), Malaysia. The M.Sc dissertation was about the Exergy Analysis of Photovoltaic Thermal (PVT) Air Collector. Her M.Sc thesis under supervisor by Ahmad Fudholi, Ph.D. Upon graduation her current research focuses on solar energy technology.



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Dr Majid Khan joined the School of Mathematical Sciences, USM, as a lecturer (Operational Research) in May, 2017. He is a researcher and appointed fellow working in the field of seaweed cultivation, solar drying systems, processing, modelling and simulation. His research uses application of IoT, big data and simulation methods to improve model predictions of moisture losses during drying in control and uncontrolled environment. He is also interested in modelling the problems in engineering and other biological systems such as tissue culture and aquamarine. He uses the techniques from statistical theory, approach and existing application tools to develop mathematical model and finally to transform the model in industry application and to answer a range of inspired questions.



Prof Dato' Dr. Kamaruzzaman Sopian graduated with the BS Mechanical Engineering from the University of Wisconsin-Madison in 1985, the MS in Energy Resources University of Pittsburgh in 1989 and PhD in Mechanical Engineering from the Dorgan Solar Laboratory, University of Miami at Coral Gables in 1997. He has been involved in the field of renewable energy for more than 25-years. He has secure research funding from the Malaysian Ministry of Science and Malaysian Ministry of Education and industry for more than USD 6 million. He has conducted renewable energy courses the Asian School of Energy (2007-2014) funded by ISESCO, COMSAT, TIKa and UNESCO. He has published over 800 research papers in journals and conferences (SCOPUS h index = 53, no. of citation = 9386) (Google Scholar h index = 64, no. of citation = 15531). A total of 32 MSc (coursework), 15 MSc (research mode) and 50 PhD candidates from various countries. He has undertaken short assignments in about 10 countries for international agencies and programs such as UNDP-GEF, UNIDO, ASEAN EU-Energy Facility, ASEAN-Australia Economic Co-operation Program, ASEAN-CIDA, JSPS-VCC, British Council CHICHE, ISESCO and UNESCO related to renewable energy technology. He has been appointed as the Honorary Professor of Renewable Energy, at University of Nottingham, United Kingdom (2009-2013). In addition, he has been appointed as the associate editors in high impact journals. He won several international awards for his academic contribution in renewable energy including the IDB (Islamic Development Bank) S&T Prize 2013, World Renewable Energy Network Pioneer Award 2012, Malaysia Green Technology Award 2012, and the ASEAN Energy Awards (2005, 2007, 2013 and 2014). He has 4 patents, 20 patents pending, 6 copyrights, and 1 trademark for his innovation in renewable energy technology. The innovation and invention in renewable energy technology have won 80 medals in national and international innovation and invention competitions including special innovation awards such as Prix de L'Environnement by the Swiss Society for Environmental Protection, 2001, Geneva, Sustainable Development Award INNOVA 2007, Special Prize, Korea Invention Promotion Association at the INPEX Pittsburgh 2008 and Energy and Environmental Award, at INNOVA 2013 in Brussels. His Royal Highness The Sultan of Perak conferred the Paduka Mahkota Perak and the Dato' Paduka Mahkota Perak in 2013. He was conferred as a Fellow of the Malaysia Academy of Sciences (FASc) in 2011.